MDPI

Climate Change and Environmental Sustainability

Volume 6

Edited by

Baojie He, Ayyoob Sharifi, Chi Feng and Jun Yang

Printed Edition of the Topics Published in *Atmosphere, Buildings, Land, Remote Sensing and Sustainability*

www.mdpi.com/topics

Climate Change and Environmental Sustainability-Volume 6

Climate Change and Environmental Sustainability-Volume 6

Editors

Baojie He
Ayyoob Sharifi
Chi Feng
Jun Yang

MDPI • Basel • Beijing • Wuhan • Barcelona • Belgrade • Manchester • Tokyo • Cluj • Tianjin

Editors
Baojie He
Chongqing University
China

Ayyoob Sharifi
Hiroshima University
China

Chi Feng
Chongqing University
China

Jun Yang
Northeastern University
China

Editorial Office
MDPI
St. Alban-Anlage 66
4052 Basel, Switzerland

This is a reprint of articles from the Special Issue published online in the open access journal *Sustainability* (ISSN 2071-1050) (available at: https://www.mdpi.com/topics/Climate_Environmental).

For citation purposes, cite each article independently as indicated on the article page online and as indicated below:

LastName, A.A.; LastName, B.B.; LastName, C.C. Article Title. *Journal Name* **Year**, *Volume Number*, Page Range.

ISBN 978-3-0365-4539-4 (Hbk)
ISBN 978-3-0365-4540-0 (PDF)
194 k words

Cover image courtesy of Baojie He

Contents

About the Editors

Baojie He

Dr. Baojie He is a Research Professor of Urban Climate and Built Environment at the School of Architecture and Urban Planning, Chongqing University, China. Prior to joining Chongqing University, Baojie He was a PhD researcher at the Faculty of Built Environment, University of New South Wales, Australia. Baojie is working on the Cool Cities and Communities and Net Zero Carbon Built Environment project. Baojie has strong academic capability and has published around 80 peer-reviewed papers in high-ranking journals and given oral presentations at reputable conferences. Baojie acts as the Topic Editor-in-Chief, Leading Guest Editor, Associate Editor, Editorial Board Member, Conference Chair, Sessional Chair, and Scientific Committee of a variety of international journals and conferences. Dr. He received the Young Investigator Award (MDPI Sustainability) in 2022, Green Talents Award (Germany) in 2021 and National Scholarship for Outstanding Self-Funded Foreign Students (China) in 2019. Dr. He was ranked as one of the 100,000 global scientists (both single-year and career top 2%) by the Mendeley, 2021.

Ayyoob Sharifi

Prof. Dr. Ayyoob Sharifi works at the Graduate School of Humanities and Social Sciences, Hiroshima University. He also has a cross-appointment at the Graduate School of Advanced Science and Engineering. Ayyoob's research is mainly at the interface of urbanism and climate change mitigation and adaptation. He actively contributes to global climate change research programs such as the Future Earth and is currently serving as a lead author for the Sixth Assessment Report (AR6) of the Intergovernmental Panel on Climate Change (IPCC). Before joining Hiroshima University, he was the Executive Director of the Global Carbon Project (GCP)—a Future Earth core project—leading the urban flagship activity of the project, which is focused on conducting cutting-edge research to support climate change mitigation and adaptation in cities.

Chi Feng

Prof. Chi Feng received his joint PhD training in South China University of Technology (China) and KU Leuven (Belgium). He is now a research professor in the School of Architecture and Urban Planning, Chongqing University (China) and is leading a research group of more than 10 members. His research topics cover coupled heat and moisture transfer in porous building materials, as well as the hygrothermal performance of building envelopes and built environments. He has led eight international and national research projects, including the China–Europe round robin campaign on material property determination (nine countries participated), the National Natural Science Foundation of China, and the National Key R&D Program of China. He has published more than 60 peer-reviewed journal/conference papers at home and abroad. He is drafting two Chinese standards and participating in another nine international/national ones.

Jun Yang

Prof. Dr. Jun Yang is working at the Urban Climate and Human Settlements Lab, Northeastern University (Shenyang China). His research expertise involves urban climate zones, urban ecology, urban human settlements, and sustainability. As PI or Co-PI, he has been involved in 50 research projects, receiving a total of 15 million RMB from EGOV.CN (e.g., NFC, MOST, and MOE) since 2002. He has authored and co-authored more than 160 papers and book chapters and published more than 50 English papers and more than 110 Chinese papers in academic journals. He is now the Associate Editor of the *Social Sciences* section of the *International Journal of Environmental Science and Technology*, sits on the Editorial Board of *PLOS One*, *PLOS Climate*, and *Frontiers in Built Environment*, is a Lead Guest Editor of *Complexity*, and a Guest Editor of *IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing*.

Preface to "Climate Change and Environmental Sustainability-Volume 6"

The Earth's climate is changing; the global average temperature is estimated to already be about 1.1 °C above pre-industrial levels. Indeed, we are now living in conditions of a climate emergency. Climate change leads to many adverse events, such as extreme heat, flooding, bushfire, drought, and many other associated economic and social consequences. Further warming is projected to occur in the coming decades, and climate-induced impacts may exceed the capacity of society to cope and adaptive in a 1.5 °C or 2 °C world. Therefore, urgent actions should be taken to address climate change and avoid irreversible environmental damages.

Climate change is interrelated with many other challenges such as urbanisation, population increase and economic growth. For instance, cities are now the main settlements of human being and are major sources of greenhouse gas emissions that are key contributors to climate change. Moreover, rapid and unregulated urbanisation in some contexts further causes urban problems such as environmental pollution, traffic congestion, urban flooding and heat island intensification. In the absence of well-designed measures, increasing urbanisation trends in the next two–three decades are likely to further aggravate such problems. Overall, climate change and many other challenges have deteriorated the sustainable development of the world.

The United Nations proposed the Sustainable Development Goals in 2015. Goal 13, Climate Action, emphasises the need for urgent action to combat climate change and its impacts in order to enhance sustainability. To achieve this, there is a need to develop a holistic framework that considers mitigation—the decarbonisation of society—to address the challenge of climate change from the root, and adaptation—an immediate action—to increase the resilience of and protect society from climate-induced hazards. The framework prioritises the transformation of the traditional methods of environmental modifications in various fields, including transportation, industry, building, energy generation, agriculture, land use and forestry, towards sustainable ones to limit greenhouse gas emissions. The framework also highlights the significance of sustainable environmental planning and design for adaptation in order to reduce climate-induced threats and risks. Moreover, it encourages the involvement and participation of all stakeholders to accelerate climate change mitigation and adaptation progress by developing sound climate-related governance systems.

The framework also calls for the support and engagement of all societal stakeholders. To support the achievement and implementation of the framework, this book focuses on climate change and environmental sustainability by covering four key aspects, including climate change mitigation and adaptation, sustainable urban–rural planning and design, decarbonisation of the built environment in addition to climate-related governance and challenges. Climate change mitigation and adaptation covers topics of greenhouse gas emissions and measurement, climate-related disasters and reduction, risk and vulnerability assessment and visualisation, impacts of climate change on health and well-being, ecosystem services and carbon sequestration, sustainable transport and climate change mitigation and adaptation, sustainable building and construction, industry decarbonisation and economic growth, renewable and clean energy potential and implementation in addition to environmental, economic and social benefits of climate change mitigation.

Sustainable urban–rural planning and design deals with questions of climate change and regional economic development, territorial spatial planning and carbon neutrality, urban overheating mitigation and adaptation, water-sensitive urban design, smart development for urban habitats, sustainable land use and planning, low-carbon cities and communities, wind-sensitive urban planning and design, nature-based solutions, urban morphology and environmental performance in addition to innovative technologies, models, methods and tools for spatial planning. Decarbonisation of the built environment addresses issues of climate-related impacts on the built environment, the health and well-being of occupants, demands on energy, materials and water, assessment methods, systems and tools, sustainable energy, materials and water systems, energy-efficient design technologies and appliances, smart technology and sustainable operation, the uptake and integration of clean energy, innovative materials for carbon reduction and environmental regulation, building demolition and material recycling and reusing in addition to sustainable building retrofitting and assessment. Climate-related governance and challenges concerns problems of targets, pathways and roadmaps towards carbon neutrality, pathways for climate resilience and future sustainability, challenges, opportunities and solutions for climate resilience, the development and challenges climate change governance coalitions (networks), co-benefits and synergies between adaptation and mitigation measures, conflicts and trade-offs between adaptation and mitigation measures, mapping, accounting and trading carbon emissions, governance models, policies, regulations and programs, financing urban climate change mitigation, education, policy and advocacy of climate change mitigation and adaptation in addition to the impacts and lessons of COVID-19 and similar crises.

Overall, this book aims to introduce innovative systems, ideas, pathways, solutions, strategies, technologies, pilot cases and exemplars that are relevant to measuring and assessing the impact of climate change, mitigation and adaptation strategies and techniques in addition to public participation and governance. The outcomes of this book are expected to support decision makers and stakeholders to address climate change and promote environmental sustainability. Lastly, this book aims to provide support for the implementation of the United Nations Sustainable Development Goals and carbon neutrality in efforts aimed at achieving a more resilient, liveable and sustainable future.

This volume of Climate Change and Environmental Sustainability covers topics on green finance and investment, collaboration building and public engagement, and industry governance towards carbon neutrality and environmental sustainability. First, it presents issues related to embodied carbon in the international trade, impacts of the green finance system on carbon emissions, the implementation of green deal strategies, linkage between foreign direct investment and carbon emissions, and the implications of COVID-19 for decarbonisation actions. Following such critical problems, theoretical conceptualisation of new green deals, international research team collaboration for sustainability, nature conservation communication in social networks, and the efficiency of environmental policies in emission reduction are discussed. Next, close attention is paid to various industries, including agriculture, tourism, and manufacturing, by analysing topics relevant to the impacts of climate-related factors, assessment indicator systems or appraisal systems, and value chain systems. In addition, the book also presents disaster risk mapping studies for assessing vulnerability, best practices of risk management, and cases on environment-induced impacts on health. Results reported in this book are conducive to a better understanding of green finance and investment regimes, community engagement, and industry sustainability. We expect the book to benefit decision-makers, practitioners, and researchers in different fields and contribute to carbon neutrality and economic growth.

Prof. Baojie He acknowledges Project NO. 2021CDJQY-004, supported by the Fundamental Research Funds for the Central Universities. We appreciate the assistance from Mr. Lifeng Xiong, Mr. Wei Wang, Ms. Xueke Chen, and Ms. Anxian Chen at the School of Architecture and Urban Planning, Chongqing University, China.

Baojie He, Ayyoob Sharifi, Chi Feng, and Jun Yang
Editors

sustainability

MDPI

Article

Can Green Finance Development Reduce Carbon Emissions? Empirical Evidence from 30 Chinese Provinces

Xi Chen [1,2] and Zhigang Chen [1,2,*]

[1] Institute of Central China Development, Wuhan University, Wuhan 430072, China; 2019106320002@whu.edu.cn
[2] Institute of Regional and Urban-Rural Development, Wuhan University, Wuhan 430072, China
* Correspondence: czgangzc@whu.edu.cn

Abstract: Dealing with the relationship between environment and economic development is the core issue of China's sustainable development. At present, China's economic transformation is urgent, and green finance is being widely concerned. This paper measured the development level of China's green finance from the perspective of green credit, green securities, green investment, and green insurance. Then, it used a spatial dynamic panel model to empirically test the mechanism of the impact of green finance on carbon emissions with panel data of 30 Chinese provinces from 2005 to 2018. The following can be seen from the results: (1) The development of green finance contributes to carbon emission reduction. (2) The spatial spillover effect of green finance is significant. Specifically, the development of green finance can not only reduce the carbon emissions of the local region but also inhibit that of adjacent areas. (3) The development of green finance indirectly leads to a decrease in carbon emissions by reducing financing constraints and boosting green technology innovation. In order to stimulate the carbon emission reduction effect of green finance to a greater extent, we should further support the development of green finance, reduce the financing constraints of energy-saving and environmental-protection enterprises, and encourage the research and development of green innovative technologies.

Keywords: green finance; carbon emission; spatial spillover effect; mediating effect; China

Citation: Chen, X.; Chen, Z. Can Green Finance Development Reduce Carbon Emissions? Empirical Evidence from 30 Chinese Provinces. *Sustainability* **2021**, *13*, 12137. https://doi.org/10.3390/su132112137

Academic Editors: Baojie He, Ayyoob Sharifi, Chi Feng and Jun Yang

Received: 27 September 2021
Accepted: 29 October 2021
Published: 3 November 2021

1. Introduction

Since the industrial revolution, the economies of all countries in the world have grown rapidly [1]. However, increased environmental problems such as global warming and sea-level rise, caused by economic development, have seriously threatened human health and social development. Based on this, the developed countries earlier in industrialization actively carried out financial innovation to reduce environmental pollution [2]. Meanwhile, they have provided valuable experience for the construction of green financial systems [3]. Since then, scholars have linked resource and environmental issues with economic development. They further explored how to incorporate environmental factors into financial decision making to achieve the sustainable development of economy and environment [4]. In this context, the concept of green finance came into being. Green finance refers to economic activities that could utilize resources efficiently, mitigate climate change, and support environmental improvement [5]. Through the rational allocation of financial resources, green finance aims to guide industrial enterprises to use less resources and energy to achieve more economic and ecological benefits [6]. Thereby, we should promote the development of green finance and guide more capital to flow into green industries to enhance the sustainability of economic growth [7].

For China, serious environmental problems have come simultaneously with rapid economic growth [8]. From Figure 1, we find that China's carbon emissions in 2019 exceeded the total emissions of OCED countries [9]. Therefore, environmental governance is urgent. Then, in 2020, the Chinese government announced during the 75th United

Nations General Assembly that its carbon emissions would reach a peak before 2030, and it would achieve the goal of "carbon neutrality" by 2060 [10]. Compared with the United States, Europe, and other developed countries, China has had a difficult time reaching its peak of carbon emissions and achieving its goal of carbon neutrality. It requires a systematic change involving the R&D of green technologies, the transformation of industries, and a low-carbon lifestyle [11]. Related calculations show that China needs hundreds of billions of yuan of green and low-carbon investment to achieve the "30·60" target [12]. In addition to government funding, most of the funds need to be obtained by market-oriented methods. The development of green finance can encourage more "greener" social capital into the financial system [13]. Therefore, it is particularly essential to limit greenhouse gas emissions through a green financial system, which will provide the investment and financing support needed to transform high-pollution enterprises.

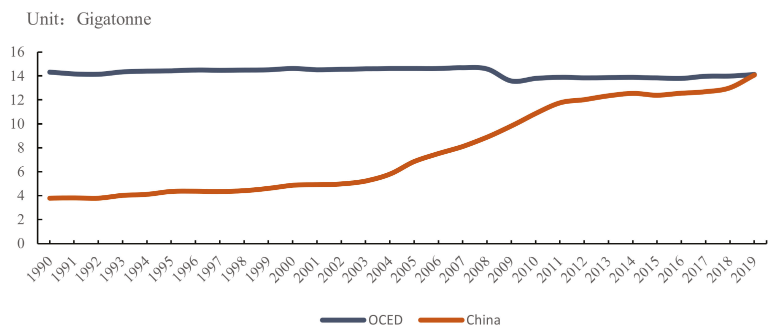


Figure 1. Carbon emissions of China and OCED countries from 1990 to 2019.

Recently, the Chinese government had carried out a series of green financial policies at the national level, which has sent a signal that "the country is taking action to develop green economy vigorously" [14]. So, what impact will the development of green finance have on China's carbon emission intensity? While promoting the return on investment of green projects and improving the availability of financing, can the diversified green financial policies of Chinese government inhibit the investment in polluting projects and reduce carbon emissions?

This paper answered the above questions through basic facts, theoretical analysis, and empirical tests. The marginal contributions are from the following three aspects: (1) We used a comprehensive index system to measure the development level of green finance rather than a single index, since China's green financial system is developing rapidly, involving securities, insurance, credit, and other fields [15]. According to the framework of green finance development in China, green credit, green securities, green investment, and green insurance are taken as the four indicators in this paper to measure the development level of green finance in Chinese 30 provinces. (2) Compared with ordinary panel regression, spatial econometrics can reduce the estimation error caused by ignoring the spatial correlation among variables. It will overcome the assumption that the traditional econometric model ignores spatial correlation among variables [16]. Therefore, we empirically analyzed the impact of green finance development on carbon emissions with a spatial measurement model. (3) This paper used the mediating effect model to examine the transmission mechanism between carbon emissions and green finance. The results obtained herein are helpful for more accurate understanding of the implementation effects of China's green finance policies. Furthermore, it also provided theoretical guidance and policy recommendations for China to realize a low-carbon-recycling economy.

2. Literature Review

2.1. Financial Development and Carbon Emission

Existing literature holds that the effect of financial development on environmental pollution has two sides. On one side, it fits the view that financial development will increase carbon emissions. Firstly, the improvement of financial development stimulates investment growth by alleviating the financing constraints of enterprises, thereby expanding the economic scale and energy consumption and further increasing carbon emissions. For example, Sadorsky (2010) [17] found that financial development made it easier to obtain credit, stimulating consumers to purchase energy-intensive products such as cars, air conditioners, and refrigerators, increasing regional carbon emissions. Secondly, financial development can reduce financing constraints and the production costs of enterprises. It also promotes enterprises to purchase large-scale equipment and build new production lines to expand their production scale, which will inevitably increase carbon emissions. However, another side holds the view that financial development will reduce carbon emissions. With the improvement of finance, sufficient R&D funds can provide financial support for researching clean technologies, guiding the transformation of the energy consumption structure of high-consumption enterprises, which will decrease carbon emissions [18]. Meanwhile, Tamazian et al. (2009) [19], Jalil and Feridun (2011) [20], and Gu et al. (2012) [21], based on data from other countries, have found a similar conclusion that carbon emission was inhibited by financial development using different methods.

2.2. Green Financial Development and Carbon Emission

In the early stage, scholars mainly focused on the definition of green finance, including connotation, functional, development paths, and the important role of green finance in bank risk control, pollution treatment, and green economic development in developing countries [22]. Relevant studies have shown that green finance raises the loan threshold for high-emission and high-pollution activities. It also provides low-carbon industries with low-interest rates to meet their financing needs, which is conducive to the rapid growth of low-carbon sectors [23]. For example, Xiu et al. (2015) [24] built a non-linear threshold panel model. They found that green credit policies contribute significantly to emission reduction and energy saving under the constraints of industrial growth. Liu et al. (2017) [25] constructed a financial CGE model and found that green credit policies effectively curb investment in energy-intensive industries. In brief, the improvement of green finance can alleviate the financing constraints of enterprises in environmental protection, new energy, new materials, etc., and help provide more low-carbon products or services to support the development of environment-friendly enterprises [26]. What is more, it will reduce the capital supply to high-pollution and high-emission enterprises, forcing them to carry out technological transformation and upgrading, or reducing the scale of production to reduce carbon emissions [27].

2.3. Summary

To sum up, scholars have carried out many research studies on the relationship between green financial development and environmental pollution. However, there are still some shortcomings: (1) Existing research usually adopted a single green credit measuring green finance. However, according to the connotation of green finance, green credit is the most important part of green finance [28]. Furthermore, green investment, green insurance, and green securities are equally crucial parts of green finance [29]. (2) Existing research has mostly studied the relation between green finance development and environmental pollution in China from a horizontal perspective, thus ignoring the spatial spillover effect [30]. However, whether it is green finance or environmental pollution, the provinces are not independent of each other. Taking carbon emission as an example, due to geographical proximity and the pollution flow between provinces, environmental pollution has spatial spillovers [31]. If the empirical research neglects pollutants outside the provinces through environmental media, the results will be biased. (3) Most research only focused on the direct impact of green finance on carbon emissions, but it did not reveal the internal mechanism of the impact of green finance on carbon emissions, which needs to be further expanded [32].

3. Theoretical Hypotheses

From a theoretical perspective, green finance can penetrate environmental protection into the entire industrial development system through the three mechanisms of funding: orientation, policy guidance, and risk sharing [33].

Funding-oriented mechanism. Banks, acting as depository institutions for social capital, can achieve large-scale capital concentration in a short period. Following the principle of "differentiated treatment", green finance uses financial tools to increase the financing constraints of high-polluting enterprises and guide capital inflow to low-energy, low-emission, and low-polluting industries [34]. Meanwhile, it is also leading more funds into green industries, forcing the transformation and upgrading of high-polluting enterprises, which all have positive impacts on carbon emission reduction [35].

Policy guidance mechanism. "Accelerate the development of green finance" is a national-level fiscal policy of China, which is destined to have broad and strategic prospects [36]. Hence, green finance policies can support the development of green industries through government procurement, financial support, tax reduction, fee reduction, etc. What is more, it will ultimately guide the improvement and attainment of a greener industrial structure. Therefore, the financing cost of the environmental protection industry will be much lower than that of the high-pollution manufacturing industry, thus boosting the profitability and competition of the environment-friendly industries [37]. Furthermore, with the resources from national policies, it will effectively reduce carbon emissions as well as speed up the transformation and improvement of high-pollution industrial structures.

Risk-sharing mechanism. Due to its ecological and environmental benefits, green projects usually have the characteristics of significant capital demand and slow recovery [38]. Therefore, green financial institutions can rely on professional risk identification and control capabilities to conduct comprehensive risk management for supporting green projects. It will force enterprises to consider ecological and environmental factors in production and operation activities, and it can reduce social risks caused by climate change, environmental pollution, and other environmental damage [39].

Accordingly, the development of green finance can lead more funds to flow into low-carbon industries, provide more financing and investment opportunities, and enable the environmental protection industry to have further development. The high-pollution industries will be punished by high interest rates when lending, which may act as a "warning effect" on other high-pollution companies. Therefore, the development of green finance will not only reduce local carbon emissions but also reduce those of the surrounding areas [38].

A flow chart of theoretical analysis is shown in Figure 2. The first hypothesis is put forward here on this basis:

Hypothesis 1. *The development of green finance is conducive to reducing carbon emissions.*

The development of green finance can affect carbon emissions through financing constraints. Firstly, the implementation of green finance provides loan support to environmental-friendly companies with preferential low interest rates. However, it will change the financing costs of pollution enterprises through the restriction of loan amount and the punitive high interest rates, thereby forcing enterprises to cleaner production [40]. Secondly, the development of green finance makes companies invest with low environmental risks to avoid financing constraints brought by environmental regulation. More importantly, it gives more impetus to low-carbon environmental protection industries, thus contributing to the reduction of carbon emission.

At the same time, the development of green finance affects carbon emission by stimulating green technological innovation. On one hand, "green technology" is increasingly demanded when green finance is widely developed [41]. In the carbon emission background in China, most high-polluting and high-emission companies have generated colossal market demand for environmental protection technologies. On the other hand, green financial development can stimulate enterprises' willingness to innovate independently. What is more, it will increase R&D investment in low-energy, high-value-added industries, further forcing polluting companies to adopt cleaner technologies to reduce carbon emissions.

Accordingly, Hypothesis 2 is proposed:

Hypothesis 2. *The development of green finance may affect carbon emissions through transmission channels such as financing constraints and green technology innovation.*

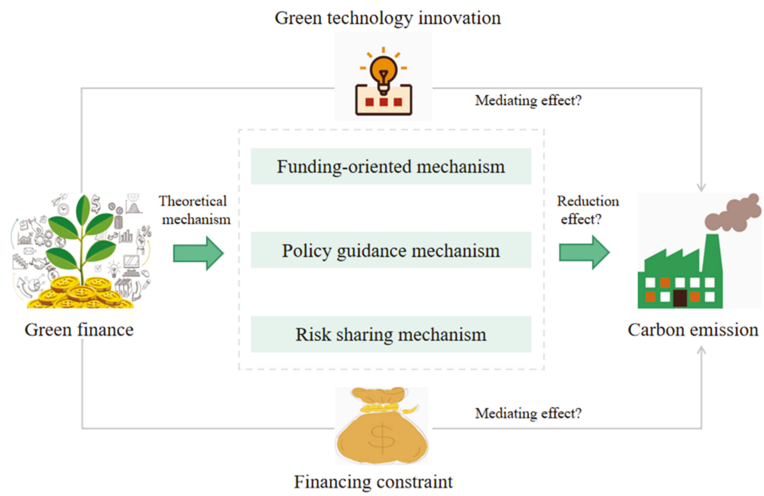


Figure 2. Flow chart of theoretical analysis.

4. Empirical Model and Data Explanation

4.1. Spatial Econometric Model

The spatial econometric model integrates the influence of region, location, and space, and it believes that there will be a spatial dependence relationship between variables in different regions [42]. Under the influence of industrial transfer, atmospheric flow, and other similar natural and economic activities, carbon emissions may have a strong spatial correlation among regions [43]. As shown in $C_{it} = E_{it} + S_{jt} - S_{it}$, there are three parts in the sources of carbon emission in a region. In this equation, C stands for the measurement of carbon emissions; i stands for cross-section unit; t stands for the year; E_i stands for the amount of carbon emission produced in local region i; S_j stands for the amount of carbon emission diffused from surrounding areas to region i; S_i stands for the region's carbon emission diffused to other regions. In accordance with the theory of spatial econometrics, $S_{jt} - S_{it}$ reflects the "contributions" of surrounding areas to the local region's carbon emissions and represents the spatial dependence between regions. It can be expressed as the spatial error characteristic ($S_{jt} - S_{it} = \mu_{it} = \lambda\rho\sum_j w_{ij}\mu_{it} + \varepsilon_{it}$) or the current spatial dependence ($S_{jt} - S_{it} = \rho\sum_j w_{ij}C_{jt}$).

There are three types of spatial econometric models: the spatial lag model (SAR), spatial error model (SEM), and spatial Durbin model (SDM). The SDM integrates the characteristics of the SAR and the SEM, and the intensity of the influence of adjacent spatial units is represented by the spatial weight matrix [44]. Therefore, green finance (*Gfin*) is introduced into the model, where Formula (1) is the spatial lag form (SAR) and Formula (2) is the spatial error form (SEM):

$$C_{it} = \alpha_0 + \alpha_1 Gfin_{it} + \alpha_2 X_{it} + \rho \sum_j w_{ij} C_{jt} + u_{it} \tag{1}$$

$$C_{it} = \beta_0 + \beta_1 Gfin_{it} + \beta_2 X_{it} + \lambda \sum_j w_{ij} \mu_{it} + \phi_{it} \tag{2}$$

where α and β are coefficient vectors; X denotes a series of control variables; $\phi_{it} = \varepsilon_{it} + u_{it}$, ε_{it}, and u_{it} are the perturbation terms with normal distribution; λ is the coefficient of the spatial error term; and ρ is the spatial lag coefficient, respectively. Relatively speaking, the spatial Durbin model (SDM) can comprehensively express the characteristics of the spatial lag model and the spatial error model [45], and its manifestation is as follows:

$$C_{it} = \delta_0 + \delta_1 \mathrm{Gfin}_{it} + \delta_2 X_{it} + \rho_1 \sum_j w_{ij} C_{jt} + \rho_2 \sum_j w_{ij} \mathrm{Gfin}_{jt} + \rho_3 \sum_j w_{ij} X + u_{it}. \tag{3}$$

Among them, δ is the coefficient vector. Since the environmental pollution variables have the characteristic of path dependence [46], the environmental pollution level of the previous period will have a greater impact on the current period. Therefore, this paper introduces the lag phase of carbon emissions into Equation (3), constructing the dynamic SDM model as follows:

$$C_{it} = \delta_0 + \delta_1 \mathrm{Gfin}_{it} + \delta_2 X_{it} + \delta_3 C_{i,t-1} + \rho_1 \sum_j w_{ij} C_{jt} + \rho_2 \sum_j w_{ij} \mathrm{Gfin}_{jt} + \rho_3 \sum_j w_{ij} X + u_{it}. \tag{4}$$

Obviously, the time and space lag effect of carbon emission can be comprehensively reflected by the dynamic spatial panel from the time dimension and the space dimension, thus leading to a more robust estimation result. This paper constructs a geographical distance weight (W1) in accordance with the geographical distance between provinces in China to reveal the impact of geographical factors on carbon emission. In addition, the economic distance weight (W2) in China is constructed by the GDP of each province, and it reflects the impact of economic factors on carbon emission.

4.2. Description of Variables

4.2.1. Explained Variable: Carbon Emission (C)

The method of IPCC (2006) [47] is adopted to measure the amount of carbon emission of Chinese 30 provinces, which is an internationally recognized carbon emission calculation method. The data of energy comes from the "China Energy Statistical Yearbook", and the amount of carbon emission is calculated according to the following formula:

$$C_{it} = \sum_i E_i \times CF_i \times CC_i \times COF_i \times \frac{44}{12}. \tag{5}$$

Among them, E_i represents fossil energy consumption, CF_i is the low calorific value, CC_i is the carbon content per unit of heat, COF_i is the oxidation rate of energy, and 44/12 is the mass ratio of carbon dioxide molecules to carbon atoms.

We use acrgis software to draw the 2005 and 2018 distribution maps of carbon emission in China (Figure 3). It can be found that carbon emissions were increasing from 2005 to 2018 in various Chinese regions, and there was an obvious spatial correlation between provinces. Compared with the central and western regions, the eastern region has a much higher level of carbon emission. Therefore, a spatial econometric model can be used to measure the impact of green finance on carbon emission.

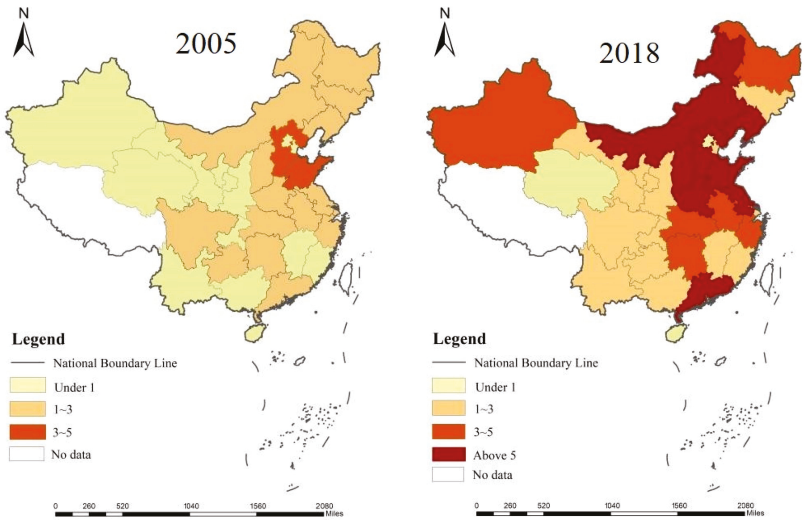


Figure 3. Carbon emission distribution map 2005 and 2018.

4.2.2. Core Explanatory Variable: Green Finance Development (GFin)

The Chinese Green Finance Professional Committee proposed four dimensions of green finance: green credit, green securities, green investment, and green insurance. As a typical bank-dominated country, China is mainly driven by commercial banks, where green credit is the core content of green finance. This paper used the available data of six high energy-consuming industries and the ratio of interest expenditure to total industrial interest expenditure as a reverse index to measure green credit [48]. Green investment promotes the treatment of environmental pollution. This paper applied the ratio of expenditure on environmental pollution to GDP to measure green investment. Compared with bank loans, insurance funds are long-term capital, which is in line with the long-term financing and investment needs of green projects. However, agricultural production is a major source of carbon emissions [49]. Therefore, this paper used agricultural insurance scale and loss ratio to measure the depth of green insurance. The scale of environmentally friendly companies can be measured by green securities to some extent, so the market value of environmentally friendly companies is used to measure green securities in this paper [50]. In summary, this paper gave weight by the entropy method, and the index system of green finance development is shown in Table 1.

Table 1. Green finance development index system.

	Index	Index Description
Green credit	Proportion of interest expense of high-energy consumption industry	Interest expense of six high-energy consuming industries/total industrial interest expense
Green securities	Proportion of market value of environmental protection enterprises	Market value of environmental protection enterprises/total market value of listed companies
Green investment	Proportion of investment in environmental pollution control in GDP	Investment in environmental pollution control/GDP
Green insurance	Proportion of agricultural insurance scale	Agricultural insurance expenditure/total insurance expenditure
	Agricultural insurance loss ratio	Agricultural insurance expenditure/agricultural insurance income

4.2.3. Control Variables

As a serious environmental problem, carbon emission results from many aspects of economic and social development. Therefore, this paper introduced the economic development level, energy structure, industrial structure, openness, and urbanization level into the model to control their impacts on carbon emission. The reasons for the selection of control variables are as follows:

(1) Economic development level (Pgdp): In terms of per-capita GDP, its primary and secondary terms are introduced into the model in accordance with the EKC hypothesis to explore whether economic growth and carbon emissions have an inverted U-shaped relationship [51]. (2) Energy structure (Estru): The burning of fossil energy is a major source of carbon emissions. Obviously, the higher the proportion of fossil energy, the less conducive it is to carbon emission reduction [52]. (3) Industrial structure (Indu): Industrial production is another primary source of carbon emissions. The higher level of industrial structure, the less conducive it is to reducing carbon emissions [53]. (4) Opening up (Open): Developed countries usually have more serious environmental pollution control policies, which will correspondingly increase the production costs of polluting enterprises. On the contrary, developing countries usually have more relaxed environmental regulations, and they are more inclined to absorb the transfer of high-polluting industries from developed countries, which is not conducive to environmental governance [54]. (5) Urbanization level (City): The development of urbanization may also cause more energy consumption and environmental pollution, which is not conducive to carbon emission reduction.

4.2.4. Mediating Variable

Financing constraints (Fcon): Companies with poor financing channels will be subject to financing constraints. Most of these companies show insufficient internal funds, debt financing, equity financing, etc., which is not conducive to obtaining more "green" capital support. Furthermore, it will adverse to carbon emission reduction. Thus, this paper refers to the cash flow sensitivity model [55] to calculate the degree of financing constraints on companies. We used the regional level to match the corporate data of listed companies.

Green technology innovation (Gtech): The number of green patent applications in each province is adopted to express the level of green technology innovation. The development of green finance will support the enterprise to make more effort to explore environmental protection technologies, which help reduce an enterprise's innovation risk and thereby reduce carbon emissions.

4.3. Data Source

Table 2 gives the description of each variable and its data source.

Table 2. Data selection and description.

Variable	Index Selection	Sign	Description	Data Source
Dependent variable	Carbon emission	C	Calculated based on Formula (1)	China Energy Statistics Yearbook (2006–2019) China Financial Statistics Yearbook (2006–2019)
Core independent variable	Green finance	Gfin	The index system is constructed from the four dimensions of green credit, green insurance, green investment and green securities, and the weight is given by the entropy method	China Statistical Yearbook (2006–2019) China Insurance Statistical Yearbook (2006–2019) Wind database CSMAR database Flush Ifind database

Table 2. *Cont.*

Variable	Index Selection	Sign	Description	Data Source
Control variable	Economic development	Pgdp	Per-capita GDP	China Energy Statistics Yearbook (2006–2019) China Statistical Yearbook (2006–2019)
	Energy resource structure	Estru	Proportion of coal consumption in energy consumption	
	Openness	Open	Total import and export/GDP	
	Industrial structure	Instu	Industrial added value/GDP	
	Urbanization	City	Urban population/total population	
Mediating variable	Financing constraints	Fcon	Calculated by cash flow sensitivity model	Wind database
	Green technology innovation	Gtech	Number of green patent applications	Wind database

5. Empirical Regression

5.1. Impact of Green Finance Development on Carbon Emission

5.1.1. Selection of Spatial Econometric Model

The LM test and LR test are applied to identify the form of the spatial econometric model. According to Elhorst (2014) [45], if LM-lag and LR-lag are both significant at 1%, as well as the LR-error and LR-error test, we should choose spatial Durbin model (SDM) for empirical analysis.

Table 3 presents the LR and LM test results based on W1 and W2. It can be found that the LM and LR test results of both static and dynamic spatial models pass the significance test. Hence, this paper chose the SDM model to explore the impact of green finance on carbon emissions.

Table 3. LR test and LM test in spatial model.

Model	Static Spatial Model		Dynamic Spatial Model	
W	W1	W2	W1	W2
LR-lag	132.78 ***	135.40 ***	110.59 ***	112.49 ***
LR-error	101.35 ***	98.56 ***	82.23 ***	78.90 ***
LM-lag	167.87 ***	168.45 ***	231.25 ***	227.82 ***
LM-error	186.12 ***	194.62 ***	276.77 ***	287.90 ***

Note: *** represent the significance levels of 1%.

5.1.2. Benchmark Regression Test

In this paper, a panel regression model (OLS) and dynamic panel regression model (GMM) without considering spatial factors are firstly used to test the impact of green finance development on carbon emission, respectively. Then, the static SDM and dynamic SDM model, considering spatial factors, are also used for empirical analysis. Table 4 gives the results of benchmark regression tests. Firstly, the development of green finance can significantly reduce the carbon emissions under the four types of models. Secondly, from the significance of variables, the dynamic spatial Durbin model shows better statistical characteristics. This is because the carbon emissions of the local region are also affected by the surrounding areas. It also indicates that carbon emission, energy consumption, and economic activities between regions show obvious spatial autocorrelation. Hence, ignoring the spatial proximity effect in research may lead to estimation errors. In addition, due to human activities and economic behaviors occurring simultaneously in a certain space–time, we should consider the space–time dimension when conducting economic and social research. Therefore, the dynamic SDM model is the focus of the following discussion.

Table 4. Benchmark regression test.

Variable	OLS M1	GMM M2	Static SDM M3	Dynamic SDM M4
L.C		0.7456 ***		0.5591 ***
		(12.59)		(13.60)
Gfin	−1.3757 *	−1.0190 **	−1.7991 **	−0.9857 ***
	(−1.70)	(2.02)	(−1.98)	(−3.05)
Pgdp	0.4232	0.0421 **	1.1007 ***	0.2503 ***
	(1.10)	(2.13)	(2.83)	(5.66)
sPgdp	−0.0512 ***	−0.0142 *	−0.06975 ***	−0.0160 ***
	(−2.62)	(−1.93)	(−3.43)	(−3.82)
Estru	0.1539 **	0.3405 *	0.1001 **	0.0490 ***
	(2.68)	(1.65)	(2.23)	(6.30)
Indu	0.0527	0.0663 **	0.0337	0.0369 **
	(0.85)	(2.21)	(0.43)	(2.02)
Open	−0.0617 **	−0.0563 *	−0.0094	−0.0404 **
	(−2.23)	(−1.82)	(−0.39)	(−2.25)
City	0.0784	0.0238	0.1384 *	0.0813 ***
	(1.28)	(1.48)	(1.84)	(4.63)
Log			389.8303	834.7580
Rho			0.8819 ***	0.7625 ***
			(3.88)	(3.49)
R2	0.8527	0.8902	0.6103	0.9407
AR(2)		2.0232		
[P]		(0.3341)		
Sargan		156.38		
[P]		(0.9331)		
Obs	420	390	420	420

Note: ***, **, and * represent the significance levels of 1%, 5%, and 10% respectively.

Firstly, the spatial lag coefficient is at a 1% significance level under the setting of spatial weight (W1), which proves that China's provincial carbon emissions have significant spatial correlation. That is, regions with relatively high carbon emissions will gather together as will the regions with low carbon emissions. For example, in Figure 2, we can find that the carbon emissions in China's eastern regions are higher than those in China's central and western regions. This is because under the multiple factors of atmospheric circulation, industrial transfer, population migration, and other economic and natural factors, the carbon emissions of local area are inevitably affected by the surrounding regions. The time lag term of carbon emission (L.C) elasticity coefficient is 0.5591, which is significant at a 1% level. If the carbon emissions in the current period are at a high level, the amount of carbon emissions might continue to rise in the next period. It reveals the path dependence characteristics of carbon emissions for a specific region.

From the core explanatory variables (Gfin), −0.9857 is the value of the elasticity coefficient of green finance to carbon emission, which is significantly negative at a 1% level. It indicates that the development of green finance is conducive to reducing carbon emission. Thus, Hypothesis 1 is verified. As we know, the most basic function of the financial system is to gather and distribute funds. Therefore, green finance mainly forms the financial capital necessary for the development of green industry by collecting funds and guiding funds to industries with cleaner structures. It effectively reduces the cost of raising capital and makes it easier for green industry to have further development, thereby decreasing the proportion of high-polluting industries and carbon emissions. Meanwhile, green finance enables investors to take the potential environmental impacts into account when making investing and financing decisions. Capital can be ceaselessly poured into environment-friendly industries. Furthermore, green finance not only has an impact on producers, but it also enhance the consumption willingness of consumers to purchase more low-carbon products. In addition to the above theoretical analysis, the relevant data also prove that the development of green finance contributes to carbon emission reduction. According to relevant data, as of June 2017, China's green credit has reduced its emissions by 490 million tons of carbon dioxide. Therefore, China should further accelerate the development of green finance, improve China's green financial system, and strive to achieve China's 2030 carbon peak and 2060 carbon neutralization goals.

From the perspective of control variables, (1) the elastic coefficient of Pgdp is positive and the coefficient of the Pgdp is negative. That is, economic development and carbon emission have a significant inverted U-curve relationship. We have the same conclusion as Ke et al. (2021) [56] and Chen et al. (2021) [57]. It shows that economic development first promotes carbon emission and then suppresses it. (2) The elasticity coefficient of energy consumption structure is 0.0490, which is significant at a 5% level. This is because coal-based fossil fuel combustion is still one of the main sources of carbon emissions in China. (3) Industrial structure also can promote the increase in carbon emission, and its elasticity coefficient is 0.0369, which is significant at the level of 1%. It indicates that China's current industrial structure will still aggravate carbon emissions. Therefore, the transformation of the industrial structure is imminent. (4) There is a significant negative correlation between opening up and carbon emissions, which is at a 5% significance level. In the initial stage of economic development, China's coastal areas have absorbed a large number of high-pollution industries from abroad. However, with the improvement of economic development, their environmental regulation has become strict, and the high-polluting industries in coastal areas have transferred to inland areas. Therefore, regions with high levels of openness are more inclined to absorb green investment and acquire advanced management experience and green innovative technology so as to achieve the goal of carbon emission reductions. (5) Urbanization can significantly increase the amount of carbon emissions. With the acceleration of China's urbanization, a large amount of urban construction will increase the combustion of fossil energy, resulting in an increase in carbon emission.

5.1.3. Robustness Test

This paper mainly used three methods: replacement spatial weight matrix, replacement index, and replacement spatial model for testing the robustness of the benchmark regression. First of all, W2 is used to replace W1 in the previous regression for the robustness test, considering whether the differences of regional economic development would affect the regression results. Secondly, the index system of green finance is re-weighted using subjective and objective weighting methods. We used the reconstructed green financial development index to re-estimate the model. Finally, the model is re-estimated based on W1 by using the third-order spatial lag term of carbon emission as the instrumental variable in the generalized spatial least squares (GS2SLS) model. Meanwhile, the endogeneity of the benchmark model is also tested.

Table 5 describes the regression results of the robustness test. The global Moran index reported by the GS2SLS model is still significant, the spatial lag term of carbon emission intensity is still significant, and the core explanatory variable is still significantly negative to carbon emission. It could be inferred that the benchmark regression results have strong robustness.

Table 5. Robustness check.

Variable	Replace Weight	Replace Index	Replace Model
L.C	0.5449 *** (13.31)	0.8403 *** (14.58)	1.0434 *** (6.38)
Gfin	−0.4912 * (−1.83)	−0.2776 *** (−2.95)	−1.0453 *** (−5.61)
Pgdp	0.7351 ** (2.09)	0.3342 * (1.69)	0.5430 *** (4.07)
sPgdp	−0.0292 ** (−1.69)	−0.0850 *** (−7.98)	−0.0057 ** (−2.26)

Table 5. *Cont.*

Variable	Replace Weight	Replace Index	Replace Model
Estru	0.0475 *** (2.91)	0.2245 *** (5.84)	0.0308 * (1.80)
Indu	0.0617 ** (1.99)	0.0127 *** (4.07)	0.0023 * (1.72)
Open	−0.0938 *** (−4.35)	0.0077 *** (3.70)	0.0053 ** (2.36)
City	0.1267 *** (2.06)	0.0075 * (1.83)	0.0036 *** (6.09)
Log	177.7073	889.9060	1867.2806
Global Moran's I [P]			0.1034 *** (0.000)
Rho	0.1890 *** (2.61)	0.7002 *** (6.90)	
R2	0.9462	0.9506	0.8052
Obs	420	420	420

Note: ***, **, and * represent the significance levels of 1%, 5%, and 10%, respectively.

5.1.4. Spatial Spillover Effect

According to Lesage (2009) [58], the total effect represents the impact of green financial development on the carbon emissions of all provinces; the direct effect refers to the impact that the green financial development that the local region receives has on carbon emissions; and the indirect effect is equivalent to the mean of the impact that green financial development has on the carbon emissions of the surrounding regions. The dynamic SDM model is still used in this paper to explore the spatial spillover effect of green financial development on carbon emission. Table 6 gives the details of the regression results.

Table 6. Spatial spillover effect test.

Variable	Direct Effect		Indirect Effect		Total Effect	
	W1	W2	W1	W2	W1	W2
Gfin	−0.9857 *** (−3.05)	−0.4912 * (−1.83)	−0.0436 * (−1.89)	−0.0042 ** (−1.97)	−1.0293 ** (−2.01)	−0.4954 ** (−2.12)
Pgdp	0.2503 *** (5.66)	0.7351 ** (2.09)	0.0158 ** (2.02)	0.0075 ** (2.32)	0.2261 * (1.79)	−07426 *** (−4.70)
sPgdp	−0.0160 *** (−3.82)	−0.0292 ** (−1.69)	0.0139 * (1.89)	0.0280 * (1.69)	−0.0021 * (−1.68)	−0.0012 (1.57)
Estru	0.0490 *** (6.30)	0.0475 *** (2.91)	0.0139 (0.73)	0.0528 (1.01)	0.1880 (0.76)	0.1003 *** (4.48)
Indu	0.0369 ** (2.02)	0.0617 ** (1.99)	0.0560 * (1.69)	0.1827 (1.01)	0.0929 * (1.71)	0.2444 *** (8.04)
Open	−0.0404 ** (−2.25)	−0.0938 *** (−4.35)	0.1693 * (1.71)	0.1561 *** (3.25)	0.1289 *** (4.40)	0.0623 *** (3.56)
City	0.0813 *** (4.63)	0.1267 *** (2.06)	0.3385 (1.22)	0.1240 (0.98)	0.5011 * (1.80)	0.2507 (0.57)
Log	834.7580	177.7073	834.7580	177.7073	834.7580	177.7073
Rho	0.7625 *** (3.49)	0.1890 *** (2.61)	0.7625 *** (3.49)	0.1890 *** (2.61)	0.7625 *** (3.49)	0.1890 *** (2.61)
R2	0.9407	0.9462	0.9407	0.9462	0.9407	0.9462
Obs	420	420	420	420	420	420

Note: *** means significant at 1%, ** means significant at 5%, and * means significant at 10%.

To be specific, Table 6 shows the calculation results of the decomposition effect based on model 4 in Table 4. It can be found that under the setting of geographical distance spatial weight and economic distance spatial weight that the development of green finance contributes to carbon emission reduction, whether it is a direct effect, indirect effect, or total effect. This paper took the result of geographical distance spatial weight (W1) as an example. As shown in the results, the effect of green finance development on the carbon emissions of a local region is negative, that on the surrounding regions is still negative, and its elastic coefficients are −0.9857 and −0.0436, respectively, which are significantly negative at a 1% and 10% level. From these figures, it can be seen that the development of green finance reduces the carbon emissions of the local region, and it also reduces the carbon emissions of adjacent areas. Furthermore, whether it is the elasticity coefficient or significance degree, the carbon reduction effect of local regions is larger than that of the surrounding areas.

First of all, the initial stage of green finance development needs to be led by the government, and there is a competitive effect between regional governments, so the environmental regulation behavior of the local province will "infect" surrounding areas. Secondly, due to the financing constraints of green finance, the enterprises with high pollution in the region have increased loan interest rates, which forces the transformation and development of those enterprises to reduce their carbon emissions. Additionally, high-carbon enterprises in other areas will also reduce their carbon emissions due to this "warning effect". Therefore, the improvement of green finance in the local region will also affect the surrounding areas and then reduce the carbon emissions of adjacent areas.

5.2. Analysis on the Intermediary Effect of Green Finance on Carbon Emission

According to the dynamic SDM model, this part used the stepwise regression method to set the following intermediary effect test steps.

$$M_{it} = \pi_0 + \pi_1 \mathrm{Gfin}_{it} + \pi_2 X_{it} + \pi_3 M_{i,\mathrm{t}-1} + \rho_1 \sum_j w_{ij} M_{jt} + \rho_2 \sum_j w_{ij} \mathrm{Gfin}_{jt} + \rho_3 \sum_j w_{ij} X + u_{it} \quad (6)$$

$$C_{it} = \omega_0 + \omega_1 \mathrm{Gfin}_{it} + \omega_2 X_{it} + \omega_3 M_{i,t} + \omega_4 C_{i,\mathrm{t}-1} + \rho_1 \sum_j w_{ij} M_{jt} + \rho_2 \sum_j w_{ij} \mathrm{Gfin}_{jt} + \rho_3 \sum_j w_{ij} X + \rho_4 \sum_j w_{ij} M + u_{it} \quad (7)$$

Among them, M is the mediating variable, and Formulas (4), (6) and (7) constitute the intermediary effect test equation [59]. If the coefficients of ω_1 and π_1 are significant, compared with δ_1, the coefficient of ω_1 decreases or decreases significantly, indicating that M is an intermediary variable.

The estimation results of the mediating effect are given in Table 7. The coefficient of green finance is significant in either Equation (4) or Equation (6), and it is higher in Equation (4) than in Equation (7) with a reduced degree of significance when financing constraints are considered to be the mediating variable. Therefore, it can be determined that financing constraints are one of the mediating variables between green finance and carbon emission. That is, green finance development can significantly reduce financing constraints and then contribute to carbon emission reduction. This is because the development of green finance indirectly increases the cost of high pollution projects and then restrains polluting investment by reducing the costs of green investment and financing, making environmental risks explicit. The development of green finance makes environmental risks explicit, reduces green investment and financing costs, and increases the expenditure for high-pollution projects indirectly, thus restraining polluting investment.

The coefficient of green finance is significant in either Equation (4) or Equation (6), and it is higher in Equation (4) than in Equation (7) with a reduced degree of significance when green technological innovation is considered to be the intermediary variable. Therefore, it can be determined that the relation between green finance and carbon emission is mediated by green technological innovation. That is, green finance development reduces the amount of carbon emissions through improving the ability of green innovation. This is because with the improvement of the green finance, more funds can provide green innovation capital for the new energy industry and environmental protection industry. It will help to reduce the innovation risk of enterprises and stimulate the green innovation behavior of enterprises. Under the constraints of China's policies aiming to reduce emissions and save energy, high-energy consumption and high-pollution industrial enterprises tend to encounter more and more obstacles in the pursuit of development. On the contrary, the green industries that actively adopt cleaner production and emission reduction technologies get the support of green finance policies and enjoy higher development prospects.

Table 7. Mediating effect test.

Variable	M = Fcon			Variable	M = Gteh		
	(4)	(6)	(7)		(4)	(6)	(7)
L.Fcon		0.0423 ** (5.38)		L.Gteh		0.6054 *** (5.78)	
L.C	0.5591 *** (13.60)		0.4514 *** (13.80)	L.C	0.5591 *** (13.60)		0.6374 *** (12.50)
Fcon			0.0890 *** (3.09)	Gteh			0.3643 *** (5.74)
Gfin	−0.9857 *** (−3.05)	−0.0347 ** (2.10)	−0.6709 ** (−2.20)	Gfin	−0.9857 *** (−3.05)	0.0147 *** (2.80)	−0.0466 ** (2.03)
Control	Yes	Yes	Yes	Control	Yes	Yes	Yes
Log	834.7580	653.0568	853.6860	Log	834.7580	645.5168	850.156
Rho	0.7625 *** (3.49)	0.2891 * (1.69)	2.1709 *** (17.70)	Rho	0.7625 *** (3.49)	0.3451 *** (2.67)	1.4570 *** (17.08)
R2	0.9407	0.6670	0.9691	R2	0.9407	0.7593	0.9451
Obs	420	420	420	Obs	420	420	420

Note: *** means significant at 1%, ** means significant at 5%, and * means significant at 10%.

6. Conclusions, Suggestions, and Discussion

To improve the ecological environment substantially, we should not only rely on powerful pollution treatment measures but also use financial means to change the incentive mechanism of resource allocation. Therefore, in order to decrease carbon emission and achieve the goal of eco-environmental governance, green finance is indispensable. Therefore, this paper used the dynamic spatial econometric model to explore the impact mechanism, transmission mechanism, and the spatial spillover effect of green financial development on carbon emission, and we obtained the following conclusions and policy enlightenments.

6.1. Conclusions

Through the analysis of the spatial econometric model, it can be found that carbon emission has a strong space–time dependence effect. In the spatial dimension, the carbon emissions between regions show a significant spatial positive correlation, which indicates that the current implementation of China’s carbon emission reduction must form a synergistic linkage effect among regions. From the time dimension, the carbon emission may continue to rise in the next period if it is at a high level in the previous period.

Under the setting of geographical and economic distance spatial weight, green financial development can significantly reduce carbon emission. Furthermore, it is still valid, under three robustness tests, including spatial weight matrix, replacement explanatory variable index, and replacement spatial econometric model. In addition, whether the impact of green finance on carbon emissions is a direct effect, indirect effect, or total effect, the development of green finance contributes to the reduction of carbon emissions. Furthermore, the development of green finance, due to its significant spatial spillover effect, inhibits the growth of carbon emissions in the local region, and it also reduces the carbon emissions of adjacent regions. Moreover, the carbon emission in the local region receives a much higher inhibitory effect from green financial development than that in adjacent regions in terms of elasticity coefficient and significance.

The improvement of green finance has an indirect impact on carbon emissions by increasing green technology innovation and cutting down financing constraints. That is, financing constraints and green technology innovation both constitute the transmission path of green finance to carbon emissions.

6.2. Suggestions

Firstly, commercial banks should further increase the proportion of green credit, gradually tighten the funds flowing to high-emission industries, and increase the investment in credit funds for environmental protection and green industries. In addition, it is pressing to expand participants in the green financial market and give more impetus to the growth of green insurance business. For example, we can push the mandatory environmental pollution liability insurance system and develop other innovative types of green insurance, such as green vehicle insurance, green construction insurance, etc.

Secondly, we should invest more in the research and development of technologies for preventing pollution, reducing emissions, and saving energy, and motivate companies to take more active participation in the activities targeting green technology innovation through tax reduction from appropriate fiscal support.

Finally, it is essential to constantly reduce the share of oil, coal, and other traditional sources in energy consumption, fiercely advocate promoting the application of new energy, strictly implement the total control of regional coal consumption, speed up the construction of market-oriented energy pricing mechanism, and rely on the market-oriented mechanism to realize the gradual substitution of green and clean energy for traditional energy.

6.3. Discussion

In the context of the global pandemic of new crown pneumonia, whether the social living environment is green and healthy is of vital importance. A green revolution to reduce carbon emissions would also reduce the destruction of mineral resources, force countries to accelerate research and the use of renewable and green energy, and then promote the transformation of the world economy toward a green and sustainable direction. However, these processes cannot be realized without the support of green finance, so the importance of green finance is self-evident. As the world's largest carbon emitter in recent years, the Chinese government has promised the world a carbon peak by 2030 and carbon neutrality by 2060. How will China fulfill this promise? The key point of the primary consideration is how to effectively use green finance to promote the transformation of economic development mode and reduce the total amount of fossil energy combustion and industrial pollution emission. Considering the temporal and spatial diffusion of carbon emissions in different regions, this paper mainly adopted a dynamic measurement model to explore the relationship between the development of green finance and carbon emission, and it obtained the main conclusion that the development of green finance can help reduce carbon emission. At the same time, a variety of methods are used to verify the validity of the conclusions of this paper. In future studies, if the data can be more segmented and precise, more accurate and time-sensitive conclusions and relevant policy recommendations will be obtained. For example, further questions include how to rank the carbon emission reduction effects of different types of green financial instruments and how to break the space and administrative barriers to better promote the development of green finance in different regions.

Author Contributions: All the authors contributed extensively to the work equally to the work. All authors have read and agreed to the published version of the manuscript.

Funding: This work was supported by the Humanities and Social Science Foundation of the Ministry of Education of China (Grant no. 17JJD790017), and the National Social Science Foundation of China (Grant no. 18ZDA040).

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: No new data were created or analyzed in this study. Data sharing is not applicable to this article.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Daniel, G.A.; Herman, D.J. Optimism or pessimism? A composite view on English living standards during the Industrial Revolution. *Eur. Rev. Econ. Hist.* **2021**, *25*, 1–19.
2. Gennaioli, N.; Shleifer, A.; Vishny, R. Neglected risks, financial innovation, and financial fragility. *J. Financ. Econ.* **2012**, *104*, 452–468. [CrossRef]
3. Dikau, S.; Volz, U. Central bank mandates, sustainability objectives and the promotion of green finance. *Ecol. Econ.* **2021**, *184*, 10–70. [CrossRef]
4. Andrew, M.; Mary, A.S.; Emily, T.; Williams, A.P. Barriers and opportunities facing the UK Peatland Code: A case-study of blended green finance. *Land Use Policy* **2021**, *108*, 105594.
5. Freebairn, J. Policy Forum: Designing a Carbon Price Policy: Reducing Greenhouse Gas Emissions at the Lowest Cost. *Aust. Econ. Rev.* **2012**, *45*, 96–104. [CrossRef]
6. Gu, B.; Chen, F.; Zhang, K. The policy effect of green finance in promoting industrial transformation and upgrading efficiency in China: Analysis from the perspective of government regulation and public environmental demands. *Environ. Sci. Pollut. Res.* **2021**, *28*, 1–18. [CrossRef] [PubMed]
7. Peng, H.; Jiang, R.; Zhou, C. Literature Review of the Study of Carbon Emission Rights. *Low Carbon Econ.* **2017**, *8*, 133–138. [CrossRef]
8. Liu, L.C.; Gang, W. Relating five bounded environmental problems to China's household consumption in 2011–2015. *Energy* **2013**, *57*, 427–433. [CrossRef]
9. Chen, T.; Gozgor, G.; Koo, C.K. Does international cooperation affect CO_2 emissions? Evidence from OECD countries. *Environ. Sci. Pollut. Res.* **2020**, *27*, 8548–8556. [CrossRef]
10. Jung, H.; Song, S.; Song, C.K. Carbon Emission Regulation, Green Boards, and Corporate Environmental Responsibility. *Sustainability* **2021**, *13*, 4463. [CrossRef]
11. Sbia, R.; Shahbaz, M.; Hamdi, H. A contribution of foreign direct investment, clean energy, trade openness, carbon emissions and economic growth to energy demand in UAE. *Econ. Model.* **2014**, *36*, 191–197. [CrossRef]
12. Yu, X.; Wu, Z.; Wang, Q. Exploring the investment strategy of power enterprises under the nationwide carbon emissions trading mechanism: A scenario-based system dynamics approach. *Energy Policy* **2020**, *140*, 111409. [CrossRef]
13. Schmidt, T.S. Low-carbon investment risks and de-risking. *Nat. Clim. Chang.* **2014**, *4*, 237–239. [CrossRef]
14. Li, W.; Zhang, P. Relationship and integrated development of low-carbon economy, food safety, and agricultural mechanization. *Environ. Sci. Pollut. Res.* **2021**, *17*, 1–11.
15. Wang, A.; Tong, Z.; Du, W. Comprehensive Evaluation of Green Development in Dongliao River Basin from the Integration System of "Multi-Dimensions". *Sustainability* **2021**, *13*, 4785. [CrossRef]
16. Ke, H.; Dai, S.; Yu, H. Spatial effect of innovation efficiency on ecological footprint: City-level empirical evidence from China. *Environ. Technol. Innov.* **2021**, *22*, 101536. [CrossRef]
17. Sadorsky, P. The Impact of Financial Development on Energy Consumption in Economies. *Energy Policy* **2010**, *38*, 2528–2535. [CrossRef]
18. Shahbaz, M.; Solarin, S.A.; Mahmood, H. Does Financial Development Reduce CO_2 Emissions in Malaysian Economy? A Time Series Analysis. *Econ. Model.* **2013**, *35*, 145–152. [CrossRef]
19. Tamazian, A.; Chousa, J.P.; Vadlamannati, K.C. Does higher economic and financial development lead to environment degradation? evidence from BRIC countries. *Energy Policy* **2009**, *37*, 246–253. [CrossRef]
20. Jalil, A.; Feridun, M. The impact of growth, energy and financial development on the environment in China: A cointegrationanalysis. *Energy Econ.* **2011**, *33*, 284–291. [CrossRef]
21. Gu, H.M.; He, B. Research on China's provincial financial development and carbon emissions. *China Popul. Resour. Environ.* **2012**, *22*, 22–27.
22. Li, W.; Hu, M. An overview of the environmental finance policies in China: Retrofitting an integrated mechanism for environmental management. *Front. Environ. Sci. Eng.* **2014**, *8*, 316–328. [CrossRef]
23. Aizawa, M.; Yang, C. Green credit, green stimulus, green revolution? China's mobilization of banks for environmental cleanup. *J. Environ. Dev.* **2010**, *19*, 119–144. [CrossRef]
24. Xiu, J.; Liu, H.Y.; Zang, X.Q. The industrial growth and prediction under the background of green credit and energy savingand emission reduction. *Model Econ. Sci.* **2015**, *37*, 55–62.
25. Liu, J.-Y.; Xia, Y.; Fan, Y.; Lin, S.M.; Wu, J. Assessment of a green credit policy aimed at energy-intensive industries in China based on a financial CGE model. *J. Clean. Prod.* **2017**, *163*, 293–302. [CrossRef]

26. Taghizadeh-Hesary, F.; Yoshino, N.; Han, P. Analyzing the Characteristics of Green Bond Markets to Facilitate Green Finance in the Post-COVID-19 World. *Sustainability* **2021**, *13*, 5719. [CrossRef]
27. Huang, H.; Zhang, J. Research on the Environmental Effect of Green Finance Policy Based on the Analysis of Pilot Zones for Green Finance Reform and Innovations. *Sustainability* **2021**, *13*, 3754. [CrossRef]
28. Iqbal, S.; Taghizadeh-Hesary, F.; Mohsin, M. Assessing the Role of the Green Finance Index in Environmental Pollution Reduction. *Stud. Appl. Econ.* **2021**, *39*. [CrossRef]
29. Eyraud, L.; Clements, B.; Wane, A. Green investment: Trends and determinants. *Energy Policy* **2013**, *60*, 852–865. [CrossRef]
30. Liu, Z.; Zhang, X.; Yang, L. Access to Digital Financial Services and Green Technology Advances: Regional Evidence from China. *Sustainability* **2021**, *13*, 4927. [CrossRef]
31. Zhou, P.; Ang, B.W.; Han, J.Y. Total factor carbon emission performance: A Malmquist index analysis. *Energy Econ.* **2010**, *32*, 194–201. [CrossRef]
32. Liu, N.; Liu, C.; Xia, Y.; Ren, Y.; Liang, J. Examining the Coordination Between Green Finance and Green Economy Aiming for Sustainable Development: A Case Study of China. *Sustainability* **2020**, *12*, 3717. [CrossRef]
33. Eichholtz, P.; Quigley, J.M. Green building finance and investments: Practice, policy and research. *Eur. Econ. Rev.* **2012**, *56*, 903–904. [CrossRef]
34. Wang, Y.; Zhi, Q. The Role of Green Finance in Environmental Protection: Two Aspects of Market Mechanism and Policies. *Energy Procedia* **2016**, *104*, 311–316. [CrossRef]
35. Liang, G.; Yu, D.; Ke, L. An Empirical Study on Dynamic Evolution of Industrial Structure and Green Economic Growth—Based on Data from China's Underdeveloped Areas. *Sustainability* **2021**, *13*, 8154. [CrossRef]
36. Xra, B.; Qspd, B.; Rza, B. Nexus between green finance, non-fossil energy use, and carbon intensity: Empirical evidence from China based on a vector error correction model. *J. Clean. Prod.* **2020**, *277*, 122844.
37. Hu, Y.; Jiang, H.; Zhong, Z. Impact of green credit on industrial structure in China: Theoretical mechanism and empirical analysis. *Environ. Sci. Pollut. Res.* **2020**, *27*, 1–14. [CrossRef]
38. Tu, C.A.; Sarker, T.; Rasoulinezhad, E. Factors Influencing the Green Bond Market Expansion: Evidence from a Multi-Dimensional Analysis. *J. Risk Financ. Manag.* **2020**, *13*, 1–14.
39. Chakraborty, D.; Mukherjee, S. How do trade and investment flows affect environmental sustainability? Evidence from panel data. *Environ. Dev.* **2013**, *6*, 34–47. [CrossRef]
40. Mao, W.; Wang, W.; Sun, H. Driving patterns of industrial green transformation: A multiple regions case learning from China. *Sci. Total Environ.* **2019**, *697*, 1341–1367. [CrossRef]
41. Qin, J.; Zhao, Y.; Xia, L. Carbon Emission Reduction with Capital Constraint under Greening Financing and Cost Sharing Contract. *Int. J. Environ. Res. Public Health* **2018**, *15*, 750. [CrossRef]
42. Anselin, L. Some robust approaches to testing and estimation in spatial econometrics. *Reg. Sci. Urban Econ.* **1990**, *20*, 141–163. [CrossRef]
43. LeSage, J.; James, P. What Regional Scientists Need to Know about Spatial Econometrics. *Rev. Reg. Stud.* **2014**, *26*, 56–87. [CrossRef]
44. Elhorst, J.P. Software for spatial panels. *Int. Reg. Sci. Rev.* **2014**, *37*, 389–405. [CrossRef]
45. Shao, S.; Yang, L.L.; Yu, M.B.; Yu, M.L. Estimation, Characteristics and Determinants of Energy-related Industrial CO_2 Emissions in Shanghai (China) 1994–2009. *Energy Policy* **2011**, *39*, 6476–6494. [CrossRef]
46. The Intergovernmental Panel on Climate Change (IPCC). *2006 IPCC Guidelines for National Greenhouse Gas Inventories*; Institute for Global Environmental Strategies (IGES): Hayama, Kanagawa, Japan, 2006.
47. Tu, C.A.; Rasoulinezhad, E.; Sarker, T. Investigating Solutions for the Development of a Green Bond Market: Evidence from Analytic Hierarchy Process. *Financ. Res. Lett.* **2020**, *34*, 101457. [CrossRef]
48. Mashud, A.H.M.; Roy, D.; Daryanto, Y.; Chakraborty, R.; Tseng, M.L. A controllable carbon emission and deterioration inventory model with advance payments scheme. *J. Clean. Prod.* **2021**, *296*, 126608. [CrossRef]
49. Mishra, U.; Mashud, A.; Tseng, M.L.; Wu, J.Z. Optimizing a Sustainable Supply Chain Inventory Model for Controllable Deterioration and Emission Rates in a Greenhouse Farm. *Mathematics* **2021**, *9*, 495. [CrossRef]
50. Li, L.; Wu, W.; Zhang, M. Linkage Analysis Between Finance and Environmental Protection Sectors in China: An Approach to Evaluating Green Finance. *Int. J. Environ. Res. Public Health* **2021**, *18*, 2634. [CrossRef]
51. Mashud, A.H.M.; Pervin, M.; Mishra, U.; Daryanto, Y.; Tseng, M.L.; Lim, M.K. A sustainable inventory model with controllable carbon emissions for green-warehouse farms. *J. Clean. Prod.* **2021**, *298*, 126777. [CrossRef]
52. Rodriguez, M.C.; Dupont-Courtade, L.; Oueslat, W. Air Pollution and Urban Structure Linkage Evidence from European Cities. *Renew. Sustain. Energy Rev.* **2016**, *53*, 1–9. [CrossRef]
53. Shen, N.; Wang, Q.W.; Zhao, Z.Y. Trade linkages, spatial agglomeration and carbon emissions. *Manag. World* **2014**, *1*, 22–34.
54. Ding, W.; Gilli, M.; Mazzanti, M.; Nicolli, F. Green inventions and greenhouse gas emission dynamics: A close examination of provincial Italian data. *Environ. Econ. Policy Stud.* **2016**, *18*, 1–17.
55. Beck, T.; Levine, R.; Loayza, N. Finance and the sources of growth. *J. Financ. Econ.* **2004**, *58*, 261–300. [CrossRef]
56. Ke, H.; Dai, S.; Yu, H. Effect of green innovation efficiency on ecological footprint in 283 Chinese Cities from 2008 to 2018. *Environ. Dev. Sustain.* **2021**, 1–20. [CrossRef]

57. Chen, X.; Chen, Z. Can China's Environmental Regulations Effectively Reduce Pollution Emissions? *Int. J. Environ. Res. Public Health* **2021**, *18*, 4658. [CrossRef]
58. LeSage, J.; Pace, R.K. *Introduction to Spatial Econometrics*; CRC Press: New York, NY, USA, 2009.
59. Baron, R.M.; Kenny, D.A. The Moderator-mediator Variable Distinction in Social Psychological Research: Conceptual, Strategic, and Statistical Considerations. *J. Personal. Soc. Psychol.* **1986**, *51*, 1173–1182. [CrossRef]

sustainability

Article

On European Green Deal and Sustainable Development Policy (the Case of Romania)

Melania-Gabriela Ciot

Department of European Studies and Governance, Faculty of European Studies, Babeș-Bolyai University, 1 Emmanuel de Martonne Street, 400090 Cluj-Napoca, Romania; melania.ciot@ubbcluj.ro

Abstract: Reaching the EU climate-neutrality objective in 2050 is very ambitious, especially for the Member States from Central-Eastern Europe. All the Member States will face challenges of transformational changes, but a good preparation of their administrative capacity will be a consistent support. The aim of this article is to analyze Romania's decision-making process for the implementation of the European Green Deal Strategy, reflected in its administrative capacity. For achieving this goal, an interesting model of analysis was elaborated, which takes into consideration three levels and dimensions: strategic (with executive and legislative dimensions), administrative (national and regional dimensions) and outcomes (assessed from a well-being lens and public opinions surveys). The model will be applied at the European and national levels (Romania). It uses qualitative research strategies and methods. The transversal character of the EGD strategy, the coordination needed for its implementation, and the interdependencies and regional approach are important components that pave the way for the elaboration of the National Green Deal Plan, which becomes compulsory for an adequate design of the sustainable, adaptive, and mature Romanian administrative capacity. In addition, the article proposes a few recommendations at the national and local levels for the preparation of a better implementation of the EGD.

Keywords: Green Deal; climate action; sustainable development; interdependence; administrative capacity

Citation: Ciot, M.-G. On European Green Deal and Sustainable Development Policy (the Case of Romania). *Sustainability* **2021**, *13*, 12233. https://doi.org/10.3390/su132112233

Academic Editors: Jun Yang, Ayyoob Sharifi, Baojie He and Chi Feng

Received: 8 October 2021
Accepted: 1 November 2021
Published: 5 November 2021

1. Introduction

The European actions against climate changes and the degradation of the natural environment is not exactly new. The European Union has long been a leader in policies to combat climate changes. It has been adopting a climate change strategy since 1992, and since 1996, it has approved the goal of limiting global warming to 2 °C above pre-industrial levels. The EU consolidated the international leader position in approaching climate changes in 2001, when it had sufficient supporters for the approval of Kyoto Protocol, despite the US's withdrawal [1]. The ambitious public policies supported the EU's global role, launching the Emission trading scheme in 2005, the world's most important greenhouse gas emission trading system and the emblem of EU climate policy [2]. Even if the international community failed to reach a global agreement on limiting greenhouse gas emissions at the UNO Conference regarding climate changes at Copenhagen in 2009, the EU continued to pursue its internal climate targets and has developed new ones for 2030 [3]. The Paris Agreement from 2015 was a success of European diplomacy and encouraged the Union to review the emission reduction targets, renewable targets, or energy efficiency targets [4]. The European Union's actions at s global level were intensified in the field of fighting against climate change [5], even though other political leaders (such as Donald Trump in the USA and Jair Bolsanaro in Brasil) treated with hostility the field of climate.

The European policies are decided in Brussels, but the implementation's responsibility belong to each Member State. In Europe, growing concerns about climate change have been reflected in stronger electoral support for green parties in 2019 European elections, especially in some Western Member States, as well as the emergence of grassroots movements such as Fridays for Future or the Youth Strike for Climate [6].

Moreover, the environmental activists consider the degradation of the natural environment as a "climate emergency", one of the strongest voices in this regard being that of Swedish activist Greta Thunberg. In her records, she emphasized the need for imperative actions against climate changes, drawing attention to the fact that our planet is only about 11 years away from an irreversible catastrophe:

> "We are not fighting for the future of young generations only; we are fighting for everybody's future. We have started to clean up this mess and we will not stop until we are done" [7]

> "The EU must lead the way. You have the moral obligation to do so. And you have a unique economic and political opportunity to become a real climate leader." [8]

Member States' efforts are also focused on strengthening the EU's leadership in meeting the long-term goal of Paris Agreement, ensuring the transition to a low carbon economy, and continuing to integrate actions to address climate change across policies of EU [9]. Attention is also paid to ensuring the quality of drinking water, the efficient use of water resources, and the promotion of biodiversity. Environment and climate change policies shape Europe's future and new development trends, and the transition to a circular economy and low-carbon development will help increase the quality of life of European citizens.

If we refer to the contribution of the Member States on the environment, during the rotating Presidency of the Council of the European Union, Romania has contributed to advancing the EU's agenda on decarbonisation, the implementation of the Paris Agreement, and to the promotion of sustainability and sustainable growth. It has facilitated debates on the long-term strategic vision for a climate-neutral economy and has mainly aimed at protecting the competitiveness of the EU economy, while enabling the transition to a low carbon economy [9]. Moreover, it is committed contributing to the decarbonisation of the transport sector, and the new rules on clean vehicles are an important step in this direction. Under the Romanian Presidency, CO_2 reduction targets for heavy vehicles have also been adopted for the first time in the European Union [9].

In the face of growing evidence of the climate crisis, the EU continued to make environmental policy a priority, with the European Commission led by Ursula von der Leyen making the fight against climate change one of its main goals. To this end, the European Green Deal (EGD), the new growth strategy for the EU, was published by the European Commission on 11 December 2019. It supports Member States in achieving the goal of climate neutrality and sets the guideline for various European public policies for the coming years, being closely linked to a number of legislative and non-legislative initiatives in multiple areas, such as the environment, climate changes, energy, industry, transports, agriculture, digitalization, and the financial sector [10].

This paper will address the current gap and will improve the literature by focusing attention on the sustainable effects of the implementation of EGD in a Member State, offering an example—Romania. In this way, the empirical analysis will facilitate the implementation by the national and local administrations and a better understanding of this European strategy. For reaching this aim, an innovative model of analysis was designed which will provide a coordinated, interdependent, and integrated implementation. The model was inspired by the mechanisms and procedures of National coordination system of the European affairs in Romania [11]. It will use qualitative strategy for research, with specific methods (documents analysis, comparative analysis, discourse analysis, and case study). The option for the qualitative research is coming from the specificities of policy analysis, supporting the objectivity, validity, and consistency of the research. The material of investigation will consist in official public speeches of European and national leaders with responsibilities in the implementation of EGD, reports, policy briefs, and EU documents. The period of analysis is December 2019 (the launching of EGD) to present (October 2021).

The novelty of this research consists in the new model of analysis of EGD's implementation, with its multiple levels and dimensions. The conception of this model is based on the general development and sustainable international policies and new strategic European Green Deal policy, maintaining the interdependent character and taking into account the legislative and executive dimensions, which will impact the implementation and administrative capacity. Each level of this model will be described with a theoretical approach, which will create the framework for the qualitative interpretation of the results. For a better understanding of the model, an empirical analysis, applied on the European level and at a national level of a Member State (Romania), will be provided. From this perspective, it is the first article approaching the Romanian decision-making process for the implementation of the EGD based on the model that this study generates. Deeper research is not possible at this moment, due to the lack of studies on the policies' implementations under the EGD. There only a few articles and books on this topic, for example, for Romania, only one study refers in a comparative framework to Energy Policy. The contribution of the epistemic communities in this particular topic are quite missing. Due to the lack of sufficient academic bibliography, the reports and media intervention in political decisions were used. The suggested solutions are based on the professional experience of the author.

2. Research Design

The present research brings a new element into the study of sustainability through the analysis of the decision-making process, using a top-down approach: from the strategic level (elaborating a decision) to its basic level (the outcomes of the implemented decisions). The new model of analysis elaborated with this research was based on a combination between the major key elements of the EGD (which will be described further on) and on the coordination system of European affairs at a national level of a Member State (Romania), which offered a good example of the harmonization of different European policies according with common European and national interests [11]. The model is intended to be a useful instrument for the decision makers because it gives feedback on the effects of the political decisions. It opens new ways for other investigations in the field of sustainability, climate change, environmental policies, the EGD, and European Affairs. A detailed description of the new model will be provided in Section 3: New Model of Analysis.

As it was mentioned previously, the present research was organized in seven parts, beginning with the formulation of the problem and motivation of the research from the introduction chapter, continuing with the research design chapter describing the methodology used (type of strategy, methods of research, research questions, and hypothesis), the third chapter will focus on the new elaborated model of analysis, which will be used for the analysis of the EGD implementation at European and national level of a Member State (Romania); discussion and findings represents the next chapter, and the study will end with the presentation of conclusions.

The present work has been organized in accordance with reporting standards in the field of social sciences. This research is a qualitative one, and this is important and quite new in the field of sustainability studies, as well as political sciences or international relations, where quantitative research methods are present in high enough proportion. The option for the qualitative research is based on the possibility of an interdisciplinary approach to a specific topic. This type of research favours the interpretation of data, usually few in number, within the cultural and social context, for a specific period of time [12]. Another argument of the use of qualitative research is its own interpretive and creative character [13]. Qualitative research provides a holistic approach of a topic, and it is reflective regarding the role of the researcher in the researching process.

The research questions are: What are the political, social, and cultural elements that influenced the decision-making process of the implementation of the EGD to the European Union? Are there any specific characteristics for the decision-making process regarding the implementation of EGD in Romania?

The hypothesis: The impact of the EGD's implementation in Romania differs according to the political decisions at national level.

The research methods are: the case study, document analysis, discourse analysis and comparative method. The case study is represented by the Romania's decision-making process for the implementation of EGD.

The period of study is: December 2019 (the launching of EGD)–present (October 2021).

3. The New Model of Analysis of the Decision-Making Process for European Green Deal Implementation

The EGD is the integrated growth strategy of the European Commission [14], used mainly to implement the United Nation's 2030 Agenda, other sustainable development goals, and the political priorities of the current Commission. It aims:

> "to transform the EU into a fair and prosperous society, with a modern, resource-efficient and competitive economy where there are no net emissions of greenhouse gases in 2050 and where economic growth is decoupled from resource use" [15]

It addresses several key issues: the energy transition (clean energy sources), changes in industry (circular economy models), the energy efficiency of buildings, organic food systems, regions that will need increased support for the transition (mining, those were agriculture is affected by climate change, etc.), and the fair transition fund. Through these directions of actions, the EC seeks to interconnect all relevant EU policies in the fight against and the prevention of pollution.

The EC's Communication is a roadmap of the key policies, actions, and measures to be followed; in fact, all of the EU actions and policies will be circumscribed to this strategy, using the synergies between them [16]. There are four important benefits that would be achieved: health, quality of life, resilience, and competitiveness. The elements of the EGD strategy are shown in Figure 1.

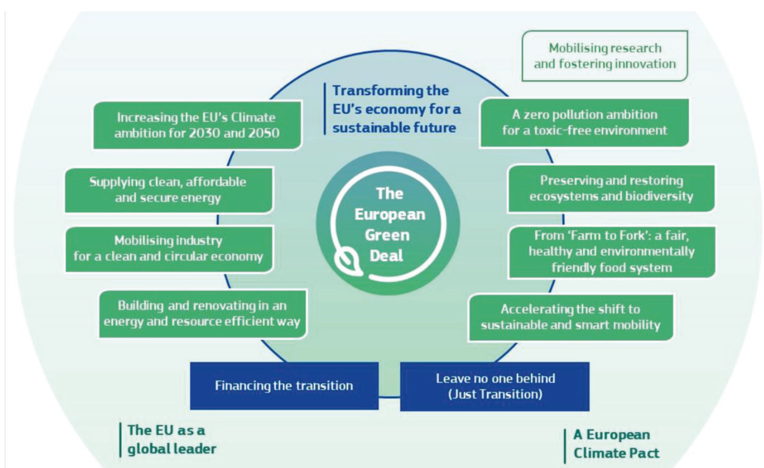


Figure 1. The elements of European Green Deal (source: COM (2019) 640 final, 11 December 2019, p. 3).

We can see that sustainability and the well-being of the European citizens represents the central elements of the strategy, along with economic policy. The EU and national policymakers should follow the sustainable development goals when they elaborate the future regional, sub-regional and sectoral strategies, actions, and measures [17–19].

By taking into account the key policies of the EGD and the coordination system of European affairs at the national level of a Member State [11], a new model is proposed; it easily could be applied in any other Member State. The model covers all the relevant elements for a policy analysis (especially on the efficacy of its implementation) (Figure 2).

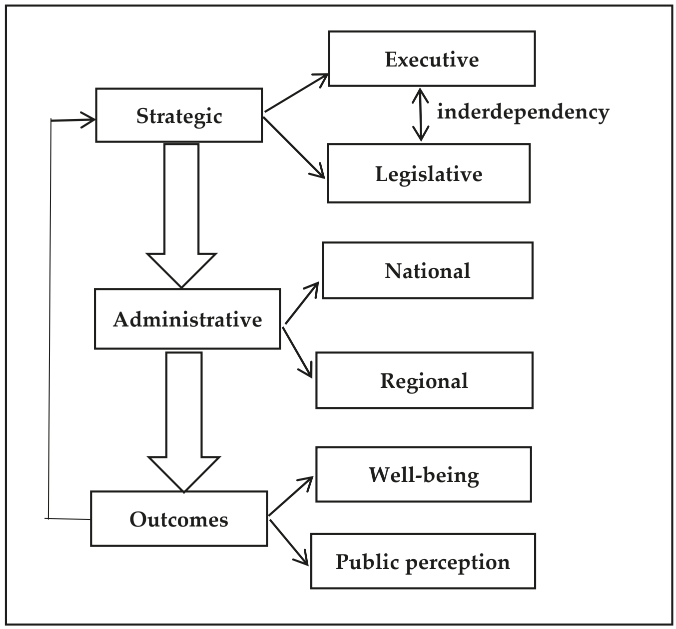


Figure 2. The model of analysis of EGD implementation.

The model is organized on three levels, from the strategic level of decision-making, through administrative level of implementation to the basis of the decision-making process, namely—outcomes. Each level has several dimensions describing its efficiency:

First level: strategic—it is the decision-making level, in which efficiency is analysed from the executive, legislative, and interdependency dimensions.

Second level: administrative—at the policy-making level, with national and regional dimensions.

Third level: outcomes—the basis of the decision-making level, which will be assessed from the lenses of well-being and public perceptions.

Each level has political, economic, and social elements and all dimensions are interconnected. The outcomes of the implementation will give feedback on the strategic level, aiming to adapt the decisions accordingly.

The model is important because it will provide a useful instrument for the measurement of the sustainability of the EGD's implementation decisions, which could be detected in its outcomes regarding the well-being of citizens and public opinions and support. By following the three levels of the decision-making process, periodical investigations (twice a year) could be organized. The limitations of the present model are the contextual and political factors, for which decisions cannot be foreseen with accuracy due to the pandemic situation. The economic implications, especially for the Central and Eastern EU, are other factors which could influenced the changes in the objectives regarding terms and conditions of EGD's implementation.

4. Analysis of the European Green Deal Decisions for Implementation at the European Level

In this chapter, the implementation of the EGD from a decision-making perspective will be analysed, according to the multilevel and dimensions models. This analysis will offer the general framework for the implementation of EGD at Member States' level, taking into consideration the interdependent effects of political decisions that will impact its sustainability in terms of outcomes and public support.

4.1. Strategic Dimension at EU Level

The key actions of the EGD strategy are organized in main field, in fact, deriving from the main European policies: climate ambition (Climate Policy); clean, affordable, and secure energy (Energy Policy); industrial strategy for a clean and circular economy (Industrial Policy); sustainable and smart mobility (Transport Policy); greening the Common Agricultural Policy / 'Farm to Fork' Strategy (for Common Agriculture Policy); preserving and protecting biodiversity (Environmental Policy); ambition towards a zero-pollution for a toxic free environment (Environmental Policy) and mainstreaming sustainability in all EU policies (to address to the integrated character between European policies); the EU as a global leader (Common Foreign and Security Policy); and working together—a European Climate Pact (as the final juridical outcome). There are seven main European policies to which the GD strategy is addressing, six of them for the internal environment and one for the external environment.

It is a very ambitious project which tries to put the EU in a leader position in the field of climate change at international scale. The investments are included in the Sustainable Europe Investment Plan, committed to mobilize at least EUR 1 trillion of sustainable investments by using relevant policy levers and private and public investments. It includes the Just Transition Mechanism to administratively and financially support the regions to adapt better to the new challenges [16].

However, now, after one year from the launch of the EGD strategy, the international context is different. We experienced one of the worst health crises and economic crises since the end of the Second World War, as Frans Timmermans, Vice-President of the EC and responsible for the EGD, mentioned in a speech held on 25 May 2021:

> "The Green Deal is our new strategy for sustainable growth, based on fairness, innovation, and decoupled from resource use. It is our roadmap for the EU to become climate neutral by 2050 and for addressing the biodiversity crisis. And as we build back our economy, we also need to build back our nature, because forests and oceans are being polluted and destroyed. When we first presented the Green Deal, it was relatively lonely on the world stage. But more than one year later, we are joined by many others in this global race to net zero. China, South Korea, South Africa, Japan, and most recently the United States, are joining with ambitious commitments of their own. That is great news. Because this is a race where we can all win." [20]

The Green Deal is a transversal and sectoral strategy, acting at global, European, regional, national, and local levels in a very different context than the one when it was initiated. And that means that it needs an adaptive capacity of administrative structures involved in its implementation. The intensification of the global and regional interdependencies, accelerated by the sanitary crisis, brought into attention the need for an integrated coordination in decision-making and policy-making processes between state and non-state actors and private and public actors from administration, economic, and social sector: governments and interested stakeholders (market structures, professional associations and NGOs, and other social groups, etc.).

The implementation of the EGD, at the European level, has two important dimensions: executive (concrete strategies, actions, measures of European Commission) and legislative (legislative acts adopted by the European Parliament). From this approach, specific guidelines will be derived for the national administrative structures.

The executive dimension—as a response to the effects of the sanitary crisis, the EU level begins a recovery process. Even if the current crisis is not driven by climate action, the EGD could support the recovery [21]. The present crisis has to be interpreted also from the perspective of the opportunities that it opens, including the speeding up other Green Deal targets of economic modernisation by achieving the Paris Agreement on decarbonisation but also initiating a new discussion at national levels between Member States regarding taxation, innovation, infrastructure, entrepreneurship, reforms of some of European policies, etc. [21]. In addition, it is important that the guiding principle for recovery should be the low-carbon targets for energy and materials [16]. For climate policy, possible areas for transformations mentioned by the previous authors are the creation of a low-carbon lead markets (for example, the New Industrial Strategy for Europe), the fast start of the hydrogen economy, or emphasizing the basic material value chain [21].

In the context of the crisis generated by COVID-19, the process of implementing EGD was slowed down due to the reorientation of actions to get out of the health crisis (for example, the New Climate Change Adaptation Strategy and Forestry Strategy were postponed). However, the European Commission announced that the targets for 2030 remained unchanged and came with the initiative of the European Investments Plan for the European Green Pact aimed at "mobilising at least 1 billion euros of sustainable investment over the next decade". It includes a Fair Transition Mechanism, which should provide "targeted support to help mobilize at least EURO 100 billion over the period 2021–2027" in order to mitigate the socio-economic impact of the transition in the regions based on the use of fossil fuels. The mechanism will focus on the regions and sectors most affected by the transition, its objectives being to support investments in territories where its negative effects are most pronounced. The territories concerned will include the coal-bearing regions, but also other heavily industrialized regions [22].

In the context, is worth mentioning that the financial support will consist in EUR 1.8 trillion for a "greener, more digital and more resilient Europe" [23], from which EUR 1.0743 billion represents the amount of the Multiannual Financial Framework (MFF) and EUR 750 million represents the recovery instrument—Next Generation EU (NGEU).

The interdependent nature of the EU is another aspect to be considered for the analysis of the implementation capacity of EGD by the Member States. It is the reason for cooperation, and, for the prospections on climate actions, it will be the framework for the understanding of new policies, politics, and decisions [24]. The mentioned study considers that, in the future, regions, local authorities, and cities will become crucial players in climate change (in addition diplomacy and conflict resolution) and that alliances between states will be used for countering climate change. Power will be determined by the leaders in the new technologies (the USA and China are now leading), and so Europe will have to fill the gap [24].

The legislative dimension will consider the European Parliament assumed a role of advocating for ambitious climate actions, endorsing the EGD: The Resolution from 17 April 2020 underlined the need to align the response to the pandemic crisis with the EU's climate neutrality objective and that EGD and digital transition should be the central elements of the recovery [25], and the Resolution from 15 May 2020 mentioned that the EGD, the digital agenda, and European sovereignty should be the strategic sector [26,27].

The actions and measures which will transpose the EGD strategy in a sustainable manner will address three dimensions: social, economic, and environmental [28].

4.2. The Administrative Dimension at National and Regional Level

The EU's climate action can contribute to the recovery by concentrating the funds on the EGD at national levels, in this way taking the opportunity to accelerate the transition to a climate-neutral economy and advance toward the leading position in using green technologies [26]. The authors of the previously mentioned and referenced study identified five windows of opportunity derived from pandemic period that can be used for supporting the implementation of the EGD at the administrative level: new habits (important for the reconfiguration of the policy-making process, taking into account the new forms of communicating and working—teleworking, virtual education, conferences, etc.—which could be used to reduce the time and costs spent in traffic business trips, reduce CO_2 emissions by developing digital infrastructure and instruments); the shift in values for European citizens (solidarity with people at risk and medical staff is similar with the solidarity for the people in vulnerable regions affected by the climate crisis and for the future of young generations—it could be addressed in the Conference Future of Europe and European Climate Pact); international cooperation (the value of it was demonstrated once again by the coronavirus crisis with sharing information about viruses, sharing equipment, coordinating the re-opening of the borders, and developing medicines and vaccines; for the EGD, there are opportunities for strengthening international cooperation by climate diplomacy, cooperation in United Nations framework, with sectoral organizations or sectoral domains with like-minded countries); preparedness (it emphasized the role of strong health system and stocks of medicines or planning but also a lesson to prevent a climate crisis and to adapt to the climate change; the EGD could be leading in risk assessment and coordination); focus on inequalities (the impact of the pandemic crisis was not the same for different age categories, economic sectors, or regions; in the same way, the climate crisis could be prevented with the EGD if the inequalities can be identified and will be addressed directly, by using, for example, the Just Transition Mechanism and the Just Transition Fund) [27]. Another important element to be taken into consideration is the EU's interdependency [29].

However, the challenges for the EU regarding the recovery and restructuring after the pandemic crisis stands not only on strategic and administrative capacities of institutions and states but also in the investment gap of EUR 180 billion yearly needed for the clean economy in order to achieve the 2030's climate and energy objectives [29]. The investments are necessary for the reductions of EU's gaps and for supporting the increase in the EU's competitiveness, its transition to a climate-neutral economy, and a more cohesive EU [30]. The administrative structures of Member States could develop public–private partnerships for a clean economy in the framework of transition policies, offering patterns of solutions for different key priorities of the EGD. Fisher proposes a useful model for the partnerships as shown in Figure 3.

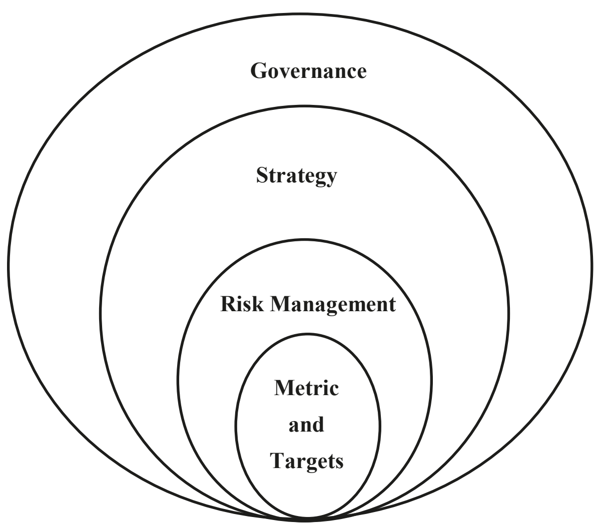


Figure 3. Core-elements of recommended climate-related financial disclosure (source: Fisher, 2019, p. 9).

In the implementation of the EGD, the regional cross-border approach provides the general framework [31]. The authors consider that a successful implementation of the EGD using a regional approach is possible because of the progress in the organization of markets and regulations. Cooperation is also needed because a climate-neutral continent requires it between the EU, the Energy Community, and neighbouring countries, including Turkey [31]. The external dimension of EGD is circumscribed not only to the Common Foreign and Security policy but also to Neighbouring Policy:

> "A regional approach is important to ensure that the transition occurs simultaneously throughout the region in order to avoid, for example, the risk that more ambitious countries replace domestic higher carbon electricity production with other carbon-intensive imports from neighbours." [31]

However, one of the challenges that the EGD faces is the lack of the regional strategies or competition for regional leadership in regard of different key priorities [31]. Previous regional initiatives could be used to prepare the administrative structures and strategic capacity for better implementation of EGD.

4.3. Outcomes of the Implementation of the EGD Will Be Assessed from a Well-Being Lens and Public Perceptions

The central element around which the implementation was designed is the well-being of the European citizens—and this adds the interdependent dimension of this strategy and a refocusing of the European policies. This approach could support Member States in the identification and implementation of the suitable measures needed for reducing greenhouse gas emissions, for avoiding the blocking of carbon-intensive technologies, and reducing the CO_2 emissions in the long term to zero. It has to be adapted to the juridical and particularities of each Member State or region by taking into consideration challenges and opportunities. In this way, the achievement of climate and well-being targets will be easier. There are some specific incentives that researchers recommend [32]: placing citizens' well-being in the centre of the decision-making process is the pre-requisite for political and social support for more ambitious actions and overcoming the barriers that may come with the challenges (well-being concepts encompass not only economical aspects but also social aspects, education, health system, security, and environmental standards); reducing climate change will bring benefits for actual generations and provide resources for the future ones (decisions will create a proper balance between the objectives of mitigation of climate change and well-being objectives by using negotiations and compromises between climate policy and other circumscribed policies of EGD, in terms of affordability, competitiveness, and job constrains); a well-being approach will favour decisions to deliver multiple well-being objectives (on climate, economic perspectives, not only on individual, separate ones) and applying a well-being approach to key sectors (reassessing policies priorities, evaluations' and decisions' indicators will support authorities and their capacities in building the "two-way alignment" between climate and other objectives of well-being—for example, for electricity, heavy industry, residential, surface transport, agriculture).

The incentives that could increase the benefits of well-being for European citizens by implementing EGD and adapting the administrative capacities is well represented in Table 1.

The redesign of policy priorities needs not only political will and structural and administrative adaptations but also strong social support. The last Eurobarometer on Climate Change [33] indicated that almost one quarter of European respondents considered climate change as a serious problem of the contemporary world, placing it on the second place after "poverty, hunger and lack of drinking water" (27%). It is an increase in the proportion of respondents of 11% from the last survey in 2017, when climate action was in third place [33]. When it comes to Member States and the perceptions of climate change as a global problem, the differences are significant, especially from a geographical and economic points of view: 50% of Swedish people consider it a serious problem, 43% of

Danish people, and 33% of Finnish people, in contrast with 10% of Bulgarians, Croats, Latvians, Greeks, and Romanians [33].

Table 1. Incentives for climate actions using a well-being approach (adapted after OECD, 2019, p. 16).

Strong Climate Action Is the Foundation of Our Future Economic and Wider Well-Being					
with a production lens:				with a well-being lens:	
Material conditions	Wealth Consumption GDP Growth	Income		Education	Pollution
				Health development Material condition Wealth access Affordability Mitigation Security consumption	Natural disasters Resources Climate Change Hunger Degradation
Synergies between climate policies and larger societal goals					
Mitigation				Economic, social, and environmental goals	
Achieving climate goals and delivering societal benefits by focusing on 5 important sectors: • Electricity; • Heavy industry; • Residential; • Surface transport; • Agriculture.					
Enhanced measurement system could improve policy design					

Having analysed the EGD and its implementation perspectives, the same multilevel and multidimensional model of analysis will be applied to assess the administrative capacity of implementation for a Member State—Romania.

5. Analysis of Romania's Capacity for Implementing European Green Deal

As the health crisis is approaching the end, the European Member States should focus on emergency problems and mitigation, and finding sustainable, affordable, and efficient solutions aimed at the well-being of European citizens are the priority. When the European economies will approach the final of recovery, the emergency will not disappear, and the risk of neglecting climate actions will severely hit the administrative initiatives taken or prospected to be taken in line with the EGD's implementation or with respect to the Paris Agreement's targets.

Nowadays, there are some Member States asking for a reorientation of investments and priorities to other priorities generated by the sanitary crisis, neglecting the former engagements under the EGD. Regarding Romania, the Recovery and Resilience Plan provoked many discussions between political actors, market structures, and social groups and all interested stakeholders, but the essence of discussions was not for the recovery by deepening the European integration but for absorbing the funds. It was missing a concrete, correct, and useful dialogue with all the interested stakeholders, especially epistemic communities who supported with high quality insights.

5.1. Strategic Dimension at Romanian National Level

The executive dimension was active through strategic decisions regarding the division of European funds allocated by the EC through the NextGenerationEU fund. For Romania, for the Just Transition Fund was allocated EUR 1112 billion from NextGenerationEU and EUR 834 billion under MFF, a total of EUR 1947 billion. These funds are financial instruments for the implementation of the EGD at the national level, to which it was added interconnected projects from other fields circumscribed to EGD.

The RRP has six basic pillars [21]: transition toward a green economy; digital transformation; intelligent, sustainable, and inclusive economic growth; social and territorial cohesion; health and institutional resilience; and children, youth, education, and competences. The package of public investments and reforms is based on the Specific Country Recommendations 2019–2020. All the proposed investments and reforms of National RRP has to contribute 37% to the climate change target and 20% to the digitization target. The fields where NRRP could intervene are transport; environment, climate change, and capitalization of natural and heritage and tourism; agriculture and rural development; health; education; business environment; research, innovation, and digitization; improving the built fund; and resilience in crisis situations.

Concrete in terms of budget and allocations, the NRRP gave a total of EUR 29.2 billion to Romania with the following components: Water Management; Afforestation of Romania and the Protection of Environment; Waste Management; Sustainable Transport; Fund for the Wave of Renovation; Renewable Energy and Hydrogen Gas Infrastructure; Governmental Cloud and Interconnected Public Digital Systems; Fiscal Reforms and the Reform of Public Pensions; Support for Private Sector, Research, Development, and Innovation and Reform of State's Companies; Local Fund for Green and Digital Transition; Tourism and Culture; Fund for Hospital and for Increasing the Access to Health; Reforms in Social Field; Reform of Public Administration, Strengthening Social Dialogue and Increasing the Justice's Efficiency; and Educated Romania.

The complexity of the programs will also put pressure on Romanian's administrative capacity for implementation, generating unwanted situations in which central administration on a specific field renounced to a part of financial allocation because of the lack of administrative capacity (the case of the Ministry of Education) [33].

Regarding the legislative dimension, the intervention of a Romanian political actor, MEP, asking for the abandonment of EGD and for the reorientation of the funds for the national economies and health system is to be mentioned [21].

During the period of rotating the Presidency of the Council of the EU (January–June 2019), Romania proved its ability to contribute to the added-value of the EU [9]. On the first pillar from Romania's Rotating Presidency program, Europe of convergence, climate change was an important point. Facilitating reflections on the development of a common long-term vision toward climate neutrality and adopting the first regulation in the field of emissions standards for heavy vehicles were important achievements, along with the adoption of the proposal to amend the Directive Natural Gas, which, for the first time, provided a uniform and transparent regulatory framework for natural gas interconnections with third countries [9].

5.2. The Administrative Dimension at Romanian Level

The EGD is a strategy to interconnect the European policies in the field of climate change. The EU Climate Law proposed by the EC addresses the climate neutrality objective for 2050 and transposes it into EU legislation, encountering some obstacles from some Member States (Poland, Czech Republic and Romania), and the absence of a National Energy and Climate Plans [21]. The new initiative of the Romanian Ministry of Foreign Affairs for developing a pilot network of climate diplomacy represents an important incentive [34], aiming to develop a pragmatic answer to climate change through multilateral cooperation. It is the first administrative capacity development initiative under the impact of the EGD strategy.

The need for decarbonisation has led to changes in the overall strategies of governments and companies in terms of energy efficiency and renewable energy sources. In Romania, the decarbonisation of the energy sector is largely based on the support provided by the EGD, and the potential of renewable energy on the local market can become the engine of decarbonisation of the Romanian energy sector, as long as public initiatives are synchronized with business intentions [35].

In a research study dedicated to the southeastern part of Europe, a group of researchers analysed the need for a special approach to delivering the EGD (in energy field) [31]. According to the study, the energy market in Romania is fairly competitive, with too many electricity producers, the majority of producers being state-companies, and many household consumers covered by regulated tariffs (some recently opted for the competitive market). The evolution of the gas market toward liberalization was difficult. There are two main companies (OMV Petrom and Romgaz) dominating 95% of the production. The Governmental Emergency Ordinance (GEO) 114/2018 introduced a stop in the liberalization course for energy and gas price, because it introduced a 2% turnover tax on energy companies. The measures were revised, and the Romanian government is working now on defining the vulnerable consumers. In addition, the study indicates that Romania has one of the EU's biggest onshore wind farms and with a good potential on the shore of the Black Sea (announcement of the Romanian Hidroelectrica of enhancing renewable development to reach 300 MW capacity by 2026).

Romania and Slovenia are the only countries from the SEE region integrated into the EU power market, with an interconnection capacity of 7%, expected to increase to 10% [30]. The gas interconnection capacity is only 15% with other EU Member States, being the most vulnerable in the EU if Russian gas supplies are interrupted. One possible solution for additional interconnectors is the BRUA gas corridor project of the EU (linking Bulgaria, Romanian, Hungary, and Austria). The researchers concluded that for the implementation of the EGD in the SEE of the EU, a regional cross-border approach is needed, with an energy transition business and the participation of civil society driven by stakeholders' engagement. Regarding the implementation of EGD in the region, the above-mentioned authors suggested a design of an organizational structure (meaning designing the administrative capacity) to sustain the "tailor made solutions jointly developed by the governments in the region and the European Commission" [31].

The development of a circular economy is an opportunity to make Europe more competitive through a modern economy and a revitalized industry which would generate new jobs. At the national level, Romania needs to move toward a clear vision and strategy, promoting research, innovation, and good practice in the field of circular economy. Buildings are a key segment of EU energy efficiency policy, as they are responsible of about 40% of final energy consumption and CO_2 emissions. This area needs trained skills, qualified staff, and major investments. With regard to organic food system, the new European provisions on organic production will guarantee food quality, environmental protection, and animal welfare throughout the whole supply chain [36].

5.3. Outcomes of Romania's Implementation of EGD

The results of the EGD's implementation will be find in the Romania's sustainable development in the next years and decades. For the moment, only Romania's National Sustainable Strategy 2030 [37] is the framework for EGD implementation.

6. Discussions and Findings

Starting from the opportunities generated by the EGD, through this paper, an analysis of the authorities' decision-making process to coordinate and implement the EGD at European and national level of a Member State was operated. Taking into consideration the novelty of this strategy and the political debates regarding its implementation in the Central and Eastern EU, it was difficult to provide sustainable evidence that supports the findings. Because the model intends to provide a framework for analysis, the findings are accompanied by some recommendations that could orient further interpretations.

For the Romanian case, the lack of a national coordination at the first two levels (strategic and administrative) is detected. The EGD topic is not present in public debates, nor in the decisions' priorities. In Romania, political parties did not incorporate the EGD subject in their political program and discourse. The media does not show an interest for qualitative consequences of EGD, and only non-relevant opinions are presented to the public. The studies of epistemic communities are lacking. The Romanian public opinion and corporate's discourse is not convergent with the European one, and this is the reason for which the intervention of the epistemic groups is needed along with several studies with interdisciplinarity and rational approaches. The analysis model elaborated with this study on decision-making process' levels tries to offer arguments for decisions in the political and business areas and to offer a rational approach for a better analysis, understanding, and foresight of the current European debate in the field.

At strategic and administrative level, for the executive dimension, there are inaccuracies in the coordination of the decisions of political actors. The EGD is a European transversal policy requiring a transversal approach in the coordination and implementation. A good model to be used is the European affairs' coordination of Romanian Ministry of Foreign Affairs [11]. One starting point could be the introduction of the weekly agenda of discussions on EGD-related subjects. From an administrative point of view, creating a specific structure at the central level in each ministry with clear responsibilities on the EGD's implementation will support the future complex actions and projects with members of the European affairs departments from each ministry. Subsequently, at the local level, this structure could be replicated in the County Councils and City Councils.

At the executive level, the elaboration of a National Green Deal Plan is compulsory. It has to be elaborated by political, economic, and social actors. The discussions should focus on the European policies and their implementation rather than on the allocated funds. In this way, the European integration will advance, and the European procedures and mechanisms will become the administrative normative for Romanian authorities. The policymakers will have to take the regional approach into consideration, with territorial and social specificities for each region of Romania (especially for the disadvantaged area, former coal mining).

For a better preparation for possible crisis situations, the Multistreams Model for Decision Making could be followed [38]. In essence, the model is based on regional interdependencies, which consists in the pre-elaboration of a certain solution for a specific category of problems that might arise. The model is specifically designed for the administrative sector, approaching adaptability, political innovation, and sustainability.

For the legislative dimension, there are not any legislative measures taken by the Romanian authorities for transposing the newest EU legislation in the field circumscribed to the EGD nor to begin the debates on the EGD with all political actors represented in the National Parliament. There is a need for a large consensus between political and economic structures and social groups in order to generate a national EGD. Universities and epistemic communities deserve a special role for the valuable insights they generate.

The interdependent nature of the EGD will impact its implementation at the national and regional levels, and the actions and projects will have been designed by taking into account the sustainability and impact of outcomes of the circumscribed EGD's policies. The regional approach will assure the sustainability of the projects and claims for coordination and cooperation between national and European regions. Climate diplomacy will facilitate the achieving of the goals of the projects. That is why the local initiatives will play an important role and the political decisions from the national level have to encourage these initiatives.

For the third category of the analysis model, the outcomes, the last public opinion survey indicated that Romania scores poorly for climate actions emergency. There is a need for a promotion campaign organized by the involved authorities focused on the well-being of citizens, which will support the internal climate for the future administrative measures that will be adopted. The economic factors are the main limitations and arguments used by the Romanian authorities to motivate the lack of actions and measures in the direction of the EGD's implementation.

Last but not least, the development of administrative capacity for the implementation of EGD needs, especially for Romania, a large support from the educational actors and institutions which are called on for partnership programs and initiatives, mainly at the local level.

It can be seen that a deeper analysis could not be realized due to the lack of sufficient data for it. The topic of the present research is barely present at the strategic level, only tangential. One of the present research aims is to analyse the decision-making process for the implementation of the EGD and to signal the state of art by offering a new model of analysis and advice which could provide a useful guide and framework for action for decisions and administrative capacity. One of the directions for future research will be the observation of the progress in the EGD's implementation.

To conclude this chapter, the strengths for Romania for an efficient EGD implementation are as follows: (1) the strategic involvement in the transition to the green economy and green recovery; (2) the configuration in the NRRP of some projects which will impact important key fields of EGD, such as Water Management, Afforestation of Romania and the Protection of Environment, Waste Management, Sustainable Transport, the Fund for the Wave of Renovation, Renewable Energy and Hydrogen Gas Infrastructure, Governmental Cloud and Interconnected Public Digital Systems, and the Local Fund for Green and Digital Transition; and (3) Romania joined the four major UE's objectives as a global leader by (a) maintaining a leading position in the international negotiations regarding climate change and biodiversity, (b) consolidating the framework of international policies, (c) consolidating the network of Green Diplomacy—Romania has launched a concrete pilot project for building a network with some of its abroad diplomatic missions—and (d) intensifying bilateral efforts of international partners' actions and assuring comparative policies and actions for a Green Agenda for Western Balkans [10].

Regarding the weaknesses spotted for Romania's implementation of the EGD, the following could be mentioned: (1) the lack of a national strategy of implementation of the EGD in Romania; (2) the developmental and economic gaps for green transition; (3) the improbability of a just transitions of carboniferous regions from Romania; (4) missed opportunities of using the European funds from the Modernisation Fund—the calls from June 2021 and weakly hopeful for December 2021; and (5) many infringement procedures in the environment field opened by the European Commission for forest exploitation, for waste, and for the intervention ways on protect areas.

As "Fit for 55" [39,40] contains measures such as 40% of energy production from renewable resources, a "new price for pollution", and the renovations of buildings or zero carbon emission cars after 2035, Romania has a lot of work to do.

7. Conclusions

The EU's climate neutrality goals are very ambitious and will challenge the Member States differently. The transformational changes under the EGD will favour integrated, interdependent, and regional solutions. It is already a recognized fact that some regions will require a special attention (Central-Southeastern Europe especially) because of the different level of development, integration in the Internal Market, and political discourses. The new transversal growth model will be a good example for the entire world.

The answer to the first research question indicates that political factors are the most important for a decision, more explicit the political will. By targeting climate neutrality, the EU is aiming to become a global actor, proven with a model of good practice. In order for this to happen, political intentions have to manifest at the reginal and national levels, and cooperation projects have to start. The social factors influenced the implementation of the EGD due to the economic impact on short time well-being, but the adjustments supported by European policies, mechanisms, and measures will soften it. The public opinion support, the media debates, and constant preoccupation in this sense will reduce the reactions of "ideal strategy/dream strategy" of political decisions used to cover the lack of actions. The cultural elements impact the implementations of the EGD at European level, favouring or opposing this new way of thinking sustainably. It is about a new culture of sustainability that has to be spoken by the decisions (at strategic level) and the administrative capacity of each Member State that will start to operationalise it, each in its own specific manner. As to conclude this answer, yes, there are political, social, cultural, and economic factors that influence and impact the implementation of the EGD at the European level, and one good model of detecting these factors is the model of analysis of decisions proposed by this study.

The second question of the research identified specific Romanian characteristics which impedet the application of eh EGD. The economic situation for harmonizing the climate neutral objectives followed by the EGD strategy are indisputable, but the specific plans of actions for each of the policies involved and activity's sectors must follow. It is the political factor's duty to establish at a national level the political mechanisms and procedures, and the administrative structures will build the frame for implementation. The topic is almost neglected from public debates, from an interdisciplinary approach. The social factors indicated anxiety regarding the implementation of the EGD from the perspective of Energy Policy because of the economic impact that it will have on a personal level. The educational sector with epistemic communities could support the understanding of EGD and its efficiency for the well-being of citizens. From the cultural factors, the group representations are presented in the arguments of political factors regarding the EGD's implementation. The membership to the EU is the only cultural factor used by political decisions, to which victimisation is added for explaining the economic burden for Central and Eastern Member States. To conclude the answer to the second question, yes, there are specific political, cultural, and social factors for Romania for EGD's implementation, but they are specific for all Member States from Central and Eastern EU.

As for the hypothesis of the study, the research confirms the political decisions' impact on the EGD's implementation in Romania, and this influence is more predominant than in other Member States or at the EU level.

The new model of analysis for the EGD's implementation is a useful instrument for political decisions and for the national and local administrations to start a complex and collaborative application of this strategy. It is a good basis for the political analysis of the effects of the decision-making process of different strategies.

The Romanian political discourse showed that it is committed to the EU's actions to become the world's leader in climate-neutrality and green technologies. It is understood that the development of its administrative capacity will favour the interdependent and sustainable approach of the EGD. The present study demonstrated that the Romanian administrative capacity needs to be reinforced with specific organizational structure, coordinated at the central and local levels. The efficiency of the implementation of the EGD in Romania requires the elaboration of a National Green Deal Plan for Romania with support from epistemic communities, especially when a European Climate Law was launch by the EC. The media vectors have to be involved in public debates in order to raise awareness and for a better understanding of the EGD's philosophy and its long-term benefits for the general public [41–43]. Regional and local solutions generated in the EGD's framework will become models of good practice that will facilitate the transfer and local adaptations, aiming at the implementation of EGD.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Conflicts of Interest: The author declares no conflict of interest.

References

1. Parker, C.; Karlsson, C.; Hjerpe, M. Assessing the European Union's global climate change leadership: From Copenhagen to the Paris Agreement. *J. Eur. Integr.* **2017**, *39*, 239–252. [CrossRef]
2. Byskov Lindberg, M. The EU Emissions Trading System and Renewable Energy Policies: Friends or Foes in the European Policy Mix? *Politi. Gov.* **2019**, *7*, 105–123.

3. Szulecki, K. European energy governance and decarbonization policy: Learning from the 2020 strategy. *Clim. Policy.* **2016**, *16*, 543–547. [CrossRef]
4. Oberthür, S. Hard or Soft Governance? The EU's Climate and Energy Policy Framework for 2030. *Politi. Gov.* **2019**, *7*, 17–27. [CrossRef]
5. Vihma, A. What's Next for UN Climate Negotiations? The UNFCCC in the Era of Populism and Multipolar Competition. FIIA Briefing Paper 257. 2019. Available online: https://www.fiia.fi/wp-content/uploads/2019/03/bp257_un_climate_negotiation-1.pdf (accessed on 5 May 2021).
6. Grant, Z.; Tilley, J. Fertile soil: Explaining variation in the success of Green parties. *West Eur. Politi.* **2019**, *42*, 495–516. [CrossRef]
7. Thunberg, G. "We are Fighting for Everybody's Future", says Climate Activist Greta Thunberg at the EESC. Newsletter: EESC Info March 2019. Available online: https://www.eesc.europa.eu/en/news-media/eesc-info/042019/articles/68006 (accessed on 20 May 2021).
8. Thunberg, G. *No One Is Too Small to Make a Difference*; Penguin Books: New York, NY, USA, 2019.
9. Romania's Program to the Council of European Union. 1 January–30 June 2019. Available online: https://www.romania2019.eu/wp-content/uploads/2017/11/ro_program_ropres2019.pdf (accessed on 5 May 2021).
10. Ministry of Foreign Affairs of Romania, Tranziţia Verde/Pactul Ecologic European. 2021. Available online: http://www.mae.ro/node/55118, (accessed on 4 May 2021).
11. Government Decision no. 379/2013, Privind Organizarea și Funcționarea Sistemului Național de Gestionare a Afacerilor Europene în Vederea Participării României la Procesul Decizional al Instituțiilor Uniunii Europene și Pentru Completarea Art. 2 Alin. (1) din Hotărârea Guvernului nr. 8/2013 Privind Organizarea și Funcționarea Ministerului Afacerilor Externe. 2013. Available online: https://lege5.ro/Gratuit/gm3tcnrvg4/hotararea-nr-379-2013-privind-organizarea-si-functionarea-sistemului-national-de-gestionare-a-afacerilor-europene-in-vederea-participarii-romaniei-la-procesul-decizional-al-institutiilor-uniunii-europ (accessed on 5 October 2021).
12. Grix, J. *Demystifying Postgraduate Research: From M.A to Ph.D.*; The University of Birmingham Press: Birmingham, UK, 2001.
13. Băban, A. *Metodologia Cercetării Calitative*; Presa Universitară Clujeană: Cluj-Napoca, Romania, 2002.
14. Fujiwara, N.; Rizos, V.; Ferrer, J.N. *Study on Circular Economy Developments in the GCC Region and Opportunities for Collaboration with the European Union*; GFA Consulting Group GmbH: Hamburg, Germany, 2021.
15. EU Documents, Communication from the Commission. *The European Green Deal, COM (2019) 640 Final*; EU: Brussels, Belgium, 2019.
16. EU Documents, Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions. *Sustainable Europe Investment Plan. European Green Deal Investment Plan, COM (2020) 21 Final*; EU: Brussels, Belgium, 2020.
17. Claeys, G.; Tagliapetra, S.; Zachmann, G. How to Make the European Green Deal Work, Bruegel. 2019. Available online: https://www.jstor.org/stable/resrep28626 (accessed on 21 October 2021).
18. Saddi, M. The European Green Deal: Assesing Its Current State and Future Implementation, FIIA Working Paper, May 2020; p. 114. Available online: https://iris.unica.it/retrieve/handle/11584/313484/457281/WP114_European%20Green%20Deal.pdf (accessed on 25 October 2021).
19. Leonard, M.; Pissani-Ferry, J.; Shapiro, J.; Tagliapetra, J.; Wolff, G. The Geopolitics of Green Deal. *Policy Contrib.* **2021**, *4*. Available online: https://euagenda.eu/upload/publications/pc-04-grendeal-2021-1.pdf.pdf (accessed on 22 October 2021).
20. Timmermans, F. Frans Timmermans' Remarks at Eurelectric Power Summit 2021. Available online: https://ec.europa.eu/commission/commissioners/2019-2024/timmermans/announcements/frans-timmermans-remarks-eurelectric-power-summit-2021_en (accessed on 27 May 2021).
21. Elkerbout, M.; Egenhofer, C.; Nunez Ferrer, J.; Cătuți, M.; Kustova, I.; Rizos, V. *The European Green Deal after Corona: Implications for EU Climate Policy*; CEPS: Brussels, Belgium, 2020. Available online: https://www.ceps.eu/ceps-publications/the-european-green-deal-after-corona/ (accessed on 23 May 2021).
22. Ministry of European Investments and Projects of Romania, Planul Național de Redresare și Reziliență. 2021. Available online: Mfe.gov.ro (accessed on 25 May 2021).
23. European Commission. Recovery Plan for Europe. 2021. Available online: https://ec.europa.eu/info/strategy/recovery-plan-europe_en (accessed on 20 May 2021).
24. ESPAS. Global Trends to 2030: Challenges and Choices for Europe, An Interinstitutional EU Project. 2019. Available online: https://ec.europa.eu/assets/epsc/pages/espas/chapter1.html (accessed on 20 May 2021).
25. European Parliament Resolution of 17 April 2020 on EU Coordinated Action to Combat the COVID-19 Pandemic and Its Consequences, 2020/2616 (RSP). 2020. Available online: https://www.europarl.europa.eu/doceo/document/TA-9-2020-0054_EN.html (accessed on 22 May 2021).
26. European Parliament Resolution of 15 May 2020 on the New Multiannual Financial Framework, Own Resources and the Recovery Plan, 2020/2631(RSP). 2020. Available online: https://www.europarl.europa.eu/doceo/document/TA-9-2020-0124_EN.html (accessed on 22 May 2021).
27. Bassot, É. *Ten Opportunities for Europe Post-Coronavirus. Exploring Potential for Progress in EU Policy-Making*; EPRS: Brussels, Belgium, 2020.

28. World Economic Forum. A Vision for a Sustainable Battery Value Chain in 2030 Unlocking the Full Potential to Power Sustainable Development and Climate Change Mitigation, Geneva, Swizerland. 2019. Available online: http://www3.weforum.org/docs/WEF_A_Vision_for_a_Sustainable_Battery_Value_Chain_in_2030_Report.pdf (accessed on 20 May 2021).
29. Ciot, M.-G.; Sferlic, R. EU's Interdependencies in the COVID-19 Crisis. *Rom. J. Eur. Aff.* **2021**, *21*, 119–133.
30. Fisher, L. *Financing a Sustainable and Competitive Economy. Next Steps for the EU*; Wilfried Martens Centre for European Studies: Brussels, Belgium, 2019. Available online: https://www.martenscentre.eu/publication/financing-a-sustainable-and-competitive-economy-next-steps-for-the-eu/ (accessed on 22 May 2021).
31. Cătuți, M.; Kustova, I.; Egenhofer, C. *Delivering the European Green Deal for Southeast Europe: Do We Need a Regional Approach?* CEPS: Brussels, Belgium, 2020. Available online: https://www.ceps.eu/ceps-publications/delivering-the-european-green-deal-for-southeast-europe/ (accessed on 23 May 2021).
32. OECD. *Accelerating Climate Action: Refocusing Policies through a Well-Being Lenses*; OECD Publishing: Paris, France, 2019. Available online: https://doi.org/10.1787/2f4c8c9a-en (accessed on 20 May 2021).
33. European Commission. Special Eurobarometer 490 Climate Change Report. 2019. Available online: https://ec.europa.eu/commfrontoffice/publicopinion (accessed on 20 May 2021).
34. Ministry of Foreign Affairs of Romania. Găzduirea de Către Ministrul Afacerilor Externe Bogdan Aurescu a Evenimentului de Lansare a Rețelei–Pilot de Diplomație Climatică a României. 2021. Available online: https://www.mae.ro/en/node/56098 (accessed on 27 May 2021).
35. EY România. Raport EY România: Energiile Regenerabile pot Accelera Decarbonizarea Sectorului Energetic din România, dar Inițiativele Publice Trebuie Să Se Sincronizeze cu Intențiile de Business. 2021. Available online: https://www.ey.com/ro_ro/news/2021/04/ey-romania-report--renewables-can-accelerate-the-decarbonisation (accessed on 20 May 2021).
36. Clubul Fermierilor Români. Poziția Comună a Clubului Fermierilor Români și European Landowners' Organization (ELO) privind Pactul Ecologic European. 2020. Available online: https://cfro.ro/pozitie-comuna-privind-green-deal/ (accessed on 20 May 2021).
37. Department of Sustainable Development. Romania's Sustainable Development Strategy 2030. 2021. Available online: http://dezvoltaredurabila.gov.ro/web/about/ (accessed on 25 May 2021).
38. Ciot, M.-G. European decision-making model in pandemic crisis. In *Searching for Decision-Making Models in International Politics*; Ciot, M.-G., Ed.; Editura Presa Universitară Clujeană: Cluj-Napoca, Romania, 2020; pp. 13–30.
39. European Commission. Fit. for 55. 2021. Available online: https://www.consilium.europa.eu/en/policies/green-deal/eu-plan-for-a-green-transition/# (accessed on 27 October 2021).
40. Deutche Welle. Project-E.ro: Fit. for 55, Proiectul UE care Obligă România la Reforme Radicale. 2021. Available online: Dw.com/ro/project-ero-fit-for-55-proiectul-ue-care-obligâ-romănia-la-reforme-radicale/a-58289556 (accessed on 27 October 2021).
41. European Commission. Pactul Verde European: Comisia Propune Transformarea Economiei și a Societății UE în Vederea Atingerii Obiectivelor Ambițioase în Materie de Climă. 2021. Available online: https://ec.europa.eu/commission/presscorner/detail/ro/ip_21_3541 (accessed on 27 October 2021).
42. Ziarul Financiar. Provocările României în Faţa Fit. for 55, Pachetul Care va Schimba Industria Europeană în Numele Aerului Curat. România Deja şi-a Atins Ţinta Reducerii de Emisii de CO_2 şi este Una dintre Cele Mai Verzi Ţări la Producţia de Energie. 2021. Available online: https://www.zf.ro/companii/provocarile-romaniei-fata-fit-for-55-pachetul-schimba-industria-20190054 (accessed on 27 October 2021).
43. Economica. Care este Impactul Pachetului European "Fit. for 55" Asupra Viitorului Sectorului Clădirilor în România. 2021. Available online: https://www.economica.net/care-este-impactul-pachetului-european-fit-for-55-asupra-viitorului-sectorului-cladirilor-in-romania_525340.html (accessed on 27 October 2021).

sustainability

Article

CO_2 Emissions Embodied in International Trade and Economic Growth: Empirical Evidence for OECD and Non-OECD Countries

Hyunsoo Kang

Department of International Trade, Wonkwang University, Iksan 54538, Korea; agkang75@wku.ac.kr

Abstract: This study examined the relationship between CO_2 emissions embodied in international trade and economic growth for OECD and non-OECD countries between 2005 and 2015. Unlike the traditional environmental Kuznets curve (EKC) hypothesis, which does not account for trade patterns, CO_2 emissions embodied in trade balances were adopted in several models. To analyze the panel series, this study utilized econometric procedures: panel regression, the panel unit root test, the panel cointegration test, and panel Granger causality. To investigate evidence supporting the pollution haven hypothesis (PHH), this study constructed an equation including CO_2 emissions embodied in net exports as a proportion of consumption. The results from the panel regression model validated the EKC hypothesis, even considering the CO_2 emissions embodied in trade. Results of the panel unit root, panel cointegration, and Granger causality tests showed that CO_2 emissions embodied in trade and economic growth have bi-directional Granger causality. This study provided evidence for the PHH, although some upper countries of net exporters or net importers for CO_2 emissions can be observed. This study highlighted the need to intensify international cooperation to decrease environmental pollutants in both developed and developing countries, and considered the importance of CO_2 emissions embodied in trade by expanding globalization.

Keywords: CO_2 embodied in trade; economic growth; the EKC hypothesis; pollution haven; Granger causality

Citation: Kang, H. CO_2 Emissions Embodied in International Trade and Economic Growth: Empirical Evidence for OECD and Non-OECD Countries. *Sustainability* **2021**, *13*, 12114. https://doi.org/10.3390/su132112114

Academic Editors: Jun Yang, Ayyoob Sharifi, Baojie He and Chi Feng

Received: 5 October 2021
Accepted: 28 October 2021
Published: 2 November 2021

1. Introduction

Carbon dioxide emissions have crucially affected natural ecosystems and sustainable development throughout human history, but controversy remains regarding global climate change [1]. While the Covid-19 pandemic has temporarily reduced emissions, carbon dioxide emission levels are still at record highs and rising. Under such conditions, the international community have begun to discuss carbon neutrality. Carbon neutrality ensures that net carbon emissions are zero, so that the concentration of carbon dioxide is no longer increased, also referred to as "Net-Zero". Carbon neutrality can be achieved by balancing carbon dioxide emissions from human activities with global carbon dioxide absorption. For this purpose, we need to reduce greenhouse gases, and the substantial emissions must be reduced to zero by increasing the amount of absorption, such as through forest restoration, or removed using reduction technology.

However, carbon emissions are the result of economic activities, and energy consumption is still a source of economic growth [2]. If we ignore economic growth and emphasize reducing greenhouse gases from carbon dioxide emissions, with zero economic growth, capital accumulations can be stopped early, and long-term economic growth can be disrupted [3]. The relationship between CO_2 emissions and economic growth has been analyzed and most studies are based on the environmental Kuznets curve (EKC) hypothesis [4–6]. The EKC hypothesis implies that environmental deterioration first rises and then falls as economic development proceeds. This has become one of the "stylized facts" of environmental economics, but it has been varied for different indicators, with the trend reversing [7,8]. In particular, the EKC hypothesis has an advantage in the setup of the model based on the nonlinearity of the independent variable, the U-shaped or N-shaped relationship of the CO_2 emissions. Furthermore, environmental policy can be presented through income turning points. In recent years, the EKC hypothesis has expanded to analyze various factors such as trade openness, energy efficiency, industrial structure, food security, and technology innovation [9–12].

With regard to the role of the EKC in carbon emissions, it can be considered an important aspect of international trade in economic development and the CO_2 emissions embodied in international trade. Historically, international trade played an important role in economic growth through the efficient allocation of resources. In addition, globalization steadily increased international trade and specialization, and therefore, gains from trade now vary between exporting and importing countries. In this process, production is mainly generated in regions with poor environmental performance, but consumption mainly occurs in regions with strong environmental legislation. Consequently, we can expect the separation of production and consumption in the global market and the implications of international trade for global pollutants [13].

The differences between production and consumption of products result in the international trade of products; in the same way, the amount of carbon indirectly contained in product in the international trade is the difference between the amount of carbon emissions from the production process and the amount of carbon emissions from consumption that are indirectly contained. That is, we consider both CO_2 produced in one country through domestic production and CO_2 embodied in trade. For example, China is a net exporter of CO_2 emissions but the United States is a net importer, and in general, developed countries consume more CO_2 than they emit, while developing or poor countries have the opposite situation.

Previous studies have pointed out the divergence and transfer of CO_2 emission trends between developed and developing countries with rapidly increasing international trade [14,15]. Peters et al. [15] mentioned that international trade causes a gradual separation between consumption and production, and reduces domestic pollution at the expense of foreign producers. Hotak et al. [1] highlighted the responsibility of high-income countries that are mainly emission-importers for the global emission, and for the improvement of energy saving, including emission intensive technology.

This study aimed to investigate the nexus between CO_2 emissions embodied in international trade and economic growth by adopting panel data for OECD and non-OECD members between 2005 and 2015, based on the EKC hypothesis. The divided countries between OECD and non-OECD are useful to investigate by national income levels, trade scales, and trade patterns. Furthermore, this study analyzed the causal relationship of estimated variables using Granger causality, and quantified the situation of CO_2 emission exporters and importers in international trade based on the concept of the pollution haven. Therefore, this study addressed a small niche in the literature on the EKC hypothesis by focusing on the role of CO_2 emissions embodied in international trade. This study also emphasized international cooperation and efforts to reduce CO_2 emissions to avoid environmental issues, and presented a need for continuous monitoring of CO_2 emissions embodied in international trade. Through this study, it is possible to get some answers to questions about who has more responsibility in CO_2 emissions, and who has more impact on CO_2 emissions embodied in international trade.

The remainder of this study is organized as follows. Section 2 introduces the previous literature on the relationship between CO_2 emissions and economic growth, based on CO_2 emissions embodied in international trade. Section 3 describes the empirical model specification and data description. Sections 4 and 5 present the results and conclusions, including policy implications, respectively.

2. Literature Review

The EKC hypothesis explains the empirical existence of a relationship between environmental pollution and economic growth, especially the inverted U-shaped nexus between

CO_2 emissions and income level [16]. This section introduces literature on the basic aspects of the EKC model and the importance of CO_2 emissions embodied in international trade.

The old debates on the EKC hypothesis are mainly based on the fundamental determinants of long-term improvements in environmental correction and the changes in a certain income threshold [17]. Traditionally, Grossman and Krueger [4] demonstrated an inverted U-shaped relationship between environmental degradation and income level, in which environmental pollution levels rise in the early stage of economic growth, while we can experience a reduction in pollution beyond the income threshold. In addition, this inverted U-shape was assumed to be a dynamic process of economic structural changes and environmental quality through three channels: scale effect, composition effect, and technical effect [18–21].

Since the establishment of the World Trade Organization system, several studies have analyzed the economic effect of increasing international trade, especially in terms of expanding on the EKC hypothesis. Mahmood et al. [19] investigated the relationship between trade openness and CO_2 emissions in Tunisia from 1971 to 2014. They suggested that the effect of increasing trade openness contributes to a positive effect on CO_2 emissions and that an increase in foreign trade is associated with environmental degradation. Similarly, Managi et al. [20] found that trade is beneficial to the environment in OECD countries, while it has detrimental effects in non-OECD countries. Bernard and Mandal [21] examined the impact of trade openness on environmental quality using a dynamic panel model for 60 emerging countries and highlighted that CO_2 emissions and trade have a crucial effect on negative environmental quality.

Most previous studies utilized trade openness, which is measured as the sum of exports and imports as a percentage of gross domestic product (GDP), capturing the nexus between trade and CO_2 emissions [19–21]. However, a more complex global value chain enables a country to import carbon-intense products, and more cross-border transfer of production processes induce the reallocation of energy use [1]. Therefore, existing trade openness has a disadvantage in that the recent international trade situation is not well reflected.

From another perspective, Peters and Hertwich [13] argued that international trade plays a significant role in economic development by providing a mechanism for efficiently allocating resources. They also mentioned that production may occur in regions with poor environmental performance, without costing externalities. That is, if environmentally unfriendly production was moved to other regions, the originating country would enjoy a reduction in CO_2 emissions or environmental pollution, and then the issue of pollution embodied in international trade can be stimulated by the separation of production and consumption in the global market. Similarly, Hotak et al. [1] addressed how carbon trade balances are related to carbon emissions under fragmented production, including 58 countries during the period between 1990 and 2014. They provided the important implications of emissions embodied via international trade and mentioned that emission importers, partially high-income countries, need to have more responsibility for global emission issues.

Although this study tried to analyze the nexus between pollution embodied in trade and economic growth, focusing on the existing EKC hypothesis, there are several research gaps. First, this study constructed an economic model by expanding on the EKC hypothesis, including CO_2 emissions embodied in international trade. That is, this study suggested important implications for pollution emissions separated from production and consumption through a comparison of traditional EKC and expanded EKC hypotheses. Second, during the period of 2005 to 2015, this study compared the panel data from OECD and non-OECD countries; therefore, conclusions offered more plentiful implications by income levels. Finally, this study adopted the concept of the pollution haven using pollution embodied in trade, and compared net exporters and importers for CO_2 emissions embodied in international trade.

3. Methodology and Data

3.1. Traditional EKC Model

Traditional EKC was hypothesized as the nexus between various indicators of environmental degradation and income, which implies that the environmental impact indicator had an inverted U-shaped function of income and also a quadratic function of the logarithm of income [7]. In addition, since Grossman and Krueger [4] highlighted the EKC hypothesis, this approach has been the popular methodology, including ambient pollution concentrations and aggregate emissions.

First, this study introduced the one-person model of Andreoni and Levinson [21], which assumed the utility of agents from the consumption of one private good, denoted *C*, and from pollution, *P*. The model of Andreoni and Levinson [21] is very useful for supporting economic modeling by CO_2 emissions and economic growth, and it includes the main channel between pollution and energy consumption. The simple utility function is as follows:

$$U = U(C,\ P) \tag{1}$$

where $U_C > 0$ and $U_P < 0$. In addition, pollution is an increasing function of *C* and a decreasing function of environmental effort, *E*:

$$P = P(C,\ E) \tag{2}$$

Finally, each individual maximizes *U* subject to a limited endowment, *M*. Consider a simple linear utility function substituting Equation (2) into Equation (1) as follows:

$$U = -C^a E^b \text{ subject to } C + E = M \tag{3}$$

In Equation (3), *C* is gross pollution before abatement and $C^a E^b$ represents abatement. Solve Equation (3) and determine the optimal levels:

$$C^* = \frac{a}{a+b}M,\ E^* = \frac{b}{a+b}M \tag{4}$$

Substituting Equation (4) into Equation (3), we obtain the optimal pollution level:

$$P^*(M) = \frac{a}{a+b}M - \left(\frac{a}{a+b}\right)^a \left(\frac{b}{a+b}\right)^b M^{a+b} \tag{5}$$

Differentiating Equation (5) with respect to *M*:

$$\frac{\partial P^*}{\partial M} = \frac{a}{a+b} - (a+b)\left(\frac{a}{a+b}\right)^a \left(\frac{b}{a+b}\right)^b M^{a+b-1} \tag{6}$$

Therefore, the optimal pollution-income paths of EKC depend on "$a + b$", in which abatement exhibits increasing returns to scale if $a + b > 1$, and then evidence of an inverted U-shaped relationship exists.

In terms of Equation (6) and the EKC hypothesis, this study constructed the traditional EKC model as follows:

$$CO_2 = f(\text{GDPP, EC, REEC}) \tag{7}$$

where CO_2 is CO_2 emissions, GDPP is GDP per capita, EC is energy consumption, and REEC is renewable energy consumption. In various studies, the nexus of CO_2 emissions, energy consumption, and economic growth of independent variables for Equation (7) is related to the input factor in production, and energy consumption affects both economic growth and the level of CO_2 emissions [22–30]. Also, Leitão and Lorente [29] denoted that renewable energy allowed decreasing climate change and greenhouse gas, and this negative relationship between the renewable sources and CO_2 emissions stimulated energy efficiency within the energy mix. Furthermore, this study utilized the panel data set to estimate pollution across the OECD and non-OECD countries, and the econometric model for country levels (i) taking a natural logarithm is as follows:

$$\ln(CO_{2it}) = \alpha_0 + \alpha_1 \ln(GDPP_{it}) + \alpha_2 \ln(EC_{it}) + \alpha_3 \ln(REEC_{it}) + \delta_{it} \quad (8)$$

In addition, to identify the non-linear form of the EKC, this study included the GDPP squared variable in Equation (8) and specified the model.

3.2. CO_2 Emissions Embodied in International Trade on the EKC Model

Emissions embodied in trade (EET) can explain the relationship between the production and consumption of the country for global climate change while calculating the EET can become complex because of the linkage of production and consumption systems through international trade data [13]. Nevertheless, the most general method for EET is environmental input-output analysis (IOA), which requires the decomposition of IOA into domestic and traded components [31]. In particular, Peters and Hertwich [13] utilized a simple IOA to obtain EET and the total CO_2 emissions for each country are as follows:

$$f_k = F_k(I - A_{kk})^{-1}\left(y_{kk} + \sum_l e_{kl}\right) \quad (9)$$

where f_k is the total CO_2 emissions for country "k", F_k is a row vector with each element for CO_2 emissions per unit output, I is the identity matrix, y_{kk} is the products produced and consumed domestically in country "k", and e_{kl} is the bilateral exports from country "k" to country "l". In particular, e_{kl} is divided by intermediate and final consumption, and then domestic demand on domestic production (country "k") and the EET from country "k" to country "l" are as follows:

$$f_{kk} = F_k(I - A_{kk})^{-1} y_{ll} \quad (10)$$

$$f_{kl} = F_k(I - A_{kk})^{-1} e_{kl} \quad (11)$$

Therefore, the total emissions embodied in exports (f_k^{ex}) from country "k" to all other countries and the total emission embodied in imports (f_k^{im}) from all other countries to country "k" are as follows:

$$f_k^{ex} = \sum_l f_{kl} \quad (12)$$

$$f_k^{im} = \sum_l f_{lk}. \quad (13)$$

The important indicator discussed in this study is the balance of emissions embodied in trade (BEET), (As a result of analyzing CO_2 emissions for 87 countries by Peters and Hertwich [13], approximately 21.5% of the global CO_2 emissions were embodied in international trade.) and the BEET for country "k" can be calculated by the difference between total emissions embodied in exports and imports ($f_k^{ex} - f_k^{im}$). If the BEET for one country is greater (or less) than zero, that country can be regarded as a net emission exporter (or importer). As mentioned in previous section, the main issue of this study is to investigate the relationship between CO_2 emissions embodied in international trade and economic growth, and the BEET is a key factor that can be identified as direct and indirect channels of trade. Similar to Hotak et al. [1], this study constructed a CO_2 emissions equation including the EKC hypothesis as follows:

$$BEET_{it} = \beta_0 + \beta_1 \ln(GDPP_{it}) + \beta_2 \ln(EC_{it}) + \beta_3 \ln(REEC_{it}) + \varepsilon_{it} \quad (14)$$

where $BEET_{it}$ is the balance of CO_2 emissions embodied in trade for country "i". Equation (14) is very close to Equation (8) which includes the EKC hypothesis, while the dependent variable in

Equation (14) contains the pollution embodied in trade to determine the nexus between net emission exporters (or importers) and economic growth. In addition, Equation (14) is accomplished by a model specification to test for nonlinearity, including the GDDP squared variable.

3.3. Econometric Procedures: Pooled OLS, Fixed Effects, Random Effects

Panel data can be referred to multilevel data including two-level structures of upper and lower levels (for example, upper and lower levels can be "country" and "time", respectively). In addition, panel analysis has some advantages, such as analyzing the common and individual behaviors of groups, containing more information, and minimizing estimation bias [32]. In this study, three types of panel data regressions were utilized as pooled ordinary least squares (OLS), fixed effects, and random effects. The pooled OLS is a simple method of estimating OLS, which needs to qualify for assumptions of homogeneity across panel groups, unbiased estimator, and homoscedasticity [32]. However, based on the properties of panel data, the pooled OLS can violate these assumptions; therefore, we may adopt another panel regression estimation to solve this problem. Among the general alternative estimations of pooled OLS, fixed effects can explore the relationship between predictor and outcome variables within a group including heterogeneity of time-invariant error and time-varying error. In addition, random effects assume that error terms within the model are not constant but random variables; therefore, we can include time-invariant variables and allow generalization of the inferences beyond the sample [33]. To determine the appropriate regression analysis method, this study ran a Hausman test to determine whether the unique errors were correlated with regressors, as well as using the Breusch-Pagan Lagrange multiplier to determine whether variances across entities were zero.

3.4. Panel Unit Root Test, Panel Cointegration, and Panel Granger Causality Test

Before testing the relationship between two variables, especially the causality relation, we need to investigate the stationarity of each variable to gain statistical power and to avoid spurious regression [34]. First, this study utilized several types of tests for variables, such as the Levin-Lin-Chu [35], Harris-Tzavalis [36], Breitung [37], Im-Pesaran-Shin [38], Fisher-type [34], and Hadri [39]. In particular, the previously mentioned tests (except for Hadri) have the null hypothesis that all the panels contain a unit root, and all test results show panel specific means and time trends in the model.

After testing the stationarity for each variable, some non-stationary series can be stationary by the first difference, known as I(1). If some data tend to wander by non-stationary series, the result of cointegration analysis implies that there will not be a long-run equilibrium relationship among the series. Therefore, to check the cointegration in panel data, this study used Pedroni's cointegration test [40] which includes the null hypothesis of no cointegration in non-stationary panels. Pedroni [40] introduced cointegration test statistics that allow for heterogeneity in the panels, both the long-run slope and intercept coefficients [41]. This test has some advantages in that does not consider normalization and simply shows the degree of evidence among variables.

Finally, this study estimated the causal relationships between the two variables. Granger [42] introduced a methodology for analyzing causal relationships in time series as follows:

$$y_t = \pi + \sum_{k=1}^{K} \delta_k y_{t-k} + \sum_{k=1}^{K} \sigma_k x_{t-k} + \delta_t \quad \text{with } t = 1, \ldots, T \tag{15}$$

where x_t and y_t are two stationary series. Equation (15) means that if past values of x are significant of the current value of y, then we can conclude that x has a causal relationship for y based on the F test as follows:

$$H_0: \sigma_1 = \cdots = \sigma_K = 0$$

As this study utilized the panel series, an extension Granger causality could be tested, as proposed by Dumitrescu and Hurlin [43]:

$$y_{i,t} = \pi + \sum_{k=1}^{K} \delta_{ik} y_{i,\, t-k} + \sum_{k=1}^{K} \sigma_{ik} x_{i,\, t-k} + \delta_{i,t} \\ \text{with } i = 1, \ldots, N \text{ and } t = 1, \ldots, T \tag{16}$$

where $x_{i,t}$ and $y_{i,t}$ are estimated variables for individual "i" in period "t". The powerful aspects of the Dumitrescu and Hurlin causality test can be designed to detect causality at the panel level by providing for the W-bar (the average Wald statistic), Z-bar (the standardized statistic when Wald statistics are independently and identically distributed across individuals), and Z-bar tilde (the approximated standardized statistic for a fixed T dimension with $T > 5 + 3\ K$) [44].

3.5. Pollution Haven Hypothesis

Previous studies criticized the EKC hypothesis, which may not account for international trade patterns [45]. In addition, the EKC hypothesis does not explain the phenomenon that some developed countries transfer their CO_2 emissions for developing or less developed countries through international trade, while the pollution haven hypothesis (PHH) can partially help understand the trade pattern on environmental issues between North and South problems. According to Cole [45], the PHH implies that polluting industries in developed countries relocate to jurisdictions with less environmental regulations, for example developing countries, and the PHH can be identified by using net exports as a proportion of consumption (NETXC) as follows:

$$\text{NETXC}^{j}_{ikt} = \frac{X^{j}_{ikt} - M^{j}_{ikt}}{P_{ikt} - X^{w}_{ikt} + M^{w}_{ikt}} \tag{17}$$

where X, M, and P indicate exports, imports, and production, respectively. For example, X^{j}_{ikt} is exports from developed country "i" to developing country "j", sector "k", and time period "t", with superscript w meaning the rest of the world. According to Equation (17), this study applied "CO_2 emission embodied on NETXC" (CO_2NETXC) to investigate the existence of pollution havens within OECD and non-OECD countries as follows:

$$\text{CO}_2\text{NETXC}^{j}_{ikt} = \frac{f^{ex}_{ik} - f^{im}_{ik}}{\text{FDCO}_2} \tag{18}$$

where $(f^{ex}_{ik} - f^{im}_{ik})$ is CO_2 emissions embodied in net exports as a proportion of consumption and $FDCO_2$ is CO_2 emissions embodied in domestic (country "i") final demand. Equations (17) and (18) are very similar, but Equation (18) involves the CO_2 emissions embodied in the trade variable. If the level of CO_2NETXC falls (or approaches zero), this indicates that one country's proportion of CO_2 emissions embodied in net exports on CO_2 emissions embodied in domestic final demand also decreases. That is, in the environmental pollution industry, one country experiences a reduction in its specialization relative to its consumption, and there will be no proof supporting the PHH.

3.6. Descriptive Data

This study used panel data during the period of 2005 to 2015 for 36 OECD countries and 26 non-OECD countries. (According to the OECD database, there are 28 non-OECD countries, while this study utilizes only 26 countries, due to missing data (excluding Hong Kong and Chinese Taipei). The CO_2 emissions embodied in international trade data were obtained from OECD.Stat and the rest of the data were collected from the World Bank Open database. Table 1 presents the name of the variable, the definition (including unit), and the source of each variable.

Table 1. Definition and source of estimated variables.

Variables	Definition (Units)	Source
BEET	CO_2 emissions embodied in gross export, balance (Tonnes, Millions)	OECD. Stat (https://stats.oecd.org/Index.aspx?DataSetCode=IO_GHG_2019) (accessed on 25 August 2021)
GDPP	GDP per capita, PPP (constant 2017 international $)	World Bank Open Data (https://data.worldbank.org/) (accessed on 25 August 2021)
EC	Energy Use (kg of oil equivalent per capita)	
REEC	Renewable energy consumption ($ of total final energy consumption)	
CO_2	CO_2 emissions (kt)	

Table 2 indicates the descriptive statistics of each variable, especially by the characteristics of the panel data set, and standard deviation, and min/max value are divided by overall, between, and within, respectively. In particular, deviations of "between the panel" are greater than deviation of "within the panel", implying that each variable is not significantly different within the countries than between the countries.

Table 2. Descriptive data.

Variables		Mean	Std. Dev.	Min	Max	Observations
BEET	Overall	1.95	221.78	−1021.32	1670.67	N = 682 n = 62 T = 11
	Between		221.64	−782.01	1460.19	
	Within		27.95	−240.94	212.43	
GDPP	Overall	32,877.37	20,128.13	2120.55	114,889.2	
	Between		20,167.16	2808.60	108,062.1	
	Within		2097.53	21,859.94	47,648.67	
EC	Overall	3405.53	2597.36	251.27	18,178.14	
	Between		2581.40	326.79	16,150.35	
	Within		424.85	−2219.93	5621.96	
REEC	Overall	20.60	18.77	0.01	91.64	
	Between		18.73	0.01	89.10	
	Within		2.55	10.37	31.02	
CO_2	Overall	438,671.90	1,254,303	1650	9,936,680	
	Between		1,248,438	2103.63	8,281,222	
	Within		193,816.2	−2,023,460	2,094,130	

Table 3 indicates the top 10 countries of the CO_2 emissions trade balance in 2015. The primary net exporters (importers) are China, the Russian Federation, and India (the United States, Japan, and the United Kingdom). Only one country, Korea is both a net exporter and an OECD country, while only one country, Saudi Arabia is both a net importer and a non-OECD country.

Figures 1 and 2 illustrate the simple relationship between CO_2, BEET, and GDPP. Although almost all results have a slightly negative relationship, the fitted lines between CO_2 emissions and GDPP are identified as having a negative relationship, and this implies that total countries tend to decrease CO_2 emissions by increasing GDP per capita. Also, the negative relationship between BEET and GDP per capita exists more strongly in the case of non-OECD countries and the fitted line of non-OECD countries cross the zero level of BEET, and this indicated that non-OECD countries tend to be net importers on CO_2 emissions embodied in trade by increasing GDP per capita.

Table 3. The top ten countries of the CO_2 emissions embodied in gross export balance in 2015 (Tonnes, Millions).

Rank	Country	2015	Rank	Country	2015
1	China	1308.842	1	United States †	−785.334
2	Russian Federation	320.738	2	Japan †	−158.236
3	India	124.153	3	United Kingdom †	−142.519
4	South Africa	100.552	4	France †	−131.613
5	Singapore	52.496	5	Germany †	−84.608
6	Korea †	48.207	6	Italy †	−75.838
7	Kazakhstan	46.252	7	Saudi Arabia	−55.027
8	Malaysia	28.571	8	Switzerland †	−48.831
9	Thailand	28.351	9	Turkey †	−38.925
10	Viet Nam	20.783	10	Australia †	−33.578
	Top 10 average	207.89		Top 10 average	−155.45

Notes: † indicates OECD member.

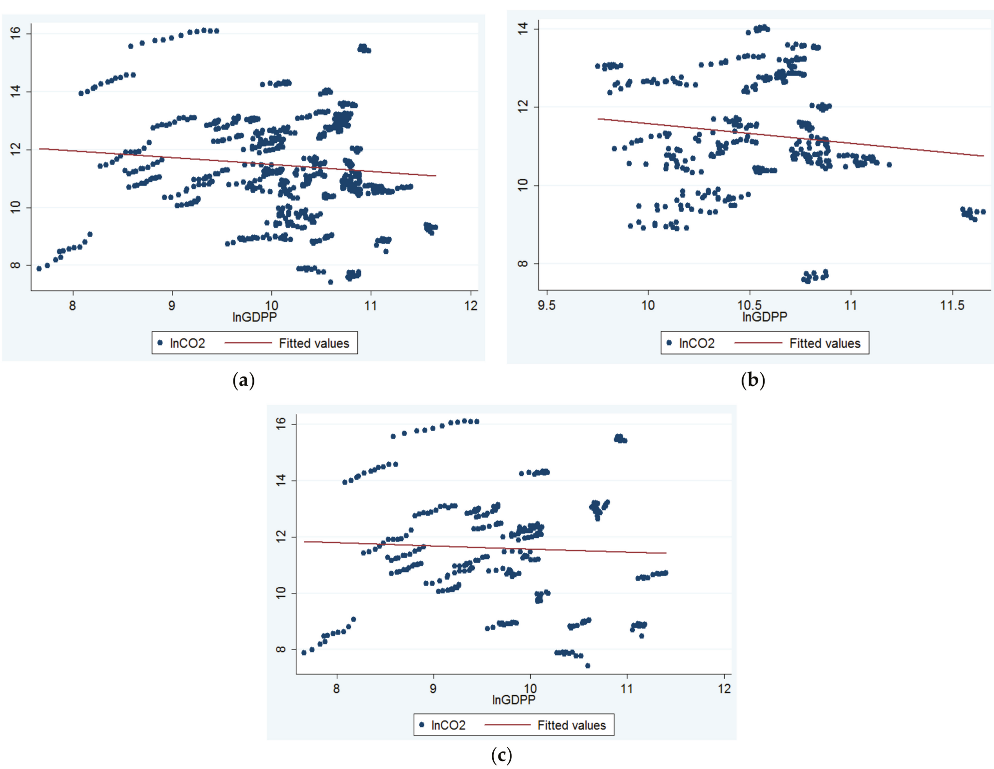
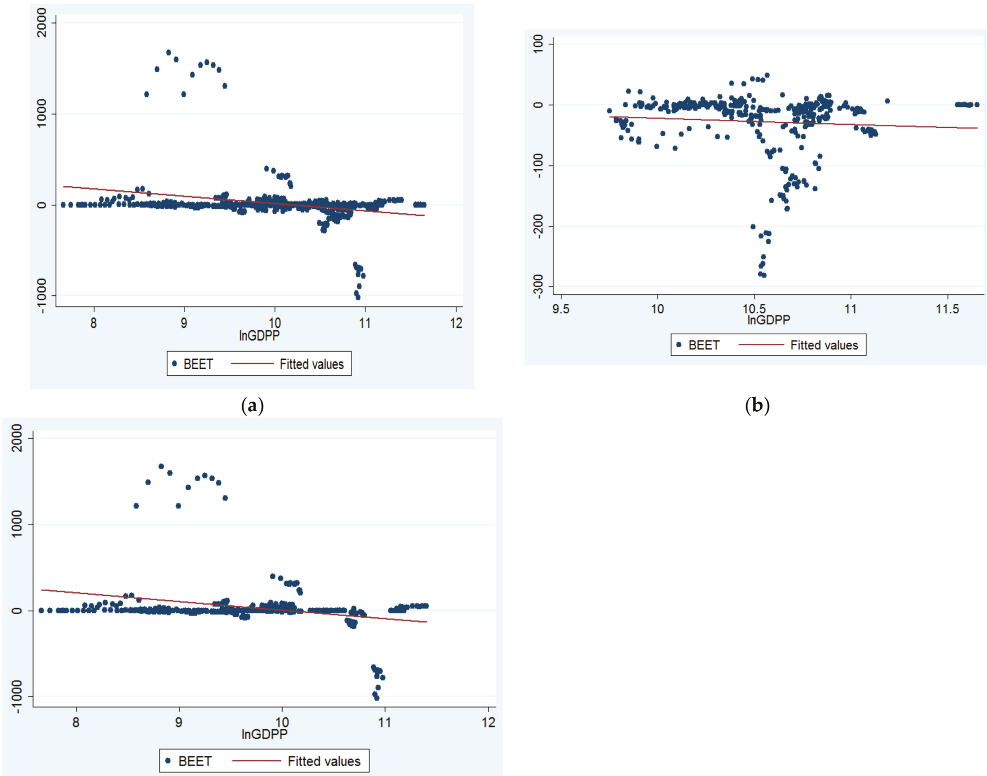


Figure 1. Simple relationship between CO_2 and GDP per capita. (**a**) Total countries. (**b**) OECD countries. (**c**) Non-OECD countries.



(**a**) (**b**)

(**c**)

Figure 2. Simple relationship between BEET and GDP per capita. (**a**) Total countries. (**b**) OECD countries. (**c**) Non-OECD countries.

4. Empirical Results

4.1. Panel Regression Results

Tables 4–6 show the results of the panel regression for the traditional EKC model with respect to the pooled OLS, fixed effects, and random effects. Model 1 presents the linear relationship between CO_2 emissions and economic growth, and Model 2 shows the quadratic form using the GDPP squared. In the pooled OLS results of Model 1, the coefficients of GDP per capita (GDPP) for total and non-OECD countries are negative and statistically significant at the 1% level. However, the coefficient of GDPP for OECD countries is positive and statistically significant at the 5% level, implying that the economic growth of OECD countries results in a 0.11% increase in CO_2 emissions. The energy consumption (EC) for total countries, OECD countries, and non-OECD countries has a positive effect on CO_2 emissions while the coefficient of EC for non-OECD countries has the largest value (=3.23), with statistical significance at the 1% level. In the pooled OLS results of Model 2, the coefficients of GDPP and GDPP squared for total countries are positive and negative, respectively, and are statistically insignificant. On the other hand, in OECD and non-OECD countries, there is evidence of an inverted U-shaped relationship with a positive GDPP and a negative GDPP squared.

Table 4. Panel regression results of EKC model for Total countries.

Variable	Total Countries (Number of Observations = 682)					
	Pooled OLS		Fixed Effects		Random Effects	
	Model 1	Model 2	Model 1	Model 2	Model 1	Model 2
ln(GDPP)	−1.33 *** (−7.43)	5.12 (0.58)	0.48 *** (13.04)	2.65 *** (7.07)	0.47 *** (12.55)	2.76 *** (7.28)
$[\ln(GDPP)]^2$		−0.32 (−0.83)		−0.11 *** (−5.80)		−0.11 *** (−6.06)
ln(EC)	1.04 *** (6.18)	0.98 *** (5.88)	0.59 *** (14.62)	0.53 *** (12.59)	0.58 *** (14.30)	0.52 *** (12.64)
ln(REEC)	−0.13 *** (−3.17)	−1.44 *** (−3.49)	−0.12 *** (−11.13)	−0.12 *** (−11.11)	−0.12 *** (−10.94)	−0.12 *** (−10.94)
constant	17.10 *** (17.09)	−14.13 * (−1.72)	2.13 *** (6.36)	−7.76 *** (−4.47)	2.31 *** (5.71)	−8.12 *** (−4.60)
R-squared	0.08	0.08	0.67	0.69	0.67	0.69
Hausman test					Prob>chi2 = 0.19	Prob>chi2 = 0.55
Breusch-Pagan					Prob>chi2 = 0.00	Prob>chi2 = 0.00

Notes: *, **, and *** indicate the significant level of 10%, 5%, and 1%, respectively. The numbers in parentheses are t-values.

Table 5. Panel regression results of EKC model for OECD countries.

Variable	OECD Countries (Number of Observations = 396)					
	Pooled OLS		Fixed Effects		Random Effects	
	Model 1	Model 2	Model 1	Model 2	Model 1	Model 2
ln(GDPP)	0.11 ** (2.11)	45.95 *** (7.41)	0.30 *** (5.92)	1.06 (0.71)	0.29 *** (5.80)	0.63 (0.41)
$[\ln(GDPP)]^2$		−2.16 *** (−7.44)		−0.06 (−0.91)		−0.04 (−0.61)
ln(EC)	0.48 *** (2.67)	0.74 *** (4.31)	0.54 *** (10.79)	0.54 *** (10.81)	0.52 *** (10.30)	0.52 *** (10.20)
ln(REEC)	−0.80 *** (−11.03)	−0.84 *** (−12.40)	−0.15 *** (−10.75)	−0.15 *** (−10.76)	−0.16 *** (−10.89)	−0.16 *** (−10.85)
constant	18.65 *** (10.38)	−22.30 *** (−6.86)	4.05 *** (7.13)	11.07 (1.43)	4.23 *** (6.85)	9.05 (1.15)
R-squared	0.28	0.38	0.63	0.63	0.63	0.63
Hausman test					Prob>chi2 = 0.79	Prob>chi2 = 0.93
Breusch-Pagan					Prob>chi2 = 0.00	Prob>chi2 = 0.00

Notes: *, **, and *** indicate the significant level of 10%, 5%, and 1%, respectively. The numbers in parentheses are t-values.

Before investigating the results of the fixed and random effects, this study utilized the Hausman test to decide between two panel regressions. In Tables 4–6, the chi-squared statistic results of all cases are greater than 0.05, and, therefore, the random effect is the preferred model because it rejects the null hypothesis. In addition, this study adopted the Breusch-Pagan Lagrange multiplier, in which the null hypothesis is that variances across entities are zero, and the results of the chi-squared statistic results of all cases can reject the null hypothesis. Finally, we can choose the random effects model rather than pooled OLS.

In the random effect model results of Tables 4–6, the case of total countries and non-OECD countries have an inverted U-shaped relationship, while OECD countries do not. This result suggests that OECD countries have no effect on reducing CO_2 emissions according to economic growth.

Table 6. Panel regression results of EKC model for non-OECD countries.

Variable	Non-OECD Countries (Number of Observations = 286)					
	Pooled OLS		Fixed Effects		Random Effects	
	Model 1	**Model 2**	**Model 1**	**Model 2**	**Model 1**	**Model 2**
ln(GDPP)	−2.58 *** (−10.86)	0.96 *** (3.42)	0.56 *** (9.72)	3.01 *** (5.40)	0.59 *** (10.46)	3.16 *** (5.54)
$[\ln(GDPP)]^2$		−0.84 *** (−4.71)		−0.12 *** (−4.36)		−0.13 *** (−4.56)
ln(EC)	3.23 *** (13.82)	3.20 *** (13.44)	0.56 *** (8.56)	0.46 *** (7.18)	0.55 *** (8.68)	0.47 *** (7.07)
ln(REEC)	0.30 *** (5.23)	0.28 (1.41)	−0.09 *** (−5.66)	−0.09 *** (−5.89)	−0.10 *** (−6.23)	−0.09 *** (−5.40)
constant	12.13 *** (7.87)	4.66 (0.44)	2.08 *** (3.80)	−8.71 *** (−3.51)	1.95 *** (4.59)	−9.35 *** (−3.65)
R-squared	0.38	0.38	0.71	0.73	0.71	0.73
Hausman test					Prob>chi2 = 0.55	Prob>chi2 = 0.44
Breusch-Pagan					Prob>chi2 = 0.00	Prob>chi2 = 0.00

Notes: *, **, and *** indicate the significant level of 10%, 5%, and 1%, respectively. The numbers in parentheses are t-values.

Tables 7–9 illustrates the results of CO_2 emissions embodied in the trade model based on the EKC hypothesis. Based on the results of the Hausman and Breusch-Pagan Lagrange multiplier tests, we can also conclude that the random effect is the preferred model. According to results of the random effect, in Model 3, the coefficient of GDPP within total countries has a negative sign with statistical significance at the 1% level, and this result indicates that economic growth can contribute to a decrease in the balance of net exports for CO_2 emissions embodied. In addition, in Model 4, total countries and non-OECD countries show evidence of an inverted U-shaped relationship, similar to the traditional EKC model results. That is, even if we consider the CO_2 emissions embodied in international trade, we find that the early stage of economic growth increases the net export of CO_2 emissions in trade, before declining with net exports after a threshold.

Table 7. Panel regression results of CO_2 emissions embodied in trade model on EKC model for Total countries.

Variable	Total Countries (Number of Observations = 682)					
	Pooled OLS		Fixed Effects		Random Effects	
	Model 3	**Model 4**	**Model 3**	**Model 4**	**Model 3**	**Model 4**
ln(GDPP)	−210.95 *** (−9.51)	14.04 (0.07)	−2.68 ** (−2.23)	520.43 *** (3.21)	−11.08 *** (−2.72)	508.29 *** (3.26)
$[\ln(GDPP)]^2$		−11.37 (−1.07)		−27.12 *** (−3.24)		−26.82 *** (−3.34)
ln(EC)	130.93 *** (6.26)	129.00 *** (6.14)	−7.13 (−0.42)	−22.14 (−1.25)	−5.48 (−0.33)	−18.61 (−0.10)
ln(REEC)	−9.24 * (−1.79)	−9.66 * (−1.87)	10.86 ** (2.26)	11.65 ** (2.44)	10.41 ** (2.25)	11.06 ** (2.40)
constant	1140.78 *** (9.21)	51.50 (0.05)	59.49 (0.42)	−2323.30 *** (−3.11)	133.06 (0.98)	−2257.83 *** (−3.11)
R-squared	0.13	0.13	0.13	0.29	0.12	0.29
Hausman test					Prob>chi2 = 0.56	Prob>chi2 = 0.32
Breusch-Pagan					Prob>chi2 = 0.00	Prob>chi2 = 0.00

Notes: *, **, and *** indicate the significant level of 10%, 5%, and 1%, respectively. The numbers in parentheses are t-values.

Table 8. Panel regression results of CO_2 emissions embodied in trade model on EKC model for OECD countries.

Variable	OECD countries (Number of Observations = 396)					
	Pooled OLS		Fixed Effects		Random Effects	
	Model 3	Model 4	Model 3	Model 4	Model 3	Model 4
ln(GDPP)	−28.18 *** (−2.95)	−1401.65 *** (−5.29)	−18.29 * (−1.68)	−237.07 (−0.74)	−18.16 (−1.08)	−325.37 (−1.13)
$[\ln(\mathrm{GDPP})]^2$		64.58 *** (5.19)		10.62 (0.68)		14.85 (1.07)
ln(EC)	21.13 *** (2.82)	28.91 *** (3.91)	14.46 (1.34)	14.70 (1.36)	13.34 (1.40)	13.25 (1.39)
ln(REEC)	10.80 *** (3.58)	12.09 *** (4.13)	20.71 *** (6.58)	20.68 *** (6.57)	19.97 *** (6.87)	19.91 *** (6.86)
constant	67.81 (0.91)	7292.72 *** (5.23)	−7.60 (−0.06)	1114.89 (0.67)	2.16 (0.02)	1588.93 (1.07)
R-squared	0.67	0.13	0.13	0.13	0.13	0.13
Hausman test					Prob>chi2 = 0.82	Prob>chi2 = 0.62
Breusch-Pagan					Prob>chi2 = 0.00	Prob>chi2 = 0.00

Notes: *, **, and *** indicate the significant level of 10%, 5%, and 1%, respectively. The numbers in parentheses are t-values.

Table 9. Panel regression results of CO_2 emissions embodied in trade model on EKC model for non-OECD countries.

Variable	Non-OECD Countries (Number of Observations = 286)					
	Pooled OLS		Fixed Effects		Random Effects	
	Model 3	Model 4	Model 3	Model 4	Model 3	Model 4
ln(GDPP)	−342.22 *** (−7.79)	1468.474 *** (3.55)	7.36 (0.25)	872.74 *** (2.94)	−4.35 (0.15)	848.13 *** (3.02)
$[\ln(GDPP)]^2$		−94.13 *** (−4.40)		−46.00 *** (−2.93)		−45.12 *** (−3.05)
ln(EC)	212.12 *** (4.92)	177.25 *** (4.16)	20.93 (0.63)	52.09 (1.51)	13.42 (0.41)	42.03 (1.26)
ln(REEC)	−22.99 ** (−2.11)	−45.35 *** (−3.87)	4.53 (0.52)	7.45 (0.86)	4.48 (0.57)	6.05 (0.72)
constant	1835.01 *** (6.46)	−6849.93 *** (−3.40)	112.14 (0.51)	−3695.61 *** (−2.81)	169.73 (0.77)	−3611.48 *** (−2.87)
R-squared	0.17	0.22	0.04	0.34	0.03	0.33
Hausman test					Prob>chi2 = 0.51	Prob>chi2 = 0.49
Breusch-Pagan					Prob>chi2 = 0.00	Prob>chi2 = 0.00

Notes: *, **, and *** indicate the significant level of 10%, 5%, and 1%, respectively. The numbers in parentheses are t-values.

4.2. Panel Unit Root and Cointegration Test Results

This study performed a variety of unit root tests to determine the stationarity in panel data. Table 10 presents the results of the panel unit root test based on six methodologies with respect to raw and first differential data. The null hypothesis of non-stationarity cannot be rejected for all variables at the 10% significance level, whereas the first differential variables can be rejected for six different unit root tests. This indicates that all series are stationary levels in the first difference and then all panel data are heterogeneous unit roots with integration of order one (that is, I(1) process).

Table 10. Panel unit root test results.

Variables	Levin–Lin–Chu Test			Harris–Tzavalis Test			Breitung Test		
	T_1	T_2	T_3	T_1	T_2	T_3	T_1	T_2	T_3
BEET	−14.19 *** (0.00)	−7.02 *** (0.00)	−2.02 ** (0.02)	0.29 *** (0.00)	0.40 *** (0.00)	0.98 (0.25)	−1.33 * (0.09)	−1.92 ** (0.02)	−1.93 ** (0.02)
D. BEET	−17.60 *** (0.00)	−16.98 *** (0.00)	−19.05 *** (0.00)	0.09 *** (0.00)	0.08 *** (0.00)	0.09 *** (0.00)	−8.47 *** (0.00)	−10.02 *** (0.00)	−15.39 *** (0.00)
ln(GDPP)	−16.82 *** (0.00)	−15.30 *** (0.00)	4.15 (0.99)	0.71 (0.99)	0.68 * (0.07)	1.03 (0.99)	9.01 (0.99)	2.22 (0.98)	8.07 (0.88)
D.ln(GDPP)	−27.01 *** (0.00)	−16.84 *** (0.00)	−21.52 *** (0.00)	0.28 *** (0.00)	0.15 *** (0.00)	0.37 *** (0.00)	−10.67 *** (0.00)	−11.73 *** (0.00)	−15.49 *** (0.00)
ln(EC)	−13.55 *** (0.00)	−5.74 *** (0.00)	−2.63 *** (0.00)	0.20 *** (0.00)	0.74 (0.45)	1.01 (0.50)	−2.18 ** (0.01)	4.27 (0.99)	−1.01 (0.15)
D.ln(EC)	−14.95 *** (0.00)	−14.02 *** (0.00)	−13.89 *** (0.00)	−0.07 *** (0.00)	−0.27 *** (0.00)	−0.07 *** (0.00)	−8.93 *** (0.00)	−10.61 *** (0.00)	−14.11 *** (0.00)
ln(REEC)	−13.68 *** (0.00)	−7.56 *** (0.00)	1.11 (0.86)	0.33 ** (0.01)	0.90 (0.99)	1.00 (0.63)	0.26 (0.60)	7.23 (0.99)	−0.25 (0.39)
D.ln(REEC)	−16.28 *** (0.00)	−14.87 *** (0.00)	−10.87 *** (0.00)	0.19 *** (0.00)	−0.10 *** (0.00)	0.25 *** (0.00)	−7.79 *** (0.00)	−10.21 *** (0.00)	−11.24 *** (0.00)
ln(CO_2)	−17.52 *** (0.00)	−6.86 *** (0.00)	−0.68 (0.24)	0.16 *** (0.00)	0.85 (0.99)	1.00 (0.51)	−0.87 (0.18)	5.55 (0.99)	0.88 (0.81)
D.ln(CO_2)	−20.27 *** (0.00)	−20.32 *** (0.00)	−11.41 *** (0.00)	0.09 *** (0.00)	−0.21 *** (0.00)	0.10 *** (0.00)	−7.05 *** (0.00)	−10.31 *** (0.00)	−12.67 *** (0.00)
BEET	−5.27 *** (0.00)	−1.03 (0.15)		262.34 *** (0.00)	190.13 *** (0.00)		−0.12 (0.55)	1.01 (0.15)	
D. BEET	−9.67 *** (0.00)	−9.06 *** (0.00)		319.27 *** (0.00)	428.98 *** (0.00)		5.89 *** (0.00)	10.94 *** (0.00)	
ln(GDPP)	2.25 (0.96)	−6.88 *** (0.00)		189.10 ** (0.05)	366.74 *** (0.00)		−0.91 (0.81)	43.50 *** (0.00)	
D.ln(GDPP)	−11.27 *** (0.00)	−6.62 *** (0.00)		363.60 *** (0.00)	213.37 *** (0.00)		19.01 *** (0.00)	8.84 *** (0.00)	
ln(EC)	−6.72 *** (0.00)	1.79 (0.96)		232.52 *** (0.00)	156.77 ** (0.02)		−3.49 (0.99)	−1.38 (0.91)	
D.ln(EC)	−10.74 *** (0.00)	−10.35 *** (0.00)		329.77 *** (0.00)	430.47 *** (0.00)		9.63 *** (0.00)	33.81 *** (0.00)	
ln(REEC)	−3.44 *** (0.00)	2.73 (0.99)		273.68 *** (0.00)	142.85 (0.11)		−0.87 (0.80)	−2.55 (0.99)	
D.ln(REEC)	−9.10 *** (0.00)	−8.03 *** (0.00)		275.33 *** (0.00)	381.20 *** (0.00)		8.98 *** (0.00)	39.97 *** (0.00)	
ln(CO_2)	−5.68 *** (0.00)	2.57 (0.99)		320.88 *** (0.00)	149.38 * (0.06)		−1.72 (0.95)	−0.23 (0.59)	
D.ln(CO_2)	−9.75 *** (0.00)	−9.47 *** (0.00)		374.00 *** (0.00)	495.95 *** (0.00)		7.89 *** (0.00)	37.35 *** (0.00)	

Notes: The number of parentheses denote p-value. T_1 means test results including both constant and trend, T_2 means test results including only constant, and T_3 means test results without constant and trend. *, **, and *** indicate the significant level of 10%, 5%, and 1%, respectively. Im-Pesaran-Shin, Fisher-type, and Hadri LM tests cannot be carried out the T_3 procedure.

Table 11 shows the result of the Pedroni cointegration test if there exists a long-run relationship in the four types of models. This test includes the null hypothesis of no-cointegration in the non-stationary panel series. Thus, the Pedroni cointegration test allows both panel-specific cointegrating vectors and the autogressive coefficient to vary over panels [40]. In Table 11, three types of test statistics reject the null hypothesis with respect to the total, OECD, and non-OECD country groups, and we conclude that four types of estimated models have a long-run relationship.

Table 11. Pedroni cointegration test result.

	Statistics	Total Countries	OECD	Non-OECD
Model 1	Modified Phillips-Perron t	−6.43 *** (0.00)	−5.01 *** (0.00)	−4.86 *** (0.00)
	Phillips-Perron t	−12.68 *** (0.00)	−13.62 *** (0.00)	−3.08 *** (0.00)
	Augmented Dickey-Fuller t	−10.02 *** (0.00)	−9.03 *** (0.00)	−5.40 *** (0.00)
Model 2	Modified Phillips-Perron t	−6.08 *** (0.00)	−8.02 *** (0.00)	−6.33 *** (0.00)
	Phillips-Perron t	−11.01 *** (0.00)	−10.87 *** (0.00)	−3.01 *** (0.00)
	Augmented Dickey-Fuller t	−8.36 *** (0.00)	−7.60 *** (0.00)	−6.05 *** (0.00)
Model 3	Modified Phillips-Perron t	−6.89 *** (0.00)	−5.10 *** (0.00)	−3.11 *** (0.00)
	Phillips-Perron t	−6.66 *** (0.00)	−4.25 *** (0.00)	−3.99 *** (0.00)
	Augmented Dickey-Fuller t	−6.54 *** (0.00)	−4.00 *** (0.00)	−4.76 *** (0.00)
Model 4	Modified Phillips-Perron t	−9.12 *** (0.00)	−7.11 *** (0.00)	−5.23 *** (0.00)
	Phillips-Perron t	−11.09 *** (0.00)	−8.22 *** (0.00)	−6.00 *** (0.00)
	Augmented Dickey-Fuller t	−9.33 *** (0.00)	−3.88 *** (0.00)	−8.55 *** (0.00)

Notes: The number of parentheses denote *p*-value. *, **, and *** indicate the significant level of 10%, 5%, and 1%, respectively.

4.3. Panel Granger Causality Test Results

This study estimated causal relationships in panel series by Dumitrescu and Hurlin [43] which provided an extended Granger causality test. Table 8 indicates the bidirectional test results of panel Granger causality by W-bar, Z-bar, and Z-bar tilde. In particular, Dumitrescu and Hurlin [43] mentioned that if N is large but T is small then the Z-bar tilde should be favored, and the Z-bar statistic is not suitable for unbalanced panels. Therefore, the causal relationship in the panel data of this study was determined according to the criteria of the Z-bar tilde.

In Table 12, the null hypotheses that GDPP, EC, and REEC do not Granger cause CO_2 emissions within total countries, and GDPP and REEC do not Granger cause CO_2 emissions within OECD countries are rejected by the Z-bar tilde at the 1% significance level. This implies that changes in economic growth and renewable energy consumption in OECD countries can contribute to CO_2 emissions. In addition, we find that economic growth is the main issue for most countries, but it may cause more environmental pollution at a given income level, as suggested by Salari et al. [6].

Table 13 illustrates the Granger cause results of CO_2 emissions embodied in international trade on economic growth and energy consumption. The null hypotheses that, in total and OECD countries, BEET does not Granger cause GDPP and that GDPP does not Granger cause BEET are rejected by the Z-bar tilde at the 1% significance level. This indicates that bidirectional causality exists in the relationship between economic growth and CO_2 emissions embodied in trade balance in the case of total and OECD countries. In addition, energy consumption (EC and REEC) of total and OECD countries can be the Granger cause of BEET. Therefore, CO_2 emissions embodied in trade and energy consumption (including economic growth) in total and OECD economies exist with feedback effects. Consequently, the overall results in Tables 12 and 13 support the EKC hypothesis, even if we consider the perspective of the CO_2 emissions generated by production, consumption, and distribution of traded goods and services.

Table 12. Panel Granger causality test result within Traditional EKC hypothesis model.

Null Hypothesis	Statistics	Total Countries	OECD	Non-OECD
CO_2 ⇏ GDPP	W-bar	1.81	1.99	1.45
	Z-bar	5.52 *** (0.00)	5.01 *** (0.00)	2.03 ** (0.04)
	Z-bar tilde	1.55 (0.12)	1.77 * (0.07)	0.31 (0.75)
GDPP ⇏ CO_2	W-bar	2.99	3.54	2.54
	Z-bar	10.01 *** (0.00)	12.06 *** (0.00)	5.32 *** (0.00)
	Z-bar tilde	5.22 *** (0.00)	4.99 *** (0.00)	2.55 *** (0.01)
CO_2 ⇏ EC	W-bar	13.20	1.83	28.96
	Z-bar	67.98 *** (0.00)	3.53 *** (0.00)	100.82 *** (0.00)
	Z-bar tilde	33.21 *** (0.00)	0.92 (0.35)	50.19 *** (0.00)
EC ⇏ CO_2	W-bar	1.76	1.93	1.51
	Z-bar	4.23 *** (0.00)	3.98 *** (0.00)	1.85 * (0.06)
	Z-bar tilde	3.01 *** (0.00)	1.15 (0.24)	0.20 (0.83)
CO_2 ⇏ REEC	W-bar	1.81	1.54	2.18
	Z-bar	4.51 *** (0.00)	2.29 ** (0.02)	4.27 *** (0.00)
	Z-bar tilde	1.15 (0.24)	0.30 (0.76)	1.42 (0.15)
REEC ⇏ CO_2	W-bar	4.33	6.50	1.34
	Z-bar	18.56 *** (0.00)	23.35 *** (0.00)	1.32 (0.21)
	Z-bar tilde	8.26 *** (0.00)	10.93 *** (0.00)	0.10 (0.91)

Notes: The number of parentheses denote *p*-value. *, **, and *** indicate the significant level of 10%, 5%, and 1%, respectively. 'X ⇏ Y' means that X does not Granger cause Y.

Table 13. Panel Granger causality test result within CO_2 emissions embodied in trade model.

Null Hypothesis	Statistics	Total Countries	OECD	Non-OECD
BEET ⇏ GDPP	W-bar	2.25	2.64	2.09
	Z-bar	7.23 *** (0.00)	6.83 *** (0.00)	4.01 *** (0.00)
	Z-bar tilde	2.99 *** (0.00)	3.03 *** (0.00)	2.11 ** (0.03)
GDPP ⇏ BEET	W-bar	3.66	4.03	3.45
	Z-bar	13.27 *** (0.00)	14.20 *** (0.00)	6.98 *** (0.00)
	Z-bar tilde	5.99 *** (0.00)	6.09 *** (0.00)	3.04 *** (0.00)
BEET ⇏ EC	W-bar	1.68	1.56	1.85
	Z-bar	3.81 *** (0.00)	2.40 ** (0.01)	3.06 *** (0.00)
	Z-bar tilde	0.80 (0.42)	0.35 (0.72)	0.82 (0.41)
EC ⇏ BEET	W-bar	3.24	4.42	1.61
	Z-bar	12.49 *** (0.00)	14.52 *** (0.00)	2.20 ** (0.02)
	Z-bar tilde	5.18 *** (0.00)	6.47 *** (0.00)	0.38 (0.70)
BEET ⇏ REEC	W-bar	1.98	2.21	1.67
	Z-bar	5.51 *** (0.00)	5.17 *** (0.00)	2.42 *** (0.01)
	Z-bar tilde	1.65 * (0.09)	1.75 * (0.07)	0.49 (0.61)
REEC ⇏ BEET	W-bar	2.94	3.69	1.91
	Z-bar	10.84 *** (0.00)	11.42 *** (0.00)	3.29 *** (0.00)
	Z-bar tilde	4.35 *** (0.00)	4.91 *** (0.00)	0.93 (0.34)

Notes: The number of parentheses denote *p*-value. *, **, and *** indicate the significant level of 10%, 5%, and 1%, respectively. 'X ⇏ Y' means that X does not Granger cause Y.

4.4. Pollution Haven Hypothesis Test Results

Figure 3 illustrates the distribution of the PHH results based on Equation (18). Figure 3a shows that all countries are well distributed for CO_2 emissions embodied in trade balance (CO_2NETXC) during the period of 2005 to 2015, while CO_2NETXC of most countries is located under zero. In addition, Figure 3b,c indicate CO_2NETXC distributions for OECD and non-OECD countries, respectively, and CO_2NETXT in the OECD countries are almost below zero but non-OECD countries are mostly above zero. This implies that the closer CO_2NETXC is to zero, the more CO_2 emissions occurring in exports and imports for a region decrease, and this country has more responsibility for CO_2 emissions in the process of international trade.

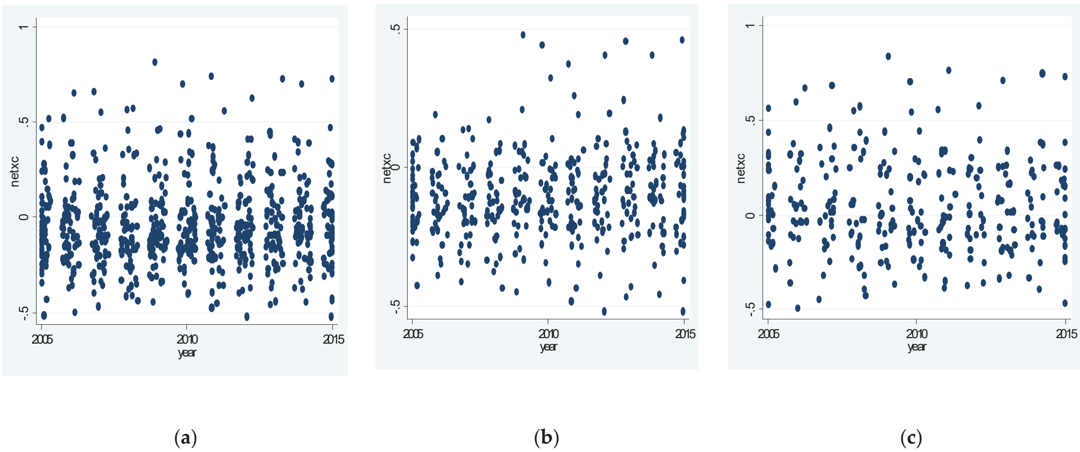


Figure 3. Pollution haven distributions from 2005 to 2015. (**a**) Total countries. (**b**) OECD countries. (**c**) Non-OECD countries.

More precisely, Figure 4 indicates the results for the top five countries based on CO_2NETXC. The results for the top five deficits and surpluses illustrate that most countries have experienced a constant pattern of CO_2NETXC from 2005 to 2015, and there appears to be support for the PHH, particularly for France, the United Kingdom, Singapore, and South Africa. Partially, Porter and van de Linde [23] suggested that environmental regulation spurs innovation, which can enhance the international competitiveness of a company and induce economic growth. Meanwhile, the evidence of PHH in this study indicated that pollution-intensive industries in developed countries move to developing or less-developed countries, with relatively weak environmental regulations, and, therefore, fewer pollution-intensive products are produced in developed countries are imported.

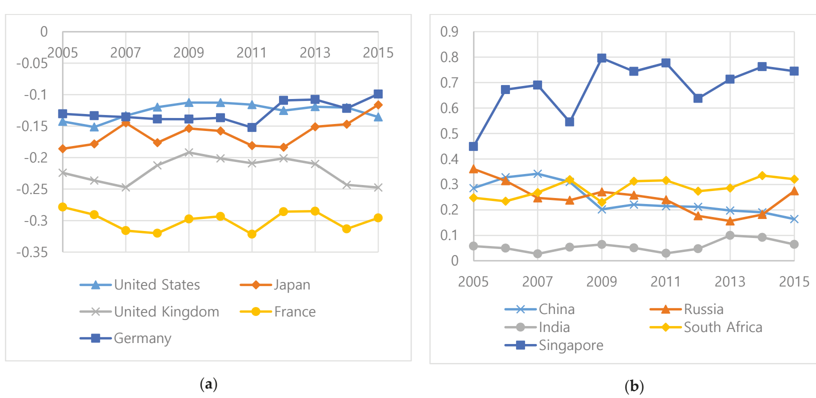


Figure 4. Pollution haven patterns for the top five countries. (**a**) Top five countries for CO_2NETXC deficits. (**b**) Top five countries for CO_2NETXC surpluses.

5. Conclusions and Implications

This study investigated the relationship between CO_2 emissions and economic growth for OECD and non-OECD countries in accordance with the traditional EKC hypothesis. In addition, in the globalized era, this study analyzed the nexus between CO_2 emissions embodied in international trade and economic growth, including several procedures of panel regression analysis, Granger causality, and the PHH. These attempts have provided meaningful results, in which environmental pollution is reflected in international trade, unlike many previous studies demonstrating a simple relationship between CO_2 and economic growth.

The main findings of this study are as follows. First, in the period of 2005 to 2015, there is evidence of an inverted-U shaped relationship between CO_2 emissions and economic growth, particularly for total and non-OECD countries. In addition, the relationship between CO_2 emissions embodied in international trade and economic growth has the same result as the traditional EKC hypothesis model. This implies that in the early stages of economic development, the CO_2 emissions in trade balance increases, whereas it decreases beyond the income turning point. That is, we find that developed countries can be relatively net CO_2 emission importers with imports, including CO_2 emissions, that exceed exports, but developing or less developed countries can be relatively net CO_2 emission exporters.

Second, economic growth and renewable energy consumption can contribute to CO_2 emissions, and CO_2 emissions embodied in trade balances have bi-directional causality for economic growth and renewable energy consumption. This result implies that there is evidence for the existence the EKC hypothesis, and economic situation and renewable energy consumption are important factors affecting CO_2 emissions embodied in trade. Finally, partially upper countries among net exporters (or importers) of CO_2 embodied in trade balance support the PHH, in which products including environmental pollution in international trade can be more exported (or more imported) depending on the economic development situation of a country. Thus, some developed countries tend to be net importers of CO_2 emissions to avoid their own countries' environmental regulations, while some less-developed countries also tend to be net exporters of CO_2 emissions to improve their economic development.

Based on the results of this study, there are two important policy implications. According to accelerated greenhouse effects, we cannot avoid CO_2 emission problems, and shift responsibility for environmental pollution to other countries. It is, therefore, clear that international debate, in which environmental pollutants are produced and consumed by the degree of economic development, should be continued, and we need to recognize the corporate responsibility for environmental issues, especially in developed countries. In addition, due to the increase in the importance of international trade, we need to consider both externalities of environmental pollutants in the production process and CO_2 emissions embodied in international trade.

Unlike the age of self-sufficiency, we all have trade, and we cannot think of economic growth without trade. Although this study utilized the concept of CO_2 emissions embodied in trade and the PHH to overcome the shortcomings of the EKC hypothesis, this study did not consider the classification of industries within a country, and this limitation leaves room for further research.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Hotak, S.; Islam, M.; Kakinka, M.; Kotani, K. Carbon emissions and carbon trade balances: International evidence from panel ARDL analysis. *Environ. Sci. Pollut. Res.* **2020**, *27*, 24115–24128. [CrossRef]
2. Saidi, K.; Hammami, S. The impact of CO_2 emissions and economic growth on energy consumption in 58 countries. *Energy Rep.* **2015**, *1*, 62–70. [CrossRef]
3. Park, H. Is carbon neutral policy compatible with sustainable economic growth? *Env. Resour. Econ. Rev.* **2021**, *30*, 347–364.
4. Grossman, G.M.; Krueger, A.B. Economic growth and the environment. *Q. J. Econ.* **1995**, *110*, 353–377. [CrossRef]
5. Nam, K.; Lee, S.; Jeon, H. Nonlinearity between CO_2 emission and economic development: Evidence from a functional coefficient panel approach. *Sustainability* **2020**, *12*, 10258. [CrossRef]
6. Salari, M.; Javide, R.J.; Noghanibehambari, H. The nexus between CO_2 emissions, energy consumption, and economic growth in the U.S. *Econ. Anal. Policy* **2021**, *69*, 182–194. [CrossRef]
7. Stern, D.I. The rise and fall of the environmental Kuznets curve. *World Dev.* **2004**, *32*, 1419–1439. [CrossRef]
8. Song, T.; Zheng, T.; Tong, L. An empirical test of the environmental Kuznets curve in China: A panel cointegration approach. *China Econ. Rev.* **2008**, *19*, 381–392. [CrossRef]
9. Rafiq, S.; Salim, R.; Apergis, N. Agriculture, trade openness and emissions: An empirical analysis and policy options. *Agric. Resour. Econ.* **2015**, *60*, 348–365. [CrossRef]
10. Kang, H.S. A study on the relationship between international trade and food security: Evidence from less developed countries (LDCs). *Agric. Econ. Czech* **2015**, *61*, 475–483. [CrossRef]
11. Jin, T.; Kim, J. Coal consumption and economic growth: Panel cointegration and causality evidence from OECD and Non-OECD countries. *Sustainability* **2018**, *10*, 660. [CrossRef]
12. Chen, F.; Jiang, G.; Kitila, G.M. Trade openness and CO_2 emissions: The heterogeneous and mediating effects for the belt and road countries. *Sustainability* **2021**, *13*, 1958. [CrossRef]
13. Peters, G.P.; Hertwich, E.G. CO_2 embodied in international trade with implications for global climate policy. *Environ. Sci. Technol.* **2008**, *42*, 1401–1407. [CrossRef]
14. Peters, G.P.; Minx, J.C.; Weber, C.L.; Edenhofer, O. Growth in emission transfers via international trade from 1990 to 2008. *Proc. Natl. Acad. Sci. USA* **2011**, *108*, 8903–8908. [CrossRef]
15. Peters, G.P.; Marland, G.; Hertwich, E.G.; Saikku, L.; Rautiainen, A.; Kauppi, P.E. Trade, transport, and sinks extend the carbon dioxide responsibility of countries: An editorial essay. *Clim. Chang.* **2009**, *97*, 379–388. [CrossRef]
16. Panayotou, T. Empirical tests and policy analysis of environmental degradation at different stages of economic development. *ILO Work. Pap.* **1993**, *WP.238*, 1–42.
17. Alvarez-Herranz, A.; Balsalobre-Lorente, D.; Shahbaz, M.; Cantos, J.M. Energy innovation and renewable energy consumption in the correction of air pollution levels. *Energy Policy* **2017**, *105*, 386–397. [CrossRef]
18. Dinda, S. Environmental Kuznets curve hypothesis: A survey. *Ecol. Econ.* **2004**, *49*, 431–455. [CrossRef]
19. Mahmood, H.; Maalel, N.; Zarrad, O. Trade Openness and CO_2 Emissions: Evidence from Tunisia. *Sustainability* **2019**, *11*, 3295. [CrossRef]
20. Managi, S.; Hibiki, A.; Tsurumi, T. Does trade openness improve environmental quality? *J. Environ. Econ. Manag.* **2009**, *58*, 346–363. [CrossRef]
21. Andreoni, J.; Levinson, A. The simple analytics of the environmental Kuznets curve. *J. Public Econ.* **2001**, *80*, 269–286. [CrossRef]
22. Kasman, A.; Duman, Y.S. CO_2 emissions, economic growth, energy consumption, trade and urbanization in new EU member and candidate countries: A panel data analysis. *Econ. Model.* **2015**, *44*, 97–103. [CrossRef]
23. Porter Michael, E.; van der Linde, C. Toward a new conception of the environment-competitiveness relationship. *J. Econ. Perspect.* **1995**, *9*, 97–118. [CrossRef]
24. Leitão, N.C.; Lorente, D.B. The Linkage between Economic Growth, Renewable Energy, Tourism, CO_2 Emissions, and International Trade: The Evidence for the European Union. *Energies* **2020**, *13*, 4838. [CrossRef]
25. Essandoh, O.K.; Islam, M.; Kakinaka, M. Linking international trade and foreign direct investment to CO_2 emissions: Any differences between developed and developing countries? *Sci. Total Environ.* **2020**, *712*, 136437. [CrossRef]
26. Kirikkaleli, D.; Adebayo, T.S. Do renewable energy consumption and financial development matter for environmental sustainability? New global evidence. *Sustain. Dev.* **2021**, *29*, 583–594. [CrossRef]
27. Safi, A.; Chen, Y.; Wahab, S.; Ali, S.; Yi, X.; Imran, M. Financial Instability and Consumption-based Carbon Emission in E-7 Countries: The Role of Trade and Economic Growth. *Sustain. Prod. Consum.* **2021**, *27*, 383–391. [CrossRef]
28. Kirikkaleli, D.; Adebayo, T.S.; Khan, Z.; Khan, Z. Does globalization matter for ecological footprint in Turkey? Evidence from dual adjustment approach. *Environ. Sci. Pollut. Res.* **2021**, *28*, 14009–14017. [CrossRef]
29. Zhang, H. Technology Innovation, Economic Growth and Carbon Emissions in the Context of Carbon Neutrality: Evidence from BRICS. *Sustainability* **2021**, *13*, 11138. [CrossRef]
30. Tachega, M.A.; Yao, X.; Liu, Y.; Ahmed, D.; Ackaah, W.; Gabir, M.; Gyimah, J. Income Heterogeneity and the Environmental Kuznets Curve Turning Points: Evidence from Africa. *Sustainability* **2021**, *13*, 5634. [CrossRef]
31. Yamano, N.; Guilhoto, J. CO_2 emissions embodied in international trade and domestic final demand: Methodology and results using the OECD Inter-Country Input-Output Database. *OECD Sci. Technol. Ind. Work. Pap.* **2020**, *11*, 1–57.

32. Lee, C.C. Energy consumption and GDP in developing countries: A cointegrated panel analysis. *Energy Econ.* **2005**, *27*, 415–427. [CrossRef]
33. Hsiao, C. Panel data analysis-advantages and challenges. *TEST* **2007**, *16*, 1–22. [CrossRef]
34. Choi, I. Unit root tests for panel data. *J. Int. Money Financ.* **2001**, *20*, 249–272. [CrossRef]
35. Levin, A.; Lin, C.F.; Chu, C.S.J. Unit root tests in panel data: Asymptotic and finite-sample properties. *J. Econom.* **2002**, *108*, 1–24. [CrossRef]
36. Harris, R.D.F.; Tzavalis, E. Inference for unit roots in dynamic panels where the time dimension is fixed. *J. Econom.* **1999**, *91*, 201–226. [CrossRef]
37. Breitung, J. The local power of some unit root tests for panel data. *Adv. Econom.* **2000**, *15*, 161–177.
38. Im, K.S.; Pesaran, M.H.; Shin, Y. Testing for unit roots in heterogeneous panels. *J. Econom.* **2003**, *115*, 53–74. [CrossRef]
39. Hadri, K. Testing for stationarity in heterogeneous panel data. *Econom. J.* **2000**, *3*, 148–161. [CrossRef]
40. Pedroni, P. Purchasing power parity tests in cointegrated panels. *Rev. Econ. Stat.* **2001**, *83*, 727–731. [CrossRef]
41. Neal, T. Panel cointegration analysis with xtpedroni. *STATA J.* **2014**, *14*, 684–692. [CrossRef]
42. Granger, C.W.J. Investigating causal relations by econometric models and cross-spectral methods. *Econometrica* **1969**, *37*, 424–438. [CrossRef]
43. Dumitrescu, E.I.; Hurlin, C. Testing for Granger non-causality in heterogeneous panels. *Econ. Model.* **2012**, *29*, 1450–1460. [CrossRef]
44. Lopez, L.; Weber, S. Testing for Granger causality in panel data. *STATA J.* **2017**, *17*, 972–984. [CrossRef]
45. Cole, M.A. Trade, the pollution haven hypothesis and the environmental Kuznets curve: Examining the linkages. *Ecol. Econ.* **2004**, *48*, 71–81. [CrossRef]

sustainability

MDPI

Article

Investigating the Impact of COVID-19 Disruption on the Decarbonisation Agenda at Airports: Grounded or Ready for Take-Off?

Peter Hemmings [1,2,*], Michael Mulheron [3], Richard J. Murphy [1] and Matt Prescott [2]

[1] Centre for Environment and Sustainability, University of Surrey, Guildford GU2 7XH, UK; rj.murphy@surrey.ac.uk
[2] Carbon Strategy Team, Heathrow Airport Ltd., Hounslow TW6 2GW, UK; matt.prescott@heathrow.com
[3] Department of Civil and Environmental Engineering, University of Surrey, Guildford GU2 7XH, UK; m.mulheron@surrey.ac.uk
* Correspondence: p.hemmings@surrey.ac.uk

Citation: Hemmings, P.; Mulheron, M.; Murphy, R.J.; Prescott, M. Investigating the Impact of COVID-19 Disruption on the Decarbonisation Agenda at Airports: Grounded or Ready for Take-Off?. *Sustainability* **2021**, *13*, 12235. https://doi.org/10.3390/su132112235

Academic Editors: Baojie He, Ayyoob Sharifi, Chi Feng and Jun Yang

Received: 30 September 2021
Accepted: 3 November 2021
Published: 5 November 2021

Abstract: COVID-19 has had wide-ranging impacts on organisations with the potential to disrupt efforts to decarbonise their operations. To understand how COVID-19 has affected the climate change mitigation strategies of Airport Operators (AOs), questionnaires and semi-structured interviews with Sustainability Managers were undertaken in late 2020 amidst a period of disruption. While all reported that COVID-19 impacted delivery of interventions and projects to mitigate climate change, the majority stated that it would not impact their long-term climate goals, such as Net Zero by 2050. The most popular climate change mitigation interventions AOs intend to deploy between now and 2030 are on-site renewables and Electric Vehicles and related infrastructure. Engineered carbon removal interventions were considered highly unlikely to be deployed in this timeframe, with potential implications for Net Zero decarbonisation pathways. Despite the severe impacts of COVID-19 on the sector, results indicate that AOs remain committed to decarbonisation, with climate change action remaining the key priority for airports. Given ongoing financial and resource constraints, AOs will need to explore new business models and partnerships and nurture collaborative approaches with other aviation stakeholders to not only maintain progress toward Net Zero but "*build back better*". Government support will also be needed to stimulate the development of a sustainable, resilient, low-carbon aviation system.

Keywords: airport operators; COVID-19; climate change; sustainability; climate change mitigation

1. Introduction

The SARS-CoV-2 (COVID-19) pandemic has been, and continues to be, highly disruptive for the aviation industry. Border closures, travel restrictions and quarantine measures imposed by governments to prevent transmission of the virus and new variants have significantly reduced air traffic movements and passenger numbers. For airports, the reduction in air traffic movements, passengers and retail tenants has significantly impacted principal revenue streams. Compared to a business-as-usual (BAU) scenario, the global impact of COVID-19 in 2020 has been estimated to represent a reduction of up to 2.9 billion passengers and a loss of operating revenue for airlines of approximately USD 391 billion gross [1]. For airports globally, estimates suggest a 64% loss in passenger traffic during 2020 and an associated USD 112 billion in airport revenues compared to a BAU scenario (*Ibid*.).

Airport Operator (AO) organisations are adapting their future strategies to respond to two significant global pressures simultaneously: the COVID-19 pandemic, and climate change. To address the latter, airports must transition to a sustainable, zero-carbon air transport system that minimises the industry's environmental impact. Principally, this will require the systemic reduction and removal of greenhouse gas (GHG) emissions in line with the Paris Agreement, through the implementation of appropriate interventions. However, such interventions come at a financial and resource cost and AOs must now address the twin challenges of both the pandemic and climate change with significantly reduced access to capital, whilst also optimising ongoing operations. They must also balance social impacts such as job losses and associated future skill shortages if they are to maintain the expertise to deliver the required changes and protect growth.

It might be assumed that the organisational disruption and reduced revenues associated with the COVID-19 pandemic would mean that climate change mitigation and sustainability interventions will be delayed or cancelled, and the underpinning strategies reviewed and altered. However, aviation organisations continue to make long-term decarbonisation commitments [2] and phrases such as "*build back better*" are prominent in the lexicon of business leaders, tying a recovery of the sector to notions of sustainability and "greening" [3].

The impact of COVID-19 on the decarbonisation agenda at airports remains to be addressed in the literature to date (see Supplementary Materials File S1 for the literature review conducted as part of this study).

With the above in mind, this research sought insight on key emerging themes on: how COVID-19 may have impacted climate change mitigation strategies at airports and any low-carbon, or carbon-saving, opportunities resulting from changes to the existing regime at airports. Consideration was also given to analysing what influence the COVID-19 pandemic may have on the decarbonisation transition of airports seeking to reach "Net-Zero" by 2050.

The research was conducted via analysis of the responses to an online, self-completion questionnaire with follow-up by semi-structured interviews with a range of Sustainability Managers at AOs in Europe and North America. This was used to assess the impacts of the COVID-19 pandemic on airport climate change mitigation efforts during the emergence of the "second wave" of the pandemic (from October 2020 [4]). Recommendations on how impacts of the pandemic on the climate change agenda of airports and aviation can be alleviated are given based on the research findings.

2. Materials and Methods

A multi-case study approach is adopted to identify high-level emerging themes on the impacts of COVID-19 on airports. The research techniques employed include an online self-completion questionnaire and follow-up semi-structured interviews with selected respondents, to explore emerging topics in further detail. Figure 1 shows the study design.

Population and Sampling—The targeted population for the questionnaire were Heads of Environment and Sustainability at AOs. This group was deemed most familiar with the climate change and sustainability strategy at their respective organisations. A limitation is recognised in exempting operational staff who could be more cognizant of potential low-carbon opportunities arising during this period.

Sixty contacts at AOs in Europe (85%), North America (10%) and the Asia-Pacific region (5%) representing both operators of single airports and multiple airports were invited to participate as respondents to the questionnaire. The invitees were selected based on their interest or expertise in environmental issues at airports or were suggested on a similar basis by other participants.

The researchers acknowledge that the small sample size cannot be assumed to be fully representative of the whole population of AOs. The responses received represent a substantial sample of approximately 60% as a proportion of passengers carried in Europe in the year prior to the COVID-19 pandemic. Overall, the sample achieved was considered suitable for a "snapshot study" to identify the key themes during the second wave of COVID-19. Adopting a multi-case study approach that seeks to identify themes common across all cases means that some level of generalisation can be applied. The limitations of the opportunistic sampling undertaken must also be recognised; however, it was deemed suitable to achieve the aims of the study and allowed for a high response rate to the questionnaire.

Ethical approval to undertake the research was gained through the research institution's ethics self-assessment process.

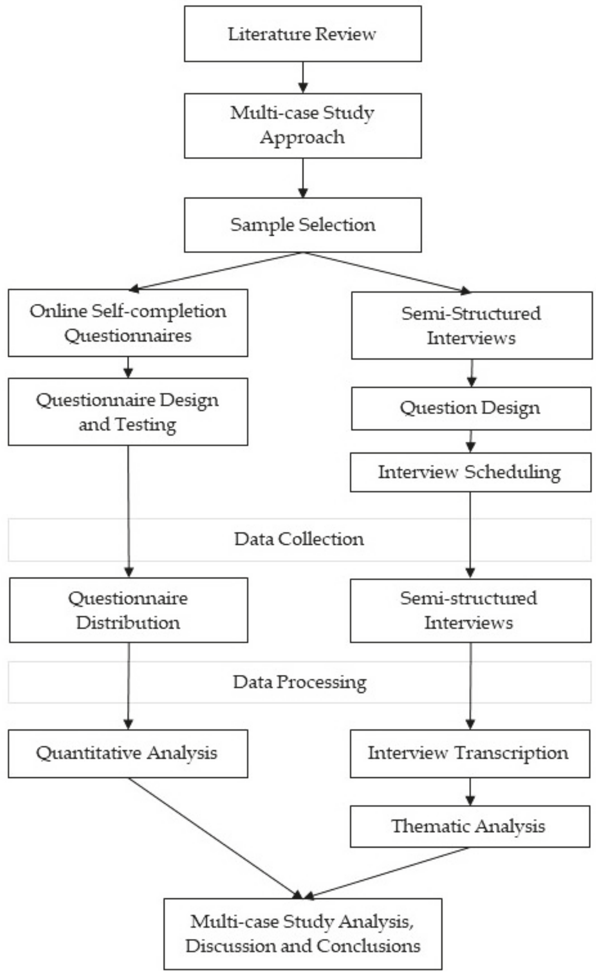


Figure 1. Study design.

Questionnaire Design and Distribution—The questionnaire was constructed and hosted on the *QualtricsXM* platform. The landing page gave an overview of the research, participation requirements including anonymity, and was followed by a consent form. The design, flow and functionality were tested within the research team prior to launch. The questionnaire comprised four questions on basic respondent information, followed by five questions on Strategy and Interventions, and six questions on COVID-19 Impact.

Strategy and Intervention Questions—These addressed which interventions AOs intend to deploy, when they intend to deploy them, and their intended funding sources. This was requested to form an understanding of the respondents' current and future plans in relation to barriers, opportunities and potential long-term goals. Details were sought on the following two questions to enable the analysis in Section 4:

1. *Planned Interventions*: Respondents were presented with a list of 22 GHG emission reduction and removal interventions compiled by the authors and considered broadly

representative of those that are technologically feasible for implementation at airports now or within the next three decades (Table 1). These range from policy advocacy to technological solutions; some are on-site solutions and some market-based. Based on their own implementation plans, the respondents were asked to group these into four categories based on their own implementation plans: (1) 2020 to 2030; (2) 2030 Onward; (3) "*We already do this*"; (4) "*We don't intend to pursue this*".

2. *Funding*: Respondents were asked "Please indicate how you intend to fund these interventions", and to distribute the (hypothetical) funding across the following three categories: (1) Internal funding; (2) External funding—Research and Innovation Grants; (3) External funding—Industrial partnerships, Other Funding Models.

Table 1. Intervention list presented in AO questionnaire. An indication is given as to which emission scopes (in line with the GHG Protocol [5]) the intervention will impact, and by what means. Reduction denotes an intervention that will reduce overall emissions compared to a business-as-usual state through reducing or avoiding fuel use. Removal denotes an intervention that will sequester carbon dioxide. LTO: Landing and Take-Off. vTOL: Vertical Take-off and Landing. HVO: Hydrotreated Vegetable Oils. BECCS: Bioenergy Carbon Capture and Storage. DACCS: Direct Air Carbon Capture and Storage.

No.	Intervention Description	Scopes Impacted	Emission Reduction or Removal
1	Decarbonising Airport Infrastructure and Heating	1	Reduction
2	On-site Renewable Electricity Generation	2	Reduction
3	Purchasing Renewable electricity (Market based instruments)	2	Reduction
4	Decarbonising Colleague Surface Access, e.g., car share schemes	3	Reduction
5	Decarbonising Passenger Surface Access, e.g., access charges, new public transport options	3	Reduction
6	Utilising low carbon construction materials and processes	3	Reduction
7	Pursuing Circular Economy, waste re-use and servicisation opportunities	3	Reduction
8	Policy Change Advocacy (National, International)	3	Reduction
9	Tackling fugitive emission sources, e.g., De-Icer and Fire Training	3	Reduction

Table 1. *Cont*.

No.	Intervention Description	Scopes Impacted	Emission Reduction or Removal
10	Provision of Fixed Electric Ground Power (FEGP)	3	Reduction
11	Enabling Sustainable Aviation Fuel (SAF) up-take at airport	3	Reduction
12	Provision of Pre-Conditioned Air (PCA)	3	Reduction
13	Tackling LTO emissions, e.g., E-taxiing, Single Engine Taxiing	3	Reduction
14	Infrastructure provision for future aircraft types, e.g., electric, hybrid, hydrogen, vTOL	3	Reduction
15	Enabling or influencing airspace improvements	3	Reduction
16	Enabling or influencing airfield and ground movements improvements	3	Reduction
17	Establish a Voluntary Carbon Offsetting Platform	3	Reduction/Removal
18	Provision of Electric Vehicles and Charging Infrastructure	1, 3	Reduction
19	Alternative fuels for ground vehicles, e.g., HVO, Hydrogen	1, 3	Reduction
20	Pursuing Carbon Capture and Utilisation technologies	1, 2, 3	Removal
21	Pursuing Engineered Carbon Removals, e.g., BECCS, DACCS	1, 2, 3	Removal
22	Pursuing Removals through Nature Based Solutions, e.g., Afforestation, Reforestation	1, 2, 3	Removal

COVID-19 Impact Questions—First, respondents were asked five questions in relation to the impact of COVID-19 on their implementation plans for climate change interventions and the perceived threat to the organisation of both external pressures. Respondents were asked to give the extent to which they agreed with the following statements on a 7-point Likert scale:

1. "The impacts of COVID have made climate change a higher priority within the business"
2. "COVID is an existential threat to our business"
3. "Climate Change is an existential threat to our business"
4. "The highest priority for the organization is business continuity"
5. "The impacts of COVID have disrupted our ability to implement planned carbon reduction and removal strategies"

Finally, they were asked to record in "free text" responses: (i) any notable low-carbon opportunities and barriers to mitigation efforts resulting from the pandemic, and (ii) asked to give their perception of longevity of the opportunities.

Questionnaire Distribution—Emails containing a link to the online survey and project overview were sent to the 60 contacts identified. No incentives were offered for completing the questionnaire. Reminder emails to encourage participation were sent to those who did not engage initially. The questionnaire ran for 42 days, from 7 October 2020 to 19 November 2020; this period was representative of a widely accepted "second wave" of confirmed COVID-19 cases within the United Kingdom (UK), Europe and North America and was prior to major announcements regarding vaccines and immunisation plans. Questionnaire responses were included for analysis at a completion rate of 40% or above, reflecting consent given and a minimum of one question answered.

Semi-structured Interviews—Semi-structured interviews were used to expand on key themes emerging from the questionnaire responses. Nine interview participants from nine different AOs were identified from questionnaire respondents who had indicated their interest in interview participation or were approached by the research team. Anonymity was offered, with any identifying information about the participant and their organisation removed. Interviews were conducted online, recorded, and transcribed.

Interviews were approximately 30 min in length, with questions focusing on four high-level topics:

1. Opinion on the current standing of climate change and sustainability agenda within the business given COVID-19 disruption: what has changed; do they recognise the recent narrative around sustainable or green recovery.
2. Potential Opportunities: do they recognise any changes in operation or working at the airport that might unlock carbon reductions or a more sustainable way of operating into the future; the perceived longevity of these opportunities.
3. Barriers: respondents were asked to identify both short-term barriers to implementation of projects, and long-term impact in regard to their climate change or sustainability targets (for many "Net Zero" by 2050 targets); the perceived longevity of these; whether some COVID-19 mitigation strategies are counter to climate change mitigation and sustainability measures; what might provide resilience to similar events in the future. Any high-level opportunities and barriers participants identified previously in the questionnaire were explored in further detail.
4. Strategy: Participants were asked to provide an overview of how their climate change mitigation strategy is set and to identify the main drivers.

Thematic analysis of the interview response transcripts was undertaken using NVivo 12 Pro using the Template Analysis approach [6,7]. This was selected as a flexible approach and allowed for the use of a priori codes followed by an iterative, inductive approach, refining the framework at stages of the data analysis. Three high-level a priori nodes were determined based on the study aims (see Table 2). The framework was refined for every two transcripts coded, with redundant codes being removed and appropriate clustering of codes, the framework subsequently being reapplied to the data. No inter-coder analysis was used.

Table 2. Name and description of a priori codes.

Level 1	Level 2	Description of Node
Impact	Barriers to implementation	New and emerging COVID-related barriers to the implementation of climate change mitigation strategies by Airport Operators.
	Long-term goal impacts	Airport Operators' perceived impact of COVID on their long-term climate change mitigation objectives and goals.
	Operational impacts	Any unexpected, new or emerging COVID-related impacts on airport or related operations that have a consequence on the climate change mitigation and wider sustainability agenda at airports.
Opportunities		Any emerging or new opportunities that Airport Operators have identified in this period as supportive to the climate change mitigation or wider sustainability agenda at airports.
Strategy		The perceived strategic importance of the climate change mitigation agenda at airports following COVID and reasons for this, including internal and external drivers.

3. Results

The results are presented in two separate sections: Section 3.1 for the responses to the online questionnaire, and Section 3.2 on the views of the interview participants.

3.1. Online Self-Completion Questionnaire

Twenty-two Airport Operators responded to the questionnaire, representing a 37% response rate. On average, respondents completed 92% of the questionnaire. The location and characteristics of the respondents are given in Table 3 (categorised for anonymity). The respondents represent a range of organisation sizes (indicated by pre-COVID passenger numbers [8,9], and revenue (organisations' 2019 Annual Report where publicly available)). The sample is mainly composed of European airport operators (82%), reflective of the European focus in the targeted sample. As noted above, although statistical generalisation is not possible given the sample size, the results can be considered meaningful, particularly for Europe, given that the AOs responding to the study represented the majority (60%) of pre-COVID-19 European passenger numbers (2019).

Planned Interventions: (detailed data are given in Supplementary Materials File S2, Figure S1a–d). In the 2020–2030 period, AOs intend to implement 66% (164) of their total intended interventions. This decade sees a focus on mitigating direct emissions with a strong focus on on-site renewables, but also an intent to explore Scope 3 emission reduction around surface access and electric vehicles (EVs), low carbon construction and enabling Sustainable Aviation Fuel (SAF).

The year 2030 onwards sees an intention to focus on supporting alternative propulsion and alternative fuels, the top 3 selected interventions for this category being: infrastructure for future aircraft types, carbon capture and utilisation technologies, and alternative fuels for ground vehicles.

AOs reported having already taken positive steps towards tackling Scope 2 emissions with 71% (n = 21) already reporting they are purchasing renewable energy. They also reported progress on enabling Scope 3 emissions reductions, particularly within aircraft at stand and LTO: 65% (n = 20) already provide FEGP, 58% (n = 20) provide PCA, and 60% (n = 20) report enabling airspace improvements.

Table 3. Characteristics of the AOs responding to the questionnaire.

AO Location	Respondents per location
Europe	18
North America	3
Asia and Pacific	1
Total Passenger numbers 2019	**Respondents per category**
<5 million	3
5 to 10 million	3
10 to 20 million	5
20 to 50 million	4
50 to 80 million	4
>80 million	3
Operating Revenue 2019 (GBP equivalent)	**Respondents per category**
<100 million	3
100 to 500 million	4
500 million to 1 billion	6
1 billion to 2 billion	4
>2 billion	1

Removal interventions scored highest as those that AOs do not intend to deploy; a particular intention to avoid engineered carbon removals such as DACCS is identified.

Funding: Figure 2 shows a clear intention on the part of AOs to rely primarily on internal funding sources to implement their chosen interventions. Comparison of intended funding sources against pre-COVID passenger numbers and revenue (as an approximate indicator of size of organisation) shows no correlation with the intent to seek external funding (Pearson's r 0.04 and r 0.08, respectively). This refutes the hypothesis that AOs with larger (pre-COVID) revenues are more likely to fund interventions with internal capital. Additionally, the multiple benefits of exploring external funding seem desirable irrespective of organisation size or revenue.

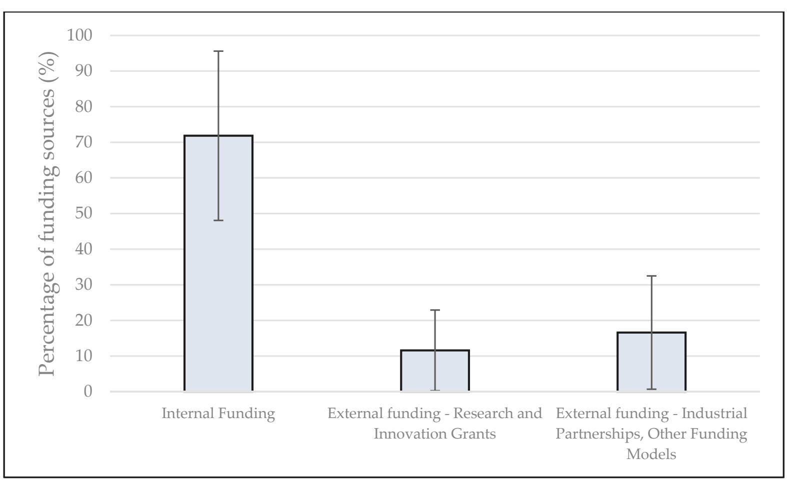


Figure 2. AO responses for intended funding sources.

Perception of risk: Fifteen (n = 19) AOs strongly agreed or agreed with the statement that COVID-19 is an existential threat to their business (Figure 3). Attitudes to the same statement but regarding climate change were noticeably less strong but AOs were still in agreement, with nine (n = 19) noting "Agree". When asked if the impacts of COVID-19 had made climate change a higher priority within the business, respondents held divergent views and six recorded "neither agree nor disagree".

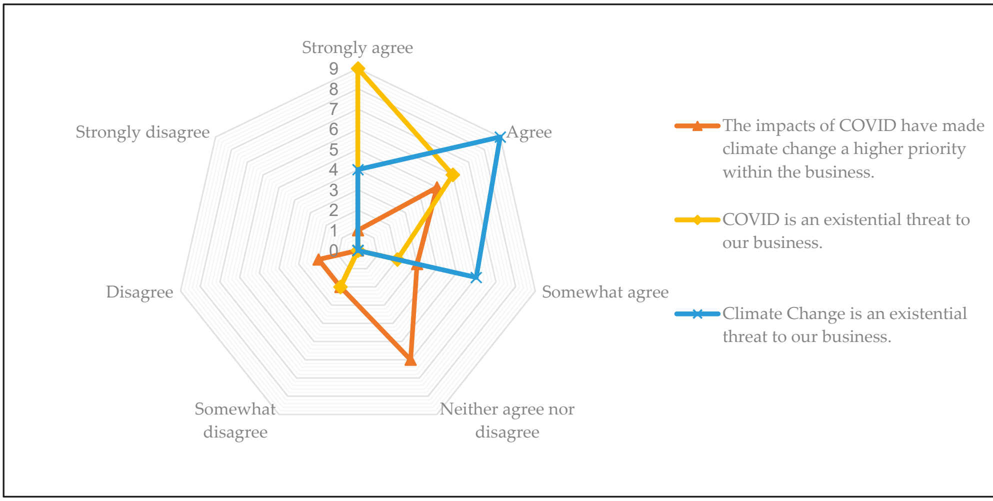


Figure 3. Business risk perceived by AOs from COVID-19 and climate change and the priority of climate change within the business.

Respondents held convergent views with regard to the statement "*the highest priority for the organisation is business continuity*", with seventeen (*n* = 19) recording "strongly agree" or "agree" (Figure 4). AOs were also largely in agreement with the statement that COVID-19 had led to the disruption of intervention implementation, with eight (*n* = 19) stating "somewhat agree"; however, there was some deviation, with one respondent strongly disagreeing.

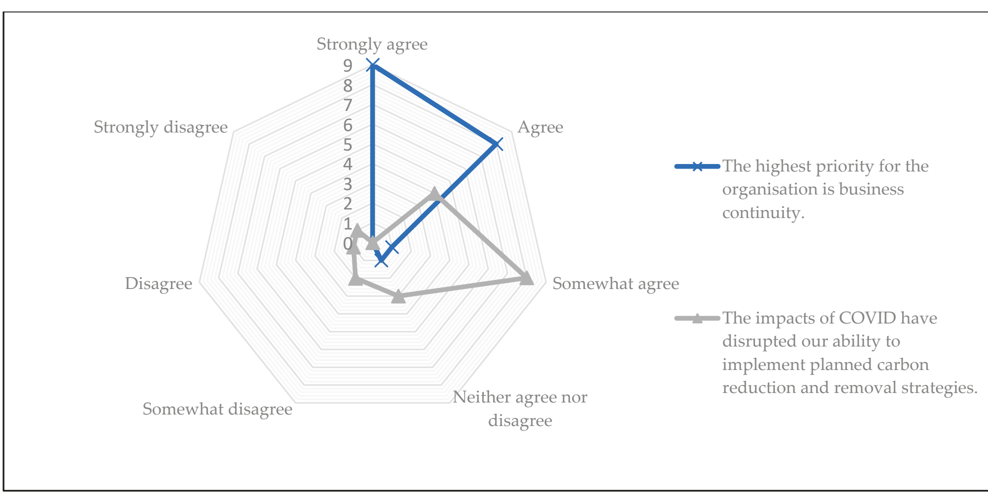


Figure 4. AO attitudes on business continuity and disruption to climate change mitigation strategies.

Opportunities and Barriers: Eleven (*n* = 19) respondents recognised potential low-carbon, or emission saving, opportunities coming out of this period. Many raised tangible benefits for Scope 3 emissions reduction through reduced air traffic, surface access and energy consumption. However, themes also emerge around changes in practice, including a change in pace unlocking opportunities, methods of working, and a potential shift to digitalisation; see Supplementary Material File S2, Table 1 for supporting quotes from AOs on this aspect.

Fifteen (n = 19) AOs recognised barriers in this period to implementing their climate change mitigation interventions. All respondents agreed on lack of funding as a barrier to their implementation plans. Some alluded to this being a temporary or short-term disruption to current projects. Another emerging theme was lack of human resources, as was the focus on health and safety, resulting in a change in priority and its potential implications for waste and energy; see Supplementary Material File S2, Table S2 for supporting quotes from AOs on this aspect.

3.2. Interviews

The nine semi-structured interviews were conducted in October and November 2020 with Heads of Sustainability and Environment at AOs in the UK, Europe and North America, representing a range of organisation structures (single or multiple airport management) and sizes (based on total annual passengers in 2019; categorised for anonymity) (Table 4). Input from an AO with a large domestic market is given through the inclusion of North American participants. The sample predominantly represents European and UK AOs.

Table 4. Characteristics of Airport Operators interviewed (passenger numbers: [8,9]).

Identifying Code	Location	Size (Passengers 2019)
A1	North America	50 to 80 million
A2	Europe	5 to 10 million
A3	Europe	10 to 20 million
A4	Europe	>80 million
A5	UK	10 to 20 million
A6	North America	50 to 80 million
A7	UK	5 to 10 million
A8	UK	>80 million
A11	Europe	50 to 80 million

The thematic analysis results are summarised in Appendix A, Table A1. Four high-level themes emerged: **Impact**, including barriers to intervention implementation and other notable sustainability impacts; **Opportunities** that support climate change mitigation or wider sustainability; **Recovery**, including perception of uncertainty and government intervention; and **Strategy**, including perceived drivers or agents influencing the climate change agenda at airports. Further detail and highlights of the interview participants' points are presented below, structured in relation to these four themes.

3.2.1. Impacts

Participants largely agreed that COVID-19 has caused significant short-term disruption to climate mitigation plans and projects—speaking of the need to "*shift to the right*" or "*change the action plan*". Views on long-term impacts were divergent: two-thirds of the participants felt COVID-19 would not impact achievement of long-term carbon reduction goals such as Net Zero by 2050. One European participant described these targets to be sufficiently distant that a recovery in the next 5 years would still allow these to be met. This was notably linked to confidence that COVID-secure travel would be enabled via medicine and/or politics. However, a third of participants were more guarded in their response, noting the potential for COVID-19 to cause long-term disruption to the aviation industry, and progress on the Net Zero agenda.

The main barrier to intervention implementation, identified by seven participants, was lack of available capital. The consequences of reduced revenue ranged from "*having to* *re-justify some expenses*", to reducing or suspending capital programmes, including climate change mitigation or sustainability projects. AOs expressed confidence in a recovery at some point and were keen to stress that financial barriers were temporary, causing delay but not termination of their plans. Stemming cash flow was reported as a challenge, given the need to maintain essential operations associated with safety, security and maintenance: "*but there's all the costs*". Some have been affected more than others, depending on the severity of travel restrictions (varying by jurisdiction), and international versus domestic market share at the airport. The strength of domestic market was reported as a factor allowing two AOs in North America to be in a more business-as-usual position than their European colleagues, one noting that large European airports "*are in survival mode*". Beyond financial barriers, five participants raised lack of human resources as a barrier to implementing climate change mitigation strategies.

AOs were asked to identify any new or emerging COVID-related impacts that may affect their climate change mitigation agenda. Four main areas were recognised: energy use, change in air traffic, operational vehicle use, and waste. In addition to these, participants noted the importance of ensuring Health and Safety as an obvious priority in this period, with one citing Maslow's Hierarchy of Needs and the basic requirement to provide safety and security for passengers. At most, any undesirable impacts on recent climate change and sustainability achievements in this period were seen as a slight frustration. Essentially, they were perceived as short-term disruptions of relatively low impact due to being largely offset by low traffic and passengers, and easy to mitigate should they persist: "*If it does go on longer there is going to be various mitigations in place to compensate for it as much as we can*". However, with one exception who noted undertaking communication with airport stakeholders on best practice around waste handling, no participants reported any measures currently in place to deal with these short-term issues.

Regarding AO energy use and Scope 1 and 2 emissions, it was noted that maximising fresh air intake and optimising heating and ventilation systems for COVID-19 were problematic. One AO recognised that this would likely cause the use of more gas in winter for terminals not yet running on renewables. The same AO spoke of the importance of indoor air quality and ventilation being part of a larger, healthy-buildings piece that needed attention within the sector: "*we really need to have a way to improve the ventilation of our spaces to* make *them healthier for the occupants*". One European AO gave the example of not seeing an expected proportionate decrease in energy consumption in line with reduced operations, triggering analysis into the source of this disparity. Another UK airport echoed having been able to undertake a forensic approach to reviewing building management systems: "*It's made us be able to understand a bit more, "OK, well what are the biggest triggers in terms of energy use?"*", adding that it is not every day one is able to switch off a terminal and interrogate its operation.

Many participants highlighted short-term impacts to air traffic and operations at the airport. Most recognised the significant reduction in air traffic as an obvious environmental benefit through avoided emissions, with one suggesting it would be likely to offer a net environmental benefit.

Two AOs offered examples of delayed climate change and environment projects. One spoke of plans to construct a new on-site plant. The same AO spoke of likely delays in the electrification of Ground Support Equipment (GSE) as they are more costly alternatives to Internal Combustion Engine (ICE) counterparts. The participants were confident that these projects had not been terminated but simply delayed pending removal of barriers and the return of revenue: "*maybe in the alternate universe, where COVID didn't hit us, maybe we would be building* this *thing in a year or two*", "*we recognize we need to accelerate our climate action, not* slow *it down*". One of them spoke to the role of the airport operator as an enabler of Scope 3 emissions reduction and delays in multi-stakeholder projects. On airline partners, they noted: "*they're still onboard ... but it may get delayed just because they simply may not have the money to do it say in the next 2 years*".

Three AOs commented on the consequences of COVID-19 impact on efforts to mitigate emissions from passenger surface access and operational vehicles. One UK AO noted that one of their suppliers had adopted a "one passenger per vehicle" policy which "*in some ways has kind of pushed things backwards*". On passenger surface access, another observed a trend in public behaviour regarding concerns over the safety of public transport and a potential preference for private vehicle use—counter to the mode shift many airports have been working to influence. The emissions impact of both examples was perceived to be negligible when compared with the perceived net environmental benefits noted in other areas by participants, but it was nevertheless seen as a behaviour to track should it persist. Giving an example, one European AO noted a recent change to a national public transport incentive that, in response to the pandemic, had been amended to include some taxi and private hire vehicles. Uncertain of the longevity of this amendment, they believed that passenger surface access would likely return to its pre-COVID state: "*as soon as the vaccine arrives and group immunity is acquired, I think the thing will return to what it was*".

In terms of impact on embodied carbon, the topic of waste received the most attention from AOs. Three AOs noted disposable face masks and Personal Protective Equipment (PPE) as an emerging waste stream, one describing it as likely to be the next high-profile waste issue after a recent focus on plastics. The lack of clarity from the government on what constitutes "appropriate" PPE was given as a limitation by one UK AO not currently using reusable PPE at the airport. Poor availability and cost of reusables was given as another limitation to moving away from disposables. Two participants spoke of many waste issues being largely out of their direct control, often the result of individual policies of airlines and retail tenants. Their frustration was highlighted over having worked hard to introduce bespoke recycling facilities for problematic waste streams, for retail tenants to adopt "disposable only" and "no ceramics" policies in their response to COVID-19.

3.2.2. Opportunities

The main opportunities identified by participants were: alternative funding sources or business models; a time for collaboration; slower pace; and a time to reprioritise or reassess strategy.

Exploration of alternative funding and business models was a common opportunity theme. Driven by reduced capital programmes, AOs are exploring external funding opportunities to implement climate change and sustainability projects: "*We're having to be more creative, so, we can't just* rely *on our capital funding because it's just not there*". One European AO reported the intention to approach investors to fund and implement interventions with potential for the AO to buy-back in the future—a change to the typical asset ownership model. They gave two examples where this may be pursued: EV charging infrastructure and on-site renewable energy infrastructure. Similarly, a North American airport noted the method of continuing to work through COVID-19 to create a "shelf-ready" design and to explore grant funding opportunities to enable the construction phase. Three UK AOs also noted an intent to investigate or signalled that they had already spent time exploring partnership or green financing options across: energy efficiency; on-site and off-site renewable energy; and EV charging infrastructure. Such options were seen as a way of being able to continue to deliver on commitments made: "*we might have to take some of our main commitments and try and bundle them up into something like that . . . then we can still drive those . . . basically a partnership agreement where the funding for this comes from the savings that are accumulated as part of a 20/25-year agreement*". Two UK AOs recognized a shift in the organizations attitude to partnership models. One stated: "*they didn't want to go into partnership agreements, and they wanted things to be with us. I suppose because it would be—these things are going to be quite long-term as well—and they obviously wanted to get the maximum benefit themselves, and whereas now, I think they're seeing that "oh actually, in order to do this, that is the only way that we are going to fund it", and so that is becoming much more attractive*".

One European AO reported seeking common interests with providers looking to demonstrate decarbonisation technology on-site that could benefit both airport and airlines, using the example of a potential partnership with a sustainable fuel producer to utilise airport waste for fuel production—and thereby benefit the circular economy: "*And if we can use also the waste that we produce in the airport that will be perfect—we will close the cycle*".

However, uncertainties were raised around asset ownership, maintenance, and the feasibility of securing green funding, with one participant arguing that difficult conversations would have to be had between lenders and airports, with the latter having to prove the case for the certainty and benefits of a long-term investment in a time of significant uncertainty for the sector.

European Commission (EC) funding competitions for airports were looked on favourably by two European AOs, who proclaimed their intention to now pursue it: "*I think this is the first time that at least our airports are facing* that *kind of possibility of funding*". Another stated EC funding "*is a good possibility to understand other airports' benchmark and to implement something at the airport, and we will get the funds back as well. So, it's a good possibility to solve and to move on with the sustainability initiatives*".

Participants noted changes in working practices and attitudes resulting from the pressure on the organisation. Two UK AOs spoke of a new spirit of interdisciplinary collaboration within the organisation and airport stakeholders to find solutions, one hoping this would carry over in to climate change mitigation solutions and remove some pushback from stakeholders who previously did not consider the agenda a priority, or not fitting operationally: "*I think that this is just showing that actually when we are faced with a problem, we can all come together and work and we can find solutions very quickly and change the way that we work quite quickly and put new things in place*". Another noted: "*to ask: can you find alternatives outside of just going to your shareholder and asking for a big capital budget? That, I would say, is as much as an opportunity as anything else because by doing that, it's making us, like a virtual team—with Engineering, Development, Ourselves, Finance—to think more holistically: what do we want out of this? How many things could we solve out of this? It's not just about reducing emissions it's also about improving resilience for the airport, being able to adapt to climate change as well*".

Three AOs from Europe and North America attributed a slow-down in the pace of operations as beneficial in some context. One spoke of the rapid pace of capital development in the US prior to COVID-19 in an attempt to keep pace with the growth of the sector, renew aging infrastructure and under pressure from airlines to increase capacity—noting this made some sustainability professionals "*very uncomfortable*". They noted this slow-down had allowed for a testing and refining of the sustainability methodologies tied to capital projects: "*By doing that, in* this *slow period, and testing things out, because that's really* what *we're doing right now, we're like, "Well, what if we did it this way? How much do we know at 30% design level that we can really impact here?". We're just learning a lot; I do think we can normalize that and have that continue into the future*". In addition, one European AO noted that the slow-down was a means to more easily implement pilot projects where, previously, the pace of operations would have caused resistance to deployment. This was not reflected elsewhere, as stated earlier, with one UK AO noting that Operational departments were particularly stretched at this time.

3.2.3. Strategy

A general theme of reassessment and prioritisation of strategy and interventions emerged. For some, this involved a change in strategy toward preparation of concepts only, with a plan to seek external funding for implementation. Others intended to use available funding as efficiently as possible, leading to a prioritisation of interventions by carbon reduction potential: "*I think what the squeeze on capital is partly doing is making us focus in a really laser-like way on: where can our investment deliver the most carbon reduction? And we've developed a Marginal Abatement Cost Curve model to look at the different investments we could make and help us prioritize, so we ensure* that *we are investing where the biggest reductions will happen*".

Six AOs recognised that the climate change and sustainability agenda remained of strategic importance or had risen in importance in their organisation throughout the pandemic. Two posited that COVID-19 had been able to promote the climate change and sustainability agenda by demonstrating the significant impacts a realised external risk can cause to the sector. The point is that COVID-19, being a comparable risk in magnitude and severity to climate change, has allowed for a greater understanding of the risk posed by climate change to the organisation. Another participant, alluding to the next major global external risk being climate change, stated: "*COVID has shown us* what *a genuine global crisis looks like. I mean, no one anticipated a year ago* that *a pandemic would bring the industry to its knees in the way it has globally—that has happened, and that's focused minds I think, because people* have *understood that ... If we think COVID's bad, climate has the potential to be significantly worse, so that's almost underlined the importance of action*".

Other perceived drivers or agents influencing the current strategic priority of the climate change and sustainability agenda at airports were reported: its current standing, the consequence of several drivers and agents and not one alone. These are briefly presented below.

Several AOs noted increasing top-down support and pressure to take action on sustainability and climate change mitigation at airports, building over recent years but continuing through COVID-19: "*I can tell you that right before COVID, so it's very recently, we have been facing huge pressure from our company in the environmental area. So right now, I can say that we are one of the most, not the most, but one of the most important things in the company, yes*". Another noted that senior management buy-in to the climate change issue was a reason for COVID-19 being unlikely to prove detrimental to their long-term climate change goal: "*No, I don't think so because I think the engagement of the management is there. And they have showed us that they care about this topic a lot. And they're willing to put money towards it when the money is available*".

Two noted the influence of investors, one participant stating that they were now wise to social pressure groups, citing *flygsham* and *Stay Grounded*, which had bolstered the importance of taking action. Similarly, one reported being owned by an investment company whose investors were prioritising the issue: "*it was really becoming a priority for them as well and their investors* were *starting to ask questions*"; the AO described that this, along with COVID-19, had led to a mindset shift from the sustainability transition being an opportunity and a "nice-to-have", to something that now has to be done. One North American participant noted that their sustainability work had started to pay off in this respect, being of financial benefit to the business, as investors and rating agencies were wanting to see sustainability improvements at the airport: "... *we've been able to improve our credit ratings and the* sale *of bonds to support projects and investments in our airports. And the reason we've been able to get really good credit ratings and have really* good *rates on bonds, is because those investors and rating agencies are definitely giving value to airports* that *can* show *a reduction in carbon emissions in their sustainability or Environmental, Social and Governance (ESG) reports*".

On organisational governance, one North American AO noted that the airport was overseen by an elected commission who, due to the politics and environmental consciousness of the electorate, had a strong environmental focus, favouring the implementation of interventions, including through COVID-19.

Public understanding of climate change and sustainability emerged as an influence, principally within the UK and Europe. Participants noted the rising pressure for climate action in aviation. In one isolated low-population European nation, public opinion was perceived to be more favourable due to understanding of the economic and social importance of the airport to the nation. Participants also noted public pressure was evident on other sustainability issues such as reduction in the use of plastics. Similarly, three AOs noted staff interest and pressure to move forward on climate change mitigation and sustainability projects within the organisation, one stating that their Operations and Retail departments had started their own sustainability groups and initiatives. This was seen as connected to the aforementioned wider public awareness: "*the 'Blue Planet effect' after the Attenborough* *documentary, that was definitely something that we could see here because, after that, staff were a lot more interested in what we were doing, and I think just questioning things a lot more*".

3.2.4. Recovery

Recovery was not identified as an a priori theme but emerged as one that occurred as a factor influencing strategy, barriers and opportunities. Within recovery, topics emerged around: calls to secure the benefits of aviation; concerns over public perception of aviation; the role of government in recovery; the role of vaccines and testing in recovery; uncertainty and complexity of recovery; and collaboration as a key element of recovery.

For UK AOs in particular, messaging around protecting the benefits of aviation was deeply tied to concern over how the sector is currently perceived by the UK public, and moreover, to the lack of government support for the sector and perceived failure to retain consumer confidence in air travel. This frustration was seemingly rooted in an underappreciation of the efforts of airports to tackle emissions across all scopes: "*I think we're kind of being seen just now as the bad guy in all of this*".

The role of government in supporting or enabling the sector's decarbonisation efforts through recovery was discussed by eight AOs. The role of government in supporting Sustainable Aviation Fuels (SAF) supply and demand was noted by two AOs, one alluding to positive recent moves within UK and European Union (EU) Governance in support for SAF. Mandate was seen at the most appropriate government measure that could be implemented, with one AO referencing the Nordic countries as an exemplar of mandating SAF: "*We need government policies to help scale up the market. We need supply* side *mandates, well designed. We need demand-side incentives to help lower the price*".

Uncertainty around the timescales and complex nature of recovery were raised by six AOs in relation to how it could impact their climate change mitigation plans. Uncertainties included: longevity of government-imposed restrictions; future demand and changes in types of travel; uncertain future of some airport stakeholders such as ground handlers. The importance of certainty to the prosperity of aviation was articulated by one AO thus: "*As an industry we were predicated on certainty, you know certainty of slots, certainty of schedules, certainty of when passengers would arrive. It's how we make our business work. And that planning element is the reason why airports have been able to be quite successful in growing and growing demand alongside the airlines*".

When questioned on how airports could be more resilient to such pressures in the future, three AOs spoke to the importance of multi-stakeholder collaboration. This was seen as a means to prosper as a sector, to unlock win–win solutions between organisations, and was also tied to responsibility for decarbonisation not being burdened on airports alone. The following three responses all carry a similar message in this regard:

- "*Cooperation with partners: because the airport itself is not enough to reduce the* CO_2 *emissions and so on efficiently. Cooperation with the airport partners, with the government, with the stakeholders, with the residents and so on . . .* "
- "*Effective collaboration between all the stakeholders. We need to be very, very close—airport, airlines, handling managers, because I think that this is going to be the key, we need to be all in the same team, but for that it is really important to increase our business in the future*".
- "*The key thing is having that partnership approach—it's not just the airport that's going to fix the problem, it's not just airlines, but how can everybody work together? How can everybody see how they can each understand their contribution and work towards a common goal?*"

4. Discussion

Impacts.

The predominant view from sustainability managers at AOs is that climate change mitigation interventions and projects will be delayed by COVID-19 but not abandoned, as might sometimes be assumed in times of crisis [10]. Given stakeholder demands, AO participants were fully cognizant of the need to maintain and accelerate, not slow down, climate change action, as hypothecated for other sectors [11]. Most AOs in our study anticipated a short-term impact on the implementation of climate change mitigation interventions at airports due to the immediate disruption from pandemic measures to their principal revenue streams (aeronautical and non-aeronautical) leading, in turn, to a concentration on business survival with delayed capital programmes and attempts to reduce costs—as hypothecated [12]. Hub airports with a large domestic share of the market appear more resilient to the impacts of COVID-19, with domestic traffic likely to continue to offer resilience if long-haul routes recover slowly as suggested [13].

Despite the severe and persistent stress of COVID-19 on aviation, the evidence gathered here suggests that climate change retains its position as a strategic priority for airports, with AOs demonstrating commitment to decarbonising the sector. A notably different response compared to previous crises, this reflects an economy-wide recognition of the need to utilize this time of disruption as an opportunity to "*build back better*". In some cases, climate change has gained increased importance as COVID-19 acts to demonstrate how the impact of a realised external risk can impact the organisation. When comparing the perception of risk from both COVID-19 and climate change, it is understandable that COVID-19 was seen as the highest immediate threat, given its rapid-onset and highly visible ongoing impacts, whereas climate change is perceived as a longer-term albeit highly significant challenge.

Further impacts on emissions and sustainability resulting from COVID-19 were reported. Virus management measures (e.g., disposable PPE) have had a substantial impact on waste streams, as was a reported increase in single-occupancy use of operational vehicles. It is important that gains made in emission mitigation and sustainability over recent years are not permanently undone through longer-term COVID-related shifts in behaviour. Changes such as those reported would become highly problematic in terms of waste volumes and emissions should they persist as passenger numbers return to pre-COVID levels. Whilst a safe and secure air transport system is clearly the priority, pragmatic solutions will be required to mitigate these issues as passenger numbers return. While low- and zero-emission solutions to operational vehicles are being developed and pursued, the use of masks could become a "new normal", suggesting that innovation is also needed to reduce and manage this waste stream. Surprisingly, no measures were reported as being in place to mitigate these impacts, although many of the drivers are beyond the direct control of the airport, emphasising a need for collaboration between all airport stakeholders, a point widely noted by AOs.

The current COVID-19 crisis has made it clear that better approaches should now be adopted to address previously underplayed sustainability issues. This recognition was evident from AOs noting the need to provide healthy buildings and prioritise passenger and colleague health, and is also reflected in the literature [14]. Epidemic management measures at airports have been called for previously [15] and are now likely to become a routine part of planning and decision making in airports. This pandemic has served as a salutary reminder that sustainability issues are multi-dimensional and need to remain in focus even when responding to particular key issues and targets such as climate change and achieving Net Zero.

Interventions and the Net Zero transition.

Greer, Rakas and Horvath (2020) [16] recommended six impactful practices for airports that can be implemented in the short-term with minimal disruption. These include: renewable electricity (on-site or local); electrification of vehicle fleet; and electrification of gate and GSE. The AOs in our research report having already deployed many of these interventions, e.g., Fixed Electric Ground Power (FEGP) was already implemented by 65% of the AOs. Furthermore, 86% intend to pursue on-site renewables in the next 10 years, with the majority already purchasing renewable electricity. Additionally, 68% of the AOs in the present work have already deployed electric vehicles or intend to do so in the next decade, with no participants reporting that they would not pursue this action.

A somewhat surprising finding was the fact that AOs stated that they do not intend to deploy engineered carbon removal interventions in the next decade. Arguably, smaller airports have limited need, or capacity, to employ these measures, but these technologies do feature as part of recognised decarbonisation pathways [17]. After carbon reduction is pushed to its limits within the sector, residual emissions removal will be required to achieve "net-zero". Rather than being reflective of the sector's lack of awareness or desire to act on removals, this finding may be the result of policy uncertainty, disrupting potential progress. What role airports intend and need to play in removals, including intended reliance on out-of-sector removals or removals credits, remains to be seen and requires further study. From the study findings, engineered removals certainly feature as a post-2030 intervention, perhaps linking to perceptions of Green Hydrogen and Synfuel production and use in the aviation sector. In the next 10 years, Nature-Based Solutions, are evidently seen by AOs as a more immediate intervention, although they diminish in favour of engineered removals in the 2030s—this may speak to a recognition that out of sector removals cannot be relied on indefinitely.

Interestingly, 66% of the AOs envisioned their climate change interventions being implemented within the next decade with these being funded principally from internal sources. This finding should be considered against the longer-term climate goals of the sector: there are questions around how realistic this aim is for the next decade, particularly given the potential for a slow recovery over the coming years [1]. If relatively near-term interventions are delayed significantly, decarbonisation paths to "net-zero" become more challenging and arguably less achievable. However, the majority of AOs clearly expressed that they felt there to be no likely impact on longer-term goals (i.e., Net Zero by 2050), and were confident in a recovery and/or felt sufficient time remained to attain the goals, even if some delay occurs in the short-term.

Solutions to barriers and opportunities were reported. Due to lack of internal funding, EC funding for airports was seen as a particular opportunity for European AOs to maintain momentum with their strategies. In creating spaces for innovation development, such big-budget projects can be likened to "Strategic Niche Management" [18]. The EC funding model is an example of government structure supporting diffusion of innovations at airports and could be replicated by national governments outside the EU to prevent a slow-down on the greening of airports. Additionally, compared to airports independently supporting niche-innovations, they arguably lessen the risks from innovation failure and requirement to subsidise innovation in the current financial environment. In the UK, early calls for fiscal recovery packages in support of climate progress [19] and government investment toward the Net Zero transition has been declared with implications for aviation [20]. For the USA, there has been a recent political shift towards supporting a sustainable transition on a national level which may prove beneficial to the Net Zero agenda. Nonetheless some States are already independently pushing this as recognised by AOs.

Conscious of letting momentum slip, sustainability managers noted a change in attitude toward partnership approaches with several having started exploring alternative financing opportunities. Here, "servicisation", or the offering of land, facilities and resources to innovation partners to fund intervention implementation, may offer significant possibility to progress while access to internal capital is difficult. This could bring opportunities for innovators in areas such as renewable energy, electric vehicles and charging infrastructure, and solutions to decarbonise airport infrastructure. However, as these are potential long-term commitments, care will be needed to avoid unintended consequences or forms of lock-in. COVID-19 presents an obvious challenge but, as noted by [21] (p. 29), such challenges are also often "*windows of opportunity*" for beneficial change and innovation. Which innovations may break through in this period remains to be seen: in terms of climate change mitigation, AOs are still seeking the same technological solutions as they were pre-COVID. However, a potential acceleration in digitalisation of operations at airports for efficiency and cost reduction is evident from the literature [12,22]. AOs will need to consider how this transition may also play into the benefit of decarbonisation efforts.

Beyond financial and technological opportunities, this study has also revealed evidence of changes in practice that would be of benefit if sustained going forward. These are noticeably tied to a change in the usual fast pace of airport operations and include: time to forensically analyse and optimise building management systems, time to explore sustainability methodologies that will benefit capital projects, airport stakeholders having more time to participate, and finally, more opportunity for and less push back against demonstrator-type and other testing opportunities due to high-pressure, dominant operational commitments. Sustainability managers should, therefore, seek to focus efforts in this period of disruption to explore and embed new practices and stakeholder relationships, so they are normalised in a post-COVID airport.

Recovery or Transformation?

COVID-19 has demonstrated the impact of a global-scale risk, exposing the vulnerability of the aviation system in its current form. In this way, it is a warning and, given the potential for climate change to cause even greater impact on the global aviation system, speaks to the inadvisability of simply returning back to the system in its pre-COVID state.

AOs highlighted that the industry is one predicated on certainty and highlighted the disorder created by the uncertainty around recovery. Some have noted that to counter this, aviation managers should "*embrace uncertainty*" into long-term decision making [23]. However, perhaps a new certainty can be found in a unified effort to fundamentally pivot the sector, with industry practitioners taking the lead to enact radical changes to accelerate the transition to a sustainable, zero-carbon air transport system. Many of the AOs in this study offered statements that suggest this is something under serious consideration.

This fundamental transition is technologically in sight and arguably inevitable should public opinion continue to mount pressure on the industry. The development of alternative propulsion systems has progressed rapidly, particularly for hydrogen (which has previously suffered hype-disappointment cycles), with commitments for entry into service in the early 2030s [24]. The call for action on climate change is arguably stronger than ever before [25]; consequently, the criticisms of aviation in its current form will continue unless the sector can demonstrate it is fundamentally and rapidly transforming and not returning to where it was pre-COVID. Studying typical patterns in the greening of industries, it can be observed that organisations often change their core business model and values as a result of public opinion forcing consumer behaviour change, supported by stringent policies [26]. However, these external forces are unpredictable and could have a positive or negative influence. Rather than being at risk to changes in public opinion and government policy, the sector should seize the opportunity to take a proactive lead—to demonstrate and communicate what is possible, utilising existing expertise and emerging technologies, thus helping to inform public opinion and policy, and steer the transition to a "built-better", Net Zero aviation system. Positives steps in consumer pro-environmental behaviour need not be in contradiction to aviation if this transition leads to new, sustainable models such as zero-carbon short-haul travel.

For airports to enact this transition to zero-carbon aviation alone is an impossible task, particularly given the financial pressure and resource constraints that look set to continue in 2021. To support the short-term climate responses of AOs, innovative solutions should be welcomed, and new partnerships may enable progress. In addition, the common calls by AOs in the present work for collaboration between all aviation stakeholders should be supported by a unified, coordinated action for Net Zero aviation—something which is as-yet lacking from the supranational bodies that could champion this. With one AO highlighting the potential variance in participants understanding of the term "Net Zero" and the emission sources they consider "in scope" for achieving it, arguably this should commence with consensus on a robust definition of Net Zero in relation to aviation and airports.

Beyond the above, policy makers must enable this transition for aviation and the pillar industries that will support it. This will require going beyond a sole focus on SAF, to stimulate the emergence of zero-carbon flight through continued investment in R&D. Political intent to support decarbonisation and sustainable transition has grown over recent years, particularly in the UK and Europe, and appears to be re-emerging in the USA;

however, with the UNFCCC Conference of the Parties (COP26) approaching, the stage is ready for governments to lay out how they intend to act to enable these changes.

5. Conclusions

This research was conducted to explore via questionnaires and semi-structured interviews what impacts the COVID-19 pandemic has had on the progress that AOs have been making, are making and plan to make to address climate change, GHG emissions and other sustainability issues. Given the lack of literature on this topic to date, the present study contributes to the knowledge of how airports have reacted to the external pressure of COVID-19 in terms of their decarbonisation agenda. The conclusions of the study are:

COVID-19 has caused immediate delay to the progress of climate change mitigation interventions and projects at airports, principally as a result of financial constraints linked to decreased passenger numbers. These delays are considered to be short term in their effects.

- The majority of AOs perceived that COVID-19 would have a negligible impact on the long-term decarbonisation goals of airports.
- Climate change has retained its position as a strategic priority, something it had attained pre-COVID-19.
- AOs have already implemented several climate change mitigation interventions and show intention to continue with their strategies. Given the current and persistent strain on capital and resources, implementation plans for the next decade are ambitious.
- The most popular interventions for deployment in the next decade are on-site renewables, EVs and related infrastructure. Engineered carbon removal interventions were recorded as being the most unlikely types to be deployed in this timeframe. This has potential implications for Net Zero because decarbonisation pathways are likely to rely at least to some degree on such interventions to achieve "zero".
- AOs should nurture collaborative approaches with other aviation stakeholders and explore partnership opportunities to implement new business models and more ambitious interventions for climate change, including those that enable and support alternative propulsion aircraft.

Despite the impacts of COVID-19 on aviation and airports, now is an opportune time for AOs to radically pivot to sustainable aviation. Failure to do so will expose the sector to further, greater risks from external forces. This transition is achievable, but Governments need to provide the supporting policy and funding to nurture the development of a sustainable, resilient, low-carbon, aviation system rather than focusing on a return to business-as-usual. Practitioners in the sector are best placed to take a lead and utilise existing expertise and insights to steer it in line with "build back better" and Net Zero and, in doing so, can help to inform policy and public opinion.

Supplementary Materials: The following are available online at https://www.mdpi.com/article/10.3390/su132112235/s1. Supplementary Material S1: Literature Review. Supplementary Material S2: Table S1. Opportunities identified for emissions reduction—results from questionnaire. Table S2. Barrier to implementation identified—results from questionnaire. Figure S1 (a). Interventions planned 2020 to 2030. Length of bar indicates number of responses. (b). Interventions planned 2030 onward. Length of bar indicates number of responses. (c). Responses for "We already do this". Length of bar indicates number of responses. (d). Responses for "We don't intend to pursue this". Length of bar indicates number of responses.

Author Contributions: Conceptualisation, P.H.; methodology, P.H., R.J.M.; validation, P.H.; formal analysis, P.H.; investigation, P.H.; data curation, P.H.; writing—original draft preparation, P.H.; writing—review and editing, P.H., M.M., R.J.M., M.P.; visualisation, P.H., M.M., R.J.M., M.P.; supervision, M.M., R.J.M., M.P.; project administration, P.H. All authors have read and agreed to the published version of the manuscript.

Funding: This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors. Financial support by Heathrow Airport Ltd. is gratefully acknowledged as part of the first author's Practitioner Doctorate in Sustainability Ph.D. in the Centre for Environment and Sustainability and the Department of Civil and Environmental Engineering, University of Surrey, UK.

Institutional Review Board Statement: The study was conducted according to the guidelines of the Declaration of Helsinki, and approved by the Institutional Review Board (or Ethics Committee) of University of Surrey (Ref. No.: 640816-640807-65708080, date of approval: 28 September 2020). Due to the nature of the study, no in-depth ethical review by an external committee was required.

Informed Consent Statement: Informed consent was obtained from all subjects involved in the study.

Data Availability Statement: The data presented in this study are not publicly available due to privacy or ethical reasons.

Conflicts of Interest: The authors declare no conflict of interest.

Appendix A

Table A1. Themes identified by the participants in the semi-structured interviews with Aos.

Level 1	Level 2	Level 3	Description of Node	Insights
Impact			**Reported short- and long-term impacts on the climate change mitigation and sustainability strategies of Airport Operators; the perceived longevity of these impacts.**	
	Barriers to implementation		New or potential barriers to the implementation of climate change mitigation strategies resulting from the COVID disruption.	
		Financial	Financial barriers to climate change mitigation strategy	Reduced or suspended capital programmes including climate change mitigation or wider sustainability projects; re-justification of expenses.
		Human Resources	Personnel impacts as a barrier to implement strategy.	Furlough; difficulty bringing together relevant stakeholders.
	Alleviating Factors		Factors which AOs perceive have provided the airport(s) and strategy some resilience from the impacts of COVID.	Strength of domestic market as an alleviating factor.
	Long-term impact		AOs' perceived impact of COVID on their long-term climate change mitigation objectives, goals, targets.	COVID not considered a threat to long-term climate change goals.

Table 1. *Cont.*

Level 1	Level 2	Level 3	Description of Node	Insights
	Short-term impact		Any unexpected, new or emerging impacts on airport or related operations that have a consequence on the climate change mitigation and wider sustainability agenda at airports.	
		Energy	Energy-related impacts from changes to operations, such as clean air requirements, pax density in terminal buildings.	Ventilation requirements counter to efficient operation.
		Prioritising Health and Safety	AO perception that assuring health and safety takes priority over negative impacts on climate change and sustainability.	Health and Safety the logical priority at this time.
		Air Traffic and Passengers	Impacts on type of aircraft received, mission type, domestic/international market share and its impact on the climate change and sustainability agenda.	Peak in cargo traffic; overall traffic reduction likely to have environmental benefit.
		Longevity	Perceived longevity of these impacts.	Undesirable impacts on climate change and sustainability considered short-term and easy to mitigate.
		Project Delays	Impacts specifically on climate change and sustainability projects.	Delay to eGSE project; delays to multi-stakeholder projects.
		Vehicles	Impact on passenger surface access or third-party operational vehicles.	One vehicle per passenger policy.
		Waste	New and emerging waste streams or issues and their perceived impact on climate change mitigation and sustainability agenda.	Waste PPE as an emerging problem.

Table 1. *Cont.*

Level 1	Level 2	Level 3	Description of Node	Insights
Opportunities			**Any new, emerging or potential opportunities that AOs have identified in this period as supportive to the climate change mitigation or sustainability agenda at airports.**	
	Alternative Funding and Business Models		Innovation; potential new methods of financing projects; potential new business models.	Exploration of green financing and partnership models for on-site renewables and EV charging infrastructure.
	Methods of Working		New methods of working that are beneficial to the climate change and sustainability agenda; new opportunities for airport stakeholder collaboration.	Teleworking; new spirit of collaboration.
	Pace		A slower pace of working unlocking new opportunities.	Time for consideration of new sustainability methods; easier to implement pilots.
	Prioritisation and Reassessment		This period as a time to review, reassess and reprioritise strategy and interventions.	Strategic review; focus on delivery of highest carbon benefit for investment.
Recovery			**AOs' comments on recovery in relation to the climate change and sustainability agenda at airports—an integral theme undercutting many responses impacting barriers, opportunities and strategy.**	
	Benefits and public perception		AO comments on the need to protect aviation's benefits; AOs' concern over public perception of aviation during this period.	Calls to protect the benefits of aviation; impact on consumer confidence.

Table 1. *Cont*.

Level 1	Level 2	Level 3	Description of Node	Insights
	Government		AO comments on government and policymakers, their interventions so far or thoughts on interventions required to support the climate change mitigation agenda at airports; AO comments on Vaccine and Testing as a driver for recovery.	Lack of government support; EU financial packages for airports beneficial; Vaccine and Rapid Testing key factor for recovery.
	Uncertainty		Uncertainty of the period and, therefore, recovery.	Awareness of complexity and multi-factors governing recovery.
	Collaboration		Emerging theme of collaboration being key to recovery.	Need for collaboration across all aviation and airport stakeholders; Airports unable to tackle pressures alone.
Strategy			**The perceived strategic importance of the climate change mitigation agenda at airports through the COVID period and the perceived reasons for its standing, including internal and external drivers.**	
	Strategic Importance		AO comments on the climate change mitigation agenda current standing in the business and influence of COVID on this.	Climate change still of strategic importance or has risen in strategic importance due to COVID.
	Drivers		AOs' comments on the drivers currently influencing the climate change mitigation strategy at airports.	
		Frameworks and Public Commitments	Perceptions of accreditation frameworks and public decarbonisation commitments and their impact on strategy at this time.	ACI ACA Net Zero Commitment beneficial but some airports ahead; National ESG commitments advantageous to top-down action.
		Directors, Investors	Senior management and investors driving or enabling climate change mitigation strategy within the business; top-down influence.	Engagement of the management in Climate Change action is present; investor voice increasingly influential.

Table 1. *Cont.*

Level 1	Level 2	Level 3	Description of Node	Insights
		Public	Public pressure influencing the agenda.	Increasing public understanding and pressure
		Staff	AO comments on colleagues within the business push the agenda; bottom-up.	Colleagues creating their own sustainability groups.

References

1. Air Transport Bureau. *Effects of Novel Coronavirus (COVID-19) on Civil Aviation: Economic Impact Analysis*; International Civil Aviation Organization (ICAO): Montréal, QC, Canada, 2021.
2. Oneworld. Oneworld Member Airlines Commit to Net Zero Carbon Emissions. 2020. Available online: https://www.oneworld.com/news/2020-09-11-oneworld-member-airlines-commit-to-net-zero-carbon-emissions-by-2050 (accessed on 1 May 2021).
3. United Nations DGC. Climate Change and COVID-19: UN Urges Nations to 'Recover Better'. 2020. Available online: https://www.un.org/en/un-coronavirus-communications-team/un-urges-countries-\T1\textquoteleftbuild-back-better\T1\textquoteright (accessed on 1 May 2021).
4. Looi, M.K. Covid-19: Is a second wave hitting Europe? *BMJ* **2020**, *371*, m4113. [CrossRef] [PubMed]
5. Ranganathan, J.; Corbier, L.; Schmitz, S.; Oren, K.; Dawson, B.; Spannagle, M.; Bp, M.M.; Boileau, P.; Canada, E.; Frederick, R.; et al. The Greenhouse Gas Protocol: A Corporate Accounting and Reporting Standard. 2015. Available online: https://ghgprotocol.org/sites/default/files/standards/ghg-protocol-revised.pdf (accessed on 3 May 2021).
6. King, N.; Brooks, J. Thematic Analysis in Organisational Research. In *The SAGE Handbook of Qualitative Business and Management Research Methods: Methods and Challenges*; SAGE Publications Ltd.: London, UK, 2018; pp. 219–236. [CrossRef]
7. King, N.; Brooks, J.M. *Template Analysis for Business and Management Students, Template Analysis for Business and Management Students*; SAGE Publications Ltd.: London, UK, 2017. [CrossRef]
8. ACI. ACI Reveals Top 20 Airports for Passenger Traffic, Cargo, and Aircraft Movements. 2020. Available online: https://aci.aero/news/2020/05/19/aci-reveals-top-20-airports-for-passenger-traffic-cargo-and-aircraft-movements/ (accessed on 10 December 2020).
9. Eurostat. AVIA_PAOA: Air Passenger Transport by Main Airports in Each Reporting Country. *Eur. Comm. Eurostat Databrowser*. 2021. Available online: https://ec.europa.eu/eurostat/databrowser/view/avia_paoa/default/table?lang=en (accessed on 1 May 2021).
10. Amankwah-Amoah, J. Stepping up and stepping out of COVID-19: New challenges for environmental sustainability policies in the global airline industry. *J. Clean. Prod.* **2020**, *271*, 123000. [CrossRef] [PubMed]
11. Jones, P.; Comfort, D. A commentary on the COVID-19 crisis, sustainability and the service industries. *J. Public Aff.* **2020**, *20*. [CrossRef]
12. Serrano, F.; Kazda, A. The future of airports post COVID-19. *J. Air Transp. Manag.* **2020**, *89*, 101900. [CrossRef]
13. Suau-Sanchez, P.; Voltes-Dorta, A.; Cugueró-Escofet, N. An early assessment of the impact of COVID-19 on air transport: Just another crisis or the end of aviation as we know it? *J. Transp. Geogr.* **2020**, *86*, 102749. [CrossRef]
14. Barreiro-Gen, M.; Lozano, R.; Zafar, A. Changes in Sustainability Priorities in Organisations due to the COVID-19 Outbreak: Averting Environmental Rebound Effects on Society. *Sustainability* **2020**, *12*, 5031. [CrossRef]
15. Chung, L.H. Impact of pandemic control over airport economics: Reconciling public health with airport business through a streamlined approach in pandemic control. *J. Air Transp. Manag.* **2015**, *44–45*, 42–53. [CrossRef] [PubMed]
16. Greer, F.; Rakas, J.; Horvath, A. Airports and environmental sustainability: A comprehensive review. *Environ. Res. Lett.* **2020**, *15*, 103007. [CrossRef]
17. Climate Change Committee, 2020. The Sixth Carbon Budget: The UK's Path to Net Zero. Available online: https://www.theccc.org.uk/publication/sixth-carbon-budget/ (accessed on 3 May 2021).
18. Kemp, R.; Schot, J.; Hoogma, R. Regime shifts to sustainability through processes of niche formation: The approach of strategic niche management. *Technol. Anal. Strateg. Manag.* **1998**, *10*, 175–198. [CrossRef]
19. Hepburn, C.; O'callaghan, B.; Stern, N.; Stiglitz, J.; Zenghelis, D. Will COVID-19 fiscal recovery packages accelerate or retard progress on climate change? *Oxf. Smith Sch. Enterp. Environ.* **2020**, *36*, S359–S381. [CrossRef]
20. HM Government. The Ten Point Plan for a Green Industrial Revolution. 2020. Available online: https://www.gov.uk/government/publications/the-ten-point-plan-for-a-green-industrial-revolution (accessed on 3 May 2021).
21. Geels, F.W. The multi-level perspective on sustainability transitions: Responses to seven criticisms. *Environ. Innov. Soc. Transit.* **2011**, *1*, 24–40. [CrossRef]

22. Drljača, M.; Štimac, I.; Bračić, M.; Petar, S. The Role and Influence of Industry 4.0. in Airport Operations in the Context of COVID-19. *Sustainability* **2020**, *12*, 10614. [CrossRef]
23. Linden, E. Pandemics and environmental shocks: What aviation managers should learn from COVID-19 for long-term planning. *J. Air Transp. Manag.* **2021**, *90*, 101944. [CrossRef]
24. Vittadini, G. Novel Aircraft Technological Concepts, in: ICAO Stocktaking. 2020. p. 4. Available online: https://www.icao.int/Meetings/Stocktaking2020/Pages/default.aspx (accessed on 11 September 2020).
25. UNDP and University of Oxford. Peoples' Climate Vote: Results. 2021. Available online: https://www.undp.org/publications/peoples-climate-vote (accessed on 3 May 2021).
26. Penna, C.C.R.; Geels, F.W. Multi-dimensional struggles in the greening of industry: A dialectic issue lifecycle model and case study. *Technol. Forecast. Soc. Chang.* **2012**, *79*, 999–1020. [CrossRef]

sustainability

MDPI

Article

Foreign Direct Investment and Environmental Quality: Revisiting the EKC in Latin American Countries

Wilman-Santiago Ochoa-Moreno [1], Byron Alejandro Quito [2] and Carlos Andrés Moreno-Hurtado [1,*]

[1] Department of Economics, School of Economics, Universidad Técnica Particular de Loja, Loja 110107, Ecuador; wsochoa@utpl.edu.ec

[2] Department of Economics, School of Economics, Universidad Nacional de Loja, Loja 110111, Ecuador; byron.quito@unl.edu.ec

* Correspondence: camoreno1@utpl.edu.ec

Abstract: In this study we aim to test the effects of foreign direct investment (FDI) on carbon emissions (CO_2) in 20 Latin American countries during the period of 1990–2018. Based on the atlas method of the World Bank, we divided the countries into three groups according to their real gross national income per capita: high-income, upper-middle-income and lower-middle-income countries. We used cointegration techniques and causality tests to evaluate the relationship between the variables. To assess the strength of the cointegration vector, we applied the dynamic ordinary least squares (DOLSs) model for individual countries and the dynamic panel ordinary least squares (PDOLSs) model for groups of countries. The results suggest that the entry of FDI into Latin American (LA) countries increases CO_2 emissions, affecting the environmental quality. These findings disagree with the environmental Kuznets curve (EKC) hypothesis but, in contrast, they are in line with the pollution haven hypothesis (PHH). Moreover, we show evidence in long-term equilibrium relationship between FDI input and CO_2 emissions, which is not the case for the short-term equilibrium. Some additional results suggest that FDI flows do not cause the CO_2 emissions in LA countries. The empirical findings suggest policymakers to design policies to "the second-best theory", targeting FDI flows to their economies to solve economic problems in the short term, but thereafter they may guarantee the reduction in environmental pollution, based on environmentally responsible FDI and stronger regulations. In other words, the transition from a pollution haven to the applicability of the environmental Kuznets curve (EKC). This study contributes with scarce empirical evidence for LA countries in this issue.

Keywords: FDI; carbon emissions; EKC; pollution haven hypothesis; Latin America; environmental quality

Citation: Ochoa-Moreno, W.-S.; Quito, B.A.; Moreno-Hurtado, C.A. Foreign Direct Investment and Environmental Quality: Revisiting the EKC in Latin American Countries. *Sustainability* **2021**, *13*, 12651. https://doi.org/10.3390/su132212651

Academic Editors: Baojie He, Ayyoob Sharifi, Chi Feng and Jun Yang

Received: 26 September 2021
Accepted: 5 November 2021
Published: 16 November 2021

1. Introduction

The hypothesis of the environmental Kuznets curve (EKC), tested as an extension to the pioneering works of Kuznets [1,2], suggests that environmental damage increases with per capita income and then decreases, denoting a quadratic relationship in the shape of an inverted U [3]. From there, after the growing process of globalization, which has brought with it an increase in the trade of capital goods and the expansion of multinationals, the flows of foreign direct investment (FDI) have been evaluated and questioned because of their potentially negative effects on environment. As a result, the EKC curve has been refuted by a more recent hypothesis that studies the effect of trade on environmental pollution, the well-known pollution haven hypothesis (PHH) [4,5] which states that highly polluting multinational corporations move to developing countries with weaker environmental standards, where the cost of complying with environmental regulations is lower.

A portion of the economic literature argues that the environmental cost due to increased emissions can undermine the economic gains associated with increases in FDI inflows [6–8]. Others highlight that FDI can be a driving force for technological innovation and, consequently, a way through which greener and cleaner modes of production are implemented [9–12]. A large body of literature, such as some of those quoted in the next section, estimates the link between FDI inputs on environmental degradation in the framework of the EKC model. In this context, we aim to test the EKC for the case of 20 Latin American countries, from 1990 to 2018, and hence, answer questions such as: Has the relationship between the FDI and the CO_2 emissions an inverted U-shape, as the EKC suggests? Are the Latin American countries pollution havens?

Our findings suggest that, for developing countries such as the Latin American countries, the FDI has a direct relationship with CO_2 emissions, even if analysed by per capita income groups, according to the World Bank's atlas method [13]. In other words, our results are in agreement with the PHH hypothesis and reject the EKC hypothesis. This study contributes to the growing literature of the hypothesis which is not fulfilled for these countries. In contrast, we support the evidence that Latin American countries can be considered pollution havens. In addition, our contribution supports the idea that there is not causation between FDI per capita and CO_2 emissions per capita (in any sense), nor short-term equilibrium, although we show some evidence that support the outcomes for long-term equilibrium between the series.

This article consists of seven sections. After the introduction, we show a brief literature review in Section 2. Thereafter, Section 3 lists the sources of information and briefly describes the data. In Section 4, we detail the stages of the methodological process. In Sections 5 and 6, we describe and discuss the results. Finally, last section reveals the main conclusions of the research.

2. Brief Literature Review

The economic literature is ambiguous with respect to the results of the EKC associated with FDI flows and it depends on the contexts in which they are analysed. For this reason, in this research, the empirical evidence on the relationship between FDI inflows and environmental degradation are classified into three large groups. The first includes studies that focus their analysis between FDI and environmental degradation at the level of regions in the world. In the Asian countries, the FDI inflows have a positive and statistically significant impact on environmental degradation, measured by the ecological footprint, especially in countries such as Bangladesh, India, Nepal, Pakistan, and Sri Lanka [14–16]. However, some studies for this same region [17,18], have highlighted that the FDI has a strong impact (in the shape of an inverted U) on the environment, which follows the traditional EKC curve. Along the same lines and by income level, results for 14 Latin American countries validate the EKC hypothesis for the full sample and hence, we found evidence against the PHH [19]. The last evidence coincides with other findings [20] that reject the PHH, but they are contradictory to those which conclude that there is a positive relationship between the FDI and pollution, supporting the idea that FDI increases the environmental degradation [21], as the PHH suggests.

Similarly, for the Middle East and North Africa (MENA) region, some studies [22,23] have shown that increases in FDI inflows improve the economic growth process, which in turn, increases the environmental degradation. Findings from [22,23] are similar to those of [24], for Africa, who revealed a significant increase in environmental degradation due to increases in FDI flows. For the MENA region, there is evidence [25] that satisfies the EKC hypothesis, as a N-shaped relationship between the economic growth and carbon emissions, by using the generalized method of moments (GMM). For the same group of countries, there is evidence [26] that found a bidirectional causality between FDI and CO_2 emissions.

On the other hand, through an autoregressive distributed delay (ARDL) model for six sub-Saharan African countries, some findings [27] support the EKC in the cases of the Democratic Republic of the Congo, Kenya, and Zimbabwe. Furthermore, the FDI appears to increase CO_2 emissions in some countries, while the opposite impact can be observed in others. On the other hand, in the region of South and Southeast Asia (SSEA) during the period of 1980–2012, the most recent evidence [28], through cointegration techniques for subgroups according to income level, found that FDI entries and CO_2 emissions are co-integrated in all subgroups of countries. In addition, the results reveal that FDI inflows are substantially positively affecting CO_2 emissions. On the contrary, in the Economic Community of West African States (ECOWAS), the large amount of FDI towards the oil, mining and agriculture sectors, has put strong pressure on the environment [29].

The second group presents studies that relate FDI inflows to environmental degradation, at the level of groups of countries that are linked politically or economically. Thus, for example, Pazienza [30] in a study for 30 countries of the Organization for Economic Cooperation and Development (OECD), showed the existence of negative relationships that characterize the technique (−0.0848), the scale (−0.0036), and the cumulative effects (−0.0044) of the FDI on CO_2 emissions. Likewise, [31] supported the hypothesis of the environmental Kuznets curve in the short term, while in the long term there are some variations in a similar sample of OECD countries. In a more recent version of the same study by Pazienza [32], the outcome revealed that the negative impact of the FDI on the emission of CO_2, decreases as the scale of its inflow increases, leading to a reconsideration of the potential effects on the CO_2 emissions. On the other hand, by analysing the G7 countries, find that FDI inflows reduce the ecological footprint (EF) of these countries, an increase of 1% of FDI inflows, reduces EF by 0.009 [33]. In another study, for 65 countries in the period of 1984–2005, it showed that increases in FDI can increase CO_2 emissions when the degree of corruption is relatively high [34].

Similarly, for a panel of 146 countries with green initiatives from 1990 to 2014, Saud et al. [35] suggested that globalization through FDI inputs attracts green and low-polluting investments, fresh production methods, technology overflow, managerial skills, etc., which can improve economic development and environmental sustainability. However, using a hazard-based duration model, for a similar group of 145 countries, recent evidence [36] showed that the speed to reach the inflection point for deindustrialized countries is 1.96 times faster than that of the industrialized. On the other hand, for the economic companies that make up the Association of Southeast Asian Nations (ASEAN-5), findings showed that FDI inflows do not generate any effect on CO_2 emissions [37]. In addition, they concluded that the hypothesis EKC in inverted U shape does not apply to ASEAN-5 economies; despite that, there is a bidirectional causality between the FDI and CO_2 emissions. However, the validity of the PHH in ASEAN-5 countries is confirmed [38,39].

Moreover, Abdouli et al. [40], in their study for countries part of the BRICS, from 1990 to 2014, showed that population density and FDI inflows increased initially, which reduced CO_2 emissions, as the population and FDI inflows reached the threshold level. However, it is not the political environment of the host country, but that of the country of origin, that determines the positive/adverse effects of FDI on the environmental performance of a host country [41]. That confirms the hypothesis of the FDI Halo, contrary to the effect of economic growth, which deteriorates environmental quality. Similar investigations that have found evidence coming from FDI inputs on CO_2 emissions or another environmental measure have been conducted by [42–50].

Finally, in the third group, we show studies that found evidence between FDI inflows and environmental degradation at the country level. Recent works for the United States between 1970 and 2015, confirmed that the FDI significantly reduces the ecological footprint in the US, with an increase of 1% in the FDI causing a reduction in 0.025 percent in the ecological footprint [51]. Similarly, for Turkey, there is evidence of the existence of an equilibrium relationship, both in the short and long term between the FDI and CO_2 emissions, with an impact positive in its initial stage, and negative in the long term, which provide evidence of the existence of the EKC hypothesis in Turkey [52,53]. For this same country, in addition to finding that the FDI has a significant positive effect on carbon dioxide (CO_2) emissions, Balibey [54] showed the existence of a two-way causal relationship between the FDI and CO_2 emissions. On the other hand, in Malaysia, Lau et al. [55] argued that the FDI promotes greater economic growth and, as in the case of France, between 1955 and 2016 [56], leads to further environmental degradation. The study by Lau et al. [55] supported the evidence from Balibey [54] regarding a two-way causality between CO_2 emissions and FDI. The results of Lau et al. [55] are similar to the findings of Minh [57] for Vietnam (1990–2015), which, through ARDL models, concluded that the FDI contributes marginally to environmental degradation, in the short and long term. Nevertheless, they are contradictory to findings for Vietnam (1986–2015) [57], with a similar methodology, Phuong and Tuyen [58] did not find statistically significant evidence to conclude that the FDI has an impact on environmental pollution. In a similar context, for Singapore, estimated long-term elasticities (through ARDL models) [59] showed that FDI inflows not only lead to higher economic growth, but also better environmental quality.

In the same issue, through a simultaneous equation model (SEM) for 16 provinces of the Republic of Korea, a recent study revealed that FDI inflows simultaneously stimulates regional economic growth and reduces air pollution intensities between 2000 and 2011 [60]. However, the overall level of air emissions mostly remains unchanged, given Korea's high level of development. Spatial studies for the provinces of China, demonstrate that the FDI has played a "double-edged sword" role in promoting China's carbon productivity [61–63]. That is, the local FDI has a positive effect on local carbon productivity. Specifically, for every 1% increase in local FDI inflows, local carbon productivity increases by 0.446% [64]. In contrast, the study of Xu et al. [65], using a STIRPAT model and using data from the panel for the provinces of China, found that the effect of FDI on air pollutants presented an inverse U shape in East China and a decreasing linear shape in western China. The FDI effect for central China was a decreasing linear shape in SO_2, an inverse N shape in NOx, and an inverse U shape in PM2.5. The FDI reduced air pollutants in all regions, contradicting the pollution haven (PHH) hypothesis. However, there must be a greater economic scale and better industrial structure to experience a greater impact of FDI on the environmental environment [66]. Finally, in the context of India, one of the largest captors of FDI in the world, [67] found a positive impact on CO_2 emissions that amplifies the deterioration of their environmental environment.

3. Data and Descriptive Statistics

The statistical information used in this research comes from the World Bank [68]. The variables extracted from the world development indicators (WDIs) for this study are carbon dioxide emissions per capita (CO_2) and inflows of FDI per capita (see Table 1). The research includes 20 countries in Latin America, during the period of 1990–2018.

Table 1. Description of variables and data sources.

Variable	Definition	Unit	Source
CO_2	Carbon dioxide emissions are those stemming from the burning of fossil fuels and the manufacturer.	Metric tons per capita	World Bank [68]
FDI	Foreign direct investment are the net inflows of investment to acquire lasting management in an enterprise operating in an economy other than that of the investor.	USD per capita	World Bank [68]

The sample of countries for the study was classified according to the atlas method of the World Bank [13], which is based on the gross national income per capita (GNI) Of each country. The groups of countries according to the method were classified into high-income countries (HICs) ($12,696 USD or more), upper-middle-income countries (UMICs) ($4096 USD and $12,695 USD), and lower-middle income countries (LMICs) ($1045 USD and $4095 USD). In the econometric regressions, the dependent variable is per capita CO_2 emissions and the independent variable is per capita FDI inflows.

Table 2 shows the descriptive statistics of the series. The variables form a perfectly balanced panel with 580 observations over 29 years ($T = 1, 2, \ldots, 29$) and 20 countries ($i = 1, 2, \ldots, 20$). Per capita carbon dioxide (CO_2) emissions in logarithms are more stable within countries than between countries; the standard deviation (SD) within countries is 0.19 and between countries, it is 0.61. Meanwhile, the FDI per capita in logarithms shows less variability between countries, than within countries; the SD between countries is 0.83, which is below the standard deviation within countries of 0.92. In relative terms, the dispersion of the data is greater in the case of CO_2 emissions per capita.

Table 2. Descriptive statistics.

Variable		Mean	Std. Dev.	Min	Max	Observations
CO_2 per capita (log)	Overall	0.55	0.63	−0.75	2.04	N = 580
	Between		0.61	−0.34	1.84	n = 20
	Within		0.19	−0.11	1.10	T = 29
FDI per capita (log)	Overall	4.78	1.23	−0.61	7.37	N = 580
	Between		0.83	3.37	6.31	n = 20
	Within		0.92	−0.45	7.00	T = 29

Figure 1 presents the evolution of the variables for the study period. This presents the annual evolution of the logarithm of CO_2 emissions per capita and the logarithm of foreign direct investment per capita, on average for the sample of Latin American countries. We observe that the trend of the two variables is positive, that is, both CO_2 emissions and FDI have maintained average growth throughout the study period. However, the behaviour of FDI, in addition to growth, maintains a more fluctuating behaviour than CO_2 emissions; this behaviour is due to the economic crises endured by the region, for example, the one produced by the 2008 global financial crisis, which reduced the FDI.

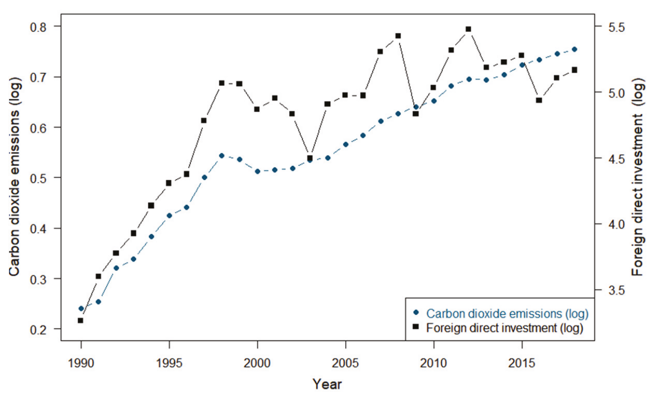


Figure 1. Average evolution of the CO_2 and FDI in the period of 1990–2018 (source: authors with World Bank [68] data).

Figure 2 shows the dispersion of the data for the entire sample of Latin American countries according to income level, and Figure 3 shows the map statistics of this data. In the first case, Figure 2 shows that the data between CO_2 emissions and foreign direct investment have a direct relationship at the global level and according to groups of countries by income level. In other words, at higher levels of FDI per capita, higher levels of CO_2 emissions per person are concentrated.

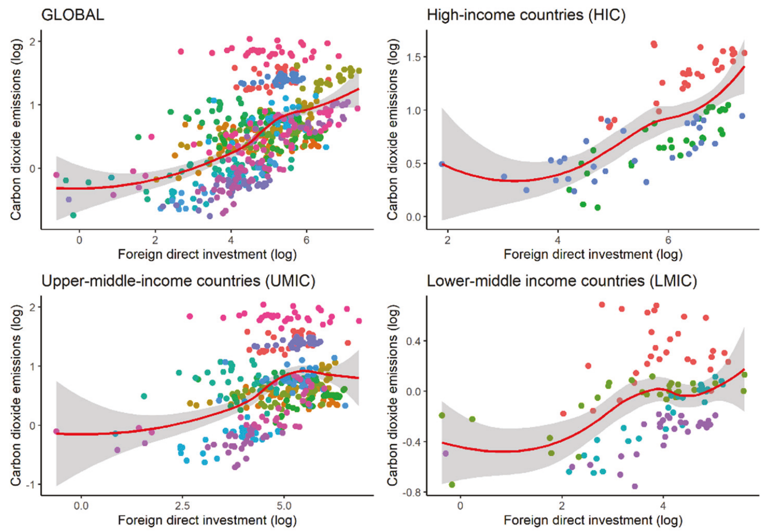


Figure 2. Correlation between CO_2 emissions per capita (log) and foreign direct investment per capita (log) (source: authors with World Bank [68] data).

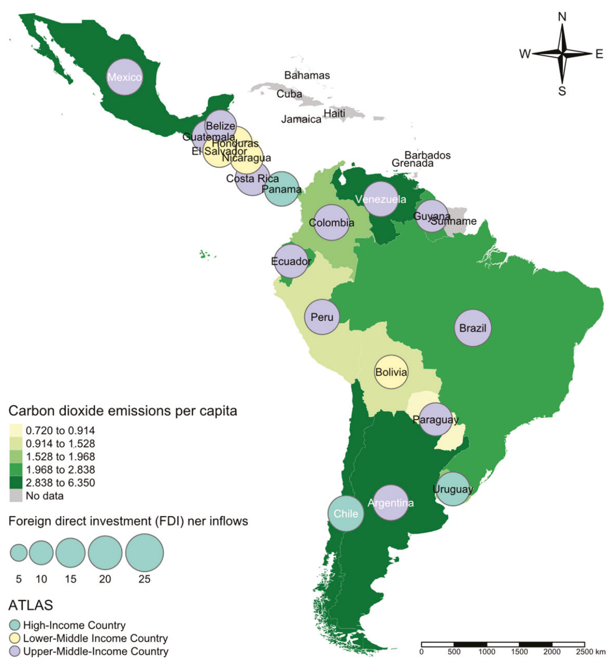


Figure 3. Map statistics of CO_2 emissions per capita (log) and foreign direct investment per capita (log) (source: authors with World Bank [68] data).

For the 20 countries, the correlation between these two variables is moderate (0.54); however, it is higher in the case of HICs (0.67). For the UMICs (0.40) and LMICs (0.39) groups, the correlation is lower, but in all cases, moderate (a colour is assigned for each country in the sample). An initial analysis of the environmental Kuznets curve (EKC) theory is the functional form of an inverted U.

Figure 2 shows the dispersion of the data for the entire set of Latin American countries and by groups (HICs, UMICs and LMICs). Nevertheless, in none of the cases do the scatter diagrams support this for the EKC; the fits clearly show a positive relationship, the quadratic trend even overlaps the linear, particularly in the UMICs and LMICs.

Likewise, Figure 3 shows the average per capita CO_2 emissions by country and the logarithm of the FDI. In this, it can be observed that countries such as Mexico, Venezuela, Argentina, and Chile concentrate higher levels of CO_2 emissions, as well as FDI inflows at the per capita level.

4. Econometric Strategy

The methodological process consists in five stages. After selecting our estimations between fixed and random effects, and test heteroscedasticity, autocorrelation and contemporary correlation for our panel, we assessed the stationary of the time series, their cointegration (by estimating the cointegration vectors) and finally, we tested the Granger causality. This procedure is explained in stages as follows.

4.1. Estimation Procedure

First, we estimated the fixed and random effects panel models to determine the direction of the relationship between CO_2 emissions per capita (in logarithms) and FDI per capita (in logarithms). Then, we applied the Hausman test [69] to decide between fixed and random effects. In this stage, we applied the modified Wald test [70] to detect heteroscedasticity and tests to detect autocorrelation in the panel and the contemporary correlation, respectively [71,72]. Likewise, recent panel data literature concludes that panel data models are likely to show cross-sectional dependence in the error [73,74]. Our balanced panel data are cross section dependent, as Table 3 shows.

Table 3. Cross-sectional dependent test.

Group	Variable	CD-Test	*p*-Value
GLOBAL	CO_2 emissions (log)	35.432	0.000
	FDI (log)	26.356	0.000
HICs	CO_2 emissions (log)	7.889	0.000
	FDI (log)	7.102	0.000
UMICs	CO_2 emissions (log)	15.775	0.000
	FDI (log)	11.291	0.000
LMICs	CO_2 emissions (log)	10.092	0.000
	FDI (log)	6.870	0.000

Findings (cross-section dependence in the panel, as well, autocorrelation, heteroscedasticity, and contemporary correlation in the estimations) suggest the use of estimates with generalized least squares (GLSs) for panel data [60]. Equation (1) expresses the empirical model in the log-log form:

$$\log CO_{2\ (i,t)} = \beta_0 + \beta_1 \log(FDI_{i,t}) + \varepsilon_{i,t} \tag{1}$$

4.2. Unit Root Tests

In the second stage, we applied the unit-roots test to identify if the series are stationary (that is if they do not have a trend effect). We used a set of tests that claim that obtaining the first difference eliminates the unit root problem. The tests used comes from Levin, Lin, and Chu (LLC) and Im, Pesaran, and Shin (IPS) respectively [75,76]. Moreover, we apply a simpler non-parametric unit root test called the Fisher type test [77] based on the ADF test [78] and, finally, the Fisher type test based on the Phillips and Perron (PP) test [79]. These four tests can be estimated from the following equation:

$$y_t = \theta_0 + \gamma y_{t-1} + \delta_1 t + \sum_{i=2}^{p} \sigma_j y_{t-i-1} + \varepsilon_t \quad (2)$$

where y_t is the series that is should contain at least the unit root, θ_0 is the intersection and δ_1 captures the trend effect of time t, ε_t is the Gaussian error and represents the length of the lag. In Equation (2), when the parameter γ is significant, we can conclude that at least one of the panels has a unit root.

4.3. Cointegration Test

In the third stage, we used cointegration techniques to verify long-term equilibria between the study variables, as well as the existence of a short-term equilibrium [80]. These techniques are based on error correction models (ECVM), globally (for the total panel) and for the different groups of countries, according to income level. We considered the null hypothesis of no cointegration versus cointegration between the variables. It considers structural dynamics rather than residual dynamics. Therefore, we did not put any restrictions on any common factor. Furthermore, the Westerlund [80] error correction model assumes that all variables are integrated in order 1 or I (1) and is written as follows:

$$\Delta\, x_{it} = \theta_i d_i + \pi_i (x_{it-1} - \beta_i' y_{it-1}) + \sum_{j=1}^{m} \pi_{ij} \Delta x_{it-j} + \sum_{j=1}^{m} \varphi_{ij} \Delta y_{it-j} + \varepsilon_{it} \quad (3)$$

where $d_i = (1-t)'$ contains the deterministic components and $\theta' = (\theta_{1i}, \theta_{2i})'$ is the vector of unknown coefficients to estimate. The error correction coefficient π_i is estimated using the ordinary least squares method. The above equation can be written as:

$$\Delta\, x_{it} = \theta_i d_i + \pi_i \left(x_{it-1} - \tau_i' y_{it-1}\right) + \sum_{j=1}^{m} \pi_{ij} \Delta x_{it-j} + \sum_{j=1}^{m} \varphi_{ij} \Delta x_{it-j} + \varepsilon_{it} \quad (4)$$

where π_i indicates the speed of adjust the system back to equilibrium. The above equation confirms that the coefficient π_i is not affected by imposing an arbitrary τ_i'. We applied the test on the least-squares estimator π_i and calculated the relation t for each cross-section of countries. These are known as group mean statistics and are written as:

$$G_1 = \frac{1}{N} \sum\nolimits_{i=1}^{N} \frac{\pi_i}{S.E(\hat{\pi}_i)} \text{ and } G_2 = \frac{1}{N} \sum\nolimits_{i=1}^{N} \frac{T\pi_i}{\hat{\pi}_i(1)} \quad (5)$$

where G_1 and G_2 test the null hypothesis that $H_0 : \pi_i = 0$ for all i against $H_1 : \pi_i < 0$ for some i. If the null hypothesis is rejected, then it shows the cointegration relationship of at least one unit of the cross-section. The other two test statistics are presented as:

$$P_1 = \frac{\hat{\pi}_i}{S.E(\hat{\pi}_i)} \text{ and } P_2 = T\hat{\pi}_i \quad (6)$$

where P_1 and P_2 test null hypothesis that $H_0 : \pi_i = 0$ for all i against $H_1 : \pi_i = \pi < 0$ for all i. The rejection of the null hypothesis implies the rejection of a non-cointegration relationship for the panel of countries as a whole. If there is a cointegration relationship between variables, then this study uses the panel technique to estimate the long- and short-term coefficients.

4.4. Cointegration Vectors

In the fourth stage to estimate the strength of the cointegration vectors [81–84], we used the dynamic ordinary least squares (DOLSs) model for individual countries and the dynamic ordinary least squares model of panel (PDOLSs), for groups of countries, following the atlas method of the World Bank [13]. The following equation raises the relationship between the two variables:

$$y_{i,t} = \sigma_i + \delta_i x_{it} + \sum_{j=P}^{P} \gamma_j \Delta x_{i,t-j} + \mu_{i,t} \tag{7}$$

where $y_{i,t}$, are the CO_2 emissions, $i = 1, 2, \ldots, 20$ countries, $t = 1, 2, \ldots, T$ is the time, $p = 1, 2, \ldots, P$ is the number of lags used in the DOLSs regression, while $\partial \log y_{i,t} / \partial \log X_{i,t} = \delta_i$ measures the change in CO_2 emissions when the variables change explanatory. The coefficients and the value were obtained as the average values in the whole panel using the method of group averages. The PDOLSs estimator is averaged across the dimension between groups and the null hypothesis states that $\beta_i = \beta_0$.

4.5. Granger Causality Test

Finally, following to Dumitrescu and Hurlin [85], we used the Granger's non-causality approach to account for the problems of heterogeneity in the panel data. The Dumitrescu–Hurlin (DH) test is a modified version of the Granger causality test [86], which is more flexible for $T < N$ and $T > N$ for both unbalanced and heterogeneous data. The DH test uses Equation (6):

$$y_{i,t} = \varphi_i + k \sum_{k=1}^{k} \gamma_i^{(k)} y_{it-k} + \sum_{k=1}^{k} \theta_i^{(k)} x_{it-k} + \varepsilon_{it} \tag{8}$$

where φ_i is the intercept of the shape; γ_i and θ_i are the slope coefficients; ε is the error term and k is the number of lengths of lag.

5. Results

Table 4 reports the results of the estimated GLS, for the logarithm of CO_2 emissions per capita as a function of the logarithm of FDI, proposed in Equation (1). We estimated that FDI inflows exert a positive and statistically significant effect on CO_2 emissions for the whole panel, where an increase of 1% in FDI inflows increases CO_2 emissions by 0.05%. Likewise, we observed that at the group level, according to the income level, the results are positive and statistically significant in the HICs, UMICs, and LMICs, at different levels of significance. An increase of 1% in FDI inflows increases CO_2 emissions by 0.08%, 0.03%, and 0.02%, respectively, with HICs accounting for the greatest effect on environmental degradation from FDI inflows. These results verify, at the regional level, the PHH hypothesis for developing countries, in which FDI inflows generate a deteriorating effect on the environment. On the other hand, they allow us to reject the EKC hypothesis. However, within the Latin American region by groups of countries, following their per capita income (GNI), we show that there is a lower effect of the FDI on CO_2 emissions in LMICs, which does not necessarily agree with the PHH hypothesis.

Table 4. Relation between CO_2 emissions (log) and FDI (log).

	GLOBAL	HICs	UMICs	LMICs
FDI (log)	0.0446 ***	0.0789 ***	0.0274 ***	0.0214 **
	(5.99)	(3.08)	(3.28)	(2.19)
Constant	0.325 ***	0.457 ***	0.506 ***	−0.241 ***
	(7.59)	(2.85)	(9.87)	(−4.35)
Observations	580	87	377	116
Autocorrelation test p-value	0.878	No	0.834	0.921
Fixed effects (time)	No	No	No	No
Fixes effects (country)	No	No	No	No
chi^2	35.89	9.490	10.74	4.806
N_g	20	3	13	4

T-statistics in parentheses; ** $p < 0.05$, and *** $p < 0.01$ denotes the significance level.

Next, using unit root tests for the panel data, we verified whether the series are stationary. To ensure the robustness of the results, we used four tests, those of [72,75], which are known respectively in the empirical literature on panel data as the LLC and IPS. The results obtained from these tests were compared with those of [76], who proposed using a simpler non-parametric unit root test called the Fisher-type test and based on the ADF test [77] and the test Fisher type based on the P&P test [78], based on what is stated in Equation (2). The tests were applied with and without the effects of time.

The results shown in Table 5 are evidence that the series have an order of integration I (1). All the tests ensure that the series used in subsequent estimates do not have the unit root problem. In the next stage of this investigation, we verified the existence of cointegration vectors in the long and short term between the variables.

Table 5. Unit root test in first differences.

		Without the Effect of Time				With the Effect of Time			
Groups	**Variable**	**PP**	**ADF**	**LLC**	**IPS**	**PP**	**ADF**	**LLC**	**IPS**
GLOBAL	$CO_2pc_{i,t}$	−23.64 ***	−9.06 ***	−21.24 ***	−21.88 ***	−22.64 ***	−8.67 ***	−15.33 ***	−18.54 ***
	$FDIpc_{i,t}$	−28.10 ***	−11.49 ***	−24.56 ***	−24.48 ***	−26.49 ***	−9.71 ***	−15.75 ***	−20.15 ***
HICs	$CO_2pc_{i,t}$	−8.76 ***	−4.78 ***	-4.83 ***	−6.61 ***	−7.76 ***	−3.69 ***	−3.79 ***	−5.71 ***
	$FDIpc_{i,t}$	−10.66 ***	−3.06 ***	−7.28 ***	−8.41 ***	−10.52 ***	−3.24 ***	−7.05 ***	−8.78 ***
UMICs	$CO_2pc_{i,t}$	−18.44 ***	−7.66 ***	−17.52 ***	−17.92 ***	−17.14 ***	−6.49 ***	−14.30 ***	15.61 ***
	$FDIpc_{i,t}$	−23.04 ***	−13.84 ***	−15.79 ***	−17.66 ***	−21.46 ***	−8.41 ***	−13.73 ***	−16.38 ***
LMICs	$CO_2pc_{i,t}$	−12.03 ***	−2.32 **	−11.47 ***	−10.91 ***	−13.01 ***	−4.50 ***	−4.92 ***	−8.39 ***
	$FDIpc_{i,t}$	−12.05 ***	−4.02 ***	−18.01 ***	−15.68 ***	−11.43 ***	−3.77 ***	−4.42 ***	−7.91 ***

Note: ** $p < 0.05$, and *** $p < 0.01$ denotes the significance level.

In the next stage, we used ECVM developed by Westerlund [79] for the panel data to determine the short-term equilibrium, according to what was stated in Equations (3) and (4). The existence of a short-term equilibrium implies that a change in foreign direct investment rapidly translates into changes in per capita CO_2 emissions.

Westerlund suggested the bootstrap approach, which makes the inference possible even under very general forms of cross-sectional dependence. From that, our results reported in Table 6 discard the existence of a short-term equilibrium, for the whole panel and for each of the groups of countries that we are considering.

Table 6. Results of the Westerlund ECVM error correction model.

Group	Stat.	Value	Z-Value	*p*-Value	Robust *p*-Value
Global	$G\tau$	−2.88	−2.89	0.002	0.270
	$G\alpha$	−14.78	−1.938	0.026	0.610
	$P\tau$	−12.68	−3.761	0.000	0.110
	$P\alpha$	−13.88	−3.690	0.000	0.270
HICs	$G\tau$	−3.43	−2.32	0.010	0.180
	$G\alpha$	−23.26	−2.96	0.002	0.050
	$P\tau$	−5.91	−2.63	0.004	0.120
	$P\alpha$	−21.14	−3.53	0.000	0.080
UMICs	$G\tau$	−2.90	−2.42	0.008	0.290
	$G\alpha$	−13.35	−0.80	0.215	0.760
	$P\tau$	−10.28	−3.10	0.001	0.150
	$P\alpha$	−12.68	−2.25	0.012	0.430
LMICs	$G\tau$	−2.39	−0.09	0.446	0.710
	$G\alpha$	−13.06	−0.35	0.363	0.690
	$P\tau$	−4.58	−0.41	0.342	0.660
	$P\alpha$	−11.91	−0.99	0.161	0.620

To determine the existence of the long-term equilibrium, from Equation (5) we used the heterogeneous panel cointegration test developed by Pedroni [81], which allows incorporating cross-sectional interdependence with different individual effects. This analytical framework allows cointegration tests on both heterogeneous and homogeneous panels, incorporating seven repressors based on seven residue-based statistics. Of these seven tests, the panel υ-statistic is a one-sided test in which high positive values reject the null hypothesis of no cointegration. While, for the rest of the statistics, high negative values reject the null hypothesis. Table 7 reports the statistics within and between dimensions. These results are ambiguous because of the heterogeneity of the panel. For LMICs (as for the entire panel), the panel ρ and PP statistic suggest the existence of cointegration between the CO_2 emissions and FDI series (similar to the group PP statistic), but the evidence of the panel υ and ADF statistic do not allow us to reject the null hypothesis of non-cointegration. For the HICs the majority of statistics within and between dimensions led us to reject the null and therefore, our results indicate that CO_2 emissions per capita and foreign direct investment have a joint and simultaneous movement during the period of 1990–2018 in high income countries. The latter is opposite for upper-middle-income countries.

Table 7. Pedroni cointegration test.

	GLOBAL	HICs	UMICs	LMICs
	Within dimension test statistics			
Panel υ-statistic	0.44	1.25	−0.04	0.72
Panel p-statistic	−1.83 *	−4.10 ***	−0.88	−2.20 **
Panel PP-statistic	−2.46 **	−4.07 ***	−1.39	−2.27 **
Panel ADF statistic	−0.33	−3.03 ***	−0.95	−1.51
	Between dimension test statistics			
Group p-statistic	−0.77	−3.11 ***	−0.07	−1.19
Group PP-statistic	−2.01 **	−4.42 ***	−0.95	−1.95 *
Group ADF statistic	0.13	−1.73 *	1.58	−0.36

Note: * $p < 0.10$, ** $p < 0.05$, and *** $p < 0.01$ denotes the significance level.

Table 8 reports the results of the DOLSs model by country. Our findings reveal that a 1% increase in FDI per capita is associated with an increase in CO_2 emissions per capita of 0.315%, 0.223%, and 0.076% for Chile, Panama, and Uruguay, respectively, which are all the higher income countries in the Latin American region. These results go in line with the outcome of Table 7. For upper-middle-income countries (65% of the panel), the results are mixed. For Brazil, Mexico, Paraguay, Peru, and Venezuela, 1% of increase in FDI per capita is associated with an increase in CO_2 emissions per capita of 0.143%, 0.293%, 0.142%, 0.626%, and 0.114%, respectively. However, in Dominican Republic and Ecuador, a 1% increase in FDI per capita is associated with a decrease in CO_2 emissions per capita of 0.209% and 0.064%, respectively. Finally, for LMICs, we only can reject the null of non-cointegration in Honduras, with a positive (0.234) weak cointegration vector (very far from 1). All statistically significant vectors are weak, except that from Peru.

To obtain the strength of the cointegration vector by groups of countries, Table 9 shows the results of the PDOLSs estimates with and without time variables. The estimators β_i of the different income levels are not close to 1. Nevertheless, in most of the cases (except for HICs, with a time dummy), we found evidence of a weak cointegration between the CO_2 emissions per capita and FDI per capita.

Finally, from Equation (6), we determined the Granger-type causality (Table 10) of the variables from the formalization developed by Dumitrescu and Hurlin [85]. Because of the evidence of cross-section dependence, we developed a bootstrap approach suggested by Dumitrescu and Hurlin [85]. We determined that there are no causal relationships between CO_2 emissions per capita and foreign direct investment, globally and by the group of countries.

Table 8. Results of the DOLSs panel.

HIC			UMICs			LIMCs		
Country	**FDI (β)**	**t-Statistic**	**Country**	**FDI (β)**	**t-Statistic**	**Country**	**FDI (β)**	**t-Statistic**
Chile	0.315 ***	3.849	Argentina	0.019	0.511	Bolivia	−0.060	−1.102
Panama	0.223 ***	3.186	Belize	−0.002	−0.012	Nicaragua	−0.082	−0.758
Uruguay	0.076 ***	4.056	Brazil	0.143 **	2.250	El Salvador	0.047	1.180
			Colombia	0.112	0.486	Honduras	0.234 ***	7.164
			Costa Rica	0.174	1.542			
			Dominican Republic	−0.209	−1.671 *			
			Ecuador	−0.064	−1.899 *			
			Guatemala	0.008	0.054			
			Guyana	−0.064	−1.321			
			Mexico	0.293 ***	5.265			
			Paraguay	0.142 ***	9.699			
			Peru	0.626 ***	6.416			
			Venezuela	0.114 ***	6.301			

Note: * $p < 0.10$, ** $p < 0.05$, and *** $p < 0.01$ denotes the significance level.

Table 9. Results of the PDOLSs panel test per country group.

	With Time Dummy		Without Time Dummy	
Groups	**PDOLSs**	**t-Stat**	**PDOLSs**	**t-Stat**
GLOBAL	0.103 ***	10.110	0.127 ***	20.650
HICs	−0.014	0.956	0.223 ***	16.240
UMICs	0.074 ***	5.688	0.111 ***	9.116
LMICs	−0.011 **	−2.035	0.106 ***	15.670

Note: ** $p < 0.05$, and *** $p < 0.01$ denotes the significance level.

Table 10. Causality tests following Dumitrescu–Hurlin (2012).

Causal Direction	Group	W-Bar	Z-Bar	*p*-Value	Z-Bar Tilde	*p*-Value
$\Delta FDIpc \rightarrow \Delta CO_2pc$	GLOBAL	1.93	−0.15	0.897	−0.51	0.629
	HICs	0.45	−1.34	0.170	−1.24	0.124
	UMICs	1.71	−0.52	0.651	−0.74	0.457
	LMICs	3.77	1.77	0.100	1.27	0.139
$\Delta CO_2pc \rightarrow \Delta FDIpc$	GLOBAL	1.39	−1.36	0.268	−1.49	0.128
	HICs	1.05	−0.82	0.450	−0.82	0.372
	UMICs	1.37	−1.14	0.331	−1.23	0.214
	LMIC	1.72	−0.28	0.801	−0.40	0.678

6. Discussion of Results

The economic literature presented ambiguous results regarding the effects that FDI flows can generate environmental degradation, even if we analyse these effects by groups of countries (developed or developing) [8]. Our findings for 20 Latin American countries in the period of 1990–2018 agree with the PHH that suggests that, in developing countries, such as Latin American, the effect of FDI is positive on environmental degradation, due to polluting multinational corporations directing their investments to countries with weaker environmental regulations [87–89]. These results are contradictory to those expressed by the EKC hypothesis, which in contrast, suggest a quadratic relationship (as an inverted U shape) between the variables [90]. These results coincide with extensive empirical evidence [14,15,28,55,57], for developing countries such as some of the Asian, African [22,24] and European countries, such as Turkey and France [54,56], and Mediterranean countries [91]. The study by Chang [34], for 65 countries, also shows that increases in FDI can increase CO_2 emissions when the degree of corruption is relatively high. In fact, if the FDI is sourced from developing countries it would be detrimental to the environmental environment of low- and lower-middle-income host countries [41].

Within the region (Latin America), our findings estimated with generalized least squares (GLSs) are supported by [21,46]. However, for this region of analysis, there are other works such as that of [19,20], who reject the PHH. It should be noted that, within Latin American countries, under the hypothesis of pollution havens, those that are in the LMICs were expected to be those where the FDI has the greatest impact on CO_2 emissions. However, the results show that the greatest impact is evidenced in those economies who are HIC. Similarly, the results shown in the CD tests coincide with those found by [92,93]. In a global context, the results showed the existence of interactions between countries caused by investment flows, political integration agreements, etc.

The results presented in this article reject the existence of a short-term equilibrium, based on the error correction model (ECVM) developed by Westerlund [80]. In contrast, we found some evidence that support a long-term equilibrium between the series; except for UMICs that contribute 65% of the panel, as Tables 8 and 9 show. The short-term results contrast with findings of [52,53]. However, the long-term cointegration results in this research are in line with those of [28], for South and Southeast Asia [52,53]. This supports the point of [88], where regardless of the level of development, there is a heterogeneous influence of the FDI.

From causality tests [85], our results contradict the conclusions of [26,54,55,94,95]. These authors reveal a unidirectional causality of the FDI to CO_2 emissions. However, our findings agree with those of [44] that show no causality, in any way, between the study variables. In that sense, despite the results of estimations in Table 4, we cannot conclude that FDI is the cause of the increase in CO_2 emissions in Latin American countries, nor the other way around.

7. Conclusions

The main objective of this study was to test the EKC and PHH hypotheses, for which the relationship between CO_2 emissions and FDI is analysed in various contexts. This article offers empirical evidence in the context of 20 Latin American economies, characterised by developing countries, and tests the relationship between CO_2 emissions and FDI over a period from 1990 to 2018. In addition, the sample of countries was classified into three subsamples (HICs, UMICs and LMICs) according to the atlas method of the World Bank [13]. For the analyses, econometric techniques are used. Firstly, it was applied in the CD test, to determine the existence of independence between transversal units. Followed by unit root tests (PP, ADF, LLC, IPS) to determine the stationarity of the set of variables, and then two cointegration tests were applied to determine the equilibrium relationships both in the short and long term. In addition, a Granger causality test was used to observe the causal links between the variables.

The results of the estimations, in a general way allow us to identify a direct relationship between CO_2 emissions and FDI, but they do not show a quadratic relationship and therefore, it is concluded in a rejection of the hypothesis of the environmental Kuznets curve (EKC). On the other hand, in developing countries, these results are related to the PHH, which establishes that highly polluting multinational companies move to developing countries with weaker environmental standards. However, the estimates formed by groups of countries offer unexpected information according to the PHH hypothesis, since the impact of FDI on CO_2 emissions is similar for lower-middle-income countries (LMICs) and upper-middle-income countries (UMICs), but it is about three times higher for high-income countries (HICs). This represents an inconsistency in the Latin American context, since the impact that we expected has a higher coefficient for the economies with lower-middle incomes (UMICs and LMICs).

The results of this article did not present causal relationships in any direction between the variables studied, nor any of the subsamples by income level. On the other hand, they only showed some evidence of a long-term equilibrium. There is no evidence of a short-term equilibrium.

Finally, the evidence demonstrated in this article might contribute with certain policy implications, such as establishing strategies to mitigate the environmental impact caused by the FDI. However, in developing countries, sustainable issues, many of them supported by the results of the EKC, have been interpreted by some policymakers as conveying a message about priorities [96]. The question in this study is which comes first, FDI flows or cleaning up the environment? Certainly, each developing economy tends to prioritize, in the short term, the solution of "immediate" problems such as economic growth, that can be driven by foreign direct investment flows (although the literature is ambiguous in this regard, see for example, the literature review in Alvarado et al. [97]. Then, in the long term, economies worry about environmental damage, as a "non-immediate" problem. This means that when thinking about a sustainable economy, responsible with future generations, caring for the environment is in the background ("the second-best theory"). In Latin American, following our results, there is no evidence that in the long term the relationship of the variables behaves similar to the environmental Kuznets curve, especially in the case of countries with a high-income, according to the atlas method of the World Bank [13]. In fact, we have some evidence that the effects of the FDI per capita on CO_2 emissions have a positive long-term equilibrium, except in UMICs such as the Dominican Republic and Ecuador. In this context, Latin American countries must design strategies that attract an environmentally friendly FDI that, despite having a negative impact (direct effect on CO_2 emissions) in the short term (due to the urgent priorities of developing economies), guarantee in the long term ("the second-best theory") a reduction in environmental pollution and, therefore, the applicability of the EKC. In other words, the region must address policies that generate the inverted U when we refer to the relationship between the CO_2 emissions and FDI.

This study has minor limitations. For example, new research presents a challenge by not confirming EKC or PHH in its estimates. Therefore, future research can expand the sample size or broaden the analysis between regions. In addition, the origin of the FDI can be identified according to the level of development of the investing economies, which can produce interesting inferences in the context of the Latin America region.

Author Contributions: Conceptualization, W.-S.O.-M. and B.A.Q.; methodology, C.A.M.-H. and W.-S.O.-M.; software, C.A.M.-H.; validation, W.-S.O.-M., B.A.Q. and C.A.M.-H.; formal analysis, W.-S.O.-M., B.A.Q. and C.A.M.-H.; investigation, W.-S.O.-M., B.A.Q. and C.A.M.-H.; resources, B.A.Q.; data curation, B.A.Q.; writing—original draft preparation, C.A.M.-H., B.A.Q. and W.-S.O.-M.; writing—review and editing, C.A.M.-H.; visualization, W.-S.O.-M., B.A.Q. and C.A.M.-H.; supervision, W.-S.O.-M. All authors have read and agreed to the published version of the manuscript.

Funding: No funding from any external institution was needed for this research.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The raw data supporting the conclusions of this article will be made available upon request.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Kuznets, S. Economic Growth and Income Inequality. *Am. Econ. Rev.* **1955**, *45*, 1–28.
2. Kuznets, S. Quantitative aspects of the economic growth of nations: Viii. distribution of income by size. *Econ. Dev. Cul. Chang.* **1963**, *11*, 1–92. [CrossRef]
3. Stern, D.; Common, M.; Barbier, E. Economic growth and environmental degradation: The environmental Kuznets curve and sustainable development. *World Dev.* **1996**, *204*, 1151–1160. [CrossRef]
4. Birdsall, N.; Wheeler, D. Trade policy and industrial pollution in Latin America: Where are the pollution havens? *J. Environ. Dev.* **1993**, *2*, 137–149. [CrossRef]
5. Copeland, B.; Taylor, S. North-South trade and the environment. *Q. J. Econ.* **1994**, *109*, 755–787. [CrossRef]

6. Bakhsh, K.; Rose, S.; Ali, M.F.; Ahmad, N.; Shahbaz, M. Economic growth, CO_2 emissions, renewable waste and FDI relation in Pakistan: New evidences from 3SLS. *J. Environ. Manag.* **2017**, *196*, 627–632. [CrossRef]
7. Shahbaz, M.; Haouas, I.; Van Hoang, T.H. Economic growth and environmental degradation in Vietnam: Is the environmental Kuznets curve a complete picture? *Emerg. Mark. Rev.* **2019**, *38*, 197–218. [CrossRef]
8. Demena, B.A.; Afesorgbor, S.K. The effect of FDI on environmental emissions: Evidence from a meta-analysis. *Energy Policy* **2020**, *138*, 111192. [CrossRef]
9. Neequaye, N.A.; Oladi, R. Environment, growth, and FDI revisited. *Int. Rev. Econ. Financ.* **2015**, *39*, 47–56. [CrossRef]
10. Shahbaz, M.; Nasreen, S.; Abbas, F.; Anis, O. Does foreign direct investment impede environmental quality in high-, middle-, and low-income countries? *Energy Econ.* **2015**, *51*, 275–287. [CrossRef]
11. Paramati, S.R.; Ummalla, M.; Apergis, N. The effect of foreign direct investment and stock market growth on clean energy use across a panel of emerging market economies. *Energy Econ.* **2016**, *56*, 29–41. [CrossRef]
12. Solarin, S.A.; Al-Mulali, U. Influence of foreign direct investment on indicators of environmental degradation. *Environ. Sci. Pollut.* **2018**, *25*, 24845–24859. [CrossRef] [PubMed]
13. World Bank. World Bank Country and Lending Groups. Washington D.C. Available online: https://bit.ly/3i7FKeJ (accessed on 22 December 2019).
14. Sabir, S.; Gorus, M.S. The impact of globalization on ecological footprint: Empirical evidence from the South Asian countries. *Environ. Sci. Pollut.* **2019**, *26*, 33387–33398. [CrossRef] [PubMed]
15. Hanif, I.; Faraz-Raza, S.M.; Gago-de-Santos, P.; Abbas, Q. Fossil fuels, foreign direct investment, and economic growth have triggered CO_2 emissions in emerging Asian economies: Some empirical evidence. *Energy* **2019**, *171*, 493–501. [CrossRef]
16. Ali, M.U.; Gong, Z.; Ali, M.U.; Wu, X.; Yao, C. Fossil energy consumption, economic development, inward FDI impact on CO_2 emissions in Pakistan: Testing EKC hypothesis through ARDL model. *Int. J. Financ. Econ.* **2021**, *26*, 3210–3221. [CrossRef]
17. To, A.H.; Ha, D.T.T.; Nguyen, H.M.; Vo, D.H. The impact of foreign direct investment on environment degradation: Evidence from emerging markets in Asia. *Int. J. Environ. Res.* **2019**, *16*, 1636. [CrossRef]
18. Muhammad, B.; Khan, S. Effect of bilateral FDI, energy consumption, CO_2 emission and capital on economic growth of Asia countries. *Energy Rep.* **2019**, *5*, 1305–1315. [CrossRef]
19. Albulescu, C.T.; Tiwari, A.K.; Yoon, S.M.; Kang, S.H. FDI, income, and environmental pollution in Latin America: Replication and extension using panel quantiles regression analysis. *Energy Econ.* **2019**, *84*, 104504. [CrossRef]
20. Cansino, J.; Román-Collado, R.; Molina, J. Quality of institutions, technological progress, and pollution havens in Latin America. An analysis of the environmental Kuznets curve hypothesis. *Sustainability* **2019**, *11*, 3708. [CrossRef]
21. Sapkota, P.; Bastola, U. Foreign direct investment, income, and environmental pollution in developing countries: Panel data analysis of Latin America. *Energy Econ.* **2017**, *64*, 206–212. [CrossRef]
22. Abdouli, M.; Hammami, S. The impact of FDI inflows and environmental quality on economic growth: An empirical study for the MENA countries. *J. Knowl. Econ.* **2017**, *8*, 254–278. [CrossRef]
23. Gorus, M.S.; Aslan, M. Impacts of economic indicators on environmental degradation: Evidence from MENA countries. *Renew. Sustain. Energ. Rev.* **2019**, *103*, 259–268. [CrossRef]
24. Bokpin, G. Foreign direct investment and environmental sustainability in Africa: The role of institutions and governance. *Res. Int. Bus. Financ.* **2017**, *39*, 239–247. [CrossRef]
25. Shahbaz, M.; Balsalobre-Lorente, D.; Sinha, A. Foreign direct Investment–CO_2 emissions nexus in Middle East and North African countries: Importance of biomass energy consumption. *J. Clean. Prod.* **2019**, *217*, 603–614. [CrossRef]
26. Abdouli, M.; Hammami, S. The dynamic links between environmental quality, foreign direct investment, and economic growth in the middle eastern and North African countries (MENA region). *J. Knowl. Econ.* **2018**, *9*, 833–853. [CrossRef]
27. Kivyiro, P.; Arminen, H. Carbon dioxide emissions, energy consumption, economic growth, and foreign direct investment: Causality analysis for Sub-Saharan Africa. *Energy* **2014**, *74*, 595–606. [CrossRef]
28. Behera, S.R.; Dash, D.P. The effect of urbanization, energy consumption, and foreign direct investment on the carbon dioxide emission in the SSEA (South and Southeast Asian) region. *Renew. Sustain. Energ. Rev.* **2017**, *70*, 96–106. [CrossRef]
29. Halliru, A.M.; Loganathan, N.; Golam Hassan, A.A. Does FDI and economic growth harm environment? Evidence from selected West African countries. *Transnatl. Corp.* **2020**, *13*, 237–251.
30. Pazienza, P. The relationship between CO_2 and foreign direct investment in the agriculture and fishing sector of OECD countries: Evidence and policy considerations. *Intellect. Econ.* **2015**, *9*, 55–66. [CrossRef]
31. De Pascale, G.; Sardaro, R.; Faccilongo, N.; Contò, F. What is the influence of FDI and international people flows on environment and growth in OECD countries? A panel study. *Environ. Impact Assess. Rev.* **2020**, *84*, 106434. [CrossRef]
32. Pazienza, P. The impact of FDI in the OECD manufacturing sector on CO_2 emission: Evidence and policy issues. *Environ. Impact Assess. Rev.* **2019**, *77*, 60–68. [CrossRef]
33. Ahmed, Z.; Zafar, M.W.; Ali, S.; Kahn, D. Linking urbanization, human capital, and the ecological footprint in G7 countries: An empirical analysis. *Sustain. Cities Soc.* **2020**, *55*, 102064. [CrossRef]
34. Chang, S.C. Threshold effect of foreign direct investment on environmental degradation. *Port. Econ. J.* **2015**, *14*, 75–102. [CrossRef]
35. Saud, S.; Chen, S.; Haseeb, A.; Sumayya, A. The role of financial development and globalization in the environment: Accounting ecological footprint indicators for selected one-belt-one-road initiative countries. *J. Clean. Prod.* **2020**, *250*, 119518. [CrossRef]

36. Du, X.; Xie, Z. Occurrence of turning point on environmental Kuznets curve in the process of (de)industrialization. *Struct. Chang. Econ. Dyn.* **2019**, *53*, 359–369. [CrossRef]
37. Chandran, V.G.R.; Tang, C.F. The impacts of transport energy consumption, foreign direct investment and income on CO_2 emissions in ASEAN-5 economies. *Renew. Sustain. Energ. Rev.* **2013**, *24*, 445–453. [CrossRef]
38. Guzel, A.E.; Okumus, İ. Revisiting the pollution haven hypothesis in ASEAN-5 countries: New insights from panel data analysis. *Environ. Sci. Pollut.* **2020**, *27*, 18157–18167. [CrossRef] [PubMed]
39. Xiong, S.Y.; Hussain, J. The implication of technological innovation and tourism development on FDI-growth-environment nexus in association of Southeast Asian countries: A simultaneity modeling analysis. *Energy Sources B Econ. Plan. Policy.* **2021**, *16*, 878–902.
40. Abdouli, M.; Kamoun, O.; Hamdi, B. The impact of economic growth, population density, and FDI inflows on CO_2 emissions in BRICTS countries: Does the Kuznets curve exist? *Empir. Econ.* **2018**, *54*, 1717–1742. [CrossRef]
41. Adeel-Farooq, R.M.; Riaz, M.F.; Ali, T. Improving the environment begins at home: Revisiting the links between FDI and environment. *Energy* **2021**, *215*, 119150. [CrossRef]
42. Udemba, E.N.; Yalçıntaş, S. Interacting force of foreign direct invest (FDI), natural resource and economic growth in determining environmental performance: A nonlinear autoregressive distributed lag (NARDL) approach. *Resour. Policy* **2021**, *73*, 102168. [CrossRef]
43. Kisswani, K.M.; Zaitouni, M. Does FDI affect environmental degradation? Examining pollution haven and pollution halo hypotheses using ARDL modelling. *J. Asian Pac. Econ.* **2021**, 1–27. [CrossRef]
44. Hassan, S.A.; Nosheen, M. Estimating the Railways Kuznets Curve for high income nations—A GMM approach for three pollution indicators. *Energy Rep.* **2019**, *5*, 170–186. [CrossRef]
45. Sarkodie, S.A.; Strezov, V. Effect of foreign direct investments, economic development and energy consumption on greenhouse gas emissions in developing countries. *Sci. Total Environ.* **2019**, *646*, 862–871. [CrossRef]
46. Dhrifi, A.; Jaziri, R.; Alnahdi, S. Does foreign direct investment and environmental degradation matter for poverty? Evidence from developing countries. *Struct. Chang. Econ. Dyn.* **2020**, *52*, 13–21. [CrossRef]
47. Essandoh, O.K.; Islam, M.; Kakinaka, M. Linking international trade and foreign direct investment to CO_2 emissions: Any differences between developed and developing countries? *Sci. Total Environ.* **2020**, *712*, 136437. [CrossRef] [PubMed]
48. Xie, Q.; Sun, Q. Assessing the impact of FDI on PM2.5 concentrations: A nonlinear panel data analysis for emerging economies. *Environ. Impact Assess. Rev.* **2020**, *80*, 106314. [CrossRef]
49. Muhammad, S.; Long, X.; Salman, M.; Dauda, L. Effect of urbanization and international trade on CO_2 emissions across 65 belt and road initiative countries. *Energy* **2020**, *196*, 117102. [CrossRef]
50. Bildirici, M.; Gokmenoglu, S.M. The impact of terrorism and FDI on environmental pollution: Evidence from Afghanistan, Iraq, Nigeria, Pakistan, Philippines, Syria, Somalia, Thailand and Yemen. *Environ. Impact Assess. Rev.* **2020**, *81*, 106340. [CrossRef]
51. Zafar, M.W.; Zaidi, S.A.H.; Khan, N.R.; Mirza, F.M.; Hou, F.; Kirmanis, A.A. The impact of natural resources, human capital, and foreign direct investment on the ecological footprint: The case of the United States. *Resour. Policy* **2019**, *63*, 101428. [CrossRef]
52. Haug, A.A.; Ucal, M. The role of trade and FDI for CO_2 emissions in Turkey: Nonlinear relationships. *Energy Econ.* **2019**, *81*, 297–307. [CrossRef]
53. Koçak, E.; Şarkgüneşi, A. The impact of foreign direct investment on CO_2 emissions in Turkey: New evidence from cointegration and bootstrap causality analysis. *Environ. Sci. Pollut.* **2018**, *25*, 790–804. [CrossRef] [PubMed]
54. Balibey, M. Relationships among CO_2 Emissions, Economic growth and foreign direct investment and the environmental Kuznets curve hypothesis in Turkey. *Int. J. Energy Econ. Policy* **2015**, *5*, 1042–1049.
55. Lau, L.S.; Choong, C.K.; Eng, Y.K. Investigation of the environmental Kuznets curve for carbon emissions in Malaysia: DO foreign direct investment and trade matter? *Energy Policy* **2014**, *68*, 490–497. [CrossRef]
56. Shahbaz, M.; Nasir, M.; Roubaud, D. Environmental degradation in France: The effects of FDI, financial development, and energy innovations. *Energy Econ.* **2018**, *74*, 843–857. [CrossRef]
57. Minh, N. Foreign Direct Investment and Carbon Dioxide Emissions: Evidence from Capital of Vietnam. *Int. J. Energy Econ. Policy* **2020**, *10*, 76–83. [CrossRef]
58. Phuong, N.; Tuyen, L. The relationship between foreign direct investment, economic growth and environmental pollution in Vietnam: An autoregressive distributed lags approach. *Int. J. Energy Econ. Policy* **2018**, *8*, 138–145.
59. Ridzuan, A.; Ismail, N.; Hamat, A. Does foreign direct investment successfully lead to sustainable development in Singapore? *Economies* **2017**, *5*, 29. [CrossRef]
60. Hille, E.; Shahbaz, M.; Moosa, I. The impact of FDI on regional air pollution in the Republic of Korea: A way ahead to achieve the green growth strategy? *Energy Econ.* **2019**, *81*, 308–326. [CrossRef]
61. Liu, Q.; Wang, S.; Zhang, W.; Zhan, D.; Li, J. Does foreign direct investment affect environmental pollution in China's cities? A spatial econometric perspective. *Sci. Total Environ.* **2018**, *613*, 521–529. [CrossRef]
62. Zhu, L.; Hao, Y.; Lu, Z.N.; Wu, H.; Ran, Q. Do economic activities cause air pollution? Evidence from China's major cities. *Sustain. Cities Soc.* **2019**, *49*, 101593. [CrossRef]
63. Liu, J.; Qu, J.; Zhao, K. Is China's development conforms to the environmental Kuznets curve hypothesis and the pollution haven hypothesis? *J. Clean. Prod.* **2019**, *234*, 787–796. [CrossRef]

64. Long, R.; Gan, X.; Chen, H.; Wang, J.; Li, Q. Spatial econometric analysis of foreign direct investment and carbon productivity in China: Two-tier moderating roles of industrialization development. *Resour. Conserv. Recycl.* **2020**, *155*, 104677. [CrossRef]
65. Xu, S.C.; Li, Y.W.; Miao, Y.M.; Gao, C.; He, Z.X.; Shen, W.X.; Wang, S.X. Regional differences in nonlinear impacts of economic growth, export and FDI on air pollutants in China based on provincial panel data. *J. Clean. Prod.* **2019**, *228*, 455–466. [CrossRef]
66. An, T.; Xu, C.; Liao, X. The impact of FDI on environmental pollution in China: Evidence from spatial panel data. *Environ. Sci. Pollut.* **2021**, *28*, 44085–44097. [CrossRef]
67. Zameer, H.; Yasmeen, H.; Zafar, M.W.; Waheed, A.; Sinha, A. Analyzing the association between innovation, economic growth, and environment: Divulging the importance of FDI and trade openness in India. *Environ. Sci. Pollut.* **2020**, *27*, 29539–29553. [CrossRef]
68. World Bank. World Development Indicators. Washington D.C. Available online: https://bit.ly/3lUF6SR (accessed on 23 January 2020).
69. Hausman, J.A. Specification tests in econometrics. *Econometrica* **1978**, *46*, 1251. [CrossRef]
70. Wooldridge, J. *Econometric Analysis of Cross Section and Panel Data*, 2nd ed.; The MIT Press Cambridge: London, UK, 2002.
71. Wooldridge, J.M. On the application of robust, regression- based diagnostics to models of conditional means and conditional variances. *J. Econom.* **1991**, *47*, 5–46. [CrossRef]
72. Breusch, T.S.; Pagan, A.R. The Lagrange multiplier test and its applications to model specification in econometrics. *Rev. Econ. Stud.* **1980**, *47*, 239–253. [CrossRef]
73. Pesaran, M. *General Diagnostic Tests for Cross Section Dependence in Panels*; Working Paper; IZA Bonn: Bonn, Germany, 2004.
74. Pesaran, M. Testing weak cross-sectional dependence in large panels. *Econom. Rev.* **2015**, *34*, 1089–1117. [CrossRef]
75. Levin, A.; Lin, C.F.; James Chu, C.S. Unit root tests in panel data: Asymptotic and finite-sample properties. *J. Econom.* **2002**, *108*, 1–24. [CrossRef]
76. Im, K.S.; Pesaran, M.H.; Shin, Y. Testing for unit roots in heterogeneous panels. *J. Econom.* **2003**, *115*, 53–74. [CrossRef]
77. Maddala, G.S.; Wu, S. A comparative study of unit root tests with panel data and a new simple test. *Oxf. Bull. Econ. Stat.* **1999**, *61*, 631–652. [CrossRef]
78. Dickey, D.A.; Fuller, W.A. Likelihood ratio statistics for autoregressive time series with a unit root. *Econometrica* **1981**, *49*, 1057. [CrossRef]
79. Phillips, P.C.B.; Perron, P. Testing for a unit root in time series regression. *Biometrika* **1988**, *75*, 335–346. [CrossRef]
80. Westerlund, J. Testing for error correction in panel data. *Oxf. Bull. Econ. Stat.* **2007**, *69*, 709–748. [CrossRef]
81. Pedroni, P. Critical values for cointegration tests in heterogeneous panels with multiple regressors. *Oxf. Bull. Econ. Stat.* **1999**, *61*, 653–670. [CrossRef]
82. Pedroni, P. Purchasing power parity tests in cointegrated panels. *Rev. Econ. Stat.* **2001**, *83*, 727–731. [CrossRef]
83. Pedroni, P. Panel Cointegration: Asymptotic and Finite Sample Properties of Pooled Time Series Tests with an Application to the PPP Hypothesis. *Econom. Theory* **2004**, *20*, 597–625. [CrossRef]
84. Neal, T. Panel Cointegration Analysis with Xtpedroni. *Stata J.* **2014**, *14*, 684–692. [CrossRef]
85. Dumitrescu, E.I.; Hurlin, C. Testing for Granger non-causality in heterogeneous panels. *Econ. Model.* **2012**, *29*, 1450–1460. [CrossRef]
86. Granger, C.W.J. Investigating causal relations by econometric models and cross-spectral methods. *Econometrica* **1969**, *37*, 424–438. [CrossRef]
87. Wang, C.; Jiayu, C. Analyzing on the impact mechanism of foreign direct investment (FDI) to energy consumption. *Energy Procedia* **2019**, *159*, 515–520. [CrossRef]
88. Ahmad, M.; Jabeen, G.; Wu, Y. Heterogeneity of pollution haven/halo hypothesis and environmental Kuznets curve hypothesis across development levels of Chinese provinces. *J. Clean. Prod.* **2021**, *285*, 124898. [CrossRef]
89. Sabir, S.; Qayyum, U.; Majeed, T. FDI and environmental degradation: The role of political institutions in South Asian countries. *Environ. Sci. Pollut. Res.* **2020**, *27*, 32544–32553. [CrossRef]
90. Adamu, T.; Haq, I.; Shafiq, M. Analyzing the impact of energy, export variety, and FDI on environmental degradation in the context of environmental Kuznets curve hypothesis: A case study of India. *Energies* **2019**, *12*, 1076. [CrossRef]
91. Gyamfi, B.A.; Adebayo, T.S.; Bekun, F.V.; Agyekum, E.B.; Kumar, N.M.; Alhelou, H.H.; Al-Hinai, A. Beyond environmental Kuznets curve and policy implications to promote sustainable development in Mediterranean. *Energy Rep.* **2021**, *7*, 6119–6129. [CrossRef]
92. Rauf, A.; Liu, X.; Amin, W.; Ozturk, I.; Rehman, O.; Sarwar, S. Energy and ecological sustainability: Challenges and panoramas in belt and road initiative countries. *Sustainability* **2018**, *10*, 2743. [CrossRef]
93. Rauf, A.; Liu, X.; Amin, W.; Rehman, O.U.; Li, J.; Ahmad, F.; Victor Bekun, F. Does sustainable growth, energy consumption and environment challenges matter for belt and road initiative feat? A novel empirical investigation. *J. Clean. Prod.* **2020**, *262*, 121344. [CrossRef]
94. Pao, H.-T.; Tsai, C.-M. Multivariate Granger causality between CO_2 emissions, energy consumption, FDI (foreign direct investment) and GDP (gross domestic product): Evidence from a panel of BRIC (Brazil, Russian Federation, India, and China) countries. *Energy* **2011**, *36*, 685–693. [CrossRef]
95. Abdouli, M.; Hammami, S. Economic growth, environment, FDI inflows, and financial development in Middle East countries: Fresh evidence from simultaneous equation models. *J. Knowl. Econ.* **2018**, *11*, 479–511. [CrossRef]

96. Dasgupta, S.; Laplante, B.; Wang, H.; Wheeler, D. Confronting the environmental Kuznets curve. *J. Econ. Perspect.* **2002**, *16*, 147–168. [CrossRef]
97. Alvarado, R.; Iñiguez, M.; Ponce, P. Foreign direct investment and economic growth in Latin America. *Econ. Anal. Policy* **2017**, *56*, 176–187. [CrossRef]

sustainability

MDPI

Article

Towards the Three Dimensions of Sustainability for International Research Team Collaboration: Learnings from the Sustainable and Healthy Food Systems Research Programme

Rashieda Davids [1,*], Pauline Scheelbeek [2], Nafiisa Sobratee [1], Rosemary Green [2], Barbara Häesler [3], Tafadzwanashe Mabhaudhi [4], Suparna Chatterjee [5], Nikhil Srinivasapura Venkateshmurthy [6,7], Georgina Mace [8,†], Alan Dangour [2] and Rob Slotow [8,9]

1 School of Agriculture, Earth and Environmental Sciences, University of KwaZulu-Natal, Pietermaritzburg 3201, KwaZulu-Natal, South Africa; SobrateeN@ukzn.ac.za
2 Centre on Climate Change and Planetary Health, London School of Hygiene & Tropical Medicine, London WC1E 7HT, UK; Pauline.Scheelbeek@lshtm.ac.uk (P.S.); Rosemary.Green@lshtm.ac.uk (R.G.); alan.dangour@lshtm.ac.uk (A.D.)
3 Department of Pathobiology and Population Sciences, Royal Veterinary College, London E16 2PX, UK; bhaesler@rvc.ac.uk
4 Centre for Transformative Agricultural and Food Systems, School of Agricultural, Earth and Environmental Sciences, University of KwaZulu-Natal, Pietermaritzburg 3201, KwaZulu-Natal, South Africa; Mabhaudhi@ukzn.ac.za
5 Ashoka Trust for Research in Ecology and the Environment Royal Enclave, Sriramapura, Jakkur Post, Bangalore 560064, India; suparna.chatterjee@atree.org
6 Public Health Foundation of India, Gurgaon 122002, India; nikhil.sv@phfi.org
7 India and Centre for Chronic Disease Control, New Delhi 110016, India
8 Department of Genetics, Evolution and Environment, University College London, London WC1E 6BT, UK; g.mace@ucl.ac.uk (G.M.); slotow@ukzn.ac.za (R.S.)
9 School of Life Sciences, University of KwaZulu-Natal, Pietermaritzburg 3201, KwaZulu-Natal, South Africa
* Correspondence: davidsr@ukzn.ac.za; Tel.: +27-823051352
† Deceased.

Citation: Davids, R.; Scheelbeek, P.; Sobratee, N.; Green, R.; Häesler, B.; Mabhaudhi, T.; Chatterjee, S.; Venkateshmurthy, N.S.; Mace, G.; Dangour, A.; et al. Towards the Three Dimensions of Sustainability for International Research Team Collaboration: Learnings from the Sustainable and Healthy Food Systems Research Programme. *Sustainability* **2021**, *13*, 12427. https://doi.org/10.3390/su132212427

Academic Editors: Jun Yang, Ayyoob Sharifi, Baojie He and Chi Feng

Received: 8 September 2021
Accepted: 2 November 2021
Published: 10 November 2021

Abstract: This paper highlights the potential for learning and virtual collaboration in international research teams to contribute towards sustainability goals. Previous research confirmed the environmental benefits of carbon savings from international virtual conferences. This paper adds the social and economic dimensions by using a combination of qualitative and quantitative methods to measure the constraints and benefits for personal development, economic costs, efficiency and team learning of holding international virtual conferences (VCs). Using the Sustainable and Healthy Food Systems (SHEFS) research programme as a case study, we analysed VC participant survey data to identify strengths, weaknesses, opportunities, and threats of VCs. We estimated 'saved' GHG emissions, costs, and time, of using VCs as an alternative for a planned in-person meeting in Chennai, India. Hosting VCs reduced North–South, gender, and researcher inclusivity concerns, financial and travelling time costs, and substantially reduced emissions. For one international meeting with 107 participants, changing to a virtual format reduced the per capita GHG emissions to half the annual global average, and avoided 60% of travel costs. The benefits of VCs outweighed weaknesses. The main strengths were inclusivity and access, with 20% more early/mid-career researchers attending. This study identified opportunities for international research partnerships to mitigate their carbon footprint (environmental benefit) and enhance inclusivity of early/mid-career, women and Global South participants (social benefit), whilst continuing to deliver effective collaborative research meetings (economic benefit). In doing so, we present a holistic view of sustainability opportunities for virtual collaboration.

Keywords: sustainability; climate change; carbon footprint; virtual conference; transdisciplinary team; virtual team; learning

1. Introduction

As research scientists, we are tasked with paving the way towards a more sustainable future. The United Nations has for decades worked with countries and the scientific community to develop policies and plans aiming to protect people and the planet, and achieve sustainability through environmental protection, social development and economic growth [1–4]. Each Strategic Plan, up to and including the 2020 Agenda for Sustainable Development and the sustainable development goals (SDGs), recognised that, to achieve sustainable development, socio-economic outcomes for basic human well-being such as poverty alleviation and the reduction of inequalities, are essential. However, equally important is the achievement of environmental goals, including urgent actions against climate change [3]. Evidence-based research is geared to identify prospects to enhance opportunities, and mitigate risks, to achieving the sustainable development goals (SDGs) [3], and targets for limiting global warming to within 1.5 °C above pre-industrial levels [5]. Despite frequently having first-hand knowledge of sustainability and climate change challenges, the international research community still contributes significantly towards greenhouse gas emissions. For example, American ecologists were found to have carbon footprints over twice that of average Americans, and more than ten times the global average (4.5 tonnes of CO_2 equivalents (eq) a year) in 2009, predominantly due to greenhouse gas emissions from air travel for one international collaborative meeting [6]. A single astronomers' conference in Europe held in 2019 was roughly equal to India's average annual per capita emissions [7]. More recently, enforced mandatory confinement during the COVID-19 pandemic majorly restricted business and leisure travel, resulting in a huge decline of CO_2 emissions in the first half of 2020 compared to 2019 (−17%) [8]. However, the drop in carbon emissions was short-lived, with the overall decline for 2020 being only 6% [9].

Scientists have become weary of the problem and responsibility of mitigating emissions associated with hosting international conferences [7]. Previous studies have confirmed the reduction of carbon emissions as a major benefit of hosting virtual vs. face-to-face international academic conferences in light of COVID-19 travel restrictions [7,10,11]. However, reducing carbon emissions is only one part of the three dimensions needed for scientists to contribute towards sustainability: a complete solution must focus on social, economic and environmental sustainability, as called for in the Sustainable Development Agenda [12].

A 'virtual team' involves interactions amongst a group of people, from different offices, places or times zones, working together on interdependent tasks towards a common goal, whereas 'virtual collaboration' is the process by which virtual teams complete collective tasks and achieve common goals [13]. Virtual project teams have become more common due to globalisation and project-based work of many contemporary organisations [14], with an explosion of virtual team research over the past decade [15]. The broad research focus has included understanding the effectiveness of virtual teams over face-to-face teams [16], overcoming issues of trust, identity [17] and knowledge sharing [18] and adapting to transition from collocated to online COVID-19 working conditions [19]. Although some research has focussed on the environmental sustainability contributions of virtual team collaboration, mainly from a carbon savings perspective [10,11,20], this study is the first to holistically also consider the other dimensions of sustainability for virtual collaboration.

Transformational changes are needed across all sectors to ensure that we bridge the science-action gap [21], actively mitigate climate change [22], and achieve global sustainability. The application of sustainability frameworks to better understand the linkages between anthropogenic actions, environmental limits and social outcomes [22–24], can be used to ensure that all three dimensions of sustainable development are considered. With adequate planning, international research teams can contribute to multiple sustainable development goals (SDGs), for example; SDG 5: Achieve gender equality and empower all women and girls; SDG 10: Reduced inequalities within and among countries; SDG 13: Take urgent climate action to combat climate change and its impacts; SDG 16: Promote peaceful and inclusive societies for sustainable development and build effective and inclusive institutions; and SDG 17: Strengthen global partnership for sustainable development. The international research community could take the lead by learning and acting upon the evidence that is generated around finding solutions, and inspire others to follow their example [6].

Despite virtual teams gaining increasing popularity, there remains uncertainty regarding the effectiveness of virtual teams over face-to-face teams [16]. Whilst there are some obvious benefits in terms of avoided costs, greenhouse gas emissions, and travel time, other more hidden advantages could contribute to sustainability. Virtual meetings could, for example, contribute to the social domain through increasing inclusivity, mainly related to attendance by researchers from the Global South, particularly females, and by early-career researchers, for whom travel budget could restrict their face-to-face participation more often than for their counterparts from the Global North. Academic literature describes the gender bias, where women have been found to publish and participate in collaborations less than their male counterparts, particularly in science, technology engineering, mathematics and medicine [25]. Furthermore, scientists with care duties could be restricted in time spent away from home but would be able to participate virtually. This calls for solutions to barriers causing inequality, often faced by women and early-career researchers in science [26].

Although there has been an upsurge in virtual collaboration due to the availability of collaborative technology, the abandonment of face-to-face interaction has its challenges [13]. The six major challenges identified from over a decade of virtual collaboration research are the virtual team 'givens' of technology, time and distance, and the virtual team 'creations,' of trust, culture and leadership [13]. Drawbacks of virtual meetings include lack of personal contact, restricted possibilities for networking, and total reliance on IT equipment. In order to ensure high-performance or sustainability of virtual teams, the challenges of both these 'givens' and 'creations' need to be addressed [13].

This research explored the various benefits and constraints of virtual communication and collaboration, with the view to identify barriers and opportunities for virtual teams to contribute to sustainability. This study investigated the three domains of sustainability frameworks plus an additional learning domain, by asking the following key questions: (1) Social: How can learning and collaboration in virtual teams assist in enhancing inclusivity for marginalised scientists, such as those in the Global South, or early-career researchers who may be constrained by funding; or women? (2) Environmental: How can international research teams effectively use virtual collaboration to actively contribute to global sustainability and climate change mitigation efforts? (3) Economic: What are the benefits and costs of hosting international research meetings, and how can they be enhanced or reduced? (4) Learning: How can systems thinking principles assist in unpacking learnings and improving virtual research collaboration processes going forward? To answer these, we used a mixed methodological approach, combining quantitative and qualitative data: learning organisation surveys and Strengths, Weaknesses Opportunities and Threats (SWOT) analyses, greenhouse gas emissions and cost analyses to compare holding large-scale multi-site and multi-disciplinary virtual conferences (VCs), over face-to-face in-country meetings. We analysed international conferences and research team dynamics of the Sustainable and Healthy Food Systems (SHEFS) research programme as our case study.

2. Materials and Methods

2.1. Description of Case Study

SHEFS is a multi-disciplinary boundary organisation operating across three countries: South Africa, the United Kingdom, and India. SHEFS aims to influence policy towards achieving sustainable food systems that deliver improved health outcomes and reduced environmental impacts [27]. The SHEFS research programme includes 13 institutions, with over 100 academics, government practitioners, and other stakeholders, from over 20 different disciplines within and related to the agriculture-environment-health nexus. Over four years of research, SHEFS has produced more than 80 internationally published research papers contributing to the food system, environment, and health domains [28]. This study formed part of a PhD undertaken by the lead Author, in her capacity as a SHEFS researcher and programme manager.

Background to SHEFS International Meetings

SHEFS started in 2017, and annual meetings have been hosted since, with staff and students from each country site personally attending the first two meetings held in London, United Kingdom (2017), and Durban, South Africa (2018). In the face of an increasing awareness of the climate costs of meeting physically, the SHEFS management team decided to host the Annual Meeting in 2019 via a VC, in place of the originally planned in-person meeting in Chennai, India. This meeting offered a unique opportunity to determine whether operations within the programme could be conducted more sustainably in terms of social development, costs, time, and carbon footprints, whilst maintaining or improving upon the level of group learning and engagement previously experienced in face-to-face conferences.

For the first VC in 2019, the team assembled physically in groups in five virtual rooms (one in the UK, two in India, two in South Africa), plus several individuals were joining from their personal computers. Zoom (Barbosa et al., 2019) virtual meeting software was used for communication during the conference, with some of the preparatory work recorded using Microsoft Collaborate [29]. Conference organisers identified innovative ways to increase opportunities for engagement at the VC. First, several presentations were recorded ahead of the meeting. Participants were encouraged to watch pre-recorded presentations and send questions and comments to the presenter ahead of the meeting. The "live" time during the VC was then used for more in-depth discussion.

Furthermore, presenters were encouraged to make use of interactive tools, such as Mentimeter [30], to facilitate active participation during the conference. In each of the "physical" rooms, a venue-leader was assigned, who registered any potential contributions (questions, comments, etc.) of participants in their respective rooms, and alerted the moderator of a session accordingly. Hand raising and 'question and answer' typing functions of the Zoom software were used in addition to this.

In March 2020, a second virtual meeting was held, with all participants attending virtually and individually, as the COVID-19 pandemic restricted movement and face-to-face meetings. The VC linked 73 participants from South Africa, United Kingdom, and India. Learnings from the first VC allowed for more effective preparation, and, this time, SHEFS early-career researchers from each country planned and prepared the agenda and conference activities before the VC. Multiple activities were facilitated for engagement and direct discussions of research before the conference, namely 'journal club discussions' which allowed participants to meet virtually to discuss publications (SHEFS outputs); 'feedback workshops' with in-depth discussions for problem-solving and enhancement of specific research projects; and 'presenter of another team member's output' where participants discussed the research of another researcher, to present the outputs to the broader team during the VC. Online presentations were delivered via the Zoom platform during the conference. Breakaway 'meeting rooms' (in Zoom), linked to the VC, were used for small group discussions. Up to five participants were able to brainstorm particular topics before returning to the main virtual room for plenary feedback.

Involvement in the above meetings provided the authors and research team with the necessary background and experience to assess the benefits and constraints of VCs, analysed in this study.

2.2. Methods

This study used mixed methods to analyse broad-ranging aspects of hosting virtual vs. face-to-face international research meetings, related to the three broad themes of sustainability plus a learning dimension, namely, (1) Environmental: analysis of greenhouse gas emissions, (2) Social: inclusivity of gender, early-career and Global South participants,

(3) Economic: costs of hosting virtual vs. face-to-face meeting; and (4) Team learnings and reflexivity (Figure 1). We used and analysed both qualitative (social and team learning: surveys) and quantitative (environmental and economic: GHG and cost) data, with the view to understand the benefits and challenges of virtual meetings by reflecting on the VC system as a whole [31].

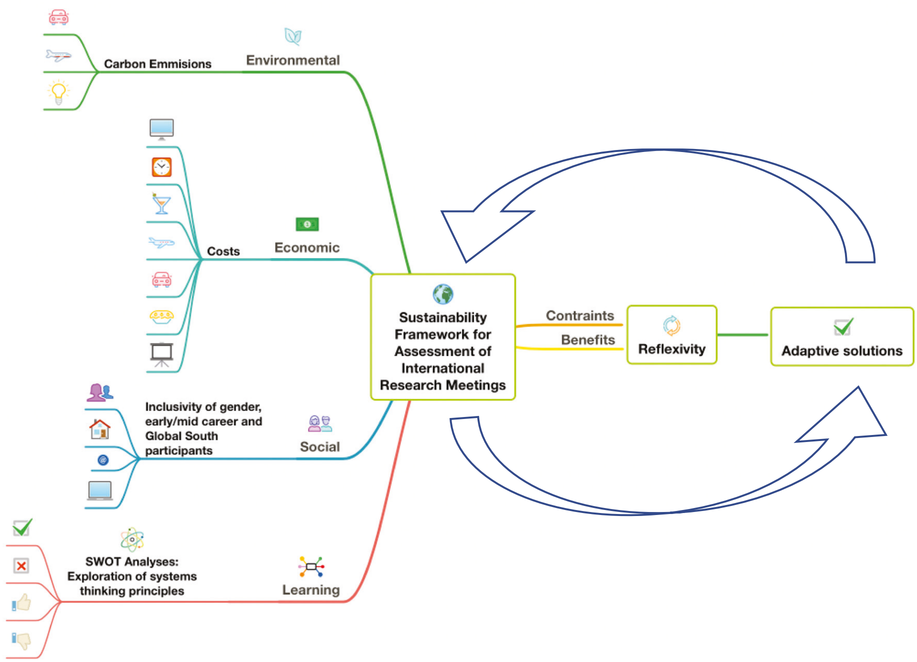


Figure 1. Methodologies used to compare virtual vs. face-to-face meetings. Environmental: Estimation of greenhouse gas emissions in kg CO_2 equivalents, from flights, using ClimateCare 2012. Economic: Calculation of costs for flights, venue hire, food, beverages, airport transfers and lodging. Social: Participant online surveys, analysis of participants (career level, gender, North vs. South) and survey data. Learning: Analyses of strengths, weaknesses, opportunities, and threats (SWOT), to identify measures to enhance project outcomes and mitigate threats of hosting VCs. Quantitative environmental and economic data combined with qualitative social and learning data, to develop a holistic view of benefits vs. constraints of VC, allowing for reflexivity and identification of adaptive solutions to challenges and opportunities for improving sustainability.

Our social analysis (surveys) focussed on the 2019 and 2020 virtual meetings (n = 4), with surveys undertaken before and after each meeting (n = 4) (Appendix A). The greenhouse gas calculations and costs for the environmental and economic components considered only the 2019 VC, as it had the highest number of attendees for all the meetings.

2.2.1. Environmental: Greenhouse Gas Emissions

We estimated the transport-related GHG emissions for the face-to-face conference that would have occurred if the 2019 virtual conference had been held in Chennai as initially planned. This was done to estimate the reductions in carbon footprint achieved by holding the 2019 conference virtually. We used the preferred flying route of the researchers—often a combination of flight time and costs—to calculate the distance from their respective locations to Chennai. Assuming economy class flights, we used the ClimateCare carbon calculator [32] to estimate flight emissions in kg CO_2 equivalents. The methods used by the ClimateCare calculator have been published elsewhere [32], but in short: the calculator estimates the orthodromic distance between two airports and estimates associated carbon emissions. Additional multipliers are applied for first or business class, long-haul flights (>3700 km), and for flying at high altitudes (the radiative forcing index multiplier). We excluded the consideration of internet-related emissions, as these were found to be negligible in other studies, calculated at less than 0.1% of total emissions for a face-to-face VC [7]. Similarly, per person daily network and laptop average emissions for attending a VC in a similar study accounted only for 0.03% of total emissions compared to face-to-face [7].

2.2.2. Economic: Costs

We estimated the flight prices at economy class fares (prices listed in August 2019) for each researcher who indicated that they were attending the annual meeting in Chennai in person, and compared these against costs incurred for the 2018 annual meeting, held in South Africa. Additionally, we included venue hire, food and beverages, airport transfers, and lodging costs of all attendees in the "Chennai scenario." We did not consider local hotel-to-venue commuting costs, nor the "usual" home-work costs for the virtual scenario. We included costs for equipment hire, needed for the online meeting for each institution—if not yet in place.

2.2.3. Social: Inclusivity of Gender, Youth and Global South Participants

We listed the level of seniority, including early-career (postgraduate students), mid-career (defined as researchers below Associate Professor level or equivalent) and senior level of each attendee of the virtual meeting, and proposed attendees of the Chennai meeting (should the meeting have been held face-to-face), and compared the proportion of early- and mid-career level attendees between the two scenarios. We also calculated the percentages of attendees, and their genders, from the Global South, which consisted of team members from South Africa and India, for both scenarios.

2.2.4. Learning: Participant Surveys and SWOT Analyses

To analyse the perceptions of participants before and after the virtual conferences, two online surveys were conducted using SurveyMonkey for each meeting. The surveys comprised both multiple choice and open questions, and aimed at capturing participants' perceptions of the advantages and disadvantages of the VCs.

The authors identified and discussed the emerging main and sub-themes, and data were extracted and categorised/coded by theme. Four authors reviewed the data and reached a consensus on coding to ensure intercoder reliability [33]. Themes were summarised using participants' quotes as an illustration, and Strength (S), Weaknesses (W), Opportunities (O), and Threats (T) (SWOT) were identified in each main and sub-theme. Each SWOT was ranked based on its significance, calculated using an online SWOT analysis tool (Mind Doodle, 2018).

The significance (or scores) of Strengths (S) and Weaknesses (W) were calculated as a product of 'importance,' ranked on a scale of 1 (Low/minimal effect)—5 (High, vitally important) and 'internal rating,' ranked on a scale of 1 (Minor, could be done better/do not do it too poorly)—3 (Major, excel at this/do it poorly).

The significance of the Opportunities (O) and Threats (T) was calculated as a product of 'importance,' and 'likelihood,' ranked on a scale of 1 (Low, unlikely)—3 (Major, highly likely). The results were displayed in a bubble graph to show the relative significance of each SWOT (Appendix B, Figure A1). Weaknesses and threats were assigned negative scores for display purposes on the graph (Appendix B, Figure A2).

We explored the learning component by assessing systems thinking principles [31] of our learning organisation through qualitative causal loop analysis. This was done to further understand the impact of the large-scale, multi-site, and multi-disciplinary virtual processes, to explore the underlying forces at play when considering research collaboration, and to express the potential for systems thinking to facilitate finding adaptive solutions, in response to identified challenges in virtual collaboration. Interlinkages among the

SWOT analysis components, reflexivity [34], and ongoing learning were heuristically expressed to demonstrate how learning can lead to desired change, i.e., mitigating identified weaknesses and threats to successful collaboration and partnership, thereby enhancing project outcomes.

3. Results

In total, 107 researchers attended the virtual meeting in October 2019. Of these, 49 indicated that they would also have attended a physical meeting if this would have taken place in Chennai (Figure 2). The numbers by location can be found in Appendix C (Table A1). In total, 63 participants completed the survey before the start of the meeting and 41 the "after" 2019 survey.

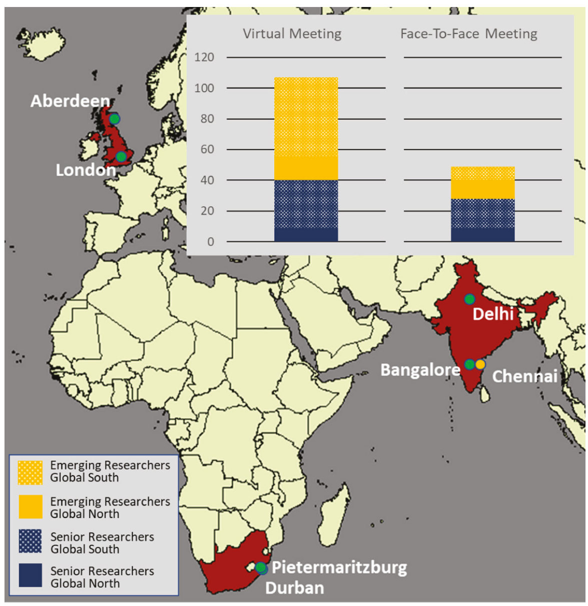


Figure 2. Location of research institutions (green), numbers and level of seniority of researchers that attended the 2019 VC and that would have attended the face-to-face meeting in Chennai (orange).

3.1. Environmental Footprints and Costs

Carbon footprints of 37 international flights and 12 national flights, plus airport transfers, were estimated to be a total 123,009 kg CO_2eq, should the meeting have been held face-to-face with 49 participants. This would have amounted to 2.5 tonnes of CO_2eq per attendee, which is just over half of the global annual average footprint of a single person in 2009 (Fox et al., 2009). The total flight time of all researchers combined was estimated to have been 881 h, and the total travel time 1080 h (i.e., 45 person-days); thus, an average of 22 h per person was saved by holding the meeting in a virtual format.

Total costs associated with the 2019 face-to-face meeting were estimated to be GBP 51,720. Approximately 60% of these costs involved air travel (Figure 3). Actual costs related to virtual annual meeting attendance were GBP 12,485 for all institutions combined, of which the majority (GBP 11,325) was spent on equipment hire and purchase. Furthermore, the amount used in purchasing equipment during this initial virtual meeting was a one-time investment, and the equipment purchased could be used for subsequent VCs, unlike costs incurred in air travel, which would keep rising in the subsequent in-person meetings. Incidentally, there were no equipment costs for the VC in South Africa, as this was already available at the institution. The average per-person cost of GBP 1055 for the initially planned face-to-face meeting with 49 attendees decreased to GBP 117 per person in the virtual meeting in which 107 researchers participated.

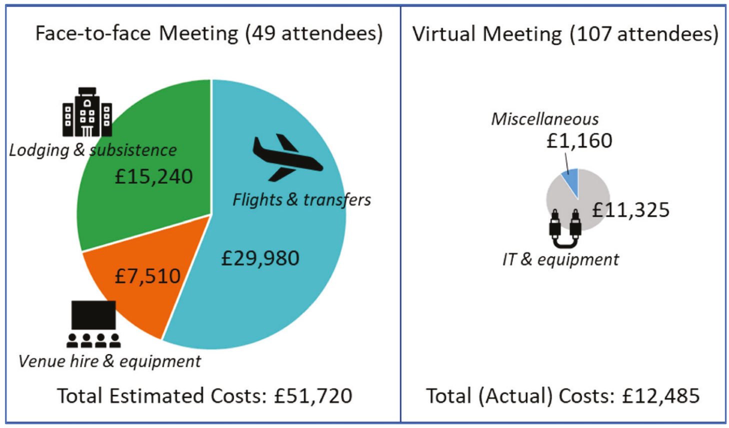


Figure 3. Estimated conference costs for face-to-face left and virtual meeting (right) for 2019 VC. Should the VC have been held face-to-face in Chennai, only 49 team members would have attended due to budgetary constraints.

Costs, greenhouse gas emissions and travel time commitments related to the preceding 2018 face-to-face meeting in Kloof, South Africa (57 participants) were slightly lower on average per person than the estimated figures of the Chennai meeting due to more in-country participants, totalling GBP 26,573 (GBP 466 per person) (Exchange rate R16.97/GBP 1 at the time of the meeting), 92,475 kg CO_2eq (1.6 tonnes of CO_2eq per person) and 880 h (15.4 h per person). For the South Africa meeting, the flights accounted for 83% of the costs.

In 2017 and 2018 the SHEFS research community held annual meetings; however, the shift to a virtual mode allowed conducting bi-annual meetings. This allowed for more frequent interaction and allowed researchers from across countries to share their work and get feedback in a more efficient manner.

3.2. Inclusion and Participation: Gender and Global South

For the 2018 meeting, a total of 57 people attended, of which 30 were from South Africa (including 5 external South African policy stakeholders external to the SHEFS team, who attended part of the meeting), 25 from the UK and 2 from India. Of attendees, 22 (39%) were early-career researchers (9 from Global South and 13 from Global North) whilst 35 (61%) were senior (23 from Global South and 12 from Global North).

In 2019, of the 107 participants that attended the virtual meeting, 63% (67) were early-career researchers, of which 59% (44) were from the Global South. In the case of the face-to-face meeting, this would have been 43% (21), with 42% (9) from the Global South (Figure 4, Appendix C). In terms of gender, the number of female participants that attended was 65% (68), compared to 59% (29) that would have participated at the face-to-face meeting. Of these, 78% (53) females who attended were from the Global South, compared to 55% (16) that would have attended the face-to-face meeting.

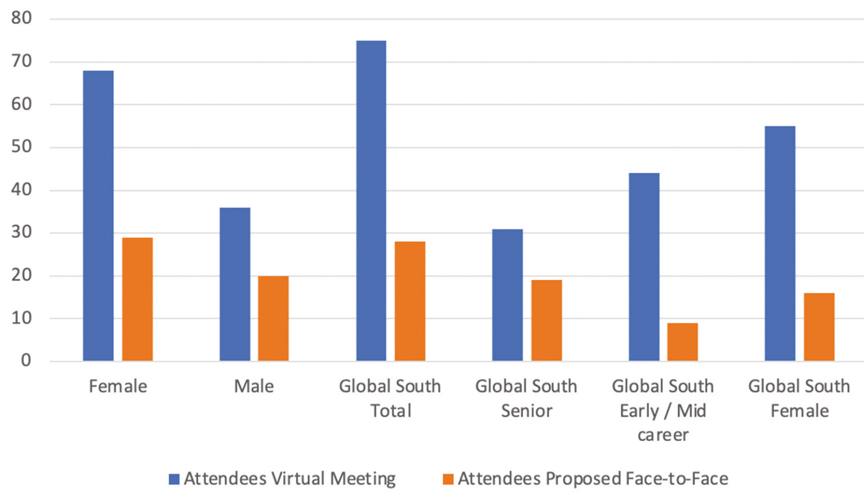


Figure 4. Gender and Global South attendees comparisons for virtual vs. proposed face-to-face conference in 2019.

3.3. Learnings and SWOT Analyses

We identified SWOT from open-ended comments participants made on their perceptions of the virtual meetings; 14 strengths, three weaknesses, 12 opportunities, and nine threats, and assigned scores for each (Appendices B and D). We identified three main themes from these: (1) project productivity, (2) personal development, and (3) opportunities for participation. Within these, we identified ten sub-themes (Appendix D, Figure A3). Figure 5 shows the top seven Strengths, Weaknesses, Opportunities, and Threats, in relation to each other.

3.3.1. Strengths (S)

The most significant strengths were under the 'participation' theme. Enhanced opportunities to participate and increased inclusivity was a recurrent comment in the surveys, especially by early-career scholars from the Global South. Furthermore, despite the limitations of the virtual meeting format, social interaction was frequently mentioned as a strength, particularly for communication across countries. This included positive views of this type of virtual communication for research progress.

> "[. . .] people who normally could not be part of international meetings could attend—socially just approach!!!"
>
> —Senior researcher, Global South

> "The virtual meeting format is an effective learning platform that allows interaction between countries."
>
> —Senior researcher, Global South

> "It is convenient and easy. All countries can share their views, knowledge and information in one "room" thus saving travelling costs"
>
> —Early-Career Researcher, Global South

> "[. . .] we could engage and share with each other in very challenging times, students of mine logged in to the conference from some of the most remote places in South Africa and just loved being part of the learning experience [. . .]"
>
> —Senior Researcher, Global South

Other key strengths of hosting the VC were under 'personal development' related to personal time management and active contribution to a low carbon economy. With the research consortium focusing on sustainability issues, the reduced environmental footprint of the VC was a frequently mentioned sub-theme, and seen as a major strength of the VC format. Participants indicated that they appreciated the fact that, in this way, they were themselves "actively" contributing to lowering environmental footprints.

> "Significantly lower carbon footprint for the meeting and, thus, for the SHEFS project as a whole."
>
> —Senior Researcher, Global North
>
> "In the current time frame, where the effects of climate change are becoming frequent and more calamitous, virtual conferences are one of the ways to reduce our carbon footprint."
>
> —Mid-Level Researcher, Global North
>
> "It was less disruptive to my workday to be able to join individually"
>
> —Early-Career Researcher, Global North
>
> "The benefit was [that] this was logistically useful as it saved a lot of valuable time which would otherwise be spent in travelling and upsetting schedules. This initiative was also feasible at a carbon-footprint level"
>
> —Early-Career Researcher, Global South

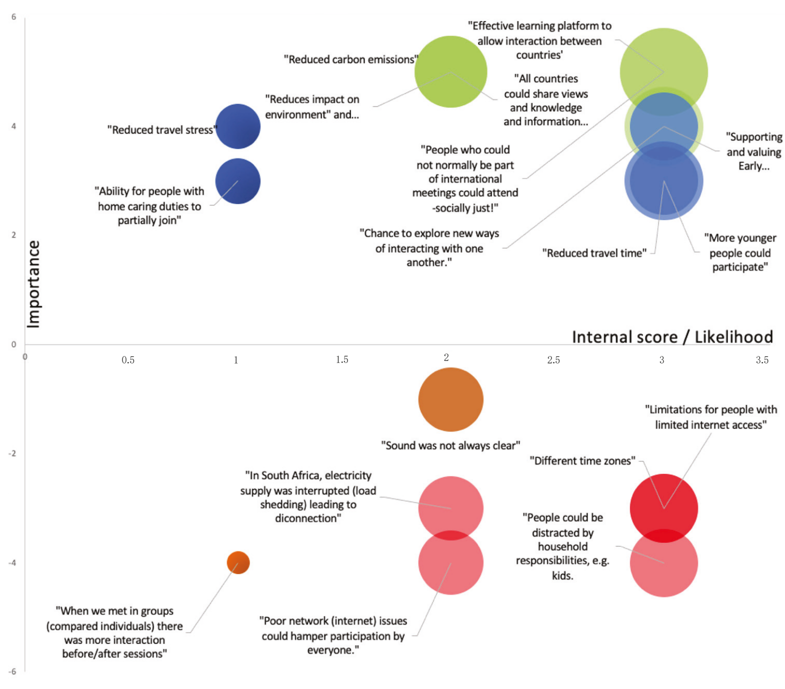


Figure 5. SWOT Analyses: Plotted based on the value of importance (X-axis), internal rating (for Strengths (green) and Weaknesses (brown) or likelihood for Opportunities (blue) and Threats (red)) (Y-axis). The size of the bubbles signify the significance (total scores) of SWOT. Only the top seven SWOT were shown here.

3.3.2. Weaknesses (W)

In terms of weaknesses, under the 'participation,' theme it was felt that social interaction was hindered at the 2020 VC, where everyone met via Zoom as individuals during

COVID-19, compared to the 2019 VC (where countries met virtually in groups). Other weaknesses related to technical issues, such as a weak internet connection, were mentioned numerous times, and identified as threats in SWOTs.

> " . . . When we met in groups (compared to individuals) there were more interactions before/after sessions, but the experience was pretty similar for me during the actual sessions."
>
> —Senior researcher, Global North

> "[Disadvantages of hosting the VC was] Not being able to have the direct connection and social interaction. Not being able to ask how people are really doing. Not being able to ask more sensitive questions to someone after a nice meal when the mood is relaxed and people have built some rapport. All the small human connections as social beings that make use of all non-verbal cues."
>
> —Senior researcher, Global North

> "I wish more time could have been given to some of the discussions as they were very interesting"
>
> —Senior Researcher, Global South

3.3.3. Opportunities (O)

Far more opportunities were identified than threats. Many opportunities were highlighted related to 'work-life balance,' for 'personal well-being,' most significantly that attending VCs resulted in reduced travel stress, the ability for more early-career researchers and people with home caring duties to participate, and a saving of personal time and energy.

> "If the meeting had been held in person I wouldn't have been able to go (as I have a young child), but with a virtual meeting I am able to attend."
>
> —Senior Researcher, Global North

> "More younger people could participate . . . More engagement by participants. Empowering for different sites as they could all participate and influence"
>
> —Senior Researcher, Global South

> "[. . .] Better use of time, resources (money and natural) and energy (human) . . . Allows part-time workers to engage etc. Just so many wins."
>
> —Senior Researcher, Global North

Opportunities related to 'social interaction' were also noted, where participants felt that the VCs provided a platform to explore new ways of connecting with each other on equal terms. Other comments were centred around the ability of the VC to facilitate continued 'research progress' despite the COVID-19 pandemic, and that the VC enabled 'progressiveness and innovation' related to learning and use of new technical skills and tools.

> "It will give a chance to connect members from different places and they can share their opinions and have discussions live. Annual meeting can be left online and be accessible in future"
>
> —Early-Career Researcher, Global North

> "Maintaining a sense of community and partnership despite [the COVID-19] pandemic. Keeping partnerships strong and driving forward research. Supporting and valuing Early-Career Researchers."
>
> —Senior Researcher, Global North

> "[. . .] Scientific side of the meeting was as good/better than face-to-face. Great for widening participation and access."
>
> —Senior Researcher, Global North

3.3.4. Threats (T)

Threats were identified under each main theme, most of which fell under the 'logistical efficiency' and 'time productivity' sub-themes. The fact that the VC had to consider different time zones across South Africa, the United Kingdom, and India meant that the conference duration for each day needed to be limited to four hours. This was about half of the time allocated for the face-to-face conference. This threat was compounded in the 2020 VC by 'time productivity', whereby participants mentioned that household distractions hindered their participation. Other issues raised were related to 'social interaction,' limited time for personal interactions, and poor internet connectivity.

> "People could be distracted by household responsibilities, for example, kids"
>
> —Early-Career Researcher, Global South

> "More difficult to remain focussed when everything is online"
>
> —Early-Career researcher, Global North

> "I think the limited time also meant that new partnerships did not have enough time to be formed"
>
> —Senior Researcher, Global South

> "Sometimes the sound was not very good. It was harder to have real back-and-forth discussions"
>
> —Early-Career researcher, Global North

> "The internet connectivity in my area was terrible and this meant that I missed parts of the meeting"
>
> —Early-Career researcher, Global South

3.4. Heuristic Model of SWOT Analyses

The main reinforcing loop (R_1 in Figure 6) highlights the interconnections among the meetings as a set of processes enabling reflexive thinking through the interplay of the linkages between various aspects of the collaborative system, namely, the benefits, constraints, opportunities for reflexivity and responses to learnings. These linkages, through learning, can be leveraged to enhance benefits and address constraints associated with the virtual meetings. Reflexivity, here, relates to how the virtual meeting processes, including the surveys, enable the researchers to evaluate how, whilst trying to achieve a specific set of sustainability objectives through the lens of sustainability, they are, in turn, actively contributing towards other aspirational goals, such as reduction of the carbon footprint through reduced international travel and social development of women and early-career researchers. The heuristic model shows that the process of learning is iterative, and only through learning and reflecting, and then amending actions, can processes of collaboration be improved.

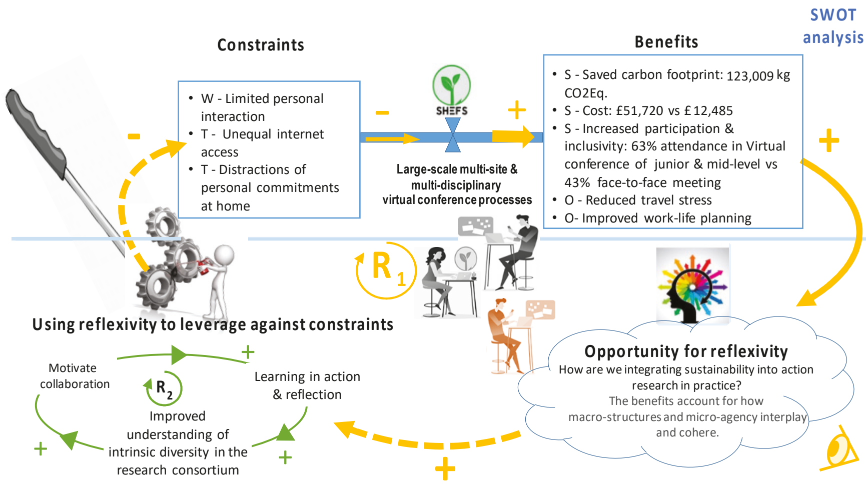


Figure 6. A heuristic model of multi-disciplinary virtual conferences as a constituent form of sustainability practice. The output of the SWOT analysis is shown in the upper half of the diagram, whilst when considered together with the lower second half, the systemic perspective, as a virtuous reinforcing loop (R_1), is designated. Solid yellow arrows: what was found through the surveys. Blue linkage highlights that virtual meeting processes give rise to benefits and constraints. Yellow dashed arrows: how to harness the virtual meeting processes to leverage against constraints. Green arrows: Core of learning processes required for effective collaboration, denoted through a virtuous reinforcing sub-loop, R_2. S = Strengths, W = Weaknesses, O = Opportunities, T = Threats.

4. Discussion

Debates around the effectiveness of virtual vs. face-to-face meetings have either shown virtual meetings as lacking effectiveness (particularly for building trust), or suitably able to meet the objectives of face-to-face meetings [16]. Our study contributes to evidence that with proper planning, understanding the benefits and constraints related to contextual organisational dynamics, and finding adaptive solutions, virtual collaboration can serve as a good alternative to face-to-face meetings [35]. This study shows three major sustainability advantages of virtual meetings above face-to-face meetings: significant contribution to avoiding greenhouse gas emissions (environmental); enhanced participation by early-career scholars and women, especially from the Global South, and lower barriers for inter-country interaction, communication, and collaboration (social) and significant reduction in costs (economic). By considering the whole system, we expressed the holistic view of the pros and cons of virtual collaboration, and the possibilities for virtual teams to be reflexive, and therefore able to address challenges and enhance opportunities through finding adaptive solutions.

Positive environmental effects such as reduced carbon are not expected to continue in the post-COVID-19 era, however, the pandemic showed the great potential for improved environmental health from redesigning multi-institutional collaboration and communication for reduced travel [36]. Since the SHEFS research community already conducted the VC in October 2019 and was planning for the one held in March 2020, many challenges of suddenly shifting to virtual meetings, because of COVID-19 lockdown restrictions, were avoided.

The option to join virtually allowed more than double the number of females and early-career researchers from the Global South to attend than would have attended the face-to-face conference. Our findings show that virtual collaboration can assist in bridging research science gaps, such as the North–South divide (for example, 10:1 ratio of scientific and technical articles produced in 2011 were by Northern vs. Southern authors) [37] and the gender gap (for example, 87 of 115 article disciplines examined had fewer than 45%

women authors) [25]. Specifically, the VC opened up opportunities for inclusion and equal participation of more early-career researchers, Global South scientists, and women. In so doing, virtual collaboration can be used as an additional tool to address gender biases in science [26].

Estimated cost savings of hosting VCs were substantial, with an approximate 76% reduction, the majority of which was from flights. Other costs, not assessed in this study, include lengthy and financially burdensome visa applications to attend international conferences, most of which are hosted in the Global North and are thus unaffordable for many Global South researchers [38]. Utilising part of the foregone travel costs to build better infrastructure in places where it is lacking could ensure further inclusivity and participation improvement.

Effective research planning is crucial for research progress through VCs, and a number of trade-offs, such as limited possibilities to network, lack of opportunities for personal interaction, technical difficulties, and distractions/disengaging from the meeting, were experienced by participants. Some trade-offs will likely be resolved or tackled over the next few years: with faster connectivity (such as fibre internet and 5G networks) being rolled out across the world, mentioned IT and connectivity problems could become less of a problem in the near future. However, other trade-offs, and particularly those related to social interaction and face-to-face networking, which have been found to be crucial for developing trust and bonding social capital in business [39], are more complicated to overcome.

Certain threats appear to have more impact on early-career to mid-career researchers, compared to senior researchers, which may be intrinsically linked with the nature of the weaknesses and threats mentioned by the researchers. This was due to limited finances or fewer previous opportunities to build relationships or network. Senior researchers typically have had more face-to-face meetings in the past years (or decades) to build up their networks, whilst early-career researchers are yet to establish their collaborations. The option of hosting participants in regional groups, in each location, can address the threat of limited opportunities to network whilst achieving avoided air travel [35].

By effectively planning opportunities around VCs for personal interaction between participants, VCs present several strengths and opportunities that not only enhance research efficiency and potential but also provide opportunities for enhancement of personal well-being of researchers [15]. Our study also supports the use of hybrid communication options: part of the reason for the success of the VCs presented here can be attributed to the hybrid nature of SHEFS, having had foundational personal face-to-face interactions and learnings before engagement in VCs, which allowed for interpersonal relationships to be built. The ongoing fostering of such relationships, including aspects of trust and shared understanding, is critical, and we show that virtual communication can effectively be used for this purpose [13]. Another contributor to the success was that the participants were in locations where time differences between countries are not too great (India, SA and UK). The VC model may not work if the locations are too far away (for example, US and India 9.5 h to 12.5 h difference).

Whilst solutions to sustainable development challenges are predominantly, and rightly, based on science [3], there is a need to give equal emphasis to the learning processes whilst conducting research, to contribute new solutions in a complementary way. Iterative reflection and learning of all participants in transdisciplinary teams should be encouraged [40], to continually evolve towards active achievement of improved sustainability outcomes. By analysing participant feedback, and through sharing of possibilities as they emerge (for example, through new interactive tools), the research experience can be further enhanced, and high-quality research collaboration can be maintained whilst reducing costs and improving research sustainability.

The challenge resides in successfully demonstrating the occurrence of concepts, such as reflexivity, that strengthen virtual research collaboration by applying a constructivist perspective [41]. As such, the SHEFS programme has overarching interdisciplinary objectives and is a complex space for collaboration. The inclusion of the virtual meeting processes promote participation in concrete problem-solving, experimentation, and learning techniques, which eventually improve the researchers' reflexivity [34]. Considering context specificity is essential when trying to sustain complex virtual meetings across sites, as it could influence the gap between short- and medium-term outcomes and perceptions of inclusivity and participation. For instance, not all organisations had the optimal technology arrangement for hosting virtual meetings.

Some limitations of the study include that the results reflect a case study for which the boundary organisation, SHEFS, is already focused on achieving sustainability outcomes. This may have influenced the responses by participants, specifically, their positivity towards hosting the VC and the identification of the 'strength' of the VC for reducing the environmental impact of the meeting. Other limitations include that the surveys were taken voluntarily, and, thus, the entire team was not represented. Despite these limitations, this study has relevance for planetary health research, policy, and practice. The case study does represent a "field study" which has been in operation since 2017 (as opposed to experimental studies on virtual collaboration) and thus offers a credible view on the ability of virtual teams to overcome challenges and achieve good outcomes [16]. Specifically, hosting VCs over face-to-face conferences can contribute to sustainability and the achievement of multiple SDGs, and the social, economic and environmental benefits outweigh the trade-offs. However, multiple improvements are needed, namely, investing in efficient IT equipment; planning for conferences to include more time for interpersonal connections, albeit online; including sufficient engagement activities during the meeting to mitigate threats of distractions or lack of focus by participants; facilitating enhanced networking for early-career researchers; finding the right balance of face-to-face vs. VCs, that is acceptable to research funders; and sharing of learnings through scientific publications.

5. Conclusions

This study confirms that virtual collaboration can contribute to environmental, economic and social sustainability, namely: (1) Virtual communication and collaboration have many benefits that—in several circumstances—appear to outweigh the constraints posed by the lack of face-to-face interaction, especially in times of severe disruptions, such as experienced in the ongoing COVID-19 pandemic; (2) Virtual collaboration is critical to reducing carbon emissions of the international scientific community; and (3) Virtual teams are more inclusive of marginalised scientists, such as those in the Global South, or early-career researchers who may be constrained by funding, or women, (4) VCs provide massive cost and time savings, which offer opportunities for use in other areas of research, and development, of researchers. This paper highlights that VCs can successfully enable continued progress of transdisciplinary research and achieve climate and sustainability goals, despite physical distances between team members. The transformative approach, based on using technology more fully, and effective planning to accentuate strengths and opportunities, and to mitigate weaknesses and threats, provided platforms for inclusion, participation, and influence on the project outputs and outcomes, vastly improving the innovation, robustness, and application of the science.

Although the current global situation in some way forces research collaboration to take place virtually [10], the benefits of VCs must not be forgotten if and when the pandemic ceases. At that time, it would be incumbent upon the research community to reflect on the multiple benefits for people and the planet, and the strengths and opportunities of VCs, that outweigh the weaknesses and threats.

Author Contributions: Conceptualisation, R.D.; methodology, R.D., P.S., N.S., R.G. and R.S.; formal analyses, R.D., P.S., N.S., R.G.; writing—original draft, R.D., P.S., N.S.; writing—review and editing, R.G., B.H., T.M., S.C., N.S.V., G.M., A.D., R.S.; supervision, R.S. All authors have read and agreed to the published version of the manuscript.

Funding: This research is part of the SHEFS—an interdisciplinary research partnership forming part of the Wellcome Trust funded 'Our Planet, Our Health' programme, with the overall objective to provide novel evidence to define future food systems policies to deliver nutritious and healthy foods in an environmentally sustainable and socially equitable manner. This research was funded by the Wellcome Trust through the Sustainable and Healthy Food Systems (SHEFS) Project (Grant number—205200/Z/16/Z).

Institutional Review Board Statement: Ethical Approval was granted by the UKZN Humanities & Social Sciences Research Ethics Committee, Ref No.: HSS/0844/018CA.

Informed Consent Statement: Informed consent was obtained from all subjects involved in the study.

Data Availability Statement: The data presented in this study are available on request from the corresponding author.

Acknowledgments: We acknowledge Kirsten Dawes for administrative support on the SHEFS programme.

Conflicts of Interest: The authors declare no conflict of interest. The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript, or in the decision to publish the results.

Appendix A

Appendix A.1. Questionaires

Appendix A.1.1. Pre-Annual Meeting Survey Questions 2019

1. This survey will be done before and after the meeting. Please add your name (or code name) for tracking in the comment box below.
2. When you first heard that the Annual Meeting would be held via Virtual Conference, what was your reaction?
3. What do you see as benefits of hosting the Annual Meeting via Virtual Conference?
4. What do you see as challenges/disadvantages of hosting the Annual Meeting as a Virtual Conference?
5. Based on the planned Agenda, do you feel there are any aspects that could be improved upon to increase the success of the Annual Meeting?
6. What do you see as reasonable objectives to be achieved though the Annual Meeting? Please rate the level of achievement you predict, given the format of the meeting being by Virtual Conference (High, Moderate, Low, Not sure).
   a Share knowledge and information
   b Network
   c Facilitate deeper collaboration between organisations
   d Develop new links between organisations
   e Showcase SHEFS capability to have policy impact
   f Achieve SHEFS objectives and outcomes
   g Develop deeper understanding of the food-health-environment nexus
   h Bridge the science-action gap
   i Build trust and mutual understanding among partners
   j Gather new ideas for exploring similar research and/or implementation in my country
   k Other (please specify).
7. Do you have any other general comments about the Annual Meeting 2019?

Appendix A.1.2. Post Annual Meeting Survey Questions 2019

1. His survey will be done before and after the meeting. Please add your name (or code name) for tracking in the comment box below.
2. After experiencing the Virtual Conference, what was your reaction?
   a I was pleased.

- b I was disappointed.
- c It didn't matter to me.

3. What did you see as benefits of hosting the Annual Meeting via Virtual Conference?
4. What did you see as challenges/disadvantages of hosting the Annual Meeting as a Virtual Conference?
5. Based on the Agenda, do you feel there were any aspects that could be improved upon to increase the success of the Annual Meeting in future?
6. Which of the following objectives do you feel were achieved during the Annual Meeting 2019 Virtual Conference? Please rate the level of achievement you experienced (High, Moderate, Low, Not sure).
   - a Share knowledge and information
   - b Network
   - c Facilitate deeper collaboration between organisations
   - d Develop new links between organisations
   - e Showcase SHEFS capability to have policy impact
   - f Achieve SHEFS objectives and outcomes
   - g Develop deeper understanding of the food-health-environment nexus
   - h Bridge the science-action gap
   - i Build trust and mutual understanding among partners
   - j Gather new ideas for exploring similar research and/or implementation in my country
   - k Other (please specify).
7. Do you have any other general comments about the Annual Meeting 2019?

Appendix A.1.3. Pre-Annual Meeting Survey Questions 2020

1. This survey is part of a series of surveys being done as part of SHEFS meetings. Please add your name (or code name) for tracking in the comment box below.
2. The last virtual annual meeting was held in October 2019. When you heard that SHEFS is hosting the next Virtual Meeting in March 2020, and that it would be more often (twice instead of once per year), what was your reaction?
   - a I was pleased
   - b I was disappointed
   - c It didn't matter to me.
3. Given that all three countries are in Lockdown due to COVID-19, the format of the virtual meeting has changed from "meeting rooms" to "individuals" linking in via Zoom. What do you see as reasonable objectives to be achieved though this format of the Bi-Annual Meeting? Please rate the level of achievement you predict (High, Moderate, Low, Not sure).
   - a Share knowledge and information
   - b Network
   - c Facilitate deeper collaboration between organisations
   - d Develop new links between organisations
   - e Showcase SHEFS capability to have policy impact
   - f Achieve SHEFS objectives and outcomes
   - g Develop deeper understanding of the food-health-environment nexus
   - h Bridge the science-action gap
   - i Build trust and mutual understanding among partners
   - j Gather new ideas for exploring similar research and/or implementation in my country
   - k Other (please specify).
4. What do you see as benefits of hosting the Bi-Annual Meeting via Virtual Conference, linking in as individuals due to COVID-19 Lockdown?

5. What do you see as challenges/disadvantages of hosting the Bi-Annual Meeting as a Virtual Conference, linking in as individuals during COVID-19 Lockdown?
6. Prior to the Annual Meeting, various activities were arranged to increase information sharing, collaboration, interaction and feedback between SHEFS Colleagues. Please ascribe the level of effectiveness for each activity that was conducted (High, Moderate, Low, Not sure).
7. Journal club discussions
    - a Presenter of someone else's output
    - b Research feedback workshop meetings
    - c Other (please specify)
8. Do you have any other general comments about the Bi-Annual Meeting 2020?
9. How has COVID-19 affected your work-life balance?
    - a I have less time to work
    - b I have more time to work
    - c My fear around the virus has overpowered my capabilities for usual work functions
    - d I have been able to focus more and reflect on doing things better
    - e My household responsibilities have taken preference
    - f I am ill or am taking care of ill relatives
    - g I'm spending more time assisting people in my community to cope with COVID-19
    - h No change
    - i Please add any "other" response below, or elaborate on your responses above.
10. Do you have any suggestions for SHEFS to contribute solutions to the COVID-19 crisis?

Appendix A.1.4. Post Annual Meeting Survey Questions 2020

1. After experiencing the Bi-Annual Virtual Conference during the COVID-19 Lockdown, what was your reaction?
    - a I was pleased
    - b I was disappointed
    - c It didn't matter to me.
2. Prior to the Annual Meeting, various activities were arranged to increase information sharing, collaboration, interaction and feedback between SHEFS Colleagues. Please ascribe the level of effectiveness for each activity that was conducted (High, Moderate, Low, Not sure).
    - a Journal club discussions
    - b Presenter of someone else's output
    - c Research feedback workshop meetings
    - d Other (please specify)
3. Given that all three countries are in Lockdown due to COVID-19, the format of the virtual meeting was changed from "meeting rooms" to "individuals" linking in via Zoom. What did you experience as reasonable objectives that were achieved through this format of the Bi-Annual Meeting? Please rate the level of achievement.

Share knowledge and information
Network

- a Facilitate deeper collaboration between partners
- b Develop new links between organisations
- c Showcase SHEFS capability to have policy impact
- d Achieve SHEFS objectives and outcomes
- e Develop deeper understanding of the food-health-environment nexus
- f Bridge the science-action gap
- g Build trust and mutual understanding among partners
- h Gather new ideas for exploring similar research and/or implementation in my country

i Other (please specify)

4. What did you see as benefits of hosting the Bi-Annual Meeting via Virtual Conference?
5. What did you see as challenges/disadvantages of hosting the Annual Meeting as a Virtual Conference?

How often would you prefer SHEFS to host Virtual Conferences of this nature?

a Bi-Annually
b Quarterly
c Annually

6. How did your experience differ, from linking in to the Virtual Conference in groups as done in October 2019, compared to linking in as an individual this time?
7. Do you have any suggestions for SHEFS research that could offer solutions to some of the challenges presented by COVID-19?
8. Do you have any other general comments about the Bi-Annual Meeting March 2020?

Appendix B

(a) SWOT Bubble diagram and (b) SWOT Analyses Scores Table. The bubble diagram was drawn in MindDoodle, using the significance calculations for each SWOT in the Table, as calculated using the formula:

$$\text{Score} = \text{Significance/Importance} \times \text{Internal ratings/Likelihood}$$

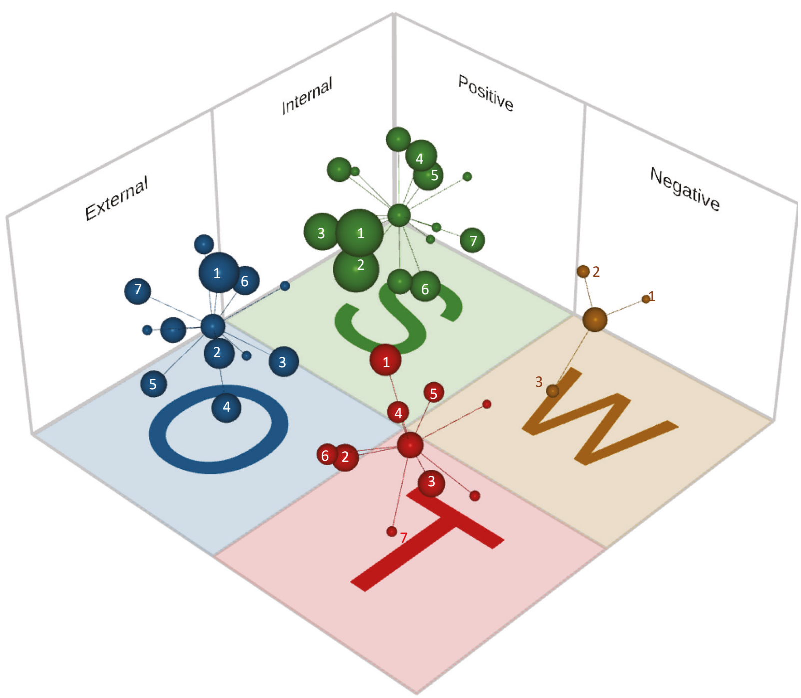


Figure A1. SWOT Bubble diagram.

No.	Strengths	Significance	Internal rating	Score	Weaknesses	Importance	Internal rating	Score	Opportunities	Importance	Likelihood	Score	Threats	Importance	Likelihood	Score
1.	"Effective learning platform to allow interaction between countries'	5	3	15	"Not enough time for discussions."	-4	1	-4	"Reduced travel stress"	3	3	9	"Different time zones"	-3	3	9
2.	"People who could not normally be part of international meetings could attend -socially just!"	5	3	15	"When we met in groups (compared individuals) there was more interaction before/after sessions"	-4	1	-4	"Reduced travel time"	3	3	9	"People could be distracted by household responsibilities, e.g. kids.	-4	2	8
3.	"Supporting and valuing Early Career Researchers."	4	3	12	"Sound was not always clear"	-1	1	-1	"Ability for people with home caring duties to partially join"	3	3	9	"Poor network (internet) issues could hamper participation by everyone."	-4	2	8
4.	"All countries could share views and knowledge and information in one 'room' without travel"	5	2	10					"Ability to still meet and keep work going despite the COVID-19 lockdown."	3	3	9	"In South Africa, electricity supply was interrupted (load shedding) leading to diconnection"	-3	2	6
5.	"Reduced carbon emissions"	5	2	10					"More younger people could participate"	3	3	9	"Lack personal interaction means we don't build collaborations"	-3	2	6
6.	"Reduces impact on environment" and "environmentally friendly"	5	2	10					"Chance to explore new ways of interacting with one another."	4	2	8	"Limitations for people with limited internet access"	-3	2	6
7.	"Cost effective and cheaper"	4	2	8					"Save my personal energy"	4	2	8	"Less sharing of individual ideas"	-3	1	3
8.	"Cost saving in terms of transport and catering" "savings used for future research"	4	2	8					"We should practice what we preach"	4	2	8	"Limited time meant new partnerships could not be formed"	-3	1	3
9.	"Could understand voices better because everyone had microphone"	4	2	8					"Annual meeting can be left online and be accessible in future""	3	2	6	"More difficult to interact electronically"	-2	1	2
10.	"People who cannot travel could join"	4	2	8					"Learn new technical knowledge"	3	1	3				
11.	"Equal participation from all three countries."	3	1	3					"We are showing global leadership on how to run virtual meetings" "the reality of future"	3	1	3				
12.	"Individual screens improve focus on presentations"	3	1	3					Everyone connecting in the same way means participation is equal"	3	1	3				
13.	"More people get to participate than just a few members from each country."	3	1	3												
14.	"More time to work on other things, less disruptive"	3	1	3												

Figure A2. SWOT Analyses Scores Table.

Appendix C

Table A1. List of actual attendees for the 2019 virtual meeting and proposed attendees for the face-to-face meeting. Attendees categorised into early-career/mid-career and senior level, male and female and Global South.

Location	Attendees Virtual Meeting		Proposed Attendees Face-to-Face Meeting	
	N	Level of Seniority	N	Level of Senioritys
Pietermaritzburg	27	15 senior researchers 12 early-career/mid-career researchers	10	9 senior researchers 1 early-career/mid-career researchers
Durban	26	4 senior researchers 21 early-career/mid-career researchers	5	5 senior researchers
London	23	8 senior researchers 15 early-career/mid-career researchers	19	8 senior researchers 11 early-career/mid-career researchers
Aberdeen	2	1 senior researchers 1 early careerng/mid-career researchers	2	1 senior researchers 1 early-career/mid-career researchers
Delhi	6	2 senior researchers 4 early-career/mid-career researchers	3	2 senior researchers 1 early-career/mid-career researchers
Bangalore	16	9 senior researchers 7 early-career/mid-career researchers	10	4 senior researchers 6 early-career/mid-career researchers
Other	7	0 senior researchers 7 early-career/mid-career researchers	0	– –
TOTAL	107	47 senior researchers 67 early careerg/mid-career 68 female, 36 male 75 Global South (31 senior; 44 early-career/mid-career, 53 female)	49	28 senior 21 early-career/mid-career 29 female, 20 male 28 Global South (19 senior; 9 early-career/mid-career, 16 female)

Appendix D

Survey Themes and Sub-Themes

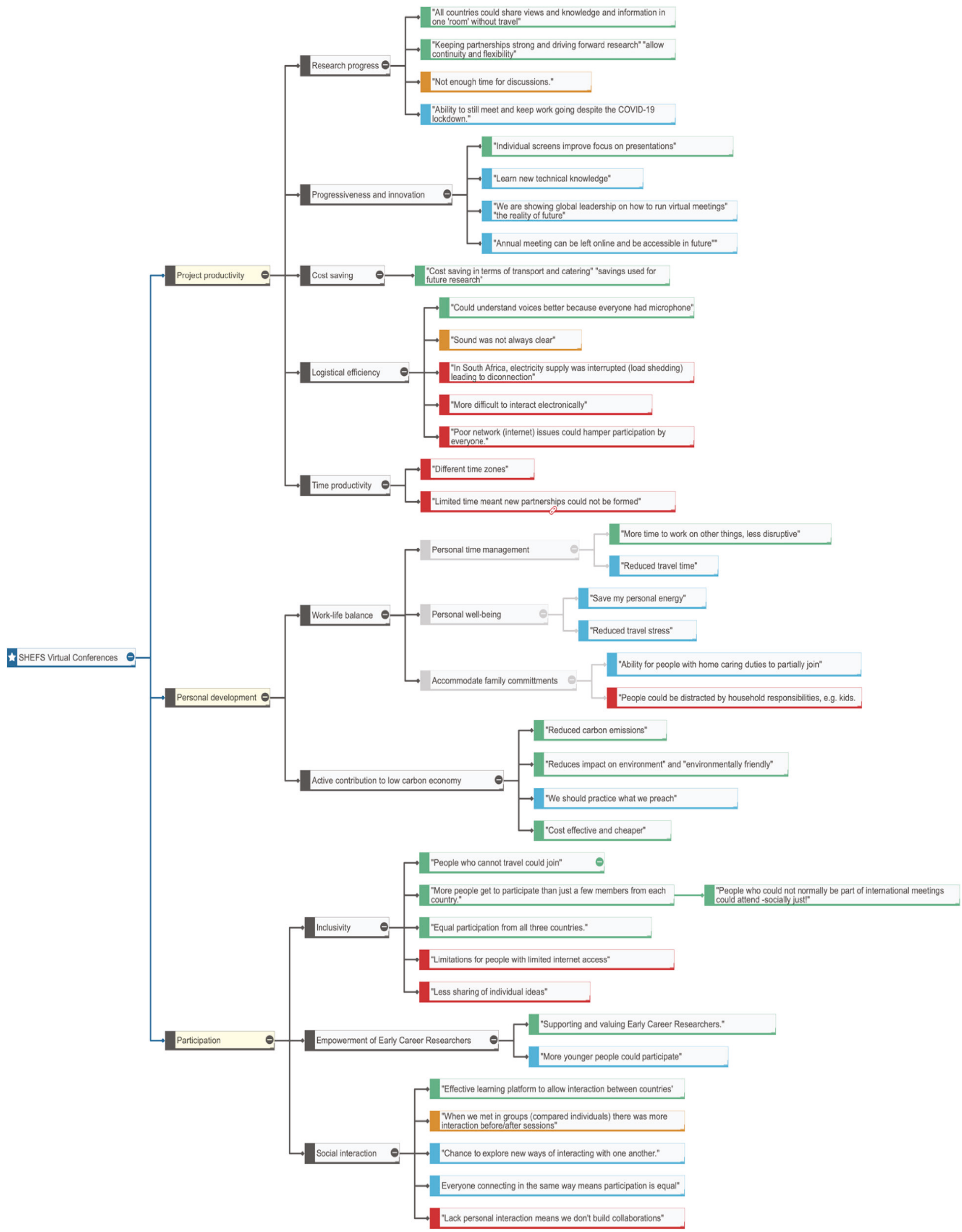


Figure A3. The figure shows the themes and sub-themes that were identified from survey responses in 2019 and 2020, before and after the two virtual conferences. Three main themes identified were: (1) Project productivity; (2) Personal Development and (3) Participation. For each sub-theme, comments were extracted for each category of the Strength (green boxes), Weakness (orange boxes), Opportunities (blue boxes) and Threats (red boxes) (SWOT).

References

1. United Nations. Agenda21. In Proceedings of the United Nations Conference on Environment & Development, Rio de Janeiro, Brazil, 3–14 June 1992. Available online: http://www.un.org/esa/sustdev/agenda21.htm (accessed on 5 June 2020).
2. United Nations. Report of the World Summit on Sustainable Development. In *Environmental Science and Technology*; United Nations: New York, NY, USA, 2002; p. 1. Available online: http://www.un-documents.net/aconf199-20.pdf (accessed on 5 June 2020).
3. United Nations. Resolution Adopted by the General Assembly on 25 Septermber 2015. In *United Nations General Assesmbly*; United Nations: New York, NY, USA, 2015; pp. 1–35. Available online: http://www.un.org/ga/search/view_doc.asp?symbol=A/RES/70/1&Lang=E (accessed on 5 June 2020).
4. United Nations. Resolution adopted by the General Assembly on 27 July 2012: The future we want. In *Rio+20*; United Nations: New York, NY, USA, 2012; pp. 1–53.
5. United Nations. *Paris Agreement*; United Nations: New York, NY, USA, 2015.
6. Govia, I.; Guell, C.; Unwin, N.; Wadende, P. Air travel for global health: Flying in the face of sustainable development? *Lancet* **2019**, *394*, 1786–1788. [CrossRef]
7. Burtscher, L.; Barret, D.; Borkar, A.P.; Grinberg, V.; Jahnke, K.; Kendrew, S.; Maffey, G.; McCaughrean, M. The carbon footprint of large astronomy meetings. *Nat. Astron.* **2020**, *4*, 823–825. [CrossRef]
8. Le Quéré, C.; Jackson, R.B.; Jones, M.W.; Smith, A.J.P.; Abernethy, S.; Andrew, R.M.; De-Gol, A.J.; Willis, D.R.; Shan, Y.; Canadell, J.G.; et al. Temporary reduction in daily global CO_2 emissions during the COVID-19 forced confinement. *Nat. Clim. Chang.* **2020**, *10*, 647–653. [CrossRef]
9. IEA. *Global Energy Review 2021*; IEA: Paris, France, 2021. Available online: https://www.iea.org/reports/global-energy-review-2021 (accessed on 16 July 2021).
10. Klöwer, M.; Hopkins, D.; Allen, M.; Higham, J. An analysis of ways to decarbonize conference travel after COVID-19. *Nature* **2020**, *583*, 356–359. [CrossRef] [PubMed]
11. Yakar, D.; Kwee, T.C. Carbon footprint of the RSNA annual meeting ARTICLE INFO. *Eur. J. Radiol.* **2020**, *125*, 108869. [CrossRef] [PubMed]
12. United Nations Development Programme. *UNDP Support to the Implementation of the 2030 Agenda for Sustainable Development*; United Nations: New York, NY, USA, 2016; p. 9.
13. Jones, R.; Oyung, R.; Pace, L.S.; Jones, R.; Oyung, R.; Pace, L.S. *The Challenges of Virtual Teams*; Jossey-Bass: San Francisco, CA, USA, 2011; ISBN 978-0-470-17642-9.
14. Muszyńska, K. A bibliometric review of research on communication in virtual project teams. *Procedia Comput. Sci.* **2021**, *192*, 4770–4779. [CrossRef]
15. Gilson, L.L.; Maynard, M.T.; Young, N.C.J.; Vartiainen, M.; Hakonen, M. Virtual Teams Research: 10 Years, 10 Themes, and 10 Opportunities. *J. Manag.* **2015**, *41*, 1313–1337. [CrossRef]
16. Purvanova, R.K. Face-to-face versus virtual teams: What have we really learned? *Psychol. J.* **2014**, *17*, 2–29. [CrossRef]
17. Kimble, C. Building effective virtual teams: How to overcome the problems of trust and identity in virtual teams. *Glob. Bus. Organ. Excell.* **2011**, *30*, 6–15. [CrossRef]
18. Alsharo, M.; Gregg, D.; Ramirez, R. Virtual team effectiveness: The role of knowledge sharing and trust. *Inf. Manag.* **2017**, *54*, 479–490. [CrossRef]
19. Whillans, A.; Perlow, L.; Turek, A. Experimenting during the shift to virtual team work: Learnings from how teams adapted their activities during the COVID-19 pandemic. *Inf. Organ.* **2021**, *31*, 100343. [CrossRef]
20. Faber, G. A framework to estimate emissions from virtual conferences. *Int. J. Environ. Stud.* **2021**, *78*, 1–16. [CrossRef]
21. Hegger, D.; Dieperink, C. Toward successful joint knowledge production for climate change adaptation: Lessons from six regional projects in The Netherlands. *Ecol. Soc.* **2014**, *19*, 34. [CrossRef]
22. Steffen, W.; Richardson, K.; Rockstrom, J.; Cornell, S.E.; Fetzer, I.; Bennett, E.M.; Biggs, R.; Carpenter, C.R.; De Vries, W.; De Wit, C.A.; et al. Planetary boundaries: Guiding human development on a changing planet. *Science* **2015**, *347*, 1259855. [CrossRef]
23. Rockstrom, J. Safe Operating Space for Humanity. *Nature* **2009**, *461*, 472–476. [CrossRef]
24. Raworth, K. A Safe and Just Space For Humanity: Can we live within the Doughnut? *Nature* **2012**, *461*, 1–26. [CrossRef]
25. Holman, L.; Stuart-Fox, D.; Hauser, C.E. The gender gap in science: How long until women are equally represented? *PLoS Biol.* **2018**, *16*, e2004956. [CrossRef]
26. Grogan, K.E. How the entire scientific community can confront gender bias in the workplace. *Nat. Ecol. Evol.* **2019**, *3*, 3–6. [CrossRef]
27. SHEFS Global. Sustainable and Healthy Food Systems (SHEFS). 2019. Available online: https://shefsglobal.lshtm.ac.uk/partners-and-researchers/ (accessed on 25 August 2020).
28. SHEFS Global. *Sustainable and Healthy Food Systems (SHEFS) Publications*; SHEFS: London, UK, 2021. Available online: https://shefsglobal.lshtm.ac.uk/publications/ (accessed on 25 August 2020).
29. Microsoft. Microsoft Collaborate. 2020. Available online: https://docs.microsoft.com/en-us/collaborate/intro-to-mscollaborate (accessed on 20 April 2020).
30. John, I. Mentimeter. *Sch. J.* **2018**, *66*, 153.

31. Morecroft, J. System dynamics. In *Systems Approaches to Managing Change: A Practical Guide*; Springer: London, UK, 2010; pp. 25–85.
32. ClimateCare. *Calculate and Offset Your Carbon Footprint*; ClimateCare: Oxford, UK, 2012.
33. Lombard, M.; Snyder-Duch, J.; Bracken, C.C. Practical Resources for Assessing and Reporting Intercoder Reliability in Content Analysis Research Projects. *Analysis* **2005**, *4*, 1–18.
34. Popa, F.; Guillermin, M.; Dedeurwaerdere, T. A pragmatist approach to transdisciplinarity in sustainability research: From complex systems theory to reflexive science. *Futures* **2015**, *65*, 45–56. [CrossRef]
35. Reshef, O.; Aharonovich, I.; Armani, A.M.; Gigan, S.; Grange, R.; Kats, M.A.; Sapienza, R. How to organize an online conference. *Nat. Rev. Mater.* **2020**, *5*, 253–256. [CrossRef] [PubMed]
36. El Zowalaty, M.E.; Young, S.G.; Järhult, J.D. Environmental impact of the COVID-19 pandemic—A lesson for the future. *Infect. Ecol. Epidemiol.* **2020**, *10*. [CrossRef]
37. Blicharska, M.; Smithers, R.J.; Kuchler, M.; Agrawal, G.K.; Gutierrez, J.M.; Hassanali, A.; Huq, S.; Koller, S.H.; Marjit, S.; Mshinda, H.M.; et al. Steps to overcome the North-South divide in research relevant to climate change policy and practice. *Nat. Clim. Change* **2017**, *7*, 21–27. [CrossRef]
38. Sidney, U. Ulrick Sidney: Visas for Global Health Events—Too Many Are Losing Their Seat at the Table. 2019. Available online: https://blogs.bmj.com/bmj/2019/07/30/ulrick-sidney-visas-for-global-health-events-too-many-are-losing-their-seat-at-the-table/ (accessed on 13 October 2020).
39. Townsend, L.; Wallace, C.; Smart, A.; Norman, T. Building Virtual Bridges: How Rural Micro-Enterprises Develop Social Capital in Online and Face-to-Face Settings. *Sociol. Rural.* **2016**, *56*, 29–47. [CrossRef]
40. Mauser, W.; Klepper, G.; Rice, M.; Schmalzbauer, B.S.; Hackmann, H.; Leemans, R.; Moore, H. Transdisciplinary global change research: The co-creation of knowledge for sustainability. *Curr. Opin. Environ. Sustain.* **2013**, *5*, 420–431. [CrossRef]
41. Kaye, H.; Barrett, J. *Making Online Teams Work*; Palgrave Macmillan: London, UK, 2018.

sustainability

Review

On the Theoretical Conceptualisations, Knowledge Structures and Trends of Green New Deals

Zaheer Allam [1,2,3,*], Ayyoob Sharifi [4], Damien Giurco [1] and Samantha A. Sharpe [1]

[1] Institute for Sustainable Futures, University of Technology Sydney, Sydney 2007, Australia; Damien.Giurco@uts.edu.au (D.G.); Samantha.sharpe@uts.edu.au (S.A.S.)
[2] Live+Smart Research Lab, School of Architecture and Built Environment, Deakin University, Geelong 3220, Australia
[3] Chaire Entrepreneuriat Territoire Innovation (ETI), Groupe de Recherche en Gestion des Organisations (GREGOR), IAE Paris—Sorbonne Business School, Université Paris 1 Panthéon-Sorbonne, 75013 Paris, France
[4] Graduate School of Humanities and Social Sciences & Network for Education and Research on Peace and Sustainability (NERPS), Hiroshima University, Hiroshima 739-8511, Japan; sharifi@hiroshima-u.ac.jp
* Correspondence: zaheerallam@gmail.com

Abstract: The increasing impacts of climate change, coupled with the Greta Thunberg effect, the findings of the Intergovernmental Panel on Climate Change (IPCC) reports, and varied environmental policy documents, are pointing to the need for urgent and cohesive climate action and mitigation frameworks. One potent solution, gaining global acceptance, is that of the Green New Deal (GND), positioned as a radical rethinking of political and economic structures in view of pushing sustainability at the forefront of national, regional, and global issues. With the model rapidly gaining ground in various geographies, and in different forms in view of contextualization needs, there is a need to better understand its evolution, knowledge structures, and trends. This paper thus sets forth to provide an understanding of the evolution and implementation of GND through a bibliometric analysis and science mapping techniques using VOSviewer and CiteSpace to identify the thematic focus of 1174 articles indexed in the Web of Science since 1995. To understand the thematic evolution of the field over time, we divided the study period into three sub-periods, namely 1995–2014, 2015–2019, and 2020–2021. These sub-periods were determined considering important milestones related to GNDs. Term co-occurrence analyses were then conducted to understand thematic focus and associated trends. Also, co-citation analysis and bibliographic coupling were other methods applied to identify major sources, authors, publications, and countries that have made more contributions to the development of research on GNDs. The findings of this paper can help both researchers and policy makers understand the evolution and trends of GNDs to better formulate GNDs strategies and policies in accordance with varying needs and geographies.

Keywords: green new deal; green growth; bibliometric analysis; environmental policy; decarbonization; COVID-19; sustainability; climate change; negative externalities

Citation: Allam, Z.; Sharifi, A.; Giurco, D.; Sharpe, S.A. On the Theoretical Conceptualisations, Knowledge Structures and Trends of Green New Deals. *Sustainability* **2021**, *13*, 12529. https://doi.org/10.3390/su132212529

Academic Editor: Marc A. Rosen

Received: 21 October 2021
Accepted: 9 November 2021
Published: 12 November 2021

1. Introduction

The increasing impacts and challenges of climate change are more apparent and have been widely documented, with consequences ranging from increasing incidences of heatwaves and increased precipitation, leading to flashfloods, such as those lately witnessed in Western Europe where over 200 deaths were reported in July 2021 alone [1]. Climate change is also credited for the increasing incidences of drought, especially in sub-Saharan Africa, affecting regions are experiencing food insecurity, increased cases of water shortage and numerous challenges amongst pastoralists as vast lands experience desertification [2,3], and, amongst others, visible water sea-levels threatening some coastal regions with submersion and increases in vector diseases, to name a few [4].

According to the latest report by the IPCC [5], it is possible that the climate goals set in a number of global accords such as the Paris Agreement, aimed at ensuring that global temperatures are kept below 2 °C, preferably 1.5 °C, will not materialize, affirming similar findings documented by the same body in 2018 [6]. In the latest IPCC report, it is made clear that Earth is likely to exceed temperatures of 1.5 °C above pre-industrial levels and by 2100 [5], with the possibility that temperatures will have risen by between 3 °C and 3.5 °C. This is reinforced in the Nationally Determined Contributions (NDC) Synthesis report, published on the 17 September, outlining that even though the global rate of carbon emissions is decreasing, it is expected to peak by 2030 (with a 16% comparative rate of increase to 2010 levels, suggesting an increase in temperature rise of about 2.7 °C). Hence, further efforts have been demanded by countries to achieve the Paris Agreement targets [7].

The Paris Agreement, as noted in the UN Climate change report [8], required that member parties commit to meet at least 45% reduction on their emissions by 2030, but it was found that commitments could only be achieved if each party doubled their efforts. The scenario has further been complicated by emergence of COVID-19, which Shan, et al. [9] posited would prompt a 16.4% global increase in emissions as from 2020 depending on economic stimulus governments advance in their economies. On this, the UNEP [10] reports that only 18% of all the global recovery spending has some 'Green' elements. Temperatures above 1.5 °C will translate to devastating climate events such as heatwaves, flooding, desertification, acidification of water sources, and tropical cyclones among others. This may be disastrous for many regions of the world, and especially for small island developing states (SIDS), where cases of forced climate migration is expected to increase with sea water level rise, with others losing considerable amount of habitable spaces, fishing ground, tourism attraction sites, and essential infrastructures, leaving little options other than to migrate [4].

Failing to meet the agreed targets in the Paris Agreement will consequently impact the achievement of other agreements, such as the sustainable development goals [11] and that of other COPs that were reached earlier. This, however, will be a result of human inducement, especially after the COVID-19 pandemic where economies have been found to revert to fossil-fuel intensive industries in their effort to revive the economies [12]. On this, Shan, Ou, Wang, Zeng, Zhang, Guan, and Hubacek [9] note that if fossil-fuel intensive activities continue to prevail, the aftermath will be a chaotic global environment that will not only be unsustainable for the current generation, but make sustainable development more difficult for future generations. As expressed by The European Commission [13], there will be need for deep re-thinking and reversal in policies to ensure global extraction of resources, production of products, and their consumption and their ultimate disposal align with sustainability agendas. Additionally, there are needs to re-assess the cost or benefits of production or consumption of goods and services in sustainability narratives, introducing the notion of 'Negative Externalities' where damages from pollution are not factored in. This however calls for a cohesive ecosystem re-think with respect to both consumers and producers.

One solution that emerged in 2019, and has been gaining traction in the past two years, is the 'Green New Deal' that was first introduced in America after years of negotiations [14], and was subsequently adopted in varying forms by numerous countries, including country blocks such as the European Union [15]. This is further explored in the next section.

2. Surveying Green New Deals

The concept of Green New Deals can be argued to be an emerging, broad, and transformative approach toward addressing a series of issues impacting modern societies. It thus aims to address climate concerns in different geographies, while attempting to solve social and economic inequalities. According to Conte [16], the idea of the Green New Deal was conceived in 2006 in the United States, under the care of a taskforce that had been formed to deliberate and propose solutions on how different sectors engage in a sustainable transition as per the concept of the 'Global Greens'. This is interesting noting that the emergence of associated terms such as 'Green Economy' and 'Green Growth' in 1989 and 2005, respectively [17], leading to foundational precepts to the Green New Deal. However, the proposed GND, as noted above and highlighted by Mastini, et al. [18], goes beyond economic growth in relative terms and aims to address other aspects such as social, economic, and environmental justice. In fact, the concept of 'growth' should not be a precursor for the GND, as expressed by Mastini, Kallis and Hickel [18], as degrowth policies also need to be part of the 'GND' narrative. This is true, noting that some green growth pursuits also have the potential to violate absolute planetary boundaries rather than solely improving environmental capital, or at least in the preservation of existing environmental resources [19]. The main inspiration for the Green New Deal is historical; its name was borrowed to mirror President Franklin D. Roosevelt's approach of helping the U.S. recover from the Great Depression by instating a total makeover of his government, or the 'New Deal' as it was called [20]. Activism on climate action began in the 1970s after the oil crisis, but progressive actions were only arguably taken in 2006 [16]. The agitation for climate change, gained more support from the political class, where some politicians with Jill Stein, a presidential candidate in 2012 and 2016 under her Green Party, banked on the climate change debate as a campaign tool for the presidential position [21]. However, the main breakthrough of the political class came in 2018 after a youthful group that was protesting on the government inaction against climate change was joined by Rep. Alexandria Ocasio-Cortez and Senator ED Markey [14], who formulated the groundwork for what became a joint resolution passed by congress in 2019. The resolution mandated the Federal Government to create a Green New Deal that would address a raft of issues, including touching on the foundational challenges of climate, economic, and social justice.

On climate, the Green New Deal (GND) as passed by the Congress targeted to have the country (U.S.) achieve net-zero greenhouse gas emissions by 2050 by adopting transition mechanisms that would not be injurious to communities or workers. The achievement of reduced emissions would be championed by ensuring the country transitions 100% to the use of alternative renewable energies in all sectors, through deep transformation of the transport sector, such as ensuring electric vehicles and mass transit systems were the main mode of transport. Since the objectives of the GND matches the calls for climate action [22], there seems to have been an increase in popularity, not just in the United States but globally, towards the model. Indeed, an analysis, represented through a line diagram in Figure 1, of the popularity of the term 'Green New Deal' for the period from 2008 to 2021 showcases a peak in 2019, aligning with the time of the GND passing in congress in the USA. Additionally, it is observed (Figure 2) that the first five geographies where interest by regions is peaking are: Guatemala, South Korea, Singapore, the United States, and New Zealand, respectively.

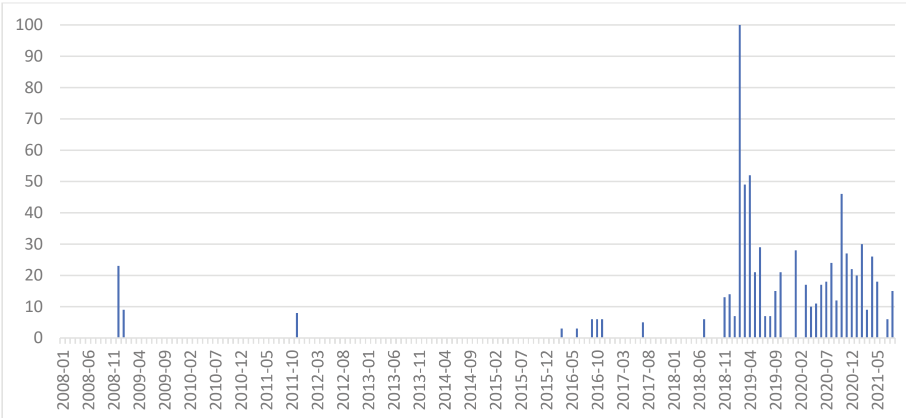


Figure 1. Web popularity of the term 'Green New Deal' from 2008 to 2021, with popularity ranging from 0 to 100. Sourced from Google Trends [23].

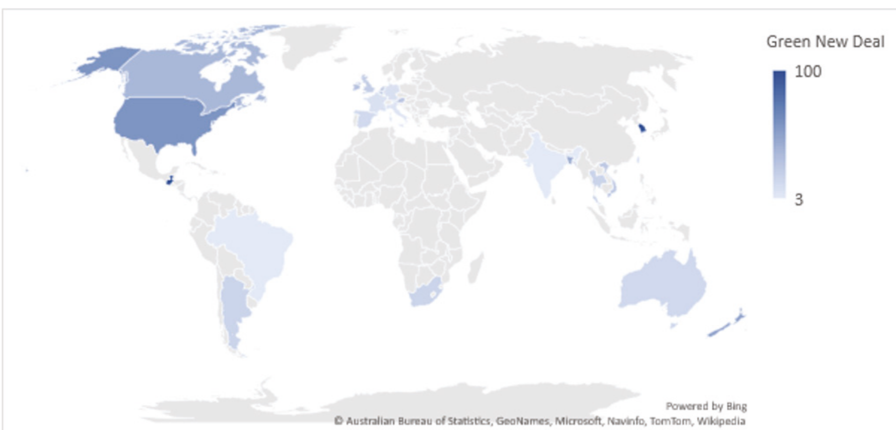


Figure 2. Web popularity of the term 'Green New Deal' (2008 to 2021), interest by region. The popularity ranges from 3 to 100, where 100 is the most popular. Sourced from Google Trends [24].

Since the adoption of the Green New Deal in the U.S Congress in 2019, there have been substantial number of other countries that have adopted similar approaches under different names, as shown in Table 1 below. Though they vary from each other, they all seem to have a convergence of intentions, especially regarding the need to reduce emissions and concentrate on attaining net-zero emissions in the future while achieving equity and inclusivity in the socio-economic fabric. In the table, China and India are included, but their commitment to reduction of emissions is not expressly defined in their Green New Deal agendas [25]. However, notable and practical actions have been taken. These include increased efforts and investments in renewable energy, adoption of technologies in their manufacturing industries, and introduction of fiscal mechanism such as the use of emission trading schemes (ETS) [26] are evident, especially in China.

Table 1. Mapping Green New Deal national policy proposals and name variations.

Country	Name of Policy	Year Proposed	Source
Canada	Pact for a Green New Deal	2019	[27]
United Kingdom	Green Recovery Act	2019	London Assembly [28]
South Korea	Green New Deal	2020	Chowdhury [29]
The European Union	European Green New Deal	2019	European Commission [15]
China	Ecological Civilization	2020	Paszak [30]
United States of America	Green New Deal	2019	Congress [14]
Mexico	Green New Deal	2020	Moreno-Brid and Gallagher [31]
Singapore	Green Plan	2021	Government of Singapore [32]

Besides individual countries and regions pursuing the GND, it is interesting that there are also notable organizations that support Green New Deal policies, pushing sectoral and thematic agendas on sustainability transitions. Those are outlined in Table 2 below. Most of those are domiciled in countries and regions such as the U.S. and Europe that have already pioneered in forming models of their GND. However, even in countries such as Australia where there is no formal announcement of the GND program, from the federal government, some states within the republic are seen to actively advocate for its acknowledgement and the embracement of deep sustainable transitions [33]. However, there appears to be clear disagreement on what constitutes a 'green deal', especially in view of criticisms on an AUD 2 billion renewable energy project between the New South Wales (NSW) government and the federal government [34].

Table 2. Mapping organizational adoption of Green New Deals.

Organizations	Year	Source
The Climate Mobilization	2017	The Climate Mobilization [35]
The European Green Party	2006	Green Party [36]
The Green-European Free Alliance	2011	The Greens/EFA [37]
The Democracy in Europe Movement 2025	2019	DiEM25 [38]
Green Party of the United States	2006	Green Party of the United States [39]
Heinrich Böll Foundation	2009	French, et al. [40]
League of Conservation Voters	2019	League of Conservation Voters (LCV) [41]
The New Economic Foundation	2008	New Economics Foundation [42]
Open Democracy	2018	Robinson [43]
The United Nations Environmental Program	2009	UNEP [44]
The Global Marshall Plan Initiative	2020	Saha, et al. [45]
The United Nations Economic and Social Commission for Asia and the Pacific	2012	Ministry of Environment [46]

Bradshaw, et al. [47] note that while the concept is gaining attention, leading to a rapid acceptability and adoption in diverse geographies and quarters (specifically with civil societies pressuring legislative makers) and underlining evidence of diversification in terms of the content advanced in the different countries or regional specific models. This has led to confusion on the specific underlying principles that the varied models aim to address thus, pointing to the need for countries to first address underlying market failures, such that the GND is not seen as a knee-jerk reaction to failures that could be sorted using other means. In fact, even in country specific models, such as the Green New Deal in the U.S., there is still confusion noted from leaders from different political divides (i.e., Democrats vs. Republicans), as to who are against the deal (notably mostly Republicans, who perceive some of the issues such as social justice as being unrealistic, and hence are dismissive of the proposal) [47]. While the variations may be deemed to represent interests that different countries have in their pursuit and conviction of the best way to address climate change, rising oil prices, and unsustainable energy consumption, there is need for some uniformity in order to address common goals and principles. This is affirmed when a critical consideration of models such as the EU's Green Deal, which will be expanded beyond EU as explained by Dartford [48]. While the intention is deemed as sincerely aiming at ensuring that Europe's pursuit of climate action is achieved, it may have deeper implications as the region's trading partners may not have any contextual plans for GND. The resulting implications from both the trading partners and the EU may be hostile with institution of stringent measures that may somehow disrupt the existing trading relationship. In the case of countries in the global south that in some ways rely on their counterparts on the global north, they may be inevitably forced to agree to some measures, which sometimes may be incoherent with their domestic policies. On this, Táíwò [49] argues that some of the policies engendered in the New Green Deal and other models, if they are eventually formalized to become guiding policies, have the potential to increase inequalities, akin to what scholars coin as being 'climate colonialism' [50]. While examples would vary in accordance to contextual needs and capacities, there are notable needs by countries for land and financial resources to develop renewable energy plants as alternatives for fossil fuel plants. This is further represented in the NDC Synthesis Report [7], stating the popularity of renewable energy projects, as a means to curb climate change, amounts to 84% in countries around the world. While this measure is welcomed globally, most economies in the global south may have sufficient land, without the associated financial capacities to support nationwide projects, and thus often rely on debt financing, grants, and other such sources [51–53]. This conventional approach could force nations to secure more debts, increasing an unsustainable dependency on developed economies, leading to the arguments of 'neo' and 'climate' colonialism [54]. In this case therefore, economies in the global south, just like is the case with their counterparts on the north should be allowed to pursue and craft their own sustainability plans, addressing their unique challenges, as well as allowing them to align with their commitments as per the Paris Agreement as well as SDGs (and hence calling towards contextualized models for Green New Deals).

While pursuing proposals for new models that would somehow apply conventionally (and hence acceptability in countries and by different organizations), it will be paramount to understand the underlying issues pertaining GND in terms of how it emerged, its evolution, and trends. This is particularly important in a time where GNDs are politically equated as an 'ecology-centered' economic stimulus program, which can help significant political attention [55]. This is key, especially when GNDs can be viewed as a strong narrative to help economic growth, hence posing as a self-funding mechanism to the crucial question as how to finance transitions. From this perspective, proponents of GNDs are largely unaligned with those of degrowth who argue growth makes it more difficult to accomplish emissions reductions [18]. This interestingly builds an alignment of agendas on GNDs between both the environmental and political class, with the agenda of economic growth as a mutual ground. Additionally, funding transitions across multiple sectors are required, and in this regard numerous innovations need to be fostered, which can also lead to white space opportunities for corporates. This is leading to emerging Green funds, aligning with the underlying GND theme, applicable at both national and regional levels, and which could provide some reprieve to global south economies without capacities to fully finance GNDs agendas.

In view of the above, countries looking at engaging in GND agendas will need to craft contextualized policies aiming at solving an array of socio-economic challenges, while introducing economic stimulus programs across numerous sectors. Of interest, would also be the careful drafting of policies to tap into emerging policies and green funds, a criteria which would be particularly key to developing and least economies and small island developing states, which often do not have the capacity to finance green transitions [53,56].

To align with this constant shift in global policies, including in view of the current COVID-19 pandemic (at the time of writing), there is a need for an updated review of literature on GNDs and associated strategies for Green Growth, as new economic challenges present itself, causing larger inequalities and posing a threat to long term sustainability agendas [57]. In view of this, a macroscopic perspective is required on the larger themes, providing an overview of its evolution over time, including during the pandemic period, to better understand past, current, and future directors. This paper thus, through a bibliometric analysis, undertakes to advance our knowledge on GNDs to present findings that can help countries seeking to associate with GNDs would have substantial information, leading to the potentiality of crafting models with the potential to address local priorities and challenges.

3. Methods

Keeping pace with the rapid growth of scholarly publication has made literature review challenging in the recent years. One way to deal with this challenge is utilizing bibliometric analysis techniques that allow gaining an overview of specific fields. Such macroscopic overviews can be used to highlight major thematic focus areas and research trends. Various bibliometric analysis software tools such as SciMAT, CiteSpace, and VOSviewer have been developed in the past two decades. All of these tools can be used to explore thematic evolution and identify keys authors, references, and sources. VOSviewer was used for the purpose of this study since it has a user-friendly interface, the outputs are more suitable for identifying and analyzing thematic clusters, and it can also provide detailed information on influential authors, references, sources, countries, and institutions [58]. Input data for bibliometric analysis using VOSviewer can be obtained from academic databases such as Scopus and the Web of Science (WoS). Here, we used WoS, given its broad coverage of quality peer-reviewed articles related to the topic. In addition. WoS bibliographic outputs are more compatible with VoSviewer and allow obtaining more detailed results. To retrieve literature relevant to GNDs, we developed the following broad-based search string that includes different related terms: TS = ("New Green Deals" OR "New Green Deal" OR "Green New Deal" OR "Green Deal" OR "Green Recovery" OR "Green Growth"). Using this search string in the WoS on 5 August 2021, returned 1403 articles. It should be noted that we only searched for English articles and the search period was not restricted (i.e., all papers indexed until 5 August 2021, were considered). We screened the titles and abstracts of these articles and 1174 articles related to the aims and objectives of this study were selected for final analysis in the VOSviewer. Three types of analyses are used in VOSviewer to map knowledge structure and trends. These are, namely, bibliographic coupling, co-citation analysis, and term co-occurrence analysis. Van Eck and Waltman [58] describes bibliographic coupling as "a link between two items that both cite the same document", where it can be used to identify major contributing countries and institutions and their interactions. Furthermore, co-citation links are described as "a link between two items that are both cited by the same document" [58]. As citation frequency is widely considered as a measure of scholarly impact, results of co-citation analysis are used to identify the most influential authors, publications, and sources. Finally, a term co-occurrence analysis is used to identify major thematic focus areas of the field. In addition to highlighting major terms, this analysis also provides information on important thematic clusters within the field. As one of the aims of this study was to explore thematic evolution over time, we divided the study period into three sub-periods considering major milestones that may have influenced the evolvement of the field and the total number of papers published in each sub-period. The first period started on 1995, coinciding with the introduction of the Environmental Bill of Rights to the U.S. Congress [59], this being a major milestone leading to subsequent green policies and increasing research in the area.

As shown in Figure 3, there has been a surge in the number of publications around 2015. This could be linked to the introduction and adoption of international policy frameworks such as the Paris Climate Agreement and the 2030 Agenda for Sustainable Development in 2015. Accordingly, 2015 was designated as the first milestone. The figure also shows another surge in 2020 which could be linked to the emergence of the COVID-19 pandemic. Based on these milestones, the study period was divided into three sub-periods, namely 1995–2014, 2015–2019, and 2020–2021. In addition to an overall term co-occurrence analysis, we conducted separate term co-occurrence analyses for the three study periods to understand thematic evolution. Outputs of all VOSviewer analyses are presented as a network of nodes and links (e.g., see Figure 4). The node size is an indication of the relative importance. For instance, in case of term co-occurrence analysis, node size is proportional to the frequency of term occurrence. Also, link width is proportional to the strength of connection between the two terms. Terms that are closely linked to each other form clusters that indicate thematic focus areas.

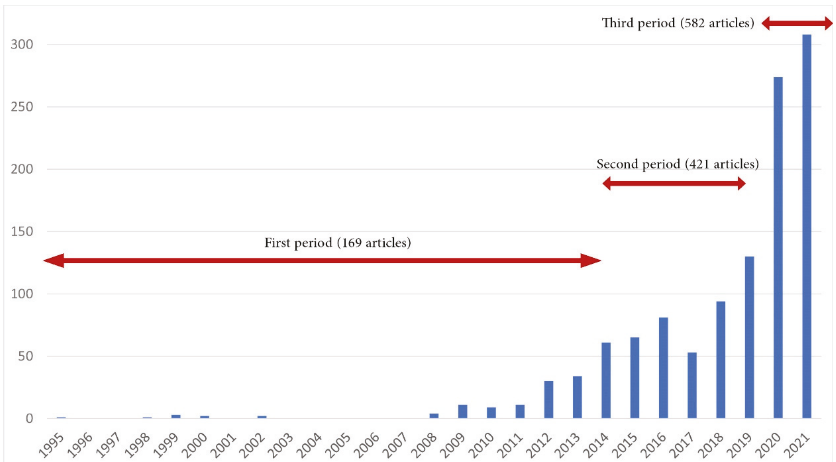


Figure 3. The number of articles published per year. Note that although the literature search was conducted in August 2021, the number of articles in this year is already larger than its previous year. This is a clear indication of increasing interest in this topic and more articles are expected to be published in the rest of 2021 and coming years, especially in view of the impacts of COVID-19 on many economies and the need for prompt recoveries aligning with both economic and sustainability pursuits [57,60,61].

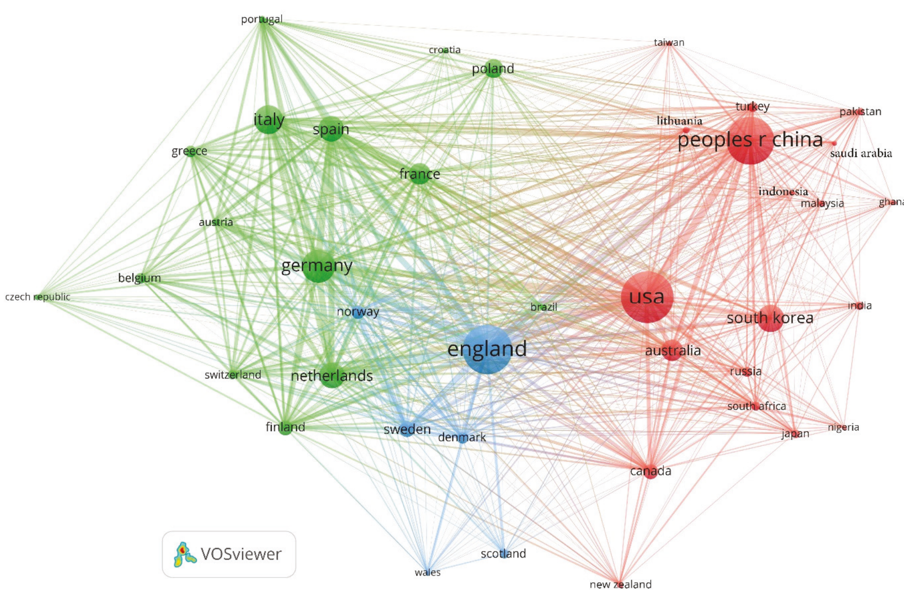


Figure 4. Countries with the most contributions to GND. Illustration by authors.

4. Results and Discussions

4.1. Countries Making the Most Contributions

The analysis supports that, as illustrated in Figure 3 above, the USA, the People's Republic of China, England, and Germany are the most popular contributors to the GND debate with 176, 156, 163, and 99 documents respectively. This is evident by the size of the nodes, which in this case the four countries have the largest (as per the number of documents noted above). The popularity of GND was further observed to be gaining traction in countries such as the Netherlands, France, Italy, South Korea, Australia and Spain and Poland. The green cluster is seen to have received much attention, followed by the red cluster, while the blue cluster comes third.

From the literature, the result obtained in Figure 3 are not surprising as the current global pressures towards the adoption of a Green Deal have been seen to concentrate more in the USA and European zone. For China, as noted by Bradshaw, Ehrlich, Beattie, Ceballos, Crist, Diamond, Dirzo, Ehrlich, Harte, Harte, Pyke, Raven, Ripple, Saltré, Turnbull, Wackernagel, and Blumstein [47], although there is no formal agenda that can be equated to the Green New Deal, there has been an increase in attention toward activities pointing toward a reduction of carbon footprint. The increased attention and research focusing on China may be due to the fact that it is the leading emitter of carbon emissions, accounting for almost 24% of the global emissions [47]. Further, being the leading country in investment on renewable energy may have contributed to increased attention on its focus on matters relating to the adoption of deeper measures, aligning with the Green New Deal. The attention in the USA also maybe multi-pronged. First, since the 1970s (as reported by Conte) [16], there has been numerous calls, proposals, and agitations for the country to adopt climate actions to avert its impacts on the environment, economy and communities. Secondly, as was expressed by Bradshaw et al. [47], it is ranked the second globally in terms of global emissions, and its commitment to global accords such as the Paris Agreement, especially in view of the previous government policies on the same, may have triggered an increased interest. Thirdly, it is the first country to have a realistic Green New Deal formulated and discussed at a congressional level [14], thus drawing global attention. In the case of England, its contribution to the discourse on GND (or Green Deal as it is known in Europe) ranks it top among European countries. From the literature, it is noted that though the Green Deal will impact the entire of European region and beyond, England, would be a major beneficially due to focus on areas such as green spaces and improvement of air quality that was noted to be fairly poor compared to its counterparts in the region [28]. Further, being the main trading partner with its European counterparts, it is understandable that the Green New Deal would impact their trading relationship. Thus, interest in understanding how the deal works would influence policies in the country.

4.2. Most Influential Organisations

Organizations were clustered into three groups depicted in distinctive colors, represented in Figure 5. The red cluster comprise of 12 organizations with larger nodes that are closely linked noting the thickness of their link lines. The blue cluster is located far right, with only three organizations (Vrije University, University Autonoma Barcelona and ICREA with 14, 14, and 11 documents each) therein with each of them having fairly large nodes and close link between themselves. However, this cluster is far linked from the rest of the clusters. The green cluster is comprised of nine organizations that are closely linked to each other but with smaller nodes, indicating that the number of publications from those organisations were fairly few compared to those obtained in other clusters. For instance, INHA University, Macquarie University, Beijing Normal University and University Manchester all had eight documents published.

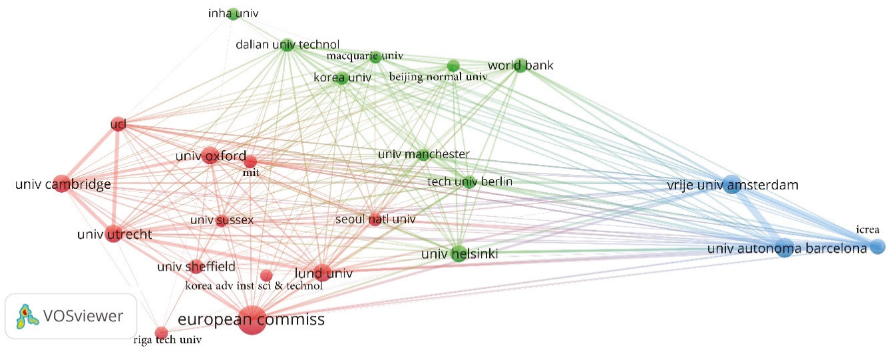


Figure 5. Organizations contributing the most to GND. Illustration by Authors.

From the literature review, the European Commission (EC) has been identified as one of the organizations that eventually managed to bring into fruition the Green Deal agenda in Europe, and from the diagram above, it had very close link with numerous learning institutions. This could explain why most of the documents that could have shaped the GND document emanated from the institution. From the results obtained, the close link between EC and other organizations clustered in red is not surprising as most of these are mostly based in Europe, save for Seoul University. This confirms that the European Green Deal emanated from different environmental knowledge shared, exerted from different quarters in the region, specially from learning institutions. This is true following realization that, indeed, there are notable concerns with issues such as increasing emission levels from the region [47], the unsustainability of the economy due to some sectors still relying on non-renewable energy sources [62], and the increasingly observable cases of social inequalities in the region as document in a report by Bubbico and Freytag [63]. One clear observation from the results above is that most of the organizations are learning institutions drawn from Euro-zone save for the few drawn from Korea, the World Bank, and the European Commission. From the analysis, the U.S. and Europe can be noted as the only two to have clear-cut GNDs. In America, the political class drawn from both the Democrats wing and other smaller parties have been credited for pushing for the realization of GND and this could be due to the fact that other institutions, such as NGOs and learning institutions are not as coordinated in research and policy work, as is the case with Europe. However, the results from Europe highlight the influence the learning institutions can have in shaping and influencing for meaningful changes in the society. Whereas it may be construed that the topic on GND is not widely understood in the public domain, hence, justifying why most organizations pushing for actions to be taken are learning institutions, evidence from the literature show otherwise. On this, youth movements [64,65], UN bodies such as the UNFCCC [66–68] and the IPCC [5,69], and other bodies, have been clear on their position on climate change. However, it is also important to appreciate that adopted GND models do not only concern the environment, but encompasses other cross-cutting issues, that learning organization, the World Bank, the EC and other organizations keenly supporting. This showcases a global consensus on expanding the GND to touch on socio-economic dimensions, hence using the rational for approaching the environment as an underlying foundation to regenerate societies.

4.3. Most Influential Journals

As depicted in Figure 6 below, the influential journals are grouped into three clusters depicted in green, blue, and red colors. The red cluster represent those associated with energy, where journals touching on this topic were popular. For instance, journals 'Energy Policy' and 'Journal of Cleaner Production' had 1810 and 1496 citations, respectively. This cluster contained 20 journals represented by nodes that closely linked, except for the journal

'Energy and Buildings'. The green cluster contained 17 journals, represented by nodes that also fairly closely linked. The most popular journal in this cluster was that of 'Ecological Economics', cited over 1078 times and had over 29,224 links. The blue cluster contain nine journals, with the most popular being 'Energy Economics' with 589 citations and a total of 18,148 links. This cluster had most of the journals with least citations, with most of them seen to be more linked to the green cluster than with the red cluster.

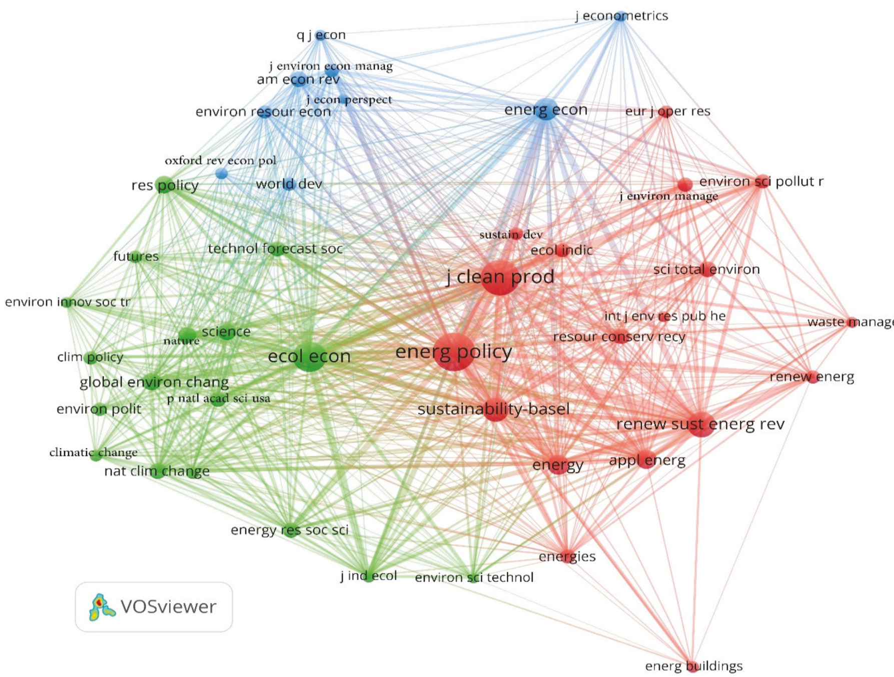


Figure 6. Journals influencing the GDN discourse. Illustration by authors.

The concentration of activities in the journals related to the energy sector is unsurprising considering the amount of effort, mobilization, and resources that have been directed toward a global shift from fossil fuels to renewable energy. In particular, from the literature, it is evident that global efforts are now amassed with energy policies, especially emanating from COP meetings, which started as early as the 1990s, the popular policy frameworks being the Kyoto Protocol (1997) [66] and the Paris Agreement (2015) [67]. These groundbreaking policies are aimed at guiding global economies in their pursuit to addressing climate concerns to ensure that global temperatures do not rise above 2 °C pre-industrial level by 2030 [6]. While the two popular GND models (American and European) covers more than just the energy sector, it is clear than the debates and publication on the energy sector greatly shaped and will further influence policies on existing and emerging Green Deals. The increasing popularity of journals related to energy in terms of citations and linkages shows that over the years, scholars have increased their attention on matters environment more so on the impacts of emissions from the energy sector. What is surprising from the results obtained is the reduced popularity of journals inclined to social and economic aspects, especially noting that Green Deals are also focused on how pursuits of social welfare in areas such as housing, water extraction and consumption and others contribute to sustainable environments. Further, it is evident (as documented in the Circular Economy Action Plan for Europe [13]) that the GND, especially the European Green Deal, is focused on changing the economic model of the region to accommodate a circular to advance the concept of sustainability, innovation, and technology use in the energy production and others.

4.4. Most Influential References

A total of 38 most influential references were identified and listed for this analysis. The results are presented in Figure 7, which has three clusters identifiable by three colors (red, blue and green), with 15, 10, and 11 references, respectively. Two references, (Dowson, et al. [70] and European Commission [71]) had zero links. Thus, they are not present in the diagram. In terms of influence, documents by the United Nations Environment Programme [72] and the World Bank [73], having a total of 158 and 171 citations respectively, are seen to dominate. All these are identified under the blue cluster just near the center of the diagram due to the extensive relationship that the energy sector (blue cluster) has with themes such as climate change and sustainability (red cluster) and the concept of green growth (green cluster). Table 3 below maps the major references, showcased in Figure 7.

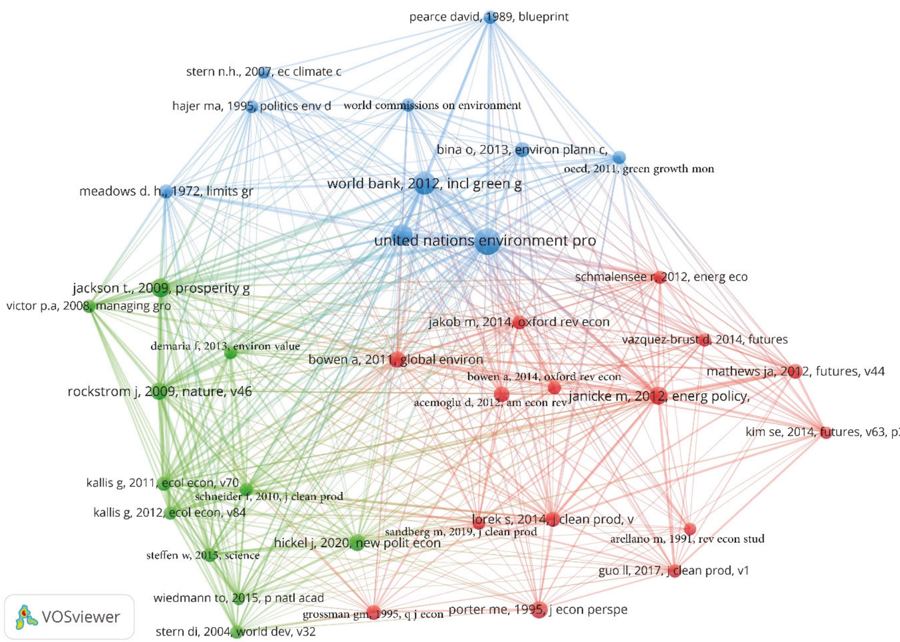


Figure 7. Major references influencing the GDN discourse. Illustration by Authors.

From the literature, it is evident that while themes in sustainability and green growth are gaining in popularity, they are guided by policies and frameworks emanating from bodies such as the United Nations Environment Program (UNEP) and the World Bank, thus justifying their influence in shaping the discourse on GND. In particular, these bodies have been observed to be consistent in advocating for green growth and have been financing diverse programs and projects across the globe aligning with the Green concept. For instance, in the article by the World Bank [73], the clarion call is for an inclusive Green Growth that would ensure that the 9 billion people that will occupy the world by 2050 would not be disadvantaged by agendas of the current generation. Adding to this, is the noticeable need to include the private sector in the common objective of sustainable transitions [74], and to introduce 'Corporate Social Responsibilities' (CSR) as key agendas [75]. To ensure that the objective of having a sustainable future is achieved, those noted organizations are observed to advocate for policies that not only address the environment and climate issues alone but extend to social and economic dimensions to ensure that prevailing issues such as inequalities, exacerbating unsustainable pursuits are minimized. In support of the discourse advanced by those institutions, many publications touching on sustainability, more so in the energy sector are seen to be increasing; thus, justifying why the red cluster has a substantial number of influential references. From the literature, it is evident that there have been numerous calls, including through global accords such as the Paris Agreement for economies to shift to use of renewable energy as alternative for the fossil fuel to reduce emissions, at least to guarantee that temperatures would not rise beyond 2 °C. This increase on publication on energy, as from 2014, as shown in Figure 7, showcases that as talks about the Paris agreement intensified, researchers worked to complement to policies to potentially influence future directions, such as the formulation of the GND, gaining traction in this dispensation.

Table 3. Major references influencing the GDN discourse, with number of citations and link strength.

Title	Authors	Journal/Organization	No. of Citations	Link Strength
The environment and directed technical change	Daron Acemoglu Philippe Aghion Leonardo Bursztyn David Hemous	American Economic Review	2243	54
Some Tests of Specification for Panel Data: Monte Carlo Evidence and an Application to Employment Equations	Manuel Rellano Stephen Bond	Review of Economic Studies	11,368	25
The Green Economy and Sustainable Development: An Uneasy Balance?	Olivia Bina	SAGE Journals	293	61
The green growth narrative: Paradigm shift or just spin?	Alex Bowen Samuel Fankhauser	Global Environmental Change	48	117
What is degrowth? From an activist slogan to a social movement	Federico Demaria Francois Schneider Filka Sekulova Joan Martinez-Alier	Environmental Values	693	86
Domestic UK retrofit challenge: Barriers, incentives and current performance leading into the Green Deal	Mark Dowson Adam Poole David Harrison Gideon Susman	Energy Policy	267	0
European Commission		European Commission	21	0
Economic growth and the environment	Gene M. Grossman Alan B. Krueger	The Quarterly Journal of Economics	8497	47
The interaction effects of environmental regulation and technological innovation on regional green growth performance	Ling Ling Guo Ying Qu Ming-Land Tseng	Journal of Cleaner Production	138	51
The Politics of Environmental Discourse: Ecological Modernisation and the Policy Process.	Maarten A. Hajer	Oxford University Press	9423	47
Is green growth possible?	Jason Hickel Giorgos Kallis	New Political Economy	515	66
Prosperity without growth? The transition to a sustainable economy	Tim Jackson	UK sustainable development commission	1042	134
Green growth, degrowth, and the commons	Michael Jakob Ottmar Edenhofer	Oxford Review of Economic Policy	128	87
"Green growth": From a growing eco-industry to economic sustainability	Martin Jänicke	Energy Policy	319	149
In defence of degrowth	Giorgos Kallis	Ecological Economics	1004	115
The economics of degrowth	Giorgos Kallis Christian Kerschner Joan Martinez-Alier	Ecological Economics	610	99
A new approach to measuring green growth: Application to the OECD and Korea	Satbyul Estella Kim Ho Kim Yeora Chae	Futures	71	58
Sustainable consumption within a sustainable economy–beyond green growth and green economies	Sylvia Lorek Joachim H. Spangenberg	Journal of Cleaner Production	556	106
Green growth strategies—Korean initiatives	John A. Mathews	Futures	129	68
The limits to growth: The 30-year update	Dennis Meadows Jorgan Randers	Taylor and Francis	4577	75
Towards green growth	OECD	OECD	79	171
Towards green growth: Monitoring progress	OECD	OECD	12	87
Blueprint 1: for a green economy	David Pearce Anil Markandya Edward Barbier	Francis and Taylor	4997	67
Toward a New Conception of the Environment-Competitiveness Relatinship	Porte Me	Journal of Economics Perspectives	34	39
A safe operating space for humanity	Johan Rockström, Will Steffen Jonathan A. Foley	Nature	10,911	127
Green growth or degrowth? Assessing the normative justifications for environmental sustainability and economic growth through critical social theory	Maria Sandberg Kristian Klockars KristofferWilén	Journal of Cleaner Production	85	56

Table 3. *Cont.*

Title	Authors	Journal/Organization	No. of Citations	Link Strength
From "Green Growth" to sound policies: An overview	Richard Schmalensee	Energy Economics	107	76
Crisis or opportunity? Economic degrowth for social equity and ecological sustainability. Introduction to this special issue	François Schneider Giorgos Kallis Joan Martinez-Aliera	Journal of Cleaner Production	1116	108
Planetary boundaries: Guiding human development on a changing planet	Will Steffen Katherine Richardson Johan Rockström Sarah E. Cornell Ingo Fetzer Elena M. Bennett Reinette Biggs Stephen R. Carpenter Wim De Vries Cynthia A. De Wit Carl Folke Dieter Gerten Jens Heinke Georgina M. Mace Linn M. Persson Veerabhadran Ramanathan Belinda Reyers Sverker Sörlin	Science	7611	70
The rise and fall of the environmental Kuznets curve	David I Stern	World Development	3587	53
The economics of climate change: the Stern review	Nicholas Stern Nicholas Herbert Stern	Cambridge University Press	1705	36
Towards a Green Economy: Pathways to Sustainable Development and Poverty Eradication—A Synthesis for Policy Makers	UNEP	UNEP	259	254
Managing the transition to critical green growth: The 'Green Growth State'	Diego Vazquez-Brust Alastair M. Smith Joseph Sarkis	Futures	60	55
Managing without growth: slower by design, not disaster	Peter A. Victor	Edward Elgar Publishing	1291	76
The material footprint of nations	Thomas O. Wiedmann Heinz Schandl Manfred Lenzen Daniel Moran Sangwon Suh James West Keiichiro Kanemoto	Proceedings The National Academy of Sciences of the United States of America	1235	79

4.5. Most Influential Authors

The authors who have had more influence on the GND discourse are presented in Figure 8 below. These are clustered in four distinctive groups symbolized by red related to sustainability and climate change, blue representing energy themes, green encompassing issues on green growth and yellow on the subject of climate neutrality with direct links to Green New Deals. The results showcase that the most popular authors are institutions such as European Commission, OECD, the World Bank, and UNEP. However, on average, the blue cluster is seen to have larger nodes, that are closely linked, followed by the green cluster and red cluster, respectively. The yellow cluster encompassing only five authors has EC as the most active author. Others in this cluster (CBC, Eurostat, FAO, and UN) are cited only the least, and are also least linked. Individual authors are seen to be more popular in matters of Sustainability, Climate Change, and Green Growth.

The results presented above showcases that the theme of Green New Deal comprises of diverse thematic areas, and those academicians drawn from different fields enrich the discourse on this matter. In particular, authors interested in Green growth, sustainability and climate change are seen to be more popular, than those concentrating on new Green Deals. Probably, the reason for this inclination is due to the fact that the three popular themes are more inclined on impacts, which are well known, unlike the GND, which can be argued to be still new and is yet to gain a widespread recognition by most people, organizations, and institutions. For instance, Steffen, et al. [76] who were exploring matters of planetary boundaries in response to sustainability agendas are seen to have been cited over 7743 times despite their article having been published in 2015. Same case with an article by Guo, et al. [77] who exploring the relationship between technological innovation and the environmental regulations in influencing green economic growth. The article has been cited over 132 times and linked over 54 times though it was published in 2017. This shows that topics related to sustainability, green growth, climate change and energy are becoming popular, especially in relation to how modern trends such as technological applications are incorporated. This augurs well with the proposals in the GND models, especially in the economic dimension, where the circular economic approach is being pursued [78]. It is evident that circular economy pursuits highly supported an extensive application of technologies in areas such as production, extraction of resources and in recycling processes to ensure an extended lifecycle of products [79], and even though the concept is noted to receive increasing global attention. In view of its merits, there are notable challenges as to its inclusion in vulnerable groups [80].

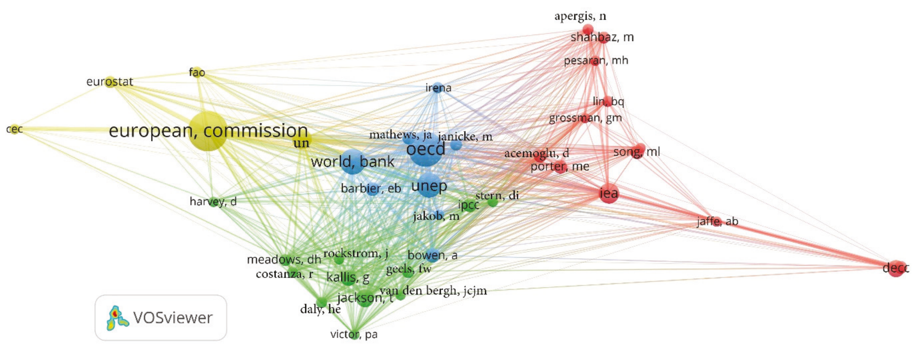


Figure 8. Authors influencing the GDN discourse. Illustration by the authors.

4.6. Term Co-Occurence

4.6.1. All Periods

Results of the term co-occurrence analysis for the whole study period are shown in Figure 9 below. The terms were categorized and clustered into three groups. The red cluster categorizes terms associated with climate change and sustainability, while the blue cluster encompasses terms associated with green growth. The green cluster was dedicated for terms associated with application of technologies and policies to foster economic growth. The red cluster had a total of 25 terms, with key terms (according to size of their node) including sustainability, which deemed to be more closely associated with terms such as green growth and green economy from the blue cluster. The term climate change was almost centrally positioned as shown in Figure 8 and is seen to be associated with terminologies from both the green and blue clusters. The green cluster had a total of 15 terms, with policy, economic growth and efficiency being the main ones and seemed to be closely linked with other terms in this cluster and from the blue and red cluster as well. Other terms that were popular in this category include efficiency, innovation, impact, technology, renewable energy, China, and CO_2. The blue cluster had only six terminologies, with the key one being green growth, which is seen to be closely associated with major terminologies such as sustainability, climate change, energy, Green New Deal and others from the Red cluster. Likewise, it has close links with terms such as Economic Growth, Impacts, Model Performance, Innovation, and Efficiencies from the green cluster.

From the literature, it is not surprising that terms such as green growth, sustainability, climate change, policy, economic growth and energy seem to have been very popular and closely associated over the period in question (1995–2021). It is worth noting that it is within this period that global community had come together to form the COPs with the first meeting happening in March 1995 [81]. Therefore, it is no coincidence that the key terminologies especially in regard to climate change and need for green growth seem to be predominant. Further, the co-occurrence of the terms such as policy, energy economic growth, sustainability and climate change may have been influenced by the global discourse that was then focused on the urgent need for introducing policy framework such as the Kyoto Protocol targeting sectors in the economy, such as energy production, sustainable agriculture, equitable economies, with no or minimum market imperfections and others [66]. Successful global meetings, and the introduction of key global agreements such as the Paris Agreement [67], the Sustainable Development Goals [11], New Urban Agenda (NUA) [82], and the Agenda 2030 on Sustainable Development [83] have prompted an emergence of new terms such as mitigations, Green Deal, circular economy and others. The dominance of the co-occurring words such as green growth, sustainability, climate change and energy and others show that the global agendas associated with those are still on course; hence, as more calls continue to stress upon the need to address global climate challenges, those terms will continue to gain in popularity. However, when studying the terms more closely in three distinct periods, we are offered with interesting insights as to their evolution across time. This is expanded in the three sections below.

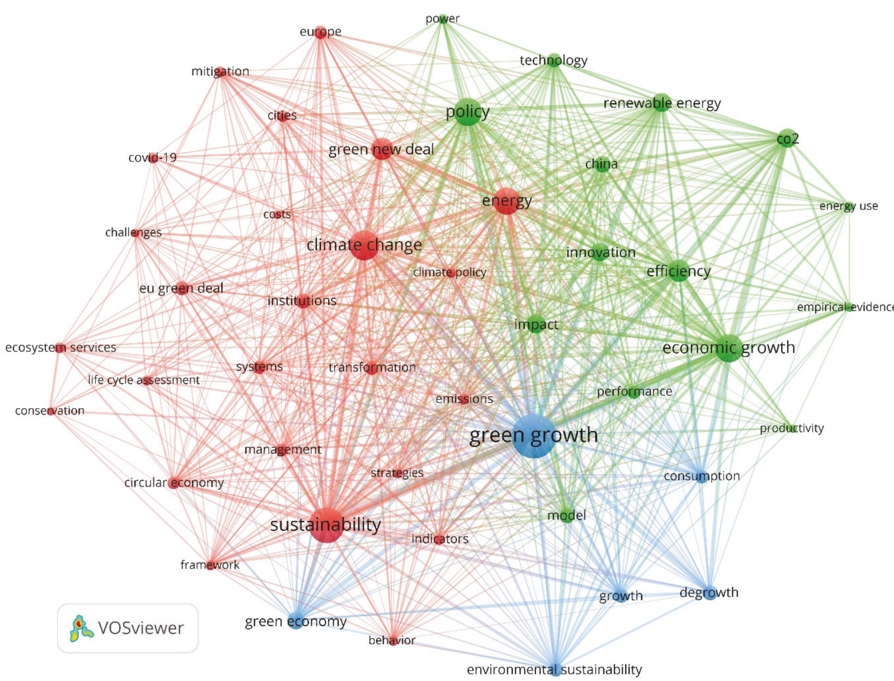


Figure 9. Analysis of terms co-occurrence from 1995 to 2021. Illustration by the authors.

4.6.2. First Period (1995–2014)

During the period 1995–2014, a number of terminologies related to the topic of GND, as shown in Figure 10 below, were already popular with most academicians. A total of 34 key terminologies were identified during this period, classified into three clusters; the red representing sustainability and climate change, the blue encompassing terms such as Green Growth, Developing Countries, and others commonly associated with the economic growth and development. The green cluster with 14 terms is observed to focus on technology, environment and innovations. The key terminologies during this period included Green Growth, Sustainability, Climate Change, Policy and Energy. However, other geographies that had begun attracting substantial attention during this period includes China and South Korea, the latter aligning with the findings of the geographical popularity as represented in Figure 2, where South Korea was noted as being the region attracting the most interest for GNDs. It is further noted that those two regions showed a particularly high interested in the terms Green Growth, Growth, Technology and Environmental Sustainability. In the sustainability and climate change discourse, terms that gained popularity include Renewable Energy, Institutions, Management, and others. Regarding technology and innovations, terms that were seen to be attraction attention, but were not yet linked to sustainability and economic growth include housing, efficiency, innovations, and others.

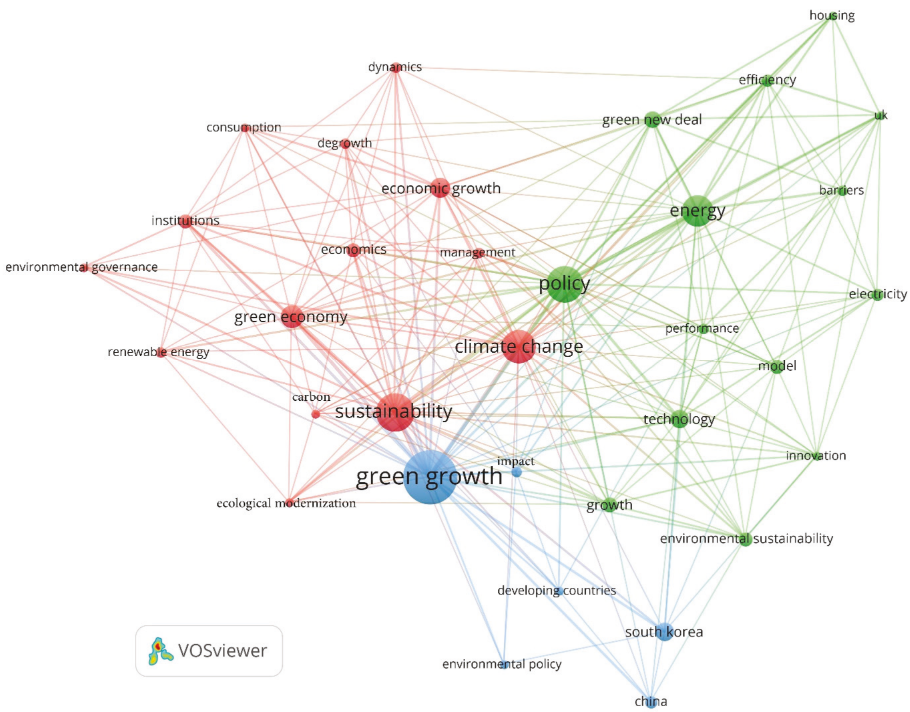


Figure 10. Analysis of terms co-occurrence from 1995 to 2014. Illustration by Authors.

From the analysis, it is not surprising that already, terms such as Climate Change, Green Growth, Sustainability, Policies and Energy were already popular and co-occurring in discourses touching the three thematic areas related to GND. Within this period, as expressed by FAS, countries such as China and South Korea were experiencing unprecedented growth, courtesy of technology and innovations that were popular in those countries. The growth in China begun in the 1970s, and by the 1990s had become a major trade destination, attracting over 445,244 foreign direct investments (FDIs) businesses in the 1990s [84]. The increase in trade was inspired by the deployment of advanced technologies in different sectors. In Korea, which is also seen to have drawn the attention of authors, as from 1995 onwards, its growth is observed to have recovered from an unprecedented decline at the beginning of the 1990s [84]. It is reported that the country had embarked on technological deployment in different sectors, and by 1996, the country had started to grow by 7.1% [85].

Growth was not only being experienced in this region alone, but other countries such as the U.S are also reported to have experienced strong growth. Such economic activities across the globe were prompted by the recovery strategies that countries had embarked on as they tried to recover from the 1990s recession [86]. As a result, coupled with ongoing environmental pressures, usage of non-renewable energy was experienced in countries such as China and the U.S. which had only 7% renewable energy with the rest coming from fossil fuel 24%, coal 23% and natural gas (23%) [87]. As a result, concerns about climate change intensified, prompting the formulation of the Kyoto Protocol that came into force in 1997 [66]. The economic growth that was being experienced prompted emergence of housing programs, especially low-cost housing in many developing regions, especially in Asia and North America; as disposal income following increase in wages started to rise [88]. Through innovations, affordable housing became the trend, and countries such as the U.S., Canada, Singapore, and others were in a rush to ensure their citizens, whose numbers were also increasing, especially in urban areas were housed [88]. However, in the course of pursuing housing projects, it is noted that concerns arise on energy efficiency and the need for the adoption of alternative clean energy. That being said, it is noted that the concept of 'green' was still not popular during this first period as showcased in the diagram (Figure 10) above.

4.6.3. Second Period (2015–2019)

During this period, as depicted in Figure 11 below, the number of terminologies increased significantly to cover emerging issues. These terms are categorized in three groups, represented by red, blue and green clusters. The red cluster captures all the terminologies directly associated with sustainability and climate change while the blue cluster is dedicated for all terminologies with greater inclination to Energy Production, Consumption, and Impacts. The green cluster encompasses terms focusing on Green Growth, as influenced by factors such as Technology, Policies and Innovations. During this period, it is evident that all the terms recorded in the first period (1995–2014) are still present here and have been reinforced by the emergence of new terms. In the red category, it is evident that new terms such as: Impacts, Cities, Power, Productivities, Transmission and others had become common, and are occurring in document focusing on all three thematic areas. Similarly, in the green cluster which was presented as the Blue cluster in the first period, in addition to the six terms that were recorded then, numerous more terms emerged during this second period. Notable new terms here include Green Economy, Europe, Renewable Energy, Emissions, Scenarios Behaviours, SDGs and others. In the Blue cluster, the number of terms that emerged were not many compared to other clusters. They include Innovation, Buildings, Retrofit and UK. This aligns with the need of not only introducing more sustainable policies for new building stock, but also to retrofit existing ones, so as to ensure a more sustainable built environment [89].

The terms Policy, Efficiency, Innovation, Green New Deal however are seen to have become slightly more popular during this period, and also highly linked with terms such as Energy, Renewable Energy, Technology, Impacts, Green Growth and others.

From the analysis, it is observed that this second period experienced major breakthroughs in the discourse on Sustainability, Equitability and Economic Growth. It is during this period that the Paris Agreement (2015), Sustainable Development Goals (SDGs) 2015, the Agenda 2030 for Sustainable Development (2015), the New Urban Agenda (2016), the Green New Deal (American model) 2019, and others were formulated, and where some are already in force. In fact, there has been numerous meetings on different agendas, especially on environment and sustainability during this period, with a large number of publications published, including notable documents such as the SDGs and the Paris Agreement. During this period still, it became apparent that the world was experiencing increasingly pressures from the (still) unprecedented challenges of climate change, impacting mostly vulnerable economies such as least developed countries (LDCs) and small island developing economies (SIDS) [4]. It is during this period also that sustainability agendas increased more with areas such as urban planning being at the forefront, with urban models such as sustainable smart city models being adopted in numerous geographies, including Songdo, South Korea [90]. Other cities include Singapore [91], Barcelona [92], and other parts of the world that have transformed, courtesy of the proliferation and ubiquity of smart technologies [93–95]. Such activities saw an increase in the academic arena with numerous co-occurring terminologies increasing and covering different aspects of Sustainability, Growth, Economy, Climate Change, Technologies and more. With the global population increasing at an average of 140 million per year since 2015 as expressed by Roser, et al. [96], substantial changes in different global sectors were observed, especially as demand for services such as energy, transport, manufactured products and other increased. These then prompted the need for policy interventions to ensure that as consumption continued, identified themes such as sustainability, Conservation, and Supply Chain Management were noted, as captured in the Paris Agreement and the New Urban Agenda (NUA) documents [82].

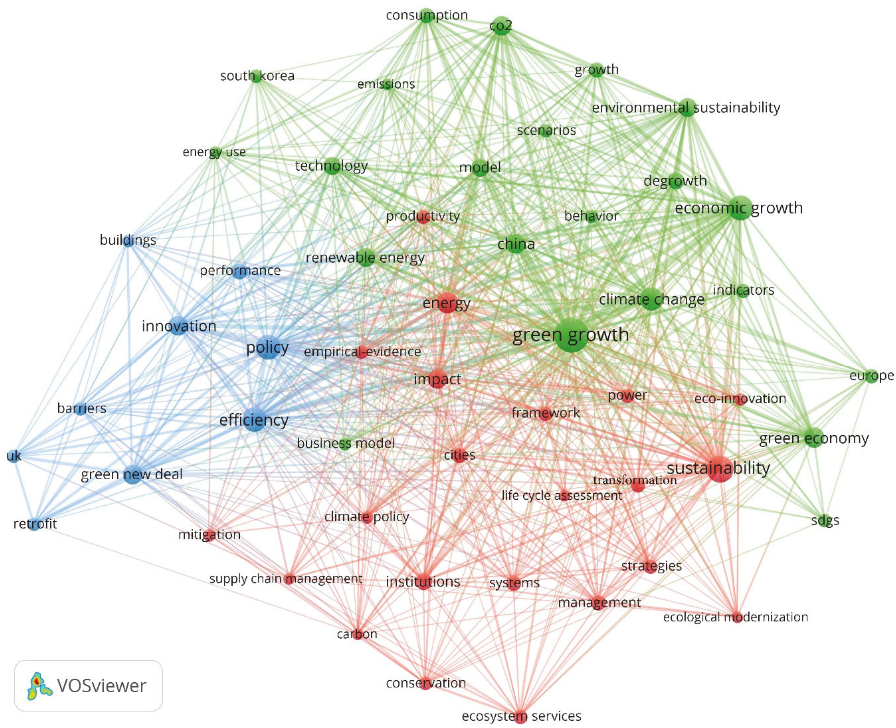


Figure 11. Analysis of terms co-occurrence from 2015 to 2019. Illustration by Authors.

4.6.4. Third Period (2020–2021)

Analysis of the period 2020–2021, as shown in Figure 12 below, further highlighted the consistency of increased terminologies shaping the discourse on GND, within the three thematic areas of sustainability and climate change categorized under the red cluster. The second thematic area is energy and renewable energies highlighted in the blue cluster, while the third thematic area categorized under the green cluster encompassing terms focusing on Green Growth, Economic Development and Technologies. The results here show that like in the previous periods (1995–2014 and 2015–2020), new terms arising from global trends emerged. These include Green Recovery, COVID-19, Agriculture, Biodiversity, Bioeconomy, Circular Economy, EU-Green Deal, Storage, Photovoltaics, Energy Transition, GHGs, LCA, Determinants, Countries, Empirical Evidence, Panel Data, Environmental Kuznets Curve and Decoupling among others. Some other terms that were common in the previous period but were no longer popular include South Korea, Behavior and Productivity.

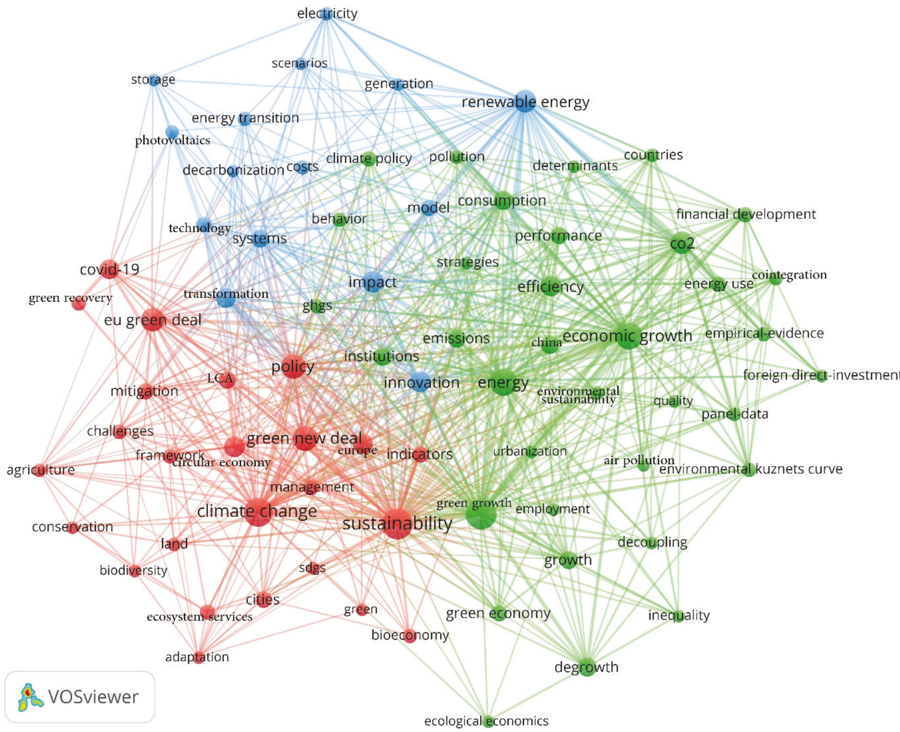


Figure 12. Analysis of terms co-occurrence from 2020 to 2021. Illustration by Authors.

From the analysis, this period portrayed mixed results for the global environment, and the discourse on sustainability, as a result of outbreak of COVID-19 early 2020 [57,60]. On the one hand, measures instituted in different countries and regions saw a reduction of activities in major sectors such as tourism, transport, manufacturing, education, hotels and hospitality industry and in retail among others, resulting into drastic reduction in emissions; by approximately 6.4% equivalent to 2.3 billion tons of CO_2 [97]. However, the pandemic also resulted into unprecedented plummeting of the global economic growth; estimated at around 3.5% by IMF [98], and more so in developed economies. Thereafter, in the third quarter of 2020, countries started to ease COVID-19 restrictions and gradually started to strategize on how to get back their economies into track, thus sparking fears that some would overlook their climate commitments and revert to the use of non-renewable energies. This may explain why terms such as Energy Transition, Decarbonization, Photovoltaic Climate Policy, GHGs, Environmental Sustainability, Panel Data and others have emerged co-concurrently with the existing ones. On this, there has been calls for economies to consider embracing renewable energies in their COVID-19 recovery plans, with solar photovoltaic being championed, especially after notable advancements in the technologies used in making solar panels and other components such as storage batteries helped reduce the prices thereof [99]. During this period also, the EU Green Deal was proposed [15], with proposals of formally adopting the circular economy concept as a means to changing the economic profile of the EU region. According to Dartford [48], this deal impacts the relationship between the EU and its trading partners, more so in respect to the sustainability aspects of raw materials and products exported from and to Europe. The bottom line during this period was for economies to emphasize on green growth, positing as a strong approach for positive impacts even for LCDs and SIDS, observed to be struggling financially due to the debt crisis exacerbated by the impacts of COVID-19 [100,101].

The focus is on implementing policy frameworks that would encourage economies to continue investing in sustainable pathways, as in renewable energy and increased use of technologies in areas such as urban planning. This, as noted by the World Bank [102] will promote a gradual economic recovery, while at the same time ensuring that the global 2030 targets for reduction in emissions are not overlooked. This, as highlighted in Figure 11, could explain why terms such as Impacts, Policies, Green Growth and Innovations are co-occurring almost at the center, showing that issues on Sustainability, Economic Growth, and Social Pursuits are gaining more popularity and co-occurring in cross-cutting in different disciplines.

5. Conclusions

This study, through the performance of a bibliometric analysis, explores the theme of Green New Deals and maps out their theoretical conceptualizations, knowledge structure, and trends across different time scales and publications. One limitation of this approach is that is caters for documents only indexed in academic milieus, in this case Web of Science, and hence omits grey literature. However, this focus on academic literature does not skew the results, as the large sample size of 1174 articles provides a robust dataset which, when analyzed, provided a deeper understanding of the evolution of the concept and can further provide researchers and policy makers with knowledge on how to better craft effective and contextually appropriate GND models. It is noted that GND adoption at a policy level is still in its infancy stage and is expected to keep gaining in popularity in the coming years, especially in view of the challenges brought about by the COVID-19 pandemic, underlining adequate and urgent economic responses aligning with national and international commitments to sustainability policies and agendas, including the Paris Agreement and the 2030 Agenda for Sustainable Development. This subject is thus expected to gain in popularity among academic circles, which will lead to further popularization and adoption. The paper further underlines that while the subject of the Green New Deal varies in interpretation, there is a strong convergence towards universally agreed principles, such as 'green growth' and 'green economy', thereby showcasing foundational precepts to the concept which can then be tailored to varied contexts in accordance with their needs and agendas. As avenues for future research, the mapping of the foundational elements of varied GND models and frameworks could be extremely interesting, and could potentially lead towards a global GND framework and application roadmap, contextualized for implementation in different economies. Finally, in view of global discussions on deep decarbonization needs at the Conference of Parties (COP) 26 at Glasgow in November 2021, aligning with the increasing need for climate financing at both local and regional levels, it could be topical to engage in metanalyses of sustainability transition models along with GND evolutions to try to map and understand what would be the most contextually appropriate GND models (accompanied with financial tools) per geographies and socio-economic groups. The topic of financing sustainability transitions will be made extremely important, and it will provide adequate research attention on this subject, rendering more effective policy outcomes aimed at accelerating much-needed sustainability transitions.

Author Contributions: Conceptualization, Z.A.; methodology, Z.A. and A.S.; validation, D.G. and S.A.S.; formal analysis and data curation, Z.A. and A.S.; writing—original draft preparation, review and editing, Z.A., A.S., D.G., and S.A.S.; supervision, D.G. and S.A.S. All authors have read and agreed to the published version of the manuscript.

Funding: This research is supported by an Australian Government Research Training Program Scholarship.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Not applicable.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Davies, R. Western Europe—Storms Case Floods in Switzerlnd, Germany and UK. Available online: https://floodlist.com/europe/storms-floods-switzerland-germany-uk-july-2021 (accessed on 10 August 2021).
2. Inman, E.N.; Hobbs, R.J.; Tsvuura, Z. No safety net in the face of climate change: The case of pastoralists in Kunene Region, Namibia. *PLoS ONE* **2020**, *15*, e0238982. [CrossRef] [PubMed]
3. Chiang, F.; Mazdiyasni, O.; AghaKouchak, A. Evidence of anthropogenic impacts on global drought frequency, duration, and intensity. *Nat. Commun.* **2021**, *12*, 2754. [CrossRef] [PubMed]
4. UNEP. *Emerging Issues for Small Island Developing States*; UNEP: Nairobi, Kenya, 2014.
5. IPCC. *The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*; Cambridge University Press: Cambridge, UK, 2021; in press.
6. Intergovernmental Panel on Climate Change. Global Warming of 1.5 °C: An IPCC Special Report on the Impacts of Global Warming of 1.5 °C Above Pre-Industrial Levels and Related Global Greenhouse Gas Emission Pathways, in the Context of Strengthening the Global Response to the Threat of Climate Change, Sustainable Development, and Efforts to Eradicate Poverty. Intergovernmental Panel on Climate Change. 2018. Available online: https://www.ipcc.ch/site/assets/uploads/sites/2/2019/05/SR15_SPM_version_report_LR.pdf (accessed on 1 September 2021).
7. UNFCCC. Nationally determined contributions under the Paris Agreement: Synthesis report by the secretariat. In Proceedings of the Conference of the Parties Serving as the Meeting of the Parties to the Paris Agreement, Glasgow, Scotland, 17 September 2021.
8. United Nations Framework Convention on Climate Change. Synthesis report on the aggregate effect of the intended nationally determined contributions. In Proceedings of the Report of the Ad Hoc Working Group on the Durban Platform for Enhanced Action, Paris, France, 30 October 2015; p. 66.
9. Shan, Y.; Ou, J.; Wang, D.; Zeng, Z.; Zhang, S.; Guan, D.; Hubacek, K. Impacts of COVID-19 and fiscal stimuli on global emissions and the Paris Agreement. *Nat. Clim. Chang.* **2021**, *11*, 200–206. [CrossRef]
10. UNEP. Are We on Track for A Green Recovery? Not Yet. Available online: https://www.unep.org/news-and-stories/press-release/are-we-track-green-recovery-not-yet (accessed on 20 September 2021).
11. United Nations Development Programme (UNDP). *Sustainable Development Goals*; UNDP: Geneva, Switzerland, 2015; p. 24.
12. Le Quéré, C.; Peters, G.P.; Friedlingstein, P.; Andrew, R.M.; Canadell, J.G.; Davis, S.J.; Jackson, R.B.; Jones, M.W. Fossil CO_2 emissions in the post-COVID-19 era. *Nat. Clim. Chang.* **2021**, *11*, 197–199. [CrossRef]
13. The European Commisision. *Circular Economy Action Plan: For a Cleaner and More Competitive Europe*; European Union: Luxembourg, 2020; p. 28.
14. Congress. 116th Congress 1st Session: H. RES. 109. 2019. Available online: https://www.congress.gov/bill/116th-congress/house-resolution/109 (accessed on 1 September 2021).
15. European Commission. The European Green Deal: Questions & Answers. Available online: https://ec.europa.eu/commission/presscorner/detail/en/QANDA_19_6690 (accessed on 23 February 2021).
16. Conte, N. Green New Deal. Available online: https://wtpartnership.co/green-new-deal/ (accessed on 24 February 2021).
17. UN. Green Economy. Available online: https://sustainabledevelopment.un.org/index.php?menu=1446 (accessed on 2 September 2021).
18. Mastini, R.; Kallis, G.; Hickel, J. A Green New Deal without growth? *Ecol. Econ.* **2021**, *179*, 106832. [CrossRef]
19. Dercon, S. Is Green Growth Good for the Poor? University of Oxford: Oxford, UK, 2011.
20. Daniels, R.; Franklin, D. *Roosevelt: Road to the New Deal, 1882–1939*; University of Illinois Press: Illinois, IL, USA, 2018.
21. Atkin, E. The Democrats Stole the Green Party's Best Idea. Available online: https://newrepublic.com/article/153127/democrats-stole-green-partys-best-idea (accessed on 23 February 2021).
22. Bloomfield, J.; Steward, F. The Politics of the Green New Deal. *Political Q.* **2020**, *91*, 770–779. [CrossRef]
23. Google Trends. Green New Deal: 2004 to 2021. Available online: https://trends.google.com/trends/explore?date=all_2008&gprop=news&q=%27green%20new%20deal%27 (accessed on 29 August 2021).
24. Google Trends. Green New Deal. Available online: https://trends.google.com/trends/explore?date=all_2008&gprop=images&q=green%20new%20deal (accessed on 29 August 2021).
25. Donato, D. The Green New Deal and China's Green Revolution. Available online: https://www.peoplesworld.org/article/the-green-new-deal-and-chinas-green-revolution/ (accessed on 25 August 2021).
26. Chatzky, A.; Siripurapu, A. Envisioning a Green New Deal: A Global Comparison. Available online: https://www.cfr.org/backgrounder/envisioning-green-new-deal-global-comparison (accessed on 25 August 2021).
27. MacArthur, J.L.; Hoicka, C.E.; Castleden, H.; Das, R.; Lieu, J. Canada's Green New Deal: Forging the socio-political foundations of climate resilient infrastructure? *Energy Res. Soc. Sci.* **2020**, *65*, 101442. [CrossRef]
28. London Assembly. A Green New Deal. Available online: https://www.london.gov.uk/coronavirus/londons-recovery-coronavirus-crisis/recovery-context/green-new-deal (accessed on 25 August 2021).
29. Chowdhury, S. South Korea's Green New Dealinthe year of transition. Available online: https://www.undp.org/blogs/south-koreas-green-new-deal-year-transition (accessed on 24 August 2021).
30. Paszak, P. The Chinese Vision of the Green Deal. Available online: https://ec.europa.eu/clima/sites/default/files/international/cooperation/china/docs/zhong_ou_he_zuo_yan_jiu_bao_gao_-20201128_en.pdf (accessed on 24 August 2021).
31. Moreno-Brid, J.C.; Gallagher, K. Mexico's Road to a Green New Deal. *NACLA Rep. Am.* **2020**, *52*, 152–157. [CrossRef]

32. Government of Singapore. Introducing the Green Plan. Available online: https://www.greenplan.gov.sg/key-focus-areas/overview (accessed on 28 August 2021).
33. Gunia, A. Could the World's Largest Green Energy Hub Redefine How Companies Work with Indigenous People? Available online: https://time.com/6080182/australia-green-energy-aboriginal-people/ (accessed on 22 September 2021).
34. Visentin, L. 'Massive Green Deal': NSW Environment Minister Spruiks $2 Billion Energy Package. Available online: https://www.smh.com.au/politics/nsw/massive-green-deal-nsw-environment-minister-spruiks-2-billion-energy-package-20200131-p53wgg.html (accessed on 20 September 2021).
35. The Climate Mobilization. About. Available online: https://www.theclimatemobilization.org/about/ (accessed on 25 August 2021).
36. Green Party. The Green New Deal. Available online: https://www.gp.org/green_new_deal (accessed on 23 August 2021).
37. The Greens/EFA. The Green New Deal: More than a Policy, a Programme for Living. Available online: https://www.greens-efa.eu/en/article/document/the-green-new-deal (accessed on 23 August 2021).
38. DiEM25. The Green New Deal for Europe. Available online: https://diem25.org/campaign/green-new-deal/ (accessed on 23 August 2021).
39. Green Party of the United States. The Green New Deal. Available online: https://gpus.org/organizing-tools/the-green-new-deal/ (accessed on 25 August 2021).
40. French, H.; Renner, M.; Gardner, G. *Toward a Transatlantic Green New Deal: Tackling the Climate and Economic Crises*; Heinrich-Böll-Stiftung: Brussels, Belgium, 2009; Volume 3.
41. League of Conservation Voters (LCV). LCV Supports Green New Deal Resolution. Available online: https://www.lcv.org/article/lcv-supports-green-new-deal-resolution/ (accessed on 22 August 2021).
42. New Economics Foundation. Green New Deal: Cutting Carbon Emissions, Boosting Nature and Creating Good Jobs. Available online: https://neweconomics.org/about/our-missions/green-new-deal (accessed on 23 August 2021).
43. Robinson, E. How are We Doing on a Green New Deal? Available online: https://www.opendemocracy.net/en/transformation/how-are-we-doing-on-green-new-deal/ (accessed on 24 August 2021).
44. UNEP. Global Green New Deal: An Update for the G20 Pittsburgh Summit. Available online: https://wedocs.unep.org/rest/bitstreams/11748/retrieve#:~{}:text=In%20response%20to%20the%20financial,change%2C%20environmental%20degradation%20and%20poverty. (accessed on 25 August 2021).
45. Saha, S.; Subramanian, N.; Menzelos, A. Memo: A Green Marshall Plan—America's Global Climate Compact. Available online: https://www.dataforprogress.org/memos/green-marshall-plan (accessed on 24 August 2021).
46. Ministry of Environment. Green New Deal to Drive Green Recovery in Asia-Pacific Region. Available online: http://eng.me.go.kr/eng/web/board/read.do?pagerOffset=0&maxPageItems=10&maxIndexPages=10&searchKey=&searchValue=&menuId=461&orgCd=&boardId=1415460&boardMasterId=522&boardCategoryId=&decorator= (accessed on 25 August 2021).
47. Bradshaw, C.J.A.; Ehrlich, P.R.; Beattie, A.; Ceballos, G.; Crist, E.; Diamond, J.; Dirzo, R.; Ehrlich, A.H.; Harte, J.; Harte, M.E.; et al. Underestimating the Challenges of Avoiding a Ghastly Future. *Front. Conserv. Sci.* **2021**, *1*, 1–10. [CrossRef]
48. Dartford, K. How can the European Green Deal Avoid "Potential Frictions" with Other Countries? Available online: https://www.euronews.com/green/2021/02/03/how-can-the-european-green-deal-avoid-potential-frictions-with-other-countries (accessed on 28 August 2020).
49. Táíwò, O.m.O. How a Green New Deal Could Exploit Developing Countries. Available online: https://theconversation.com/how-a-green-new-deal-could-exploit-developing-countries-111726 (accessed on 26 August 2021).
50. Doreen, E.M. The Right to Be Free of Fear: Indigeneity and the United Nations. *Wicazo Sa Rev.* **2014**, *29*, 63–87. [CrossRef]
51. Allam, Z.; Jones, D.S. Attracting investment by introducing the city as a special economic zone: A perspective from Mauritius. *Urban Res. Pract.* **2019**, *12*, 201–207. [CrossRef]
52. Allam, Z.; Jones, D.; Thondoo, M. Climate Change Mitigation and Urban Liveability. In *Cities and Climate Change: Climate Policy, Economic Resilience and Urban Sustainability*; Allam, Z., Jones, D., Thondoo, M., Eds.; Springer International Publishing: Cham, Switzerland, 2020; pp. 55–81.
53. Allam, Z.; Jones, D. Climate Change and Economic Resilience through Urban and Cultural Heritage: The Case of Emerging Small Island Developing States Economies. *Economies* **2019**, *7*, 62. [CrossRef]
54. Allam, Z.; Jones, D.; Thondoo, M. *Cities and Climate Change: Climate Policy, Economic Resilience and Urban Sustainability*; Springer International Publishing: Cham, Switzerland, 2020.
55. Chohan, U. A Green New Deal: Discursive Review and Appraisal. SSRN Electron. J. 2019. Available online: https://www.vosviewer.com/documentation/Manual_VOSviewer_1.6.10.pdf (accessed on 1 September 2021).
56. Allam, Z.; Jones, D.; Thondoo, M. Economically Incentivizing Urban Sustainability and Resilience. In *Cities and Climate Change: Climate Policy, Economic Resilience and Urban Sustainability*; Allam, Z., Jones, D., Thondoo, M., Eds.; Springer International Publishing: Cham, Switzerland, 2020; pp. 83–106.
57. Allam, Z. *Surveying the Covid-19 Pandemic and Its Implications: Urban Health, Data Technology and Political Economy*; Elsevier Science: Amsterdam, The Netherlands, 2020.
58. Van Eck, N.J.; Waltman, L. VOSviewer manual. *Leiden: Univeristeit Leiden* **2013**, *1*, 1–53.
59. Hartman, H. Milestones in Environmental Protection. Available online: https://www.infoplease.com/math-science/earth-environment/milestones-in-environmental-protection (accessed on 1 September 2021).

60. Allam, Z. Chapter 7—Vital COVID-19 Economic Stimulus Packages Pose a Challenge for Long-Term Environmental Sustainability. In *Surveying the Covid-19 Pandemic and its Implications*; Allam, Z., Ed.; Elsevier: Amsterdam, The Netherlands, 2020; pp. 97–105.
61. Allam, Z.; Jones, D.S. Pandemic stricken cities on lockdown. Where are our planning and design professionals [now, then and into the future]? *Land Use Policy* **2020**, *97*, 104805. [CrossRef] [PubMed]
62. European Environment Agency (EEA). Renewable Energy in Europe: Key for Clilmate Objectives, but Air Pollution Needs Attention. Available online: https://www.eea.europa.eu/themes/energy/renewable-energy/renewable-energy-in-europe-key (accessed on 26 August 2021).
63. Bubbico, R.L.; Freytag, L. *Inequality in Europe*; European Investment Bank: Luxembourg, 2018; pp. 1–50.
64. Fridays For Future. Who we Are. Available online: https://fridaysforfuture.org/what-we-do/who-we-are/ (accessed on 23 February 2021).
65. Frank, M.R.; Sun, L.; Cebrian, M.; Youn, H.; Rahwan, I. Small cities face greater impact from automation. *J. R. Soc. Interface* **2018**, *15*, 20170946. [CrossRef]
66. United Nations Framework Convention on Climate Change. Kyoto Protocol to the United Nations Framework Conventon on Climate Change. Available online: https://unfccc.int/resource/docs/convkp/kpeng.pdf (accessed on 8 August 2021).
67. United Nations Framework Convention on Climate Change. Paris Agreement. Available online: https://unfccc.int/sites/default/files/english_paris_agreement.pdf (accessed on 8 August 2021).
68. UNFCCC. Vulnerability and Adaptation to Climate Change in Small Island Developing States. Available online: https://unfccc.int/files/adaptation/adverse_effects_and_response_measures_art_48/application/pdf/200702_sids_adaptation_bg.pdf (accessed on 8 August 2021).
69. Intergovernmental Panel on Climate Change. *Impacts, Adaptation, and Vulnerability. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*; IPCC: Cambridge, UK; New York, NY, USA, 2014.
70. Dowson, M.; Poole, A.; Harrison, D.; Susman, G. Domestic UK retrofit challenge: Barriers, incentives and current performance leading into the Green Deal. *Energy Policy* **2012**, *50*, 294–305. [CrossRef]
71. European Commission. *Communication from the Commission tothe European Parliament, the European Council, the Council, The European Economic and Social Committee and the Committee of the Regions*; European Commission: Brussels, Belgium, 2019; pp. 1–24.
72. UNEP. *Towards a Green Economy: Pathways to Sustainable Development and Poverty Eradication*; UNEP: Nairobi, Kenya, 2011.
73. Fay, M. *Inclusive Green Growth: The Pathway to Sustainable Development*; World Bank Publications: Washington DC, USA, 2012.
74. Beltramello, A.; Haie-Fayle, L.; Pilat, D. *Why New Business Models Matter for Green Growth*; OECD Publishing: Paris, France, 2013.
75. Meseguer-Sánchez, V.; Gálvez-Sánchez, F.J.; López-Martínez, G.; Molina-Moreno, V. Corporate Social Responsibility and Sustainability. A Bibliometric Analysis of Their Interrelations. *Sustainability* **2021**, *13*, 1636. [CrossRef]
76. Steffen, W.; Richardson, K.; Rockström, J.; Cornell, S.E.; Fetzer, I.; Bennett, E.M.; Biggs, R.; Carpenter, S.R.; de Vries, W.; de Wit, C.A.; et al. Planetary boundaries: Guiding human development on a changing planet. *Science* **2015**, *347*, 1259855. [CrossRef] [PubMed]
77. Guo, L.l.; Qu, Y.; Tseng, M.-L. The interaction effects of environmental regulation and technological innovation on regional green growth performance. *J. Clean. Prod.* **2017**, *162*, 894–902. [CrossRef]
78. Stahel, W.R. The circular economy. *Nature* **2016**, *531*, 435–438. [CrossRef]
79. Di Bartolo, A.; Infurna, G.; Dintcheva, N.T. A Review of Bioplastics and Their Adoption in the Circular Economy. *Polymers* **2021**, *13*, 1229. [CrossRef] [PubMed]
80. Meseguer-Sánchez, V.; Gálvez-Sánchez, F.J.; Molina-Moreno, V.; Wandosell-Fernández-de-Bobadilla, G. The Main Research Characteristics of the Development of the Concept of the Circular Economy Concept: A Global Analysis and the Future Agenda. *Front. Environ. Sci.* **2021**, *9*, 1–16. [CrossRef]
81. United Nations Framework Convention on Climate Change. Documents of the Conference of the Parties COP1 Berlin 1995 (COP1). Available online: https://unfccc.int/cop4/resource/cop1.html (accessed on 8 August 2021).
82. United Nations. *New Urban Agenda*; Habitat III: Nairobi, Kenya, 2017; pp. 1–66.
83. United Nations. *Transforming our World: The 2030 Agenda for Sustainable Development*; A/RES/70/1; Sustainable Development Branch, UN: New York, NY, USA, 2011.
84. Congressional Research Service. *China's Economic Rise: History, Trends, Challenges, and Implications for the United States*; CRS Report: Washington, DC, USA, 2019.
85. Nam, C.W. What Happened to Korea Ten Years Ago? *CESifo* **2008**, *9*, 69–73.
86. Brian, K.; Patrick, L. *OECD Insights from Crisis to Recovery the Causes, Course and Consequences of the Great Recession: The Causes, Course and Consequences of the Great Recession*; OECD Publishing: Paris, France, 2010.
87. Joskow, P.L. U.S. Energy Policy During the 1990s. Available online: https://economics.mit.edu/files/1144 (accessed on 25 August 2021).
88. Evans, D. The History and Evolution of the Affordable Housing Design Advisor: Bringing the Power of Design to Affordable Housing. *Cityscape* **2014**, *16*, 87–102.
89. Pardalis, G.; Mahapatra, K.; Mainali, B. A triple-layered one-stop-shop business model canvas for sustainable house renovations. *IOP Conf. Ser. Earth Environ. Sci.* **2020**, *588*, 022060. [CrossRef]
90. Kolotouchkina, O.; Seisdedos, G. Place branding strategies in the context of new smart cities: Songdo IBD, Masdar and Skolkovo. *Place Branding Public Dipl.* **2017**, *14*, 115–124. [CrossRef]

91. Rohaidi, N. Singapore Wins Smart City of 2018 Award. Available online: https://govinsider.asia/smart-gov/singapore-wins-smart-city-of-2018-award/ (accessed on 5 March 2019).
92. Gascó-Hernandez, M. Building a Smart City: Lessons from Barcelona. *Commun. ACM* **2018**, *61*, 50–57. [CrossRef]
93. Samad, M.E.S.; Hawken, S.; Sargolzaei, S.; Foroozanfa, M. Implementing citizen centric technology in developing smart cities: A model for predicting the acceptance of urban technologies. *Technol. Forecast. Soc. Chang.* **2019**, *142*, 105–116. [CrossRef]
94. Chamoso, P.; Gonzalez-Briones, A.; Rodríguez, S.; Corchado, J.M. Tendencies of Technologies and Platforms in Smart Cities: A State-of-the-Art Review. *Wirel. Commun. Mob. Comput.* **2018**, *2018*, 3086854. [CrossRef]
95. To, W.-M.; Lee, P.K.C.; Lam, K.-H. Building professionals' intention to use smart and sustainable building technologies—An empirical study. *PLoS ONE* **2018**, *13*, e0201625. [CrossRef]
96. Roser, M.; Ritchie, H.; Ortiz-Ospina, E. World Population Growth. Available online: https://ourworldindata.org/world-population-growth#citation (accessed on 26 August 2021).
97. Tollefson, J. COVID-19 curbed carbon emissions in 2020—Not by much. *Nature* **2021**, *589*, 343. [CrossRef] [PubMed]
98. Gopinath, G. World Economic Outlook Update: Policy Support and Vaccines Expected to Lift Activity. Available online: https://www.imf.org/en/Publications/WEO/Issues/2021/01/26/2021-world-economic-outlook-update (accessed on 13 June 2021).
99. Marcacci, S. Renewable Energy Prices Hit Record Lows: How Can Utilities Benefit from Unstoppable Solar and Wind? Available online: https://www.forbes.com/sites/energyinnovation/2020/01/21/renewable-energy-prices-hit-record-lows-how-can-utilities-benefit-from-unstoppable-solar-and-wind/?sh=29a8522d2c84 (accessed on 23 February 2021).
100. United Nations. Small Island Developing States Call for Enhanced Support for a Resilient Post COVID-19 Recovery. Available online: https://www.un.org/ohrlls/news/small-island-developing-states-call-enhanced-support-resilient-post-covid-19-recovery (accessed on 7 August 2021).
101. Allam, Z. Chapter 9—Oil, Health Equipment, and Trade: Revisiting Political Economy and International Relations During the COVID-19 Pandemic. In *Surveying the Covid-19 Pandemic and its Implications*; Allam, Z., Ed.; Elsevier: Amsterdam, The Netherlands, 2020; pp. 119–127.
102. World Bank. COVID-19 to Plunge Global Economy into Worst Recession Since World War II. Available online: https://www.worldbank.org/en/news/press-release/2020/06/08/covid-19-to-plunge-global-economy-into-worst-recession-since-world-war-ii (accessed on 15 April 2021).

sustainability

MDPI

Article

#ProtectNature—How Characteristics of Nature Conservation Posts Impact User Engagement on Facebook and Twitter

Annika Miller * and Stefan Heiland

Chair of Landscape Planning and Development, Technische Universität Berlin, 10623 Berlin, Germany; stefan.heiland@tu-berlin.de
* Correspondence: annika@millers1.com

Abstract: Social networks expand the communication tools of nature conservation. Nonetheless, to date there is hardly any scientific literature on nature conservation communication in social networks. For this reason, this paper examines 600 Facebook and Twitter posts of three German nature conservation organizations: Federal Agency for the Conservation of Nature (Bundesamt für Naturschutz, BfN), Naturschutzbund Deutschland e. V. (NABU), and World Wide Fund for Nature (WWF) Germany. Using the Mann–Whitney U method and Spearman's rank correlation analysis, it reveals how post design affects communication success and provides respective recommendations for German conservation organizations. Communication success was divided into four indicators: reactions, comments, shares, and overall engagement as a synthesis of the three. On Facebook, the use of hashtags, images, and many characters (up to 1500) leads to higher success, whereas emojis and videos can reduce it. On Twitter, links, images, and longer posts promote user interactions. Emojis have a positive influence on comments and overall engagement, but a negative influence on reactions and shares. In addition, hashtags reduce overall engagement on Twitter. These results are discussed with reference to similar studies from other political fields in order to provide recommendations for conservation organizations. A validation and expansion of the presented results is recommended due to the growing relevance of digital nature conservation communication.

Keywords: nature conservation; social media; social networks; conservation communication; user engagement; Facebook; Twitter

Citation: Miller, A.; Heiland, S. #ProtectNature—How Characteristics of Nature Conservation Posts Impact User Engagement on Facebook and Twitter. *Sustainability* **2021**, *13*, 12768. https://doi.org/10.3390/su132212768

Academic Editors: Baojie He, Ayyoob Sharifi, Chi Feng and Jun Yang

Received: 19 September 2021
Accepted: 15 November 2021
Published: 18 November 2021

1. Introduction

It is only through communication that nature conservation issues gain social relevance and acceptance. Accordingly, communication processes play a crucial role in nature conservation [1–3]. Since the beginning of the 1990s, the World Wide Web has supplemented the written communication tools of society and thus of nature conservation. As it offers a wide range of new opportunities for obtaining information, participating, interacting, and forming opinions, it quickly developed into a catalyst for a change in the way society communicates—including nature and environmental conservation actors [4,5]. A few years later, Facebook (2004) and Twitter (2006) followed. Nowadays, many nature conservation organizations around the world use social networks for their public relations work.

While various definitions for "social networks" can be found in scientific literature, we use the term as follows:

Social networks refer to Internet-based services that allow users to create a personal profile and define a list of other users with whom they share a connection. This may be based on existing social contacts or on other commonalities such as interests, views, or goals. Various functions are used to share information and media content and otherwise interact among users of the network (cf. [6,7]).

The terms "social media" and "social networks" are often used synonymously in public discourse. Yet their meanings differ, with social media being a blanket term for social networks, blogs, wikis, photo and video platforms, and many other Internet-based services that allow the creation and exchange of user-generated content [8].

Organizations active in environmental, nature, and climate protection (due to the focus of this paper, hereafter collectively and somewhat oversimplified referred to as conservation organizations) can use social networks to, among other things, initiate and lead interactive conservation debates [5], inform the public [9], recruit members [10,11], raise public awareness [12], or communicate research findings [13]. Consequently, almost all conservation organizations are now active on social networks and thereby offer interactive opportunities for communication and engagement [5,14]. Well-known examples include the #LastSelfie species conservation campaign [15] and the #EndangeredEmoji campaign of the World Wide Fund for Nature (WWF) [16].

This brief introduction clearly shows why nature conservation organizations (should) increasingly concern themselves with elevating their digital media competence. Already in 2005, Kolf et al. [17] named communication via the Internet as a standard component of good nature and environmental protection practice. Various publications show the range of ways social media can be used for conservation communication and as a data source (e.g., [18,19]) and discuss their influence on society's understanding of nature and the commercialization of the natural environment (e.g., [5,20]).

A look beyond nature conservation shows that the marketing industry has also been concerned with successful communication in social networks for some time now; social media marketing has developed into an independent and recognized marketing discipline ([21]). In this context, special methods and instruments are needed to assess communication success [22]. For this reason, so-called social media analytics are increasingly used in business circles to collect and analyze data from social media [23,24]. The aim of these procedures is to gain insights into user behavior and preferences, the course of interactions, contact networks, and above all one's own communication success (cf. [22]). Social media analytics are primarily used to analyze the design of corporate posts, as this is one of the key success factors in social media marketing [21,22].

However, these methods have yet to be fully harnessed for nature conservation communication, as the lack of research and literature on the effective design of conservation posts in social networks shows [12]. The intent of this article is therefore to provide explorative insights into how the design of nature conservation posts on Facebook and Twitter influences their communication success. In this context, we aim to confirm or reject the following hypothesis:

Communication success on Facebook and Twitter is influenced by the utilization of design characteristics commonly found in posts, such as hashtags, links, emojis, images, videos, interaction prompts, and post length.

2. Materials and Methods

During the sampling process, conservation organizations were selected based on the following criteria:

- They are associated with nature conservation by the German public.
- They are based in Germany.
- They have Facebook and Twitter profiles with at least 3000 followers.
- They predominantly communicate in German on social networks.
- Their organizational and thematic diversity ensure that the study is relevant for different types of nature conservation organizations.

Based on these criteria, the German Federal Agency for Nature Conservation (Bundesamt für Naturschutz, BfN), Naturschutzbund Deutschland e. V. (NABU, one of the biggest conservation NGOs in Germany), and World Wide Fund for Nature Germany (WWF) were chosen for our study. Table 1 shows some of their characteristics and differences.

Table 1. Overview: BfN, NABU, and WWF Germany database: [25–34].

Property	BfN	NABU	WWF Germany
Legal status	German government's scientific authority	State-recognized environmental and nature conservation organization	Non-profit foundation
Decision-making structure	Top-down	Primarily B=bottom-up	Top-down
Main sources of funding	Public funding	Membership fees, donations, public subsidies	Membership fees, donations, public subsidies, business cooperations
Employees	390	244	338
Facebook followers (July 2020)	6013	138,600	403,161
Twitter followers (July 2020)	3697	136,800	483,100

The social networks Facebook and Twitter were selected because they are the most widely used social networks in Germany with a focus on text-based communication. Facebook is used by over 258 million users per week in Germany, and Twitter by 33 million (as of 2019, [35]).

We examined 100 posts from each organization on Facebook and Twitter, resulting in a total sample of 600 posts (see Supplementary A). Only posts that were originally created by the conservation organizations (i.e., not posts shared by them) were taken into account. Additionally, sponsored posts were excluded. The data collection took place from 31 July to 7 August 2020. The last 100 posts by each organization on Facebook and Twitter from before 30 June 2020 were examined. Thus, posts from July 2020 were ignored, as the likelihood of higher attention and dissemination through likes, shares, etc. of older posts rises with their longer display time on the users' wall (Facebook) or timeline (Twitter). By analyzing posts that were at least one month old, we minimized such effects and could assume that the number of reactions, comments, and shares were (approximately) the final values (cf. [36,37]).

The posts were analyzed with respect to seven independent variables (see Table 2). Their selection was based on existing studies on post design in social networks (cf. [6,12,22,38–41].

Table 2. Independent variables used to examine posts.

Independent Variable	Scaling	Remarks
Hashtag	Categorical (yes/no)	–
Link	Categorical (yes/no)	Both platform-internal and external links
Emoji	Categorical (yes/no)	–
Image	Categorical (yes/no)	–
Video	Categorical (yes/no)	Only directly playable videos or GIFs counted
Interaction prompt	Categorical (yes/no)	Questions for users in post text or video and explicit invitations to comment; no rhetorical questions
Character count	Metric	Characters in images and videos as well as emojis and links were not counted.

Various dependent variables are used to evaluate communication success. We consider posts to be successful if they advance the following communication goals on social networks: sensitization, information, and motivation of users [42]. However, the sensitization, information uptake, and motivation gains that conservation posts actually achieve and other potentially desirable effects like increased donations could not be sufficiently determined within the scope of this study. Therefore, indicators for the (potential) communication success were developed for the three communication goals.

The basic prerequisite for achieving the aforementioned goals is to reach the addressees with the respective message and to encourage them to actively engage with the content of the post [6]. However, it should be noted that we do not know how many users actually saw a post. We can only count their interactions with it. These desirable interactions of the users with a post we refer to as "user engagement" (in a deviation from the everyday understanding of the word) [22].

Based on Ahrholdt et al. (2019) [22], engagement is measured through four indicators, with the fourth serving as an overarching, summarizing indicator in case reactions, comments and shares are of equal interest to a conservation actor:

- Reactions—users perceive the post and acknowledge it with an emoji reaction (Facebook) or a Like (Twitter).
- Comments—the post incites users to comment.
- Shares—users disseminate the post further.
- Overall Engagement—the post is acknowledged, inspires comments, and is further distributed.

When evaluating the communication success of BfN, NABU, and WWF Germany, it had to be considered that their profile pages had different numbers of followers (see Table 1). As a result, the posts by WWF Germany were displayed to significantly more users, which presumably resulted in more overall interactions (cf. [22]). Since the posts of the three organizations were analyzed together and the sample was only subdivided according to the social networks, this would have distorted the statistical results. To avoid this, for each individual post the number of interactions was therefore set in relation to the number of followers of the respective organization (cf. [22,41,43]).

According to Ahrholdt et al. (2019) [22], this results in the following formulas for calculating the success indicators for every post:

$$\text{Reactions (\%)} = (\text{\# Reactions})/(\text{\# Followers}) \times 100 \tag{1}$$

$$\text{Comments (\%)} = (\text{\# Comments})/(\text{\# Followers}) \times 100 \tag{2}$$

$$\text{Shares (\%)} = (\text{\# Shares})/(\text{\# Followers}) \times 100 \tag{3}$$

$$\text{Overall Engagement (\%)} = (\text{\# Reactions} + \text{\# Comments} + \text{\# Shares})/(\text{\# Followers}) \times 100 \tag{4}$$

To assess the influence of the post design on the communication success, two methods of inductive statistics were applied using the program R (see Supplementary B):

(1) The Mann–Whitney U test can be used to test whether categorical independent variables with two factor levels (yes/no) have a significant impact on a metric dependent variable [44]. Accordingly, the Mann–Whitney U test was used for the independent variables hashtag, link, emoji, image, video, and interaction.

(2) The influence of the metric independent variable of character count on communication success was tested using Spearman's rank correlation analysis (cf. [12]). It is used to test the linear relationship between two metric variables. We interpreted the resulting Rho values in terms of effect strength according to Cohen (1992) [45] as follows:

- Absolute value of Rho $\geq$ 0.10—weak effect
- Absolute value of Rho $\geq$ 0.30—medium effect
- Absolute value of Rho $\geq$ 0.50—strong effect

Throughout the following sections, in order to place our results in a larger context, we refer to existing findings on success factors of posts on social media in areas other than conservation, since our survey is the first so far to focus on conservation. Therefore, similarities between the results can not be expected per se, nor can direct comparisons be drawn. Nevertheless, it rounds off the picture with previous findings on the subject and at the same time shows that there is a need for further research to gain more representative knowledge.

3. Results

3.1. Descriptive Results

What follows is a descriptive insight into the collected data, i.e., the design of the conservation posts and the user engagement achieved. The results of the descriptive statistical analysis (see Table 3) show, above all, that the Facebook posts achieved higher mean values in all four success indicators than the Twitter posts. On both platforms, the average reaction values were higher than the comment and share values obtained. In addition, users preferred to share posts rather than comment on them. Table 3 also shows how often the conservation organizations used the examined design elements (hashtags, links, etc.) in their posts on Facebook and Twitter. It is noticeable that many posts contained links (91%), emojis (52%), and images (78%). Hashtags were also used frequently on Twitter—but less so on Facebook. Both videos and interaction prompts were present in less than 15% of posts. On Facebook, the conservation organizations published posts with an average length of around 385 characters. The shortest posts contained no text at all, only images or videos. The longest post was over 2000 characters. However, this was an outlier; the second longest post had just about 1500 characters. Consequently, all of the following statistical results and recommendations for action regarding post length on Facebook only apply to the actual character span of 1500 characters that was examined. Posts by conservation organizations on Twitter were much shorter than on Facebook, averaging around 196 out of 280 possible characters. The shortest Twitter post contained 16 characters, the longest 251, with more than half of the posts being published between 12 and 5 p.m. on both platforms. There were no posts before 7:30 a.m. on either Facebook or Twitter, and only rarely after 8 p.m.

Table 3. Descriptive results for all independent and dependent variables.

Platform	Variable	Mean Value	Standard Deviation	Min.	Max.
Facebook (*n* = 300)	Hashtag	0.28	0.45	0	1
	Link	0.88	0.326	0	1
	Emoji	0.6	0.491	0	1
	Image	0.85	0.358	0	1
	Video	0.147	0.354	0	1
	Interaction prompt	0.07	0.256	0	1
	Character count	384.8	296.1	0	2012
	Reactions	0.417	0.479	0.005	4.424
	Comments	0.069	0.342	0.000	5.605
	Shares	0.151	0.399	0.000	5.240
	Overall Engagement	0.638	1.106	0.006	15.670
Twitter (*n* = 300)	Hashtag	0.747	0.436	0	1
	Link	0.937	0.244	0	1
	Emoji	0.443	0.498	0	1
	Image	0.71	0.455	0	1
	Video	0.043	0.204	0	1
	Interaction prompt	0.013	0.115	0	1
	Character count	195.9	37.97	16	251
	Reactions	0.139	0.263	0.001	1.975
	Comments	0.005	0.014	0.000	0.135
	Shares	0.071	0.141	0.000	0.893
	Overall Engagement	0.025	0.036	0.000	0.317

3.2. Influence of the Post Design on the Communication Success

On Facebook, hashtags, images, and the use of many characters positively influenced communication success (see Table 4). On Twitter, links, images, and longer posts led to more user interactions. Moreover, emojis had a positive influence on commenting and overall engagement on Twitter. Conversely, emojis and videos had a negative statistical impact on several success indicators on Facebook. Emojis also had a negative impact on Twitter reactions and shares. Additionally, hashtags reduced overall engagement on Twitter.

Table 4. Post characteristics with positive (blue) or negative (red) impact on user interactions (results for empty cells are non-significant, significance levels: * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$, see Supplementary C for detailed analysis results). FB = Facebook; Tw = Twitter.

	Reactions		Comments		Shares		Overall Engagement	
	FB	Tw	FB	Tw	FB	Tw	FB	Tw
Hashtag	*				*			***
Link		***				***		
Emoji	***	*		*		*	***	***
Image	*	***	**	***		***	*	*
Video	*		**				*	
Interaction prompt								
High character count	*** [1]	*** [1]	** [2]		*** [1]	*** [1]	*** [1]	*** [1]

[1] Medium effect (absolute value of Rho ≥ 0.30) according to Cohen (1992) [45]; [2] weak effect (absolute value of Rho ≥ 0.10) according to Cohen (1992) [45].

4. Discussion

In the following, we discuss—separately for the four engagement indicators—the results as well as the possible reasons for them in more detail. We also place them in the context of already existing research. Finally, we derive design recommendations for conservation posts on Facebook and Twitter (see Section 4.5) and discuss methodology and future research needs (see Section 4.6). In each subsection, we address the seven independent variables in the same order as in Tables 2 and 4: hashtag, link, emoji, image, video, interaction prompt, and high character count.

4.1. Reactions

(a) Hashtags: On Facebook, conservation posts generated more reactions if they contained at least one hashtag, a result that has also been found for posts by local governments in Greece [39]. This is presumably because hashtags put posts in a broader thematic context (cf. [22]). This allows users to find relevant posts on a certain subject via the search function—even if the posts were not displayed on their own wall or timeline. On Twitter, hashtags had no impact on the reaction count.

(b) Links: While links on Facebook did not have an impact on reactions, they led to more likes on Twitter. We cannot explain this difference, especially since Pianosi's (2017) [6] study showed that conservation posts from De Montfort University received more likes when they did not contain a link. Conservation posts with links may have gotten more likes on Twitter because links make posts more memorable and can trigger emotions (cf. [46]). To verify this assumption and especially the differences shown, future studies could investigate what content the conservation organizations link to in their posts and whether the sentiment of user responses and comments are related to it. We hypothesize that culture-related issues or different target groups might play a role.

(c) Emojis had a negative influence on the reaction rate of conservation posts on both Facebook and Twitter. In contrast to this finding, diabetes-related Facebook posts with emojis achieved more reactions [47], as well as Twitter posts from airlines and car manufacturers [37]. We assume that these disparate results are due to the different topics and therefore target groups, although it is left to future studies to find the reasons for this by examining the relationship between emojis and user reactions in more detail.

(d) Images: On both platforms, images had a positive influence on reactions. Other studies came to the same conclusion (e.g., [12,41]).

(e) Videos: Posts with videos achieved fewer reactions on Facebook and had no impact on Twitter. The negative influence on Facebook could be due to the length of the videos and accordingly long loading times (cf. [48]). This may have led users not to view posts with videos at all and consequently not to react to them (ibid.). In contrast to our results, other studies on Greek local governments [39] and large companies [49] have shown a positive impact of videos on reactions.

(f) Interaction prompts: These had no influence on reactions on Facebook and Twitter. This could be because they were infrequent and their influence was therefore not statistically significant; only 7% of the examined Facebook posts and 1% of Twitter posts addressed questions to users or invited them directly to react, comment, or share.

(g) High character count: A higher character count positively influenced the reactions on both platforms, which was confirmed by a study by Gligorić et al. (2018) [50] for Twitter posts. A possible reason could be a preference of subscribers for detailed, informative posts.

4.2. Comments

(a) Hashtags and (b) links: Neither affected the number of comments a conservation post received on Facebook or Twitter.

(c) Emojis: While no such effect was visible on Facebook, conservation posts on Twitter generated more comments if they contained at least one emoji. This could be due to the fact that emojis can be used to communicate complex content in a lively way without taking up much space (cf. [51]). This is especially important on Twitter, due to its post length limitation of 280 characters, which does not exist on Facebook. Another reason might be that emojis can convey emotions, which entice users to comment more than neutrally minded posts (cf. [22]). However, we cannot explain why this applied neither to Facebook posts nor to reactions on Twitter and Facebook (see Section 4.1)—an issue for further research.

(d) Images: On both platforms, nature conservation posts with an image were commented on more often than posts without one. This is consistent with results of studies on corporate posts [41] and university Facebook posts in England [6]. On the other hand, university Facebook posts in Mexico received more comments when they contained only text [43]. In line with that, Löffler (2014) [52] recommends not using images when seeking comments. These different results, despite having a similar study focus, could indicate that the influence of images on the comments is dependent on other variables—for example, the post's content, cultural factors, or target groups/followers. This could, however, not be investigated further in our study.

(e) Videos: On Twitter, videos had no influence on the number of comments, whereas they had a negative effect on Facebook. As with the reactions (see Section 4.1), two other studies found an opposite, positive effect of videos [39,49]. Since there are no other studies to date that show a negative effect or no effect of videos on the number of comments, definite conclusions require further research.

(f) Interaction prompts had no impact on the number of comments received on either platform. As mentioned for reactions, the reason might be missing statistical significance. The same could also apply to the following indicators: shares (see Section 4.3) and overall engagement (see Section 4.4).

(g) High character count: Whereas character count had no influence on the number of comments on Twitter (where the number of characters is limited), it increased them on Facebook. This could be because longer posts offer more ground for comments in the form of questions, amendments, approval, or disagreement. However, the finding was statistically weak, so it should not dictate post design.

4.3. Shares

(a) Hashtags: On Facebook, hashtags led to more shares of conservation posts, presumably because hashtags situate the post within a larger topic area and are therefore shared more often by users with an interest in it. This complies with results of the already mentioned study on posts by Greek local governments [39] and is underlined by Ahrholdt et al. (2019) [22], who stated that hashtags can increase the reach of marketing posts. The Twitter posts by the three conservation organizations studied here did not obtain more shares when they contained hashtags—an issue for future research, as the reasons remain unclear.

(b) Links did not lead to more or fewer shares on Facebook. On Twitter, they had a positive influence presumably because linked content increases the informative value of posts, making users more willing to share them. In addition, links to images or videos can also contribute to increased shares, as Bruni et al. (2012) [48] showed for tourism posts.

(c) Emojis: While emojis had no impact on shares on Facebook, they decreased sharing of conservation posts on Twitter, which was also the case for Twitter posts by airlines and car manufacturers [38]. In contrast to that, Twitter posts about diabetes achieved significantly more shares with than without emojis [48]. These differences could have been caused by the respective post topic. Possibly, many subscribers to conservation organizations are strongly concerned about the matter and do not want to share posts that may, due to emojis, not be perceived as serious. However, emojis are an inherent component of communication on social networks [48] and increase the number of comments on conservation posts on Twitter (see Section 4.2). Emojis should therefore not be completely eliminated from them.

(d) Images: Facebook posts with images did not yield a change in shares, whereas Twitter posts were shared more often. The latter could be because users are more likely to share posts if they are interesting and attractive to their own followers. The difference between Facebook and Twitter could be due to the fact that many Twitter posts do not contain an image and Twitter users accordingly particularly value images and share them more often [38], whereas the use of images is more common and therefore nothing special on Facebook.

(e) Videos and (f) interaction prompts: Neither had an influence on shares on Facebook or Twitter.

(g) High character count: On both platforms, conservation posts were shared more often the longer they were, although this influence was weak on Facebook. An explanation for this effect could be that subscribers to the nature conservation organizations tend to pass on posts with a high information value to their own contacts. Löffler (2014) [52] also recommended that organizations from the marketing sector publish longer Facebook posts for more shares. According to Vries et al. (2012), the same applies to Twitter, regardless of topic and user [50].

4.4. Overall Engagement

(a) Hashtags: On Facebook, hashtags had no influence on overall engagement, whereas they reduced it on Twitter. This is surprising, as hashtags are an important part of information management on Twitter and none of the other three success indicators on Twitter was influenced positively or negatively by hashtags. Possible causes could be an excessive number of hashtags and a lack of fit with the post content. Too many hashtags might interfere with the reading flow and inappropriate hashtags might hinder the integration into an overarching topic cluster. Given the character limit on Twitter, too many hashtags could also take up valuable characters and thus reduce the meaningfulness of the post. Existing studies on the effective use of hashtags (e.g., [13,53]) have emphasized that fewer and more suitable hashtags are more useful than many generic hashtags.

(b) Links did not play a role in overall engagement on either platform. This is surprising, since they had a positive influence on reactions and shares on Twitter and should therefore be further investigated. A possible cause for the lack of statistical significance could be the low frequency of links in Twitter posts (<10%) combined with the strictness of the Mann–Whitney U test (see Section 4.6).

(c) Emojis: Emojis led to less overall engagement for conservation posts on Facebook. This is presumably because emojis reduce the number of reactions but have no influence on the other success indicators. However, there are no studies on the effect of emojis on overall engagement that demonstrate a similar negative effect. It is only known that emojis are used to increase the vividness and engagement of a post [51]. Indeed, on Twitter, emojis increased the overall engagement of conservation posts. This is somewhat surprising, as emojis had a negative impact on reactions and shares there, whereas they increased the number of comments. This positive effect dominated the calculation of overall engagement.

(d) Images: Overall engagement on Facebook and Twitter was higher for conservation posts that included an image. This finding is confirmed by other studies on marketing in social networks (e.g., [22,49]) as well as on environmental protection posts [6] and on posts of nonprofit youth organizations on Facebook [40].

(e) Videos led to less overall engagement on Facebook—certainly because they also had the same effect on reactions and comments. However, to date there are no studies that have come to similar conclusions—they show rather the opposite (cf. [39,49]). Therefore, it should be investigated whether there are specific factors of conservation posts that contribute to lower overall engagement, such as mood, style, or information content of the videos. The length of a video can also negatively influence its appeal [54]. On Twitter, videos had no influence on overall engagement.

(f) Interaction prompts did not influence overall engagement, neither on Facebook nor on Twitter.

(g) High character count: In line with the other indicators, overall engagement with nature conservation posts also increased with the character count on Facebook. This complies with Carboni and Maxwell's (2015) [40] findings on Facebook posts by nonprofit youth organizations, which were up to 4780 characters long. The authors suggested that longer posts are more substantial, making users more likely to identify with and respond to them (ibid.). However, for conservation posts on Twitter, our results show that more characters led to less overall engagement. Although this correlation is extremely weak, this is surprising, as shares and reactions correlated positively with character count. There are also no other scientific studies that confirm this, leaving it up to future studies to shed more light on this question.

4.5. Recommendations for Conservation Posts on Facebook and Twitter

Summarizing the findings presented in Sections 4.1–4.4, we now give recommendations to increase the success of German conservation posts. In any case, it should be noted that we cannot give one-size-fits-all, prescription-like recommendations since results differ between Facebook and Twitter as well as between the four success indicators used. Beyond that, our study was only based on 300 posts and tweets by three conservation organizations and studies from other fields only partly confirm our results. Consequently, the respective conservation actors should accompany their social network activities with thorough observations of their results in order to adapt their posts to the lessons learned.

Again, our recommendations follow the different design elements.

(a) Hashtags should be used in posts since they led to a higher number of reactions and shares on Facebook, without having negative effects on other success factors. The only exception is overall engagement on Twitter, which decreased for posts with hashtags. Although this effect cannot be explained beyond doubt, it can be seen as a hint to not use too many hashtags in one post, but rather to deliberately choose a few—especially to put the post in a larger thematic context and to allow for an easy search. In addition, organizations could also develop their own hashtags and actively circulate them to promote their brand identity [13,53] or topics important to them. A good example is WWF's #LastSelfie campaign [15].

(b) Links should especially be used on Twitter, as they had a positive influence on reactions and shares there, but no negative influence on any other indicator, including Facebook.

(c) Emojis should be used carefully, as they seemed to have a much more negative than positive impact on the success of posts, although they increased the number of comments and overall engagement on Twitter. Nonetheless, as they are essential elements of communication on social networks, they should not be completely excluded from posts, but rather used in particular cases only—e.g., to emphasize the intended mood of the post or to avoid misunderstandings due to ironic statements. Beyond that, conservation organizations should carefully observe the influence of emojis on the success of their own posts and apply their learnings to future posts.

(d) Images can and should be used whenever it seems to be suitable and the image fits the topic since they had a positive influence on almost all indicators on both Facebook and Twitter, but no negative one.

(e) Videos decreased the number of reactions and comments as well as overall engagement on Facebook and had no effect in any other case. Consequently, they should be used consciously and in exceptional cases only. We assume that longer videos might make a post less attractive due to different reasons and therefore suggest using short videos. Still, this is a hypothesis to be tested, particularly by conservation actors using videos.

(f) Interaction prompts did not influence any indicator of success, implying they can be used or not. However, this result is based upon a very small number of posts that actually made use of interaction prompts and therefore has to be taken cautiously.

(g) High character count was more important on Facebook than on Twitter, where only 280 characters are allowed. However, it also had an influence on Twitter, where a higher number of characters led to more reactions and shares (but also to lower overall engagement—although with very weak statistical significance). For Facebook, we suggest using longer posts (up to 1500 characters), as they were more successful than shorter ones.

4.6. Discussion of Methodology and Future Research

Some limitations of this study should be considered in future research endeavors. In this paper, Facebook and Twitter were examined. An investigation of additional social networks, such as Instagram or TikTok, could provide valuable information for the deliberate selection of social networks for specific conservation communication goals (cf. [55]).

Although the three organizations studied were deliberately chosen to have very different characteristics, they are not necessarily representative of nature conservation as a whole—not even in Germany. Future studies could therefore include even more (also international) nature conservation organizations and increase the sample size to verify whether the conclusions and recommendations for post design presented here can be applied on a broader base. In-depth studies should also be conducted for specific recommendations for individual organizations or areas of nature conservation action, as differences could also arise between them.

Moreover, it is unclear how many bots interact with the accounts of BfN, NABU, and WWF Germany, as their number and activities can only be determined through complex analytical procedures (cf. [56]). Accordingly, future studies should consider bot activities in the calculation of success metrics—for example, by mathematically adjusting the values.

Furthermore, although the Mann–Whitney U test and Spearman's rank correlation analysis impose only low requirements on the data used, they are statistically very strict, i.e., they reject results as non-significant more readily. Moreover, they cannot be used to investigate complex interactions between more than two variables, and they do not always allow for the depiction of real causality. Future studies should therefore use more extensive parametric analyses and models to test the causality of the statistical relationships identified here—for example, a multivariate analysis of variance (MANOVA), which could not be done for this paper since the data collected did not meet the necessary requirements, esp. concerning normal distribution and homogeneity of covariances.

In addition, future studies could examine how the timing, subject matter and sentiment (cf. [22]), communication intent (cf. [6,57]), and complexity and readability (cf. [58]) of a post affect its success. They could also use a variety of other dependent variables. If possible, they should match the communication goals of the conservation actors studied. The following variables could be used to complement the success indicators examined in this paper:

- Overall engagement with weighted sub-indicators (cf. [22]);
- Cost-effectiveness, i.e., the ratio of resources used to publish posts to the level of engagement achieved (cf. [22]);
- Influence on political decision-making processes (cf. [2]);
- Increases in the volume of donations (cf. [2]); or
- An increase in subscriber numbers and overall reach (cf. [6,22]).

In any case, a validation and supplementation of the presented findings is a worthwhile task for future research due to the growing relevance of digital conservation communication.

5. Conclusions

The analysis revealed that the influence of post design on communication success varies greatly depending on the social network and the success indicator under consideration. Therefore, we can only partially confirm our hypothesis that communication success on Facebook and Twitter is influenced by the utilization of design characteristics commonly found in posts. Specifically, some of the design features examined had a positive effect on one success indicator but reduced the values of another one or had no statistically significant influence at all. The strong variation depending on the platform and success indicator primarily concerned hashtags and emojis. Only a higher character count and the use of image elements had a predominantly positive influence on communication success. In addition, links on Twitter had a positive influence on reactions and shares. Conversely, videos on Facebook led to lower values in all success indicators except shares. There were no statistically significant results at all for the interaction prompt variable. The above results show many similarities with other study findings, but also some differences. This fact was taken into account when developing clear and easy-to-implement design recommendations for the four success indicators.

Through the effective and deliberate use of social networks, nature conservation can connect to a society undergoing digitalization and contribute to the sustainable shaping of this development. Communication can help reduce the gap between nature conservation and the public and bring people together to tackle the problem of the degradation of the natural environment. In this respect, new media such as social networks offer nature conservation the potential for unprecedented reach and mobilization of societal support.

Supplementary Materials: The following are available online at https://www.mdpi.com/article/10.3390/su132212768/s1. Supplementary A: Miller_Heiland_data.txt contains the data collected for the statistical analysis. Supplementary B: Miller_Heiland_script. Rmd was the R script utilized for statistical analysis Supplementary C: Miller_Heiland_statistical_results contains detailed statistical results.

Author Contributions: Conceptualization: A.M. and S.H.; methodology: A.M.; software: A.M.; validation, A.M. and S.H.; formal analysis, A.M.; investigation: A.M.; data curation: A.M.; writing—original draft preparation, A.M. and S.H.; writing—review and editing, A.M. and S.H.; visualization, A.M.; supervision, S.H. All authors have read and agreed to the published version of the manuscript.

Funding: We acknowledge support by the German Research Foundation and the Open Access Publication Fund of TU Berlin.

Data Availability Statement: The data presented in this study are available in Supplementary A.

Conflicts of Interest: The authors declare no conflict of interest. The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript, or in the decision to publish the results.

References

1. Anderson-Wilk, M. Changing the engines of change: Natural resource conservation in the era of social media. *J. Soil Water Conserv.* **2009**, *64*, 129A–131A. [CrossRef]
2. Brendle, U. Kommunikation und Naturschutz. Überlegungen zur Akzeptanzsteigerung des Naturschutzes. In *Natur zwischen Wandel und Veränderung. Ursache Wirkungen Konsequenzen*; Bundesamt für Naturschutz, Ed.; Springer: Berlin/Heidelberg, Germany, 2002; pp. 115–133.
3. Heiland, S. *Voraussetzungen Erfolgreichen Naturschutzes. Individuelle und Gesellschaftliche Bedingungen Umweltgerechten Verhaltens, ihre Bedeutung für den Naturschutz und die Durchsetzbarkeit seiner Ziele*; Ecomed-Verlag: Landsberg am Lech, Germany, 1999; 331p.
4. van der Wal, R.; Arts, K. Digital conservation: An introduction. *Ambio* **2015**, *44*, 517–521. [CrossRef] [PubMed]
5. Büscher, B. Nature 2.0: Exploring and theorizing the links between new media and nature conservation. *New Media Soc.* **2014**, *18*, 726–743. [CrossRef]
6. Pianosi, M. Can environmental Citizenship be Enhanced through Social Media? A Case Study of Engagement in a UK University. Ph.D. Thesis, Institute of Energy and Sustainable Development, De Montfort University, Leicester, UK, 2017.
7. Boyd, D.M.; Ellison, N.B. Social Network Sites: Definition, History, and Scholarship. *J. Comput. Mediat. Commun.* **2007**, *13*, 210–230. [CrossRef]
8. Fuchs, C. *Social Media: A Critical Introduction*; SAGE Publications: London, UK, 2007; 304p.
9. Shiffman, D.S. Twitter as a tool for conservation education and outreach: What scientific conferences can do to promote live-tweeting. *J. Environ. Stud. Sci.* **2012**, *2*, 257–262. [CrossRef]
10. Hemmi, A.; Crowther, J. Learning environmental activism through social networking sites? *J. Contemp. Community Educ. Pract. Theory* **2013**, *4*, 1–7.
11. Nghiem, L.T.P.; Webb, E.L.; Carrasco, L.R. Saving Vietnam's Wildlife Through Social Media. *Science* **2012**, *338*, 192–193. [CrossRef]
12. Wu, Y.; Xie, L.; Huang, S.-L.; Li, P.; Yuan, Z.; Liu, W. Using social media to strengthen public awareness of wildlife conservation. *Ocean Coast. Manag.* **2018**, *153*, 76–83. [CrossRef]
13. Bombaci, S.P.; Farr, C.M.; Gallo, H.T.; Mangan, A.M.; Stinson, L.T.; Kaushik, M.; Pejchar, L. Using Twitter to communicate conservation science from a professional conference. *Conserv. Biol.* **2016**, *30*, 216–225. [CrossRef]
14. Hamid, S.; Ijab, M.; Sulaiman, H.; Md Anwar, R.; Norman, A. Social media for environmental sustainability awareness in higher education. *Int. J. Sustain. High. Educ.* **2017**, *18*, 474–491. [CrossRef]
15. The Webby Awards, 2015, #LastSelfie. Available online: https://winners.webbyawards.com/2015/advertising-media-pr/advertising-campaigns/social-media-campaign/158176/lastselfie (accessed on 13 September 2021).
16. WWF International (World Wide Fund For Nature International) 2015: WWF Turns Tweets to Donations with #EndangeredEmoji Social Campaign. Available online: https://wwf.panda.org/?246650/WWF-turns-tweets-to-donations--with-EndangeredEmoji-social-campaign (accessed on 13 September 2021).
17. Kolf, A.; Lohmann, M.; Probst, M.; Rümmele, S.; Schaper, J.; Springmeyer, Y. Großer Fachteil. In *Erfolgreiche Umweltkommunikation im Internet. Studie: Internetanwendungen im Natur- und Umweltschutz. Initiativen zum Umweltschutz*; Erich Schmidt Verlag: Berlin, Germany, 2005; Volume 63, pp. 5–222.
18. Toivonen, T.; Heikinheimo, V.; Fink, C.; Hausmann, A.; Hiippala, T.; Järv, O.; Tenkanen, H.; Di Minin, E. Social media data for conservation science: A methodological overview. *Biol. Conserv.* **2019**, *233*, 298–315. [CrossRef]
19. Giovos, I.; Ganias, K.; Garagouni, M.; Gonzalvo, J. Social Media in the Service of Conservation: A Case Study of Dolphins in the Hellenic Seas. *Aquat. Mamm.* **2016**, *42*, 12–19. [CrossRef]
20. Koot, S.; Fletcher, R. Popular Philanthrocapitalism? The Potential and Pitfalls of Online Empowerment in "Free" Nature 2.0 Initiatives. *Environ. Commun.* **2020**, *14*, 287–299. [CrossRef]
21. Grabs, A.; Bannour, K.; Vogl, E. *Follow Me! Erfolgreiches Social Media Marketing mit Facebook, Twitter und Co*, 4th ed.; Rheinwerk: Bonn, Germany, 2017; 604p.
22. Ahrholdt, D.; Greve, G.; Hopf, G. *Online-Marketing-Intelligence. Kennzahlen, Erfolgsfaktoren und Steuerungskonzepte im Online-Marketing*; Chapters 4 and 11; Springer Fachmedien: Wiesbaden, Germany, 2019; 344p.
23. Felt, M. Social media and the social sciences: How researchers employ Big Data analytics. *Big Data Soc.* **2016**, *3*, 1–15. [CrossRef]
24. Batrinca, B.; Treleaven, P.C. Social media analytics: A survey of techniques, tools and platforms. *AI Soc.* **2015**, *30*, 89–116. [CrossRef]
25. BfN (Bundesamt für Naturschutz) Imagebroschüre 2016. Available online: https://www.bfn.de/fileadmin/BfN/wirueberuns/Dokumente/BfN_Imagebroschuere_2016.pdf (accessed on 13 September 2021).
26. Über das BfN: Organisation. Available online: https://www.bfn.de/ueber-das-bfn/organisation.html (accessed on 13 September 2021).
27. Facebook-Profil von @bfn.de. Available online: https://www.facebook.com/bfn.de (accessed on 13 September 2021).
28. Twitter-Profil von @BfN_de. Available online: https://twitter.com/BfN_de (accessed on 13 September 2021).
29. NABU (Naturschutzbund Deutschland) Jahresbericht 2019. Available online: https://www.nabu.de/imperia/md/content/nabude/nabu/200820-nabu-jahresbericht-2019.pdf (accessed on 13 September 2021).
30. Facebook-Profil von @Naturschutzbund.de. Available online: https://www.facebook.com/Naturschutzbund (accessed on 13 September 2021).
31. Twitter-Profil von @NABU_de. Available online: https://twitter.com/nabu_de (accessed on 13 September 2021).

32. Twitter-Beitrag von @WWF_Deutschland. Available online: https://twitter.com/WWF_Deutschland/status/1276122607092412417 (accessed on 13 September 2021).
33. Facebook-Profil von @wwfde. Available online: https://www.facebook.com/wwfde (accessed on 13 September 2021).
34. Twitter-Profil von @WWF_Deutschland. Available online: https://twitter.com/WWF_Deutschland (accessed on 13 September 2021).
35. Beisch, N.; Koch, W.; Schäfer, C. ARD/ZDF-Onlinestudie 2019: Mediale Internetnutzung und Video-on-Demand gewinnen weiter an Bedeutung. *Media Perspekt.* **2019**, *9*, 374–388.
36. Stephen, A.; Sciandra, M.R.; Inman, J. Is it What You Say or How You Say It? How Content Characteristics Affect Consumer Engagement with Brands on Facebook. *Saïd Bus. Sch. WP* **2015**, *19*, 1–60. [CrossRef]
37. Fiebert, M.; Aliee, A.; Yassami, H.; Dorethy, M. The Life Cycle of a Facebook Post. *Open Psychol. J.* **2014**, *7*, 18–19. [CrossRef]
38. Li, Y.; Xie, Y. Is a Picture Worth a Thousand Words? An Empirical Study of Image Content and Social Media Engagement. *J. Mark. Res.* **2020**, *57*, 1–19. [CrossRef]
39. Lappas, G.; Triantafillidou, A.; Deligiaouri, A.; Kleftodimos, A. Facebook content strategies and citizens' online engagement: The case of Greek local governments. *Rev. Socionetw. Strateg.* **2018**, *12*, 1–20. [CrossRef]
40. Carboni, J.; Maxwell, S. Effective Social Media Engagement for Nonprofits: What Matters? *J. Public Nonprofit Aff.* **2015**, *1*, 18–28. [CrossRef]
41. Pletikosa Cvijikj, I.; Michahelles, F. Online engagement factors on Facebook brand pages. *Soc. Netw. Anal. Min.* **2013**, *3*, 843–861. [CrossRef]
42. Hölderle, J. Social Media und die Energiewende. In *Die Energiewende im Spannungsfeld Energiepolitischer Ziele, Gesellschaftlicher Akzeptanz und Naturschutzfachlicher Anforderungen*; Demuth, B., Heiland, S., Luick, R., Vedel, D., Ammermann, K., Wiersbinski, N., Eds.; BfN-Skripten 433, Bundesamt für Naturschutz: Bonn, Germany, 2016; pp. 114–130.
43. Valerio, G.; Herrera-Murillo, N.; Herrera-Murillo, D.J.; Rodríguez-Martínez, M.D. Impact of Message's Length over Likes, Comments and Shares. The Mexican Universities Case. In *WEB 2014: The Second International Conference on Building and Exploring Web Based Environments*; Del Pilar Angeles, M., Astrova, I., Eds.; International Academy, Research, and Industry Association: Wilmington, DE, USA, 2014; pp. 24–26.
44. Mann, H.B.; Whitney, D.R. On a Test of Whether one of Two Random Variables is Stochastically Larger than the Other. *Ann. Math. Stat.* **1947**, *18*, 50–60. [CrossRef]
45. Cohen, J. A power primer. *Psychol. Bull.* **1992**, *112*, 155–159. [CrossRef] [PubMed]
46. Tiago, T.; Tiago, F.; Faria, S.D.; Couto, J.P. Who is the better player? Off-field battle on Facebook and Twitter. *Bus. Horiz.* **2016**, *59*, 175–183. [CrossRef]
47. Gabarron, E.; Larbi, D.; Dorronzoro, E.; Hasvold, P.E.; Wynn, R.; Årsand, E. Factors Engaging Users of Diabetes Social Media Channels on Facebook, Twitter, and Instagram: Observational Study. *J. Med Internet Res.* **2020**, *22*, e21204. [CrossRef]
48. Bruni, L.; Francalanci, C.; Giacomazzi, P. The Role of Multimedia Content in Determining the Virality of Social Media Information. *Inf. Manag.* **2012**, *3*, 278–289. [CrossRef]
49. Vries, L.; Gensler, S.; Leeflang, P.S.H. Popularity of Brand Posts on Brand Fan Pages: An Investigation of the Effects of Social Media Marketing. *J. Interact. Mark.* **2012**, *26*, 83–91. [CrossRef]
50. Gligorić, K.; Anderson, A.; West, R. How Constraints Affect Content: The Case of Twitter's Switch from 140 to 280 Characters. *Proc. Int. AAAI Conf. Web Soc. Media* **2018**, *12*, 596–599.
51. Ge, J.; Gretzel, U. Emoji rhetoric: A social media influencer perspective. *J. Mark. Manag.* **2018**, *34*, 1–24. [CrossRef]
52. Löffler, M. *Think Content! Content-Strategie, Content-Marketing, Texten fürs Web*; Galileo Press: Bonn, Germany, 2014; 683p.
53. Saxton, G.D.; Niyirora, J.; Guo, C.; Waters, R. #AdvocatingForChange: The Strategic Use of Hashtags in Social Media Advocacy. *Adv. Soc. Work* **2015**, *16*, 154–169.
54. Gao, W.; Tian, Y.; Huang, T.; Yang, Q. Vlogging: A survey of videoblogging technology on the web. *ACM Comput. Surv.* **2010**, *42*, 1–63. [CrossRef]
55. Papworth, S.; Nghiem, T.; Chimalakonda, D.; Posa, M.; Wijedasa, L.; Bickford, D.; Carrasco, L. Quantifying the role of online news in linking conservation research to Facebook and Twitter. *Conserv. Biol.* **2015**, *29*, 825–833. [CrossRef] [PubMed]
56. Guenon des Mesnards, N.; Hunter, D.; Hjouji, Z.; Zaman, T. The Impact of Bots on Opinions in Social Networks. *arXiv* **2018**, arXiv:1810.12398.
57. Tafesse, W.; Wien, A. A framework for categorizing social media posts. *Cogent Bus. Manag.* **2017**, *4*, 1–22. [CrossRef]
58. Khabiri, E.; Hsu, C.; Caverlee, J. Analyzing and Predicting Community Preference of Socially Generated Metadata: A Case Study on Comments in the Digg Community. *Proc. Int. AAAI Conf. Web Soc. Media* **2009**, *3*, 238–241.

sustainability

MDPI

Article

The Effectiveness of Environmental Spending in China and the Environmental Kuznets Curve

Lin Cui, Alistair Hunt and Bruce Morley *

Department of Economics, University of Bath, Bath BA2 7AY, UK; lc2109@bath.ac.uk (L.C.); ecsasph@bath.ac.uk (A.H.)
* Correspondence: bm232@bath.ac.uk; Tel.: +44-1225-386497

Abstract: The aim of this study is to determine whether recent environmental spending in China has enabled it to reduce its emissions of greenhouse gases in the context of an Environmental Kuznets Curve-based model and promote sustainable economic development. Following the Paris Agreement in 2015, there has been a coordinated effort to reduce the consumption of fossil fuels and prevent the excessive warming of the climate. The study uses annual regional data across China and a dynamic panel data approach for estimating an EKC model which includes measures of the increased use of fossil fuels and the spending across China to reduce environmental damage. The results suggest that the policies have been effective in controlling emissions across a variety of pollutants and that the EKC tends to hold in China but varies according to the pollutant. This suggests that these policies should be continued and where possible, extended.

Keywords: environmental spending; pollutant; EKC; dynamic panel

Citation: Cui, L.; Hunt, A.; Morley, B. The Effectiveness of Environmental Spending in China and the Environmental Kuznets Curve. *Sustainability* **2021**, *13*, 12141. https://doi.org/10.3390/su132112141

Academic Editor: Grigorios L. Kyriakopoulos

Received: 27 September 2021
Accepted: 28 October 2021
Published: 3 November 2021

1. Introduction

There is an increasing demand for countries across the world to reduce their pollution in general and fossil fuel use in particular. Since the Paris Agreement in 2015, countries around the world have agreed to reduce fossil fuel use and ensure that the temperature doesn't rise by more than 2 degrees relative to pre-industrial levels. China is currently one of the fastest growing economies in the world and is also a major producer of greenhouse gases, and to limit the growth in emissions it has implemented policies to ensure that these emissions are more controlled over the next few decades. The aim of this study is to estimate a model including measures of the recent environmental-spending policies in China, in the context of the Environmental Kuznets Curve model (EKC).

This study uses an applied approach to analysing the effectiveness of environmental expenditure from the perspective of government-based spending and the levels of investment to determine which has worked best to date, in the context of the EKC model. We have not sought to add a new model to the study; the analysis is based on the standard EKC model, augmented by energy consumption, trade and population effects, but we have also added to the approach the environmental-spending measures, which is the first time this has been done in this context, as far as we know. This study aims to contribute to the current literature in three main respects: firstly, by incorporating the environmental-spending measures and investment in the environment into a standard EKC model. In addition, we assessed the importance of these measures across a wide range of pollutants that have not been studied in such detail before. Thirdly, we used dynamic panel models to account for the partial adjustment that is inherent in pollutant-based models, using both the Arellano—Bond and Arellano—Bover approaches to ensure the results are robust.

It is has been well established that there is an association between sustainable economic development and environmental deterioration since the initial study of Grossman and Krueger (1991). This relationship is most commonly conceptualised through the EKC, and there has been a wide range of methodologically diverse research conducted on it, with many of these studies illustrating the serious impact pollution has on the economy and the existence of the EKC relationship [1,2]. There have also been studies specifically on China which support the existence of the EKC, such as [3,4]. So, the use of this model is important when analysing the environment.

Following the introduction, the first section contains the literature review on the EKC, including its development and both international and Chinese research. The second section focuses on describing the Chinese provincial data and discussing the methodology used. We then analyse the results and finally offer some conclusions and explore the policy implications.

2. Literature Review

2.1. The Genesis of the EKC

With the rise in environmental awareness in the second half of the 20th century, research on environmental economics began to attract more interest, leading to the development of the EKC hypothesis, which explores how economic growth can affect environmental degradation. The initial study considered the environmental impacts of economic growth in NAFTA and conducted an empirical study with reduced-form regression models between income per capita and air pollutant emissions [5,6]. Panayotou [7] linked the inverted U-shaped curve with the Kuznets Curve [8], naming it the Environmental Kuznets Curve for its similarity. The shape can be flattened if environmentally harmful subsidies are removed [7]. More popular discussions began with the World Bank Development Report [9], this background paper verifies the existence of an inverted U-shaped relationship between income levels and air pollutant emissions, including sulfur dioxide and suspended particulates emissions [10]. Moreover Grossman and Krueger [6] used a panel data model analysis with more comprehensive environmental indicators in GEMS and found further evidence of inverted U-shaped type relationships. From this they were able to calculate turning points at around USD 4000–8000 (Sulfur dioxide at USD 4053, smoke at USD 6151 and COD at USD 7853).

There are three mechanisms through which income can affect the environment: scale, composition and technical effects [5]. The scale effect reveals that economic growth increases with more natural resource inputs, resulting in higher relative environmental degradation. The EKC curve is split into two separate periods. The scale effect influences the rising period at the beginning, and both composition and technical effects can occur in the latter declining period of the EKC curve as income levels increase. The technical effects can be interpreted as the use of clean technology increasing productivity and facilitating transition with the aim of improving the environmental quality.

Throughout the development of the EKC theory, several criticisms and alternative theories have been raised. For example, the U-shaped curve may not be the best fit for the relationship between sustainable economic development and environmental deterioration, with an inverse N-shaped curve perhaps being a better representation, as shown by an increase in environmental deterioration after the initial period of decline.

2.2. International Research

The empirical analysis of the EKC focuses on the relationship between GDP per capita and various pollutant emissions. The research so far has included multiple comprehensive analyses, conducted across a wide range of explanatory variables to test the determinants of environmental degradation, for example, energy consumption, population characteristics, trade openness, foreign direct investment and policy indicators.

The EKC research on environmental pollutants mainly covers air pollution, water waste and solid waste. CO_2 emissions, as the main GHG contributing to global warming, are the most commonly used emissions in research on the EKC and the existence of an inverse U-shaped EKC model with CO_2 emissions is supported by a relatively large number of studies [2,11–15]. Research on other emissions includes sulfur dioxide emissions [6,16], and nitrogen oxide emissions [17]. EKC analysis has also considered various types of air pollution, including different types of particulate matter (such as smoke and dust, SPM and PM2.5) [18,19]. Panayotou [7] also accounts for deforestation rates in his EKC analysis, suggesting the EKC relationship has a greater impact on more populous and tropical countries. However, this is contradicted by some studies [20], whose deforestation-specific analysis of the EKC found deforestation is not beneficial for increasing the income level.

The ability to accurately estimate the turning point of the EKC depends on the scale of the study as well as the range and quality of the control variables used. The selection of explanatory variables tends to represent the objectives of their studies. For example, a study focusing on urban level data, using 276 metropolitan areas, obtained a turning point (USD 55,102) considerably higher than those found in country-level studies; thus policy-makers relying solely on country-level data may be misled [21]. Apergis and Ozturk [2] considered government expenditure in their research, as well as four policy indicators: political indexes, government effectiveness, regulatory activities and the level of corruption. The first three were found to have a positive relationship with pollution, while corruption was found to be negatively associated with pollution. Al-Mulali et al. [22] found that renewable energy measures exhibit highly significant inverted-U type relationships with emissions. However, renewable energy sources should not all be treated equally; for example, although an EKC analysis based in France found nuclear energy can decrease carbon dioxide emissions across both the short and long term, the application of nuclear energy should be treated with caution because the potential risks are large and there are often high safety management costs [23]. The impact of international trade is more ambiguous. On the one hand, it can increase pollution as increased exports lead to higher production, but on the other hand, it also can bring positive effects to environment quality by facilitating pollution transfer through foreign direct investment, although this may just displace to other countries [24].

The existence of the EKC may also be affected by the levels of economic development across various regions. Most studies have proven the existence of an inverted U-shaped EKC in relatively well-developed areas, suggesting the environmental problems probably improve or reduce the levels of deterioration when total income reaches a certain level. The EU 28 countries indicate an inverse U-shaped curve in the relationship between residential energy consumption and gross domestic products [25]. However, Abid [26] obtains a monotonically increasing trend between CO_2 emissions and GDP in 41 EU countries. Other studies indicate that only Denmark and Italy provide evidence in support of EKC [27]. Most EKC analyses for single countries in the EU regions find the inverted U-shaped type relationships; for example, Germany exhibits a clear EKC pattern with regard to strong energy policies [28], and a concave relationship was found to exist in Romania over the period 1980–2010, perhaps because environmental policies tend to be enacted by democratic regimes as they have more of an incentive to reduce CO_2 emissions [12]. Some studies focus on the decline of electric power consumption relative to economic growth in four different countries (Australia, USA, China and Ghana); their evidence supports the validity of the EKC in Australia and China [29]. Furthermore, they found Australia and the USA performed better in reducing electric power consumption. However, some studies indicate that the pollution—income relationships they tested do not satisfy the inverse U-shaped curve. Global economic recession and globalisation have caused fluctuations in the pollution—income relationship since 2001, so only weak evidence for the inverted U shape is found from 1971 to 2001 [28].

Across the research, there are two main methodological approaches. Some papers focus on single-country analysis, applying time series data to test the relationship between income levels and environmental degradation, whereas multi-country studies must use a panel data model approach to test this association.

2.3. Research on China

EKC studies on China have been conducted since the beginning of the 21st century. During this time, China transitioned to a phase of relatively quick economic development, benefiting from globalisation and its stable government. Public environmental awareness nearly always follows economic growth, as once people have achieved relatively satisfactory income levels, they are able to pursue other means to attain higher living standards. The research has generally been conducted between the 1990s and the most recent year they could acquire data for, as determined by the limitations of the database or quality of the data. Most research has used provincial-level data for panel data model analysis, although some single-province or country-level studies have used time-series analysis.

The literature on the Chinese EKC hypothesis focuses on three types of environmental pollutants: air pollutants, waste water and solid waste discharges. The air pollution studies focus on the key emissions of carbon dioxides, nitrogen oxides, sulfur dioxides and dust emissions. Some EKC studies with provincial annual data and the country-level data for CO_2 emissions have shown evidence of the inverse U-shaped curve [30–34]. A study in Beijing, using monthly data from 2008M04 to 2016M12 to examine PM2.5 emissions, found evidence supporting the existence of the EKC in China. Additionally, they found vehicle exhaust emissions to be a contributor to emissions, whereas natural gas consumption contributes to the reduction in PM2.5 [4].

The large variety of data available in the China Statistical Yearbook gives researchers access to a variety of control variables, as required for their research objectives. Some studies also use city-level data to identify specific geographical factors in China [17,35,36] For example, He and Wang [35] introduced 'northern city' and 'coastal city' as two indicators. Technical progress has also affected the decrease of carbon emissions in China [33], which was firstly considered in the World Bank Development Report [9]. As the most populous country, the population density could be a valuable explanatory variable when analysing the pollution—income relationships. An overlapping generations (OLG) model confirms the existence of the EKC hypothesis with 10 years of provincial-level data in China, and the population growth contributes to a higher peak in this curve via simulations [37]. Finally, policy making plays an important role in pollution control. Hence, Yin [33] uses environmental regulation as a control variable to account for the moderating effect of stricter regulations on EKC.

Regarding the current studies in the EKC area, further research needs to be conducted to compare various pollutant emissions, rather than only putting the emphasis on CO_2 emissions. More needs to be done about the recent severe environmental problems in China that are mostly influenced by industrial pollution, along with the rapid economic growth. In this chapter, I conducted the analysis with three air-pollutant emissions and the COD of wastewater discharge, using China's provincial-level data. In recent years, governments have striven to develop effective environmental policy systems; thus the effects of these policies need to be examined for their progress on pollution treatments with more empirical analyses. However, there are few EKC studies examining the determining factors behind financial inputs for environment improvements.

2.4. Environmental Spending

Although to date there has been limited analysis of the environmental-spending policy in China, there have been some studies assessing the effectiveness of fiscal policies on the environment. Zheng et al. [38] showed that environmental standards and energy-saving policies in China have reduced pollutants, based on a regional panel from 2002 to 2011. Similarly, one study] found that energy policy had reduced pollution in Shanghai based on a case study [39]. Shen et al. [40], found that the environmental policy tools available to the authorities in China were effective at improving pollution levels. Using regional data from 1997 to 2014, they also found that command and control type policies worked best.

3. Materials and Methods

3.1. Data

The Chinese regional annual data were accessed from the China Statistical Yearbook and the China Environmental Statistical Yearbook from 2004 to 2017, which consists of

31 provinces, cities and autonomous regions. The provinces are as follows: Beijing, Tianjin, Hebei, Shanxi, Inner Mongolia, Liaoning, Jilin, Heilongjiang, Shanghai, Jiangsu, Zhejiang, Anhui, Fujian, Jiangxi, Shandong, Henan, Hubei, Hunan, Guangdong, Guangxi, Hainan, Chongqing, Sichuan, Guizhou, Yunnan, Shaanxi, Gansu, Qinghai, Ningxia, Xinjiang and Tibet.

The environmental pollution variables include industrial-pollutant emissions in China, which are SO_2, CO_2, NO_x, COD and dust emissions, with all pollutant emission units measured in tons. SO_2 emissions are the major pollutant emission in terms of gaseous sulfur oxides (SO_x), which are mainly caused by industrial facilities and the burning of materials containing sulfur, releasing harmful effects into the air, as well as causing acid rain [41]. Likewise, nitrogen dioxide (NO_2) emissions can be produced from the burning of fuel in vehicles and through industrial development. The negative effects of nitrogen dioxide include acid rain and smog [41]. In China's statistics, nitrogen oxides and dust emissions include those from industry, households, motor vehicles and centralised pollution-control facilities. Sulphur dioxide (SO_2) emissions are the total volume from industrial, household and centralised pollution-control facilities. COD was chosen as the indicator of water waste, which is from industry, agriculture, households and centralised pollution-control facilities. Nitrogen oxides and dust emissions data were only considered from 2011 to 2017 because of the lack of earlier data.

The explanatory variables for the EKC are as follows: gross domestic product (GDP) per capita measured with the Chinese domestic currency Yuan; energy consumption of electricity (ECE) measured as kilowatts per hour; population density (PD); trade openness represented by total exports and imports; local government expenditures on environmental protection; and investment in the treatment of environmental pollution, measured with Yuan as well. There is no total energy consumption for the provincial data, but electricity is the most common energy source used in China for the basic demands of households and industry. The plots of the average values for the variables across the Chinese regions are included in the Appendix A Table A1. All variables are in logarithmic form. There is some evidence of an inverted U-shaped curve in the pollutant data. This is particularly the case for the cod and dust pollutants, with reductions being experienced over more recent years, following changes in the laws on pollution in China. The other variables, such as government spending on the environment, have increased very little over the time frame.

3.2. Overview of Dynamic Panel Data GMM Analysis

The dynamic panel data model suits samples with a large N and small T, so we have used this approach due to only a short time period being available for the country and provincial data. The model for a dynamic panel data approach includes the lagged dependent variables as explanatory variables, but this lagged variable can result in a problem with endogeneity. This can be overcome by introducing generalised method of moments (GMM) estimators for the autoregressive model, which can be expressed as:

$$y_{it} = \alpha y_{it-1} + \beta x_{it} + \varepsilon_{it}; \quad i = 1, 2, \ldots, N; \quad t = 2, 3, \ldots, T \tag{1}$$

where the variable y_{it-1} is the lagged dependent variable, x_{it} represents the other explanatory variables, ε_i is the composite error term, which is denoted as $\varepsilon_{it} = \mu_t + v_{it}$, containing individual effects and time-varying disturbances.

Both the Arellano—Bond (1991) [42], andArellano—Bover (1995) [43], GMM estimators can be applied with dynamic data panel models. The Arellano—Bond approach removes the error term's relationship with the fixed effects through first difference transformations, but the transformed results cannot be obtained if there are missing values. An alternative approach is the Arellano—Bover estimator, which uses an orthogonal deviation transformation for unbalanced panels which considers additional moment conditions. The results with two transformations are robust because the dynamic panel data analysis has been considered with improvements compared to least squares regression. GMM estimators use the White period robust standard errors to adjust for serial correlation and time-varying variances in the standard errors. The Sargan and Hansen tests are conducted to determine the over-identifying restrictions

3.3. Equation Specification and Results

Regarding China's provincial analysis, the quadratic functions of GDP per capita will be introduced into the EKC model to model the non-linear nature of the relationship. The instrumental variables are lagged values of all the explanatory variables to eliminate the endogeneity. The lagged independent variables are less likely to be affected by unobserved confounders when examining the causal relationship [44]. Finally, all variables have been converted to the natural logarithmic form in the regression model to ensure linearity and reduce heteroskedasticity. The EKC model can be specified as:

$$\begin{aligned}\ln(pollutants)_{it} = {} & \beta_1 ln\ Pollutant_{it-1} + \beta_2 lnGDPPC_{it} + \beta_3 lnGDPPC_{it}^2 + \beta_4 lnECE_{it} + \beta_5 lnInvestment_{it} \\ & + \beta_6 lnGovExp_{it} + \beta_7 lnTrade_{it} + \beta_8 lnPD_{it} + \varepsilon_{it}\end{aligned} \tag{2}$$

where $pollutant_t$ is the pollutant being analysed and $GDPPC_t$ is per capita GDP on a regional basis. ECE_t is electricity consumption, $investment_t$ is investment in environmental treatments, $GovExp_t$ is government expenditure on environmental protection, $Trade_t$ is trade openness and pd_t is population density. Based on the inverted U-shaped relationship between pollutants and PCGDP, we would expect the following coefficients signs:

$$\beta_1 > 0, \beta_2 > 0, \beta_3 < 0, \beta_4 > 0, \beta_5 < 0, \beta_6 < 0, \beta_7 > 0\ and\ \beta_8 > 0$$

Overall, we would expect investment and expenditure on the environment to reduce emissions and pollutants. The other signs are based on the literature.

4. Results

Table 1 shows the descriptive statistics for provincial-level original data before transforming them into logarithmic form. The large quantities of emission discharges can be interpreted with respect to the mean and maximum values at a regional level. Likewise, the large differences in the minimum and maximum values indicate the rapid economic growth experienced in China, along with the extent of the provinces' differences in severe pollution levels. Due to the short time series, the preferred specification is contained in Equation (2) above, which also follows the standard approach to EKC modelling. Despite the short time series for our data and the implications of this for the power of these tests, we have included the results of stationarity testing using the Levin, Lin and Chu (LLC) and Im Pesaran and Shin (IPS) tests of stationarity in a panel in the appendices. They show the data is I(0) except the pollutant data, which is overall I(1), although there is some evidence of Nox and Dust being I(2), although this could be due to a shorter time series than the others, as is evident in Table 1. We have then re-estimated the models with the pollutants in differenced form. The results for SO_2 and COD are similar to before, but for Dust and Nox the results are now less significant; however, this could again be due to the shorter time series for these variables, producing fewer observations as detailed below in the summary statistics. For the sulphur dioxide and COD pollutants, the EKC is clearly not affected by whether the pollutants are differenced or not as it is clearly significant. Similarly, investment still has negative effects on pollution, whereas government spending has positive effects. The trade effect is particularly evident still for all the pollutants, suggesting that trade has been one of the largest contributors to pollution in China. As with the previous results, the J-statistics are satisfactory, suggesting the instruments are appropriate.

Table 1. Summary statistics.

	Units	Mean	Maximum	Minimum	St. Dev.	Observations
Sulfur Dioxide (SO_2)	Tonnes	662,937	2,002,000	1000	448,868	434
Chemical Oxygen Demand (COD)	Tonnes	535,984	1,982,500	13,800	402,419	434
Nitrogen Oxide(NOX)	Tonnes	624,496	1,801,138	30,154	424,461	217
Smoke and Dust (DUST)	Tonnes	409,144	1,797,683	6570	326,659	217
Regional Per Capita Gross Domestic Product (GDPPC)	Yuan per person	36,451	128,994	4317	24,040	434
Energy Consumption of Electricity (ECE)	100 million KWH	1410	5960	13	1150	432
Government Expenditure on Environmental Protection (GOVEXP)	100 million Yuan	97	458	5	71	341
Investment on Pollution Treatment (INVestment)	100 million Yuan	192,756	1,416,464	129	188,663	429
Population Density in Urban Areas (PD)	Person persqKM	2576	6307	186	1320	434
Total Exports and Imports (TRADE)	$1,000,000	96,700	1,090,000	199,982	17,900	434

Regarding the results of the sulfur dioxide emissions in Table 2, the models have been estimated with both GMM estimators (first differences and forward orthogonal deviations), and both models suggest a failure to reject the null hypothesis of the overidentifying restrictions, based on the J-statistic. As there is a positive relationship between $lnGDPPC$ and pollutant emissions, but a negative relationship between log form of GDP per capita squared and emissions, this suggests there is an inverted U-shaped curve present. The coefficients of $lnGDPPC$ have the correct positive value, which is 2.89 and $lnGDPPC^2$ with -a value of 0.17 and the correct negative sign, so the EKC exists for sulfur dioxide emissions. This supports other studies on China that have found evidence of the EKC, such as [33], and [45]. The turning point for the income level is calculated using exp($-\beta_2/2\beta_3$); thus the provincial-level turning point (TP) of income per capita for SO_2 emissions is CNY 4584.

Furthermore, an increase in investment in pollution treatments leads to a decrease of SO_2 emissions, and the estimator's coefficient is statistically significant. However, local government expenditure has a positive relationship, indicating higher government spending would increase SO_2 emissions. The reverse effect of investment on pollution treatment refers to the investment's efficacy in terms of SO_2 emissions reduction. Regarding the positive relationship between SO_2 and government expenditures, this could be because the Chinese government has been carrying out the projects on environmental protection with increasing financial inputs, aiming to reduce the pollutants and improve environmental quality, but there could be a sizeable lag before these expenditures become effective.

The estimation results for COD are presented in Table 3. The indicator for waste-water discharge are similar when the regression model is run with the two transformations. Most coefficients are statistically significant, except for electric energy consumption and population density, and the probabilities of the J-statistic also suggest there is no over-identification for the instruments. The results indicate an inverted U-shaped curve relationship between COD pollutants and income levels for China's provincial data. According to the GMM estimators with orthogonal deviations transformations, the GDP per capita TP is CNY 4930. Furthermore, the investment in pollution treatment has a negative association with COD emissions, whereas the government expenditure on environmental protection are again positively associated with COD pollutants. This is the same impact observed for SO_2, indicating that the green inputs have the same effect on both.

Table 2. Sulfur Dioxide Emissions.

Sulfur Dioxide Emissions	First Differenced	Orthogonal Deviations
Estimation	Coefficient and SE	Coefficient and SE
LNSO2(-1)	0.894 ***	1.090 ***
	(0.101)	(0.037)
LNGDPPC	4.643 ***	2.892 ***
	(1.891)	(0.851)
LNGDPPC2	−0.277 ***	−0.172 ***
	(0.090)	(0.039)
LNECE	0.399 *	0.204 **
	(0.206)	(0.098)
LNINVESTMENT	−0.006	−0.049 ***
	(0.011)	(0.007)
LNGOVEXP	0.213 ***	0.072 ***
	(0.031)	(0.027)
LNTRADE	0.309 ***	0.234 ***
	(0.042)	(0.017)
LNPD	0.524 ***	0.223 ***
	(0.083)	(0.056)
J-Statistic	20.887	28.010
Prob (J-Statistic)	0.588	0.215
Instrument rank	31	31
Total Panel Unbalanced Observations	244	275

Notes: A * (**) (***) denotes significance at the 10% (5%) and (1%) levels respectively.

Table 3. Chemical oxygen demand.

COD	First Differenced	Orthogonal Deviations
Estimation	Coefficient and SE	Coefficient and SE
LNCOD(-1)	0.596 ***	0.656 ***
	(0.020)	(0.014)
LNGDPPC	10.437 ***	3.470 **
	(2.128)	(1.627)
LNGDPPC2	−0.565 ***	−0.204 *
	(0.099)	(0.079)
LNECE	−0.000	0.075
	(0.214)	(0.123)
LNINVESTMENT	−0.108 ***	−0.049 ***
	(0.017)	(0.008)
LNGOVEXP	0.430 ***	0.156 ***
	(0.076)	(0.045)
LNTRADE	0.803 ***	0.462 ***
	(0.060)	(0.035)
LNPD	0.040	0.016
	(0.140)	(0.049)
J-Statistic	30.031	31.005
Prob (J-Statistic)	0.148	0.123
Instrument rank	31	31
Total Panel Unbalanced Observations	275	275

Notes: A * (**) (***) denotes significance at the 10% (5%) and (1%) levels respectively.

Due to several unrecorded years for NOx and smoke and dust emissions data presented in Tables 4 and 5, the regression models for these two pollutant emissions are only estimated from 2011 to 2017, including 6 time series and 155 observations. Smoke and dust emissions and economic growth can be verified as having an inverse U-shaped curve, but there is an absence of the EKC between NO_x emissions and income levels. Regarding the smoke and dust emissions, GDP per capita produces a turning point of CNY 50,507 under the orthogonal deviations transformation. Although the relationship between investment in pollution treatment and NO_x emissions remained negative and government expenditure and the emissions was positive again, the EKC relationship does not apply to this type of emission in China, possibly as it is mainly associated with industrial rather than household use.

Regarding the smoke and dust emissions, the significant coefficient indicates a negative effect from environmental investment and government expenditure on dust and smoke emissions, but there is again a positive sign obtained in the estimated coefficient of $lnGovExp$ for NO_x emissions. The movements in the pollutants recently have varied, so the changes have different effects on how the environmental protection inputs are related to emissions reduction. Overall, investments have been effective in reducing emissions across the different types of pollutant; however, expenditure has only been effective for smoke and dust emissions so far. This could be because smoke and dust have been a particular problem in China, affecting health and so have been the most-targeted emissions by the authorities in terms of spending on pollutant reduction. This was particularly the case in the lead up to the Olympics in China, and this success has been repeated in subsequent years. However, other emissions such as carbon dioxide are less obvious and so have possibly received less attention.

Table 4. Nitrogen oxide emissions.

Nitrogen Oxide Emissions	First Differenced	Orthogonal Deviations
Estimation	Coefficient and SE	Coefficient and SE
LNNOX(-1)	0.803 ***	1.097 ***
	(0.094)	(0.064)
LNGDPPC	−0.895	−7.313 ***
	(3.969)	(2.748)
LNGDPPC2	−0.028	0.305 **
	(0.185)	(0.126)
LNECE	0.546 **	0.158
	(0.270)	(0.173)
LNINVESTMENT	−0.058 **	−0.109 ***
	(0.023)	(0.036)
LNGOVEXP	0.237 ***	0.350 ***
	(0.077)	(0.065)
LNTRADE	0.602 ***	0.491 ***
	(0.112)	(0.096)
LNPD	0.472 ***	0.183
	(0.115)	(0.179)
J-Statistic	20.754	18.309
Prob (J-Statistic)	0.108	0.193
Instrument rank	22	22
Total Panel Unbalanced Observations	155	155

Notes: A ** (***) denotes significance at the 5% and (1%) levels respectively.

Additionally, across all the specifications, other control variables have produced some interesting findings. Firstly, the energy consumption of electricity has the expected positive relationship with SO_2 and NO_x emissions, which illustrates its relevance regarding increases in pollutant emissions. Increasing demand for electricity by the public can lead to SO_2 emissions increasing, as it is a by-product of electricity generation. Nevertheless, the results are not conclusive; electric energy consumption is insignificant for COD and smoke and dust emissions, again due to the lower relevancy for this type of emission. Secondly, environmental deterioration can be affected by trade openness in China, which shows that all pollutant emissions have the expected, statistically significant, positive relationship with total exports and imports. Thirdly, the results of population density in China are positively associated with all emissions and statistically significant to SO_2 and NO_x emissions, which indicates that a higher population density can lead to an increase in pollutant emissions, suggesting the main cities are responsible for much of the pollution in China.

Table 5. Smoke and dust emissions.

Smoke and Dust Emissions	First Differenced	Orthogonal Deviations
Estimation	Coefficient and SE	Coefficient and SE
LNDUST(-1)	0.933 ***	0.630 ***
	(0.097)	(0.065)
LNGDPPC	−0.673	15.136 ***
	(7.993)	(3.213)
LNGDPPC2	0.077	−0.699 ***
	(0.390)	(0.159)
LNECE	−0.659	−0.344
	(0.631)	(0.247)
LNINVESTMENT	−0.0061	−0.311 ***
	(0.060)	(0.055)
LNGOVEXP	−1.047	−0.524 ***
	(0.324)	(0.137)
LNTRADE	1.570 ***	−0.023
	(0.249)	(0.169)
LNPD	0.359	0.219
	(0.381)	(0.216)
J-Statistic	18.609	24.254
Prob (J-Statistic)	0.180	0.043
Instrument rank	22	22
Total Panel Unbalanced Observations	155	155

Notes: A *** denotes significance at the 1% level.

5. Discussion and Conclusions

In conclusion, this analysis has conducted an empirical study of the relationship between pollutant emissions and income per capita. The results somewhat support the EKC hypothesis overall, finding the inverse the U-shaped curves between income per capita and three pollutant emissions (SO_2, COD, and smoke and dust emissions), as found by [44] among others. Moreover, the results reveal that the green financial inputs (investment in pollution treatment and government expenditures on environmental protection) can be effective in terms of pollution control and environmental improvement, also as found in other studies on China, such as [39,40].

Regarding the existence of the EKC with sulfur emissions in China, the turning point appears to have passed the initial stages of the EKC curve. Additionally, across the eleven-year period, COD emissions and income levels show an inverse U-shaped relationship. This compares with previous research carried out by Shen [45] which found the existence of an inverted U-shaped curve with a peak value at CNY 6547 for COD emissions during the time period 1993–2002, whilst a further study obtained a turning point at CNY 6859 within the time period 1990–2007 [46]. The turning point found here was less, due to the use of more recent data. These two results were obtained with only quadratic forms of the estimation models, so they only provide one turning point.

To capture the benefits of environmental support in China, we have included the measures of government expenditure on environmental protection and investment in pollution treatment. Investment in pollution treatments has had a negative relationship with all emissions, although not this relationship is not significant for nitrous oxide. This provides evidence that the investment in the environment supported environmental improvements over the period of 2004–2017. However, government expenditure was only significantly negative for smoke and dust, possibly due to the more obvious effects of these pollutants in China's cities and a need for action to reduce the harmful effects on health. For the other pollutants, the effect was positively signed, suggesting that this spending has been less effective. Additionally, trade openness affects pollution levels, with the results showing a positive relationship with SO_2, NO_x, COD and smoke and dust emission, implying that trade has had a negative effect in terms of water pollution and air pollution. Moreover, population density has very similar effects on emissions changes, suggesting that an increasingly heavy population burden could lead to a rise in SO_2 and NO_x emissions.

Policy Implications

The Chinese government is working on promoting green economic growth and striving to reduce pollutant emissions with increasing environmental spending. In 2016, the thirteenth Five Year Plan (FYP) proposed plans for more strict targets for the eco-environmental quality, pollution discharges and ecological restoration by 2020. For example, air quality among 338 cities needs to reach more than 80% of days with good air quality, and ground water should increase by more than 70% to reach the level III or better by 2020. Although the targets set by the central and local government appear ambitious, environmental improvement cannot be completely achieved rapidly and must be viewed as a global long-term task.

The results have several implications. Firstly, investment and government spending on environmental protection and energy saving should be encouraged by both the government and the public, targeting multiple emissions. Therefore, methods need to be introduced to increase financial inputs to encourage green growth, as well as the most effective ways to utilise the money. Secondly, the sources of air and water pollution should continue to be controled using alternative methods of production that are more environmental-friendly, thus leading to decreases in pollutant emissions. Regarding reducing vehicle exhausts, the government should encourage electric cars and invest in the research and development of new-energy vehicles and enhance its related policies, such as increasing the number of charging stations. Likewise, alternative forms of transportation can reduce the public transport burden. For example, bicycle sharing and APP-based ride hailing services are popular in both metropolitans and small cities in China. These new means of transportation can reduce the rate of private car ownership and consequently reduce vehicle emissions; however, related laws and policies should be developed with these new forms of transport to ensure their effectiveness and public safety. Thirdly, environmental trade barriers need to be investigated to reduce the pollution from trade. Fourthly, the government should use its industrial strategy to support the transition to cleaner energy sources, such as natural gas or renewable energy.

Environmental protection is not just the responsibility of the government or large enterprises; altering the behaviour of individuals is perhaps the most powerful tool in building greener societies. However, the awareness of the need for environmental protection is largely predicated on the current economic situation. In less developed regions, poverty still persists, with some citizens unable to satisfy their basic human needs, and this is the reason why the “electricity for coal and gas for coal” policy cannot effectively compete for winter heating in northern China in 2017. Therefore, the policy maker should consider how to best support poorer areas which cannot afford high environmental standards.

Further EKC research in China could use a longer time period to analyse the regional effects (e.g., the separate economic regions of the east coast, western central and northeast). Regional factors could provide better estimations to test the existence of the EKC in different economic regions and find evidence of regional contributions on pollution reduction. Additionally, the government should enhance data transparency from both governments and firms to help improve efficiency and public supervision.

Because of the existence of the EKC in China, composition and technical effects will likely play an important role in the future for low carbon sustainable economic development, which corresponds with the economic structural transformation and energy-saving technical methods needed to achieve a green economy. In terms of green finance, the financial methods should focus on financial services and products to support rising incomes but falling environmental degradation in the decreasing section of the EKC.

The benefits arising from the study in terms of their implications for the practice of environmental policy and expenditure mainly relate to the evidence of the EKC in some pollutants and the significant negative effects of environmental investments on reducing the pollutants overall. It suggests that increasing government expenditure on the environment is not as effective and efficient as increasing the private and public sector investment levels, so policies to encourage more private and public sector investment should be used, such as the use of subsidies and some taxes to promote more investment. However, it could be argued that government spending will be more orientated towards the long-term benefits of the environment, so as of now it is more difficult to pick this effect up in this analysis, whereas the investment would require a more immediate effect. It is also clear that the effect of both varies across pollutants, so policies may need to be tailored to the specific pollutant. Overall environmental projects should be encouraged with more green investment and both central and local authorities should improve the effectiveness of financial support for environmental protection.

The evidence on the EKC holding for some pollutants in China also points to differing policies for the various pollutants. It also suggests that as China becomes increasingly developed, so it will naturally be able to reduce emissions across some sectors. Increased trade seems to have exacerbated the pollution; this could be partially due to some economies exporting their pollution to China in the recent past, although this has arguably been changing more recently. Overall, the regions with greater population density have higher pollution; this could well reflect the increased urbanisation in some regions. This would suggest future policies could target those areas that have experienced the most urbanisation over recent years.

Although the effects differ across the pollutants, the one effect that is homogenous is that of trade on pollution. Its smallest effect is on sulfur dioxide, with a 1% rise in trade, producing a rise of between 0.2 and 0.3% in sulfur dioxide emissions; this may be due to much of this pollutant originating from coal, which is mostly supplied domestically, with China being the largest coal producer in the world. The largest effect from trade is on dust emissions; the differenced specification suggests a 1% rise in trade produces a 1.57% rise in smoke and dust emissions. This could be due to the amounts of imported waste burned in China, as up until 2017, China was the largest importer of waste, especially plastics in the world. However, more recently, beginning in 2017 and continuing up until 2019, China has banned the importation of large amounts of foreign waste, including plastics and textiles. This policy should improve the pollution in terms of dust and smoke, and the trade in this area needs to be monitored closely. In addition, modifications to the recent restrictions must be implemented where necessary.

Author Contributions: Conceptualization, L.C. and A.H.; methodology, L.C. and B.M.; software, L.C.; validation, L.C., A.H. and B.M.; formal analysis, L.C. and B.M.; investigation, A.H.; resources, L.C. and A.H.; data curation, L.C.; writing—original draft preparation, L.C. and A.H.; writing—review and editing, B.M.; visualization, L.C.; supervision, A.H. and B.M.; project administration, A.H. All authors have read and agreed to the published version of the manuscript.

Funding: There was no external funding for this research.

Data Availability Statement: The data are publicly available from the Chinese Statistical Yearbook and the Chinese Environmental Statistical Yearbook.

Acknowledgments: We would like to thank the Editor and two anonymous referees for their helpful and constructive comments. The usual disclaimer applies.

Conflicts of Interest: The authors declare no conflict of interest.

Appendix A

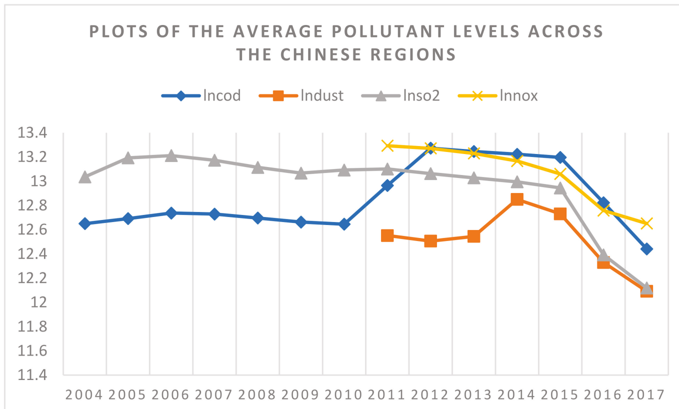


Figure A1. Plots of the average pollutant levels across all Chinese regions.

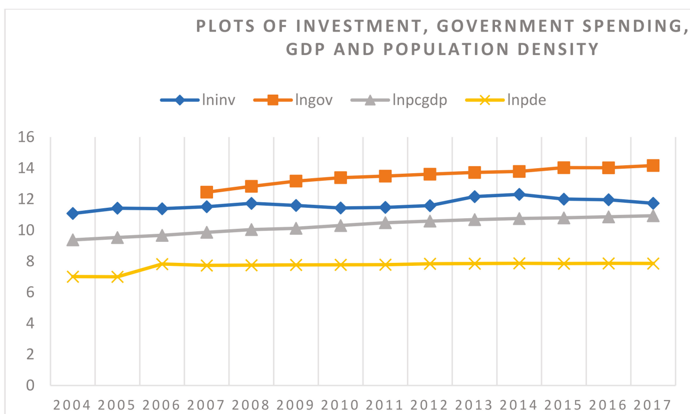


Figure A2. Plots of investment, government spending, GDP and population density.

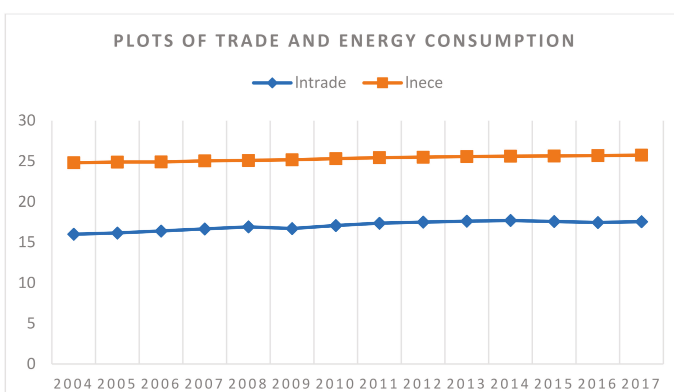


Figure A3. Plots of trade and energy consumption.

Table A1. Panel unit root tests.

	LLC		IPS	
Variable	**Level**	**Diff**	**Level**	**Diff**
Lncod	1.290	−15.845 **	0.790	−8.285 **
Lndust	6.473	−4.875 **	3.850	0.855
Lnso2	12.651	−6.248 **	11.728	−1.373 *
Lnnox	9.636	−3.474 **	8.246	−0.136
Lngov	−8.857 **		−2.376 **	
Lninv	−4.195 **		−2.462 **	
Lngdppc	−15.447 **		−5.930 **	
Lngdppc2	−13.045 **		−4.027 **	
Lnpd	−16.870 **		−11.296 **	
Lntrade	−8.760 **		−2.811 **	
lnece	−9.712 **		−2.967 **	

Notes: LLC is the Levin Lin and Chu test, IPS is the IM Pesaran and Shin test. A ** (*) indicates rejection of the null hypothesis at the 5% (10%) significance levels.

Table A2. Sulfur dioxide emissions.

Sulfur Dioxide Emissions	**First Differenced**	**Orthogonal Deviations**
Estimation	Coefficient and SE	Coefficient and SE
ΔLNSO2(-1)	0.075 ***	0.020
	(0.029)	(0.027)
LNGDPPC	7.220 ***	4.043 ***
	(1.680)	(0.589)
LNGDPPC2	−0.404 ***	−0.230 ***
	(0.080)	(0.029)
LNECE	0.282	0.258 **
	(0.286)	(0.102)
LNINVESTMENT	−0.008	−0.044 ***
	(0.010)	(0.007)
LNGOVEXP	0.233 ***	0.050 ***
	(0.018)	(0.015)
LNTRADE	0.370 ***	0.233 ***
	(0.033)	(0.020)
LNPD	0.645 ***	0.279 ***
	(0.090)	(0.064)
J-Statistic	22.979	28.260
Prob (J-Statistic)	0.462	0.191
Instrument rank	31	31
Total Panel Unbalanced Observations	244	275

Notes: A ** (***) denotes significance at the 5% and (1%) levels respectively.

Table A3. Chemical oxygen demand.

COD Emissions	**First Differenced**	**Orthogonal Deviations**
Estimation	Coefficient and SE	Coefficient and SE
ΔLNCOD(-1)	−0.236 ***	−0.114 ***
	(0.038)	(0.017)
LNGDPPC	9.167 **	4.202 ***
	(4.464)	(1.048)
LNGDPPC2	−0.521 **	−0.249 ***
	(0.221)	(0.052)
LNECE	0.478	0.008
	(0.426)	(0.142)
LNINVESTMENT	−0.251 ***	−0.124 ***
	(0.051)	(0.014)

Table A3. *Cont.*

COD Emissions	First Differenced	Orthogonal Deviations
Estimation	Coefficient and SE	Coefficient and SE
LNGOVEXP	0.336 **	0.211 ***
	(0.153)	(0.046)
LNTRADE	0.769 ***	0.495 ***
	(0.121)	(0.027)
LNPD	0.272	0.136
	(0.401)	(0.132)
J-Statistic	26.601	28.694
Prob (J-Statistic)	0.273	0.191
Instrument rank	31	31
Total Panel Unbalanced Observations	275	275

Notes: A ** (***) denotes significance at the 5% and (1%) levels respectively.

Table A4. Nitrogen oxide emissions.

NOX Emissions	First Differenced	Orthogonal Deviations
Estimation	Coefficient and SE	Coefficient and SE
ΔLNNOX(-1)	−1.211 ***	−1.273 ***
	(0.220)	(0.370)
LNGDPPC	−1.941	0.473
	(6.741)	(7.936)
LNGDPPC2	0.027	−0.094
	(0.308)	(0.366)
LNECE	−0.474	−0.754
	(0.514)	(0.718)
LNINVESTMENT	−0.041	−0.043
	(0.063)	(0.069)
LNGOVEXP	0.201	0.328 *
	(0.149)	(0.181)
LNTRADE	0.386 ***	0.297
	(0.133)	(0.186)
LNPD	0.223	0.120
	(0.158)	(0.456)
J-Statistic	14.141	12.728
Prob (J-Statistic)	0.117	0.175
Instrument rank	17	17
Total Panel Unbalanced Observations	124	124

Notes: A * (***) denotes significance at the 10% and (1%) levels respectively.

Table A5. Smoke and dust emissions.

Smoke and Dust Emissions	First Differenced	Orthogonal Deviations
Estimation	Coefficient and SE	Coefficient and SE
ΔLNDUST(-1)	0.230	0.023
	(0.178)	(0.128)
LNGDPPC	−6.091	−7.076
	(14.323)	(10.156)
LNGDPPC2	0.263	0.235
	(0.664)	(0.488)
LNECE	1.172	−0.149
	(1.307)	(0.467)
LNINVESTMENT	−0.254	−0.281 *
	(0.181)	(0.007)
LNGOVEXP	−0.747	0.146
	(0.501)	(0.378)

Table A5. *Cont.*

Smoke and Dust Emissions	First Differenced	Orthogonal Deviations
LNTRADE	1.415 ***	0.576 ***
	(0.328)	(0.194)
LNPD	0.645	−0.563
	(0.585)	(0.583)
J-Statistic	9.704	15.439
Prob (J-Statistic)	0.375	0.08
Instrument rank	17	17
Total Panel Unbalanced Observations	124	124

Notes: A * (***) denotes significance at the 10% and (1%) levels respectively.

References

1. Shahbaz, M.; Solarin, S.A.; Ozturk, I. Environmental Kuznets Curve hypothesis and the role of globalization in selected African countries. *Ecol. Indic.* **2016**, *67*, 623–636. [CrossRef]
2. Apergis, N.; Ozturk, I. Testing Environmental Kuznets Curve hypothesis in Asian countries. *Ecol. Indic.* **2015**, *52*, 16–22. [CrossRef]
3. Zhao, X.; Fan, X.; Liang, J. Kuznets type relationship between water use and economic growth in China. *J. Clean. Prod.* **2017**, *168*, 1091–1100. [CrossRef]
4. Dong, K.; Sun, R.; Dong, C.; Li, H.; Zeng, X.; Ni, G. Environmental Kuznets curve for PM2.5 emissions in Beijing, China: What role can natural gas consumption play? *Ecol. Indic.* **2018**, *93*, 591–601. [CrossRef]
5. Grossman, G.M.; Krueger, A.B. *Environmental Impacts of a North American Free Trade Agreement (No. w3914)*; National Bureau of Economic Research: Cambridge, MA, USA, 1991.
6. Grossman, G.M.; Krueger, A.B. Economic growth and the environment. *Q. J. Econ.* **1995**, *110*, 353–377. [CrossRef]
7. Panayotou, T. *Empirical Tests and Policy Analysis of Environmental Degradation at Different Stages of Economic Development. Working Paper WP238*; Technology and Employment Programme; International Labour Organization: Geneva, Switzerland, 1993.
8. Kuznets, S. Economic Growth and Income Inequality. *Am. Econ. Rev.* **1955**, *45*, 1–28.
9. IBRD. *World Development Report 1992. Development and the Environment*; Oxford University Press: New York, NY, USA, 1992.
10. Shafik, N.; Bandyopadhyay, S. *Economic Growth and Environmental Quality: Time Series and Crosscountry Evidence. Background Paper for the World Development Report 1992*; The World Bank: Washington, DC, USA, 1992.
11. Pao, H.-T.; Tsai, C.-M. Multivariate Granger causality between CO_2 emissions, energy consumption, FDI (foreign direct investment) and GDP (gross domestic product): Evidence from a panel of BRIC (Brazil, Russian Federation, India, and China) countries. *Energy* **2011**, *36*, 685–693. [CrossRef]
12. Shahbaz, M.; Mutascu, M.; Azim, P. Environmental Kuznets curve in Romania and the role of energy consumption. *Renew. Sustain. Energy Rev.* **2013**, *18*, 165–173. [CrossRef]
13. Ang, J.B. CO_2 emissions, energy consumption, and output in France. *Energy Policy* **2007**, *35*, 4772–4778. [CrossRef]
14. Hamit-Haggar, M. Greenhouse gas emissions, energy consumption and economic growth: A panel cointegration analysis from Canadian industrial sector perspective. *Energy Econ.* **2012**, *34*, 358–364. [CrossRef]
15. Rafindadi, A.A. Revisiting the concept of environmental Kuznets curve in period of energy disaster and deteriorating income: Empirical evidence from Japan. *Energy Policy* **2016**, *94*, 274–284. [CrossRef]
16. Taguchi, H. The environmental kuznets curve in Asia: The case of sulphur and carbon emissions. *Asia-Pac. Dev. J.* **2012**, *19*, 77–92. [CrossRef]
17. Brajer, V.; Mead, R.W.; Xiao, F. Searching for an Environmental Kuznets Curve in China's air pollution. *China Econ. Rev.* **2011**, *22*, 383–397. [CrossRef]
18. Akbostancı, E.; Türüt-Aşık, S.; Tunç, G.I. The relationship between income and environment in Turkey: Is there an environmental Kuznets curve? *Energy Policy* **2009**, *37*, 861–867. [CrossRef]
19. Orubu, C.O.; Omotor, D.G. Environmental quality and economic growth: Searching for environmental Kuznets curves for air and water pollutants in Africa. *Energy Policy* **2011**, *39*, 4178–4188. [CrossRef]
20. Cropper, M.; Griffiths, C. The interaction of population growth and environmental quality. *Am. Econ. Rev.* **1994**, *84*, 250–254.
21. Fujii, H.; Iwata, K.; Chapman, A.; Kagawa, S.; Managi, S. An analysis of urban environmental Kuznets curve of CO_2 emissions: Empirical analysis of 276 global metropolitan areas. *Appl. Energy* **2018**, *228*, 1561–1568. [CrossRef]
22. Al-Mulali, U.; Ozturk, I.; Solarin, S.A. Investigating the environmental Kuznets curve hypothesis in seven regions: The role of renewable energy. *Ecol. Indic.* **2016**, *67*, 267–282. [CrossRef]
23. Iwata, H.; Okada, K.; Samreth, S. Empirical study on the environmental Kuznets curve for CO_2 in France: The role of nuclear energy. *Energy Policy* **2010**, *38*, 4057–4063. [CrossRef]
24. Dinda, S. Environmental Kuznets Curve Hypothesis: A Survey. *Ecol. Econ.* **2004**, *49*, 431–455. [CrossRef]

25. Pablo-Romero, M.D.P.; Sánchez-Braza, A. Residential energy environmental Kuznets curve in the EU-28. *Energy* **2017**, *125*, 44–54. [CrossRef]
26. Abid, M. Does economic, financial and institutional developments matter for environmental quality? A comparative analysis of EU and MEA countries. *J. Environ. Manag.* **2017**, *188*, 183–194. [CrossRef] [PubMed]
27. Acaravci, A.; Ozturk, I. On the relationship between energy consumption, CO_2 emissions and economic growth in Europe. *Energy* **2010**, *35*, 5412–5420. [CrossRef]
28. Luzzati, T.; Orsini, M.; Gucciardi, G. A multiscale reassessment of the Environmental Kuznets Curve for energy and CO_2 emissions. *Energy Policy* **2018**, *122*, 612–621. [CrossRef]
29. Sarkodie, S.A.; Strezov, V. Empirical study of the Environmental Kuznets curve and Environmental Sustainability curve hypothesis for Australia, China, Ghana and USA. *J. Clean. Prod.* **2018**, *201*, 98–110. [CrossRef]
30. Wang, S.; Zhou, D.; Zhou, P.; Wang, Q. CO_2 emissions, energy consumption and economic growth in China: A panel data analysis. *Energy Policy* **2011**, *39*, 4870–4875. [CrossRef]
31. Jalil, A.; Feridun, M. The impact of growth, energy and financial development on the environment in China: A cointegration analysis. *Energy Econ.* **2011**, *33*, 284–291. [CrossRef]
32. Yang, H.; He, J.; Chen, S. The fragility of the Environmental Kuznets Curve: Revisiting the hypothesis with Chinese data via an "Extreme Bound Analysis". *Ecol. Econ.* **2015**, *109*, 41–58. [CrossRef]
33. Yin, J.; Zheng, M.; Chen, J. The effects of environmental regulation and technical progress on CO_2 Kuznets curve: An evidence from China. *Energy Policy* **2015**, *77*, 97–108. [CrossRef]
34. Riti, J.S.; Song, D.; Shu, Y.; Kamah, M. Decoupling CO_2 emission and economic growth in China: Is there consistency in estimation results in analyzing environmental Kuznets curve? *J. Clean. Prod.* **2017**, *166*, 1448–1461. [CrossRef]
35. He, J.; Wang, H. Economic structure, development policy and environmental quality: An empirical analysis of environmental Kuznets curves with Chinese municipal data. *Ecol. Econ.* **2012**, *76*, 49–59. [CrossRef]
36. Hao, Y.; Liu, Y.; Weng, J.-H.; Gao, Y. Does the Environmental Kuznets Curve for coal consumption in China exist? New evidence from spatial econometric analysis. *Energy* **2016**, *114*, 1214–1223. [CrossRef]
37. Wang, S.X.; Fu, Y.B.; Zhang, Z.G. Population growth and the environmental Kuznets curve. *China Econ. Rev.* **2015**, *36*, 146–165. [CrossRef]
38. Zheng, S.; Yi, H.; Li, H. The impacts of provincial energy and environmental policies on air pollution control in China. *Renew. Sustain. Energy Rev.* **2015**, *49*, 386–394. [CrossRef]
39. Chen, C.; Wang, B.; Fu, Q.; Green, C.; Streets, D.G. Reductions in emissions of local air pollutants and co-benefits of Chinese energy policy: A Shanghai case study. *Energy Policy* **2006**, *34*, 754–762.
40. Shen, C.; Li, S.; Wang, X.; Liao, Z. The effect of environmental policy tools on regional green investment: Evidence from China. *J. Clean. Prod.* **2020**, *254*, 120122. [CrossRef]
41. EPA. Basic information about NO2. 2016. Available online: https://www.epa.gov/no2-pollution/basic-information-about-no2 (accessed on 25 September 2018).
42. Arellano, M.; Bond, S. Some Tests of Specification for Panel Data: Monte Carlo Evidence and an Application to Employment Equations. *Rev. Econ. Stud.* **1991**, *58*, 277–297. [CrossRef]
43. Arellano, M.; Bover, O. Another look at the instrumental variable estimation of error-components models. *J. Econ.* **1995**, *68*, 29–51. [CrossRef]
44. Bellemare, M.F.; Masaki, T.; Pepinsky, T.B. Lagged Explanatory Variables and the Estimation of Causal Effect. *J. Politics* **2017**, *79*, 949–963. [CrossRef]
45. Shen, J. A simultaneous estimation of Environmental Kuznets Curve: Evidence from China. *China Econ. Rev.* **2006**, *17*, 383–394. [CrossRef]
46. Jayanthakumaran, K.; Liu, Y. Openness and the Environmental Kuznets Curve: Evidence from China. *Econ. Model.* **2012**, *29*, 566–576. [CrossRef]

sustainability

Article

Evaluation of Sustainable Development of Tourism Cities Based on SDGs and Tourism Competitiveness Index: Analysis of 221 Prefecture-Level Cities in China

Junli Gao [1,2], Chaofeng Shao [1,*], Sihan Chen [1] and Zizhang Wei [3,*]

1 College of Environmental Science and Engineering, Nankai University, Tianjin 300350, China; gaojunli0307@126.com (J.G.); chensihan26@163.com (S.C.)
2 Laboratory of Environmental Planning and Policy, Shenzhen Academy of Environmental Sciences, Shenzhen 518000, China
3 Environmental Engineering Assessment Center, Tianjin Academy of Eco-Environmental Sciences, Tianjin 300350, China
* Correspondence: shaocf@nankai.edu.cn (C.S.); wzzh73@163.com (Z.W.)

Abstract: Based on the Sustainable Development Goals and competitiveness index, an evaluation index system for sustainable development of tourism cities was established. The sustainable development level of 221 outstanding tourism cities in 2018 was evaluated, and their sustainable development paths were designed accordingly. The results show the following: (1) There is a large gap in sustainable development scores. In general, no city has achieved a strong sustainable development model. Natural and cultural resources and protection systems are the shortcomings of the systems. (2) The weights of natural and cultural resources and protection systems are the largest, and the weights of natural and cultural resources endowment, degree of tourism infrastructure construction, and economic support for natural and cultural resources are larger. Nature reserve coverage index, network popularity, and other indicators have greater weight. (3) There is a gap in the sustainable development level of tourism cities in the eight comprehensive economic zones. The economic zones in the eastern and southern coastal areas are better than those in the northwest and the middle reaches of the Yellow River. (4) The driving factors of the eight types of tourism cities distinguished by their characteristics are basically the same, but the obstacles are different.

Keywords: sustainable development goals; tourism competitiveness index; tourism city; sustainability level; path design

Citation: Gao, J.; Shao, C.; Chen, S.; Wei, Z. Evaluation of Sustainable Development of Tourism Cities Based on SDGs and Tourism Competitiveness Index: Analysis of 221 Prefecture-Level Cities in China. *Sustainability* **2021**, *13*, 12338. https://doi.org/10.3390/su132212338

Academic Editors: Baojie He, Ayyoob Sharifi, Chi Feng and Jun Yang

Received: 18 October 2021
Accepted: 4 November 2021
Published: 9 November 2021

1. Introduction

The global Agenda 21 points out that sustainable development indicators must be designated in order to provide a solid theoretical basis for decision makers at all levels and to promote an integrated and self-regulating capacity for sustainable development of the environment and development systems [1]. In September 2015, the leaders of all UN member states adopted the 2030 Agenda for Sustainable Development in the form of Sustainable Development Goals (SDGs). The 17 SDGs seek to solve economic, social, and environmental problems in a sustainable way, supported by good governance [2]. Since then, the Inter-Agency and Expert Group on SDG Indicators (IAEG-SDGs) has put forward a global monitoring indicator framework applicable at the country level [3]. There is growing recognition of the importance of implementing the United Nations 2030 Agenda for Sustainable Development Goals and achieving the SDGs at the local level [4]. Achieving these global aspirations requires local commitment and action by local governments [5]. The Global Task Force on Local and Regional Government points out that localization is about how the SDGs provide a framework for local development policies as well as how local and regional governments support achieving the SDGs through bottom-up action [6]. In terms of SDG localization, previous research has shown that the main challenges and opportunities are in cities, and they affect all SDGs, not just SDG 11 (sustainable cities and communities) [7–9].

Over the past decades, travel and tourism, with their beneficial ecosystems, have proved to be important drivers of economic growth, contributing more than 10% of global GDP and accounting for one in ten jobs globally. The sector continues to be a force for good, offering unique opportunities for developing and emerging countries to move up the value chain. In the context of the rapid development of the cultural tourism industry, evaluating the sustainability of tourism destinations is a key direction of sustainable tourism research [10]. By applying and developing sustainable development evaluations and implementing strategies at the city level, sustainability research has become integral to the current high-quality development of the tourism industry and cities. Savage [11] notes that adopting a holistic view is conducive to measuring the sustainability of urban tourism development. Lee et al. [12] pointed out that in order to achieve long-term sustainability, it is necessary to ensure the sustainable use of the ecological environment and improve the reliability of destinations and the quality of tourism services. At present, there are many studies on the sustainable development of tourism, but relatively few on the sustainable development of tourism cities. Based on previous studies, Wang [13] tried to establish an evaluation index system of sustainable development capacity of small and medium-sized tourism cities. Taking Lijiang city as an example, Li [14] discussed the roots and internal mechanism of the vulnerability of the economic systems of tourism-oriented cities, and put forward countermeasures and suggestions to realize their sustainable development. Yin [15] put forward the context of sustainable development of tourism cities in terms of the time, space, and development scales, and presented countermeasures and suggestions for sustainable development of international tourism cities. Perez et al. [16] constructed a set of indicators to measure the sustainability of urban tourism. Different from the traditional static evaluation, Blancas et al. [17] established a dynamic evaluation index suitable for tourism-oriented cities through the objective planning method.

With increased competitiveness among tourism cities, studies evaluating this competitiveness arise at a historic moment. Most studies point out that the competitiveness of tourist destinations is a complex concept with multiple dimensions [18], which should be discussed from multiple perspectives. Many studies in this field have tried to quantify the competitiveness of tourism destinations using surveys conducted directly with tourists and other stakeholders [19,20], or using official statistics. Regardless of the source of information, most studies use a series of statistical techniques to quantify comprehensive competitiveness indicators. These indicators are conceptual-based and constructed by multiple variables in different dimensions [21,22]. However, there is no competitiveness evaluation index system for sustainable development in academic research, and the existing system often lacks social and economic basic data, which cannot truly reflect the development potential of tourism cities.

From the above literature review, it can be seen that under the background of the rapid development of cultural tourism industry and the rise of tourism cities, tourism cities have gradually become an important city type. At present, the evaluation of sustainable development of tourism cities mostly stays at the level of theoretical research, such as establishing an index system and identifying problems. There are few pieces research on the quantitative evaluation and practice of sustainable development of tourism cities based on SDGs.

What is the level of sustainable development of tourism cities? What are the factors that affect the sustainable development of tourism cities? How can a tourism city choose a sustainable development path suitable for its own development? How to evaluate the sustainable development of international tourism cities in the same context? These are becoming greater concerns for the government, scholars, and the general public. It is imperative to establish a sustainable development evaluation technology system for tourism cities, to quantitatively evaluate and scientifically identify bottlenecks that hinder actual needs, and the dual pressures of internal management and competition. The effort made in this article is to answer the above questions. Taking into account that the implementation of SDGs at the city level is an important part of China's implementation of the 2030 Agenda for Sustainable Development and the availability of relatively mature and referenceable tourism competitiveness index evaluation practices in the world, this paper constructs an evaluation framework for sustainable development of tourism cities based on the SDGs and tourism competitiveness index, forms a technical evaluation system of sustainable development of tourism cities, and evaluates the sustainable development level of 221 tourism cities in China in 2018.

2. Materials and Methods

2.1. Data and Study Area

Since China started to create outstanding tourism cities in 1998, nine groups of 339 cities have passed inspection. In this study, we eliminated cities with much missing data, and finally determined 221 outstanding tourism cities (prefecture-level and above) as the research objects, and evaluated their sustainable development level in 2018.

The data mainly come from public sources such as statistical yearbooks, statistical bulletins, reports, etc. Some indicators that could not be obtained directly were calculated twice by the raw data collected by the author, and the missing data were interpolated by the Replace Missing Values tool in SPSS.

2.2. Research Methods

The research methods can be summarized into four steps: (1) put forward a comprehensive evaluation system of urban sustainable development, (2) standardize and weigh each index in the evaluation system, (3) use a linear weighting method to calculate the final score of sustainable development of tourism cities, and (4) analyze the results from the point of view of overall results and geographic and characteristic zoning. Step four presents the sustainable development level of Chinese tourism cities, and designs their sustainable development paths with different characteristics according to the results of correlation analysis and comparison with other research results.

2.3. Evaluation Index System of Sustainable Development of Tourism Cities Based on SDGs and Tourism Competitiveness Index

The construction ideas of the evaluation index is shown in Figure 1. In this paper, we construct a sustainable development index system of tourism cities, which includes a protection system (A), a sustainable utilization system (B), and a social support system for natural and cultural resources economic (C); it includes three systems, ten pillars, 22 factor indicators, and 46 specific indicators. The sustainable development index system of tourism cities is closely related to the SDGs. The index system integrates SDG1, SDG3, SDG6, SDG8, SDG9, SDG10, SDG11, SDG12, SDG13, SDG14, SDG15, SDG16, SDG17, and other target indicators, as shown in Table 1. The indicator system includes single indicators (37) and comprehensive indicators (nine). When using this indicator system for evaluation, tourism cities can make adjustments without changing the meaning of the indicators according to their own statistical caliber and capabilities.

Table 1. Index system of sustainable development of tourism cities.

Element Indicators	Specific Indicators	SDG	
Resource abundance (A1I)	Heritage index (A10) [P]	11	11.4
	Scenic spot index (A11) [P]	15	15.1
Resource influence (A1II)	Network fever (A12) [P]	12	12b
	City well-known index (A13) [P]	12	12b
Resource protection (A2I)	Percentage of forest area in total land area (%) (A20) [P]	15	15.1
	Nature reserve coverage index (A21) [P]	14, 15	14.5, 15.5
	Urban greening index (A22) [P]	11	11.7

Table 1. *Cont.*

Element Indicators	Specific Indicators	SDG	
Ecological environment quality (A3I)	Total expenditure per capita for preservation, protection, and conservation of cultural and natural heritage (international dollar/person) (A23) P	11	11.4
	Annual average concentration of $PM_{2.5}$ ($\mu g/m^3$) (A30) N	11	11.6
	Proportion of days with good air quality (%) (A31) P	3, 11	3.9, 11.6
	Proportion of water bodies with good environmental quality (%) (A32) P	3, 6	3.9, 6.3
	Ecological index (A33) P	15	15.1
Ecological environment control (A3II)	Proportion of safe treatment of waste water (%) (A34) P	6	6.3
	Rate of harmless treatment of municipal solid waste (%) (A35) P	11	11.6
	Greenhouse gas emission intensity (ton carbon dioxide equivalent/international dollar) (A36) N	9, 13	9.4, 13.1
Development and utilization of natural and cultural resources (B1I)	Natural and cultural resource development and utilization index (B10) P	11	11.4
Tourism service infrastructure (B2I)	Tourism infrastructure index (B20) P	9	9.1
	Number of public transportation vehicles per 10,000 people (vehicles/10,000 people) (B21) P	11	11.2
	Road density (km/km^2) (B22) I	9	9.1
Cultural and stylistic infrastructure (B2II)	Cultural and sports facilities index (B23) P	11	11.7
Intelligent tourism facilities (B2III)	Number of wisdom scenic spots (unit) (B24) P	9	9c
Tourism economic performance (B3I)	Per capita tourism consumption expenditure (10,000 international dollar/person) (B30) P	8	8.9
	Per capita tourist reception (person-times/person) (B31) P	8	8.9
	Average annual growth rate of tourism income (%) (B32) P	8	8.9
Contribution of tourism economy (B3II)	Proportion of GDP directly from tourism (%) (B33) P	8	8.9
Sustainability of resource utilization (B4I)	Land development utilization rate (%) (B40) M	11	11.3
	Water resource development and utilization rate (%) (B41) M	6	6.4
Tourism carrying capacity (B4II)	Intensity of tourist space utilization (B42)	12	-
	Proportion of scenic spots exceeding maximum carrying capacity on holidays (%) (B43) N	12	-
	Tourism environmental carrying capacity (B44) M	12	-
Macroeconomic stability (C1I)	GDP per capita (international dollar/person) (C10) P	8	8.2
	Annual GDP growth rate (%) (C11) P	8	8.1
	Financial self-sufficiency rate (%) (C12)	8	-
International openness (C1II)	Proportion of foreign direct investment in GDP (%) (C13) P	17	-
	Freedom of trade (%) (C14) P	17	17.4
Industrial structure (C1III)	Proportion of tertiary industry (%) (C15) I	9	-
Tourism safety and health care (C2I)	Mortality due to road traffic injuries (%) (C20) N	3	3.6
	Density of health workers (per thousand) (C21) P	3	3.8
Resource communication readiness (C2II)	Percentage of population covered by mobile network (%) (C22) P	9	9.c
Social stability (C2III)	Unemployment rate (%) (C23) N	8	8.5
	Income gap between urban and rural residents (C24) M	10	10.1
	Proportion of expenditure on basic services (education, health, social protection) in total government expenditure (%) (C25) P	1	1.a
Administrative governance (C3I)	Number of law enforcement inspections in tourism market (times/year) (C30) P	16	16.6
	Rate of tourism complaint resolution (%) (C31) P	16	16.3
Rule of law (C3II)	Number of sustainable tourism strategies or policies and action plans implemented using agreed monitoring and evaluation tools (unit) (C32) P	12	12b
Association governance (C3III)	Number of tourist associations (unit) (C33) P	12	12b

Note: The larger the positive (P) index, the better; the smaller the negative (N) index, the better; the closer the interval (I) index falls between the upper and lower limits of the interval and the closer the moderate (M) index to a certain value, the better.

System A is subdivided into three pillars, which are natural and cultural resource endowment (A1), conservation of natural and cultural resources (A2), and ecological environment protection (A3). System B is subdivided into four pillars, which are degree of exploitation and utilization of natural and cultural resources (B1), degree of tourism infrastructure construction (B2), development of tourism economy (B3), and sustainability of tourism development (B4). System C is subdivided into three pillars, which are economic support for natural and cultural resources (C1), social support for natural and cultural resources (C2), and tourism industry governance (C3).

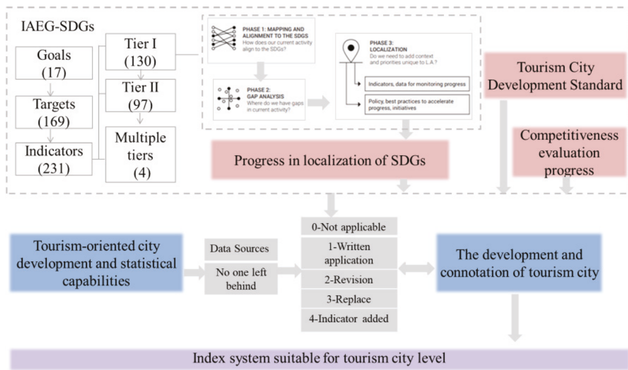


Figure 1. Construction of sustainable development index system for tourism cities. Note: SDG localization steps refer to Sustainable Development Goals of the City of Los Angeles: A Local Review of Progress in 2019 [23]; SDG localization progress mainly refers to relevant achievements at the global, regional, national, and sub-national level [24–35].

The evaluation index system adopted in this paper has the following advantages: indicators and definitions in the SDGs are adopted as much as possible, enhancing comparability and extensibility compared with other evaluation index systems, and considering the characteristics and development needs of tourism cities, elements of the index system are added, deleted, and modified in combination with the existing mature competitiveness index and tourism cities development standard. The evaluation index system is constructed according to the basic principle of systematization, and the various aspects of the sustainability of tourism cities are fully described based on hierarchical division.

2.4. Standardization and Weights

2.4.1. Standardization of Indicators

In order to eliminate the influence of dimension and attribute of indicators, this paper adopts the deviation standardization method (*i* min–max method), which improves the optimal and worst values of indicators to standardize the original data of positive and negative indicators. This paper refers to the five-step decision tree method [36] adopted in the SDG index and dashboard report released by SDSN, and determines the optimal and worst values of the selected indicators after adjustment. Tourism cities that exceed the optimal and worst values are one and zero, respectively, after standardization.

For interval and moderate indicators, the methods in Formulas (3) and (4) are adopted for standardization, in which the optimal interval of interval indicators and the optimum value of moderate indicators are determined by relevant provisions and literature review.

Standardization of positive indicators by the *i* min-max method is calculated as:

$$r_{ij} = \frac{x_{ij} - wor(x_{ij})}{opt(x_{ij}) - wor(x_{ij})},\ i = 1,\ 2,\ \ldots\ m,\ j = 1,\ 2,\ \ldots\ n \quad (1)$$

Standardization of negative indicators by the i min-max method is calculated as:

$$r_{ij} = \frac{wor(x_{ij}) - x_{ij}}{wor(x_{ij}) - opt(x_{ij})},\ i = 1,\ 2,\ \ldots\ m,\ j = 1,\ 2,\ \ldots\ n \quad (2)$$

where $opt(x_{ij})$ and $wor(x_{ij})$ represent the optimal and worst value of the ith evaluation index, respectively.

Standardization of moderate indicators is calculated as:

$$r_{ij} = 1 - \frac{x_{ij} - opt(x_{ij})'}{M},\ i = 1,\ 2,\ \ldots\ m,\ j = 1,\ 2,\ \ldots\ n \quad (3)$$

where $opt(x_{ij})'$ is the optimum value of the ith evaluation index, and M is the maximum value of the absolute value difference between all index values and the interval optimal value.

Standardization of interval indicators is calculated as:

$$r_{ij} = \begin{cases} 1 - \frac{a - x_{ij}}{M}, x_{ij} < a \\ 1, a < x_{ij} < b \\ 1 - \frac{x_{ij} - b}{M}, x_{ij} > b \end{cases},\ i = 1,\ 2,\ \ldots\ m,\ j = 1,\ 2,\ \ldots\ n \quad (4)$$

where [a,b] is the optimal interval of the ith evaluation index, and M = max {a − x_{ijmin}, x_{ijmax} − b}.

2.4.2. Weight Calculation

The average processing of all SDG index data does not conform to the 28th law of management [37]. Learning from the criticism of scholars on the weight assignment method of the tourism competitiveness index [38], this study adopts the combination weight assignment method. At present, the commonly used objective weight assignment method is the entropy weight method, but it does not consider the influence between indicators, and there is a phenomenon of unreasonable weight allocation to some extent. Therefore, this paper uses the principle of minimum information entropy to obtain the combined weight from the entropy weight and coefficient of variation methods [39].

$$minF = \sum_{i=1}^{m} w_i(lnw_i - lnw_{1i}) + \sum_{i=1}^{m} w_i(lnw_i - lnw_{21i}) \quad (5)$$

Here, $\sum_{i=1}^{m} w_i = 1$, $wi > 0$, and F is the objective function of the minimum information entropy model.

According to the Lagrange multiplier method, the above equation can be optimized as follows:

$$w_i = \frac{\sqrt{w_{1i} \times w_{2i}}}{\sum_{i=1}^{m} \sqrt{w_{1i} \times w_{2i}}} \quad (6)$$

2.5. Calculation of Sustainable Development Level of Tourism Cities Based on SDGs and Tourism Competitiveness Index

The score of the sustainable development level of tourism cities is calculated by the linear weighted function method and adjusted to the range of 0–100:

$$f(x) = (\sum_{k=1}^{a} w_{systemk} \sum_{h=1}^{b} w'_{pillarh} \sum_{o=1}^{c} w'_{Elements\ \ indicatoro} \sum_{i=1}^{n} w_i r_i) \times 100 \quad (7)$$

where i represents the number of indicators, o represents the number of index layers of each element, h represents the number of pillar layers, and k represents the number of system layers. w is the weight, and the sum of ownership weights of each layer is equal to one; *f(x)* is the score of the sustainable development level.

Sustainable development is divided into five levels (high, upper medium, medium, low, and extremely low) by referring to the internationally common isometric division method (20 points per interval as a level).

2.6. Three-Axis and Eight-Zone Classification Assessment

In this paper, the scores of systems A, B, and C are discussed in a comprehensive framework. Taking the score of system A as the x-axis, the score of system B as the y-axis, and the score of system C as the z-axis, the coordinate system to evaluate sustainable development of tourism cities was established. Taking the median scores of systems A, B, and C as the reference line, the three axes and eight districts for the evaluation are obtained, and the relevant positions for evaluating tourism cities are described. The region and sustainable development level of tourism cities are the basis for comparing and analyzing the current situation of urban sustainable development and putting forward paths for improvement.

2.7. Multiple Linear Regression Model

A multiple linear regression model is a model with multiple explanatory variables, which is used to explain the linear relationship between the explained variables and other explanatory variables [40]. Because the explained variable is a calculated numerical variable, and the explained variable is also a numerical variable, which accords with the basic conditions of phenomenal regression analysis, a multivariate linear regression model is constructed in this paper. The ordinary least square method is used to fit the regression equation and estimate the parameters [41]. The mathematical model of multiple linear regression is:

$$y = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \ldots + \beta_k x_k + \varepsilon \tag{8}$$

The above is a k-ary linear regression model, y is the explained variable, in this paper, it is the sustainable development level of tourism city; x is the explanatory variable, there are k explanatory variables, the explanatory variable in this paper is the sustainable development index of tourism city; β_0 is the constant term of the regression model; β_1, β_2, ..., β_k is the partial regression coefficient and ε is the random error of the regression model. Among them, the change of the explained variable y consists of two parts, the first part is the linear change part of y caused by the change of k explanatory variables x, and the second part is the change part of y caused by other random factors, namely ε.

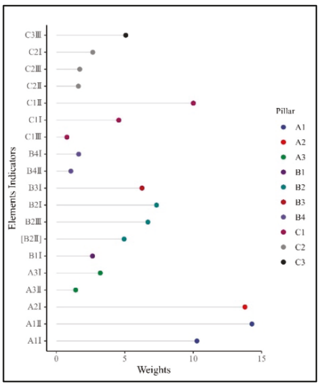
3. Results

3.1. Influence Weights of Each Indicator

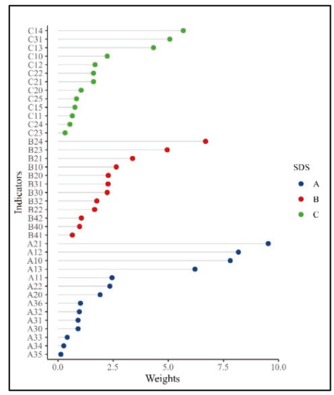
The weights of systems A, B, and C are 40, 33.35, and 26.52% respectively, indicating that natural and cultural resources and protection systems are the main drivers for evaluating the sustainability of tourism cities. The largest weights of pillars are natural and cultural resource endowment (A1), degree of tourism infrastructure construction (B2), and economic support of natural and cultural resources (C1). The weight distribution of factor indicators, and specific indicators is shown in Figure 2a,b.

As can be seen from Figure 2a, the factor indicators with the greatest weight in each pillar are resource influence (A1II), ecological environment quality (A3I), tourism service infrastructure (B2I), sustainability of resource utilization (B4I), international openness (C1II), and tourism safety and health care (C2I).

For a given index, the greater the weight, the greater the impact on the sustainable development of tourism cities. Figure 2b shows the five indicators that have the greatest impact on sustainable development: nature reserve coverage index (A21), network fever (A12), heritage index (A10), number of wisdom scenic spots (B24), and well-known city index (A13). The most important indicator is A21, and its influence weight is 9.53%. The influence weights of A12 and A13 are 8.18 and 6.21%, respectively, showing the importance of the popularity and public recognition of tourist cities. The influence weights of A10 and B24 are 7.81 and 6.69%, respectively, which shows the importance of developing intelligent tourism in the new era. The five indicators that have the least impact on the sustainability of tourism cities are income gap between urban and rural residents (C24), ecological index (A33), unemployment rate (C23), proportion of safe treatment of waste water (A34), and rate of harmless treatment of municipal solid waste (A35); the weights of these indicators are 0.54, 0.42, 0.32, 0.26, and 0.13%, respectively.



(a)



(b)

Figure 2. Weight distribution of (**a**) factor indicators and (**b**) specific indicators.

3.2. Overall Result

3.2.1. Overall Score

The score ranges for overall sustainable development and the major systems of China's tourism cities are [17.05, 62.24], [10.00, 46.61], [18.76, 76.10], and [17.59, 69.68], respectively. The three cities with the highest total scores are Beijing, Chongqing, and Chengdu. The top three cities with the highest scores in the A system are Tianjin, Beijing, and Danzhou. The three cities with the highest scores in the B system are Chengdu, Beijing, and Chengdu. In Chongqing, the three cities with the highest C system scores are Beijing, Shanghai, and Shenzhen. The average scores of the pillars under the A system are 12.59, 18.26, 78.57. The average scores of the pillars under the B system are 21.66, 23.35, 34.16, and 91.06. The average scores of each pillar under the C system are 25.23, 48.2, and 16.18, respectively.

The natural discontinuity classification method (Jenks) in ArcGIS was used to classify all of the scores into five categories. The geographical distribution of the evaluation results is shown in Figure 3.

3.2.2. Sustainability Level

On the whole, none of the tourism cities have reached a high level of sustainable development, and one city has reached upper medium level: Beijing, accounting for 0.41%, nine cities and have reached medium level: Chongqing, Chengdu, Tianjin, Shanghai, Hangzhou, Guangzhou, Xiamen, Shenyang, and Fuzhou, together accounting for 4.07%. In all, 198 cities are at a low level of sustainable development (accounting for 89.59%), while the remaining 12 cities are at a very low level (accounting for 5.43%). The level distribution of the sustainable development systems of tourism cities is similar to the overall results. There is a large gap in the levels of development among the pillars. Pillars with better overall performance are ecological environment protection (A3) and sustainability of tourism development (B4). More than 50% of the cities are at a high level of sustainable development. Pillars with poor performance are natural and cultural resources endowment (A1), conservation of natural and cultural resources (A2), and tourism industry governance

(C3), and more than 60% of the cities are at a lower level of sustainable development. Among them, the pillars conservation of natural and cultural resources (A2) in Zhoushan, degree of exploitation and utilization of natural and cultural resources (B1) in Chongqing and Beijing, degree of tourism infrastructure construction (B2) in Chengdu, and tourism industry governance (C3) in Beijing, Chengdu, Chongqing, and Shanghai are all at a high level of sustainable development.

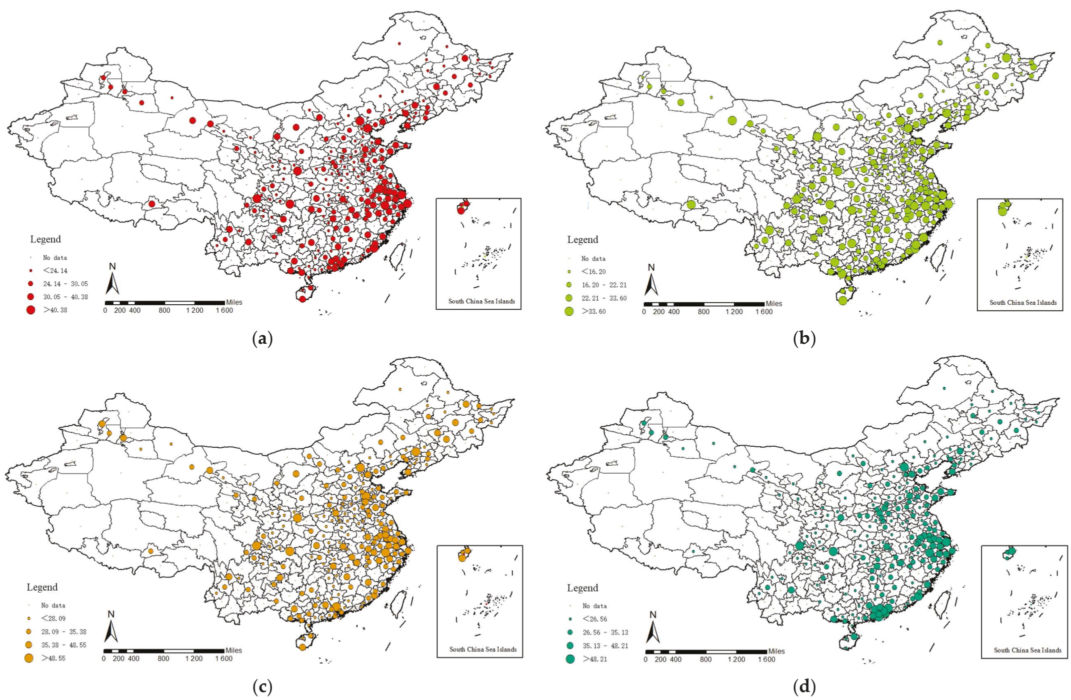


Figure 3. Geographic distribution of sustainable development scores of tourism cities: (**a**) overall score; (**b**–**d**) B, C, and D system scores.

3.3. Results and Analysis of the Eight Economic Zones

According to the report "Strategies and Policies for Coordinated Regional Development" issued by the Development Research Center of the State Council of the People's Republic of China, the mainland is divided into four plates and eight comprehensive economic zones. In order to facilitate a comparative analysis of cities in their economic zones, we obtained the regional distribution of 221 tourism cities with reference to the eight comprehensive economic zones. The average score of sustainable development of tourism cities in the eight economic zones is shown in Figure 4 As can be seen from Figure 4, the overall average score of sustainable development in the eastern coastal economic zone is the highest, while that of the middle reaches of the Yellow River is the lowest. Economic zones with the highest average scores for sustainable development in pillars A1, A2, A3, B1, B2, B3, B4, C1, C2, and C3 are the southern coastal areas, the middle reaches of the Yangtze and Yellow Rivers, the southern and eastern coastal areas, and the eastern coastal economic zone. The lowest economic zones are northwest, northern coastal, northeast, middle reaches of the Yellow River, northeast, northwest, eastern coastal, northwest, southwest, and northern coastal economic zones.

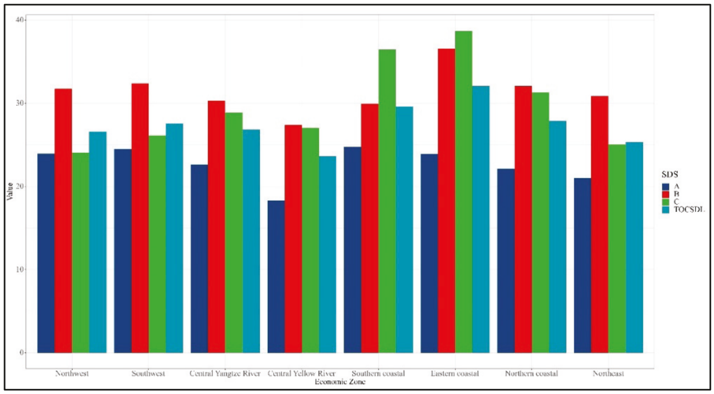


Figure 4. Average score of sustainable development of tourism cities as a whole and for 3 major systems according to economic zone.

3.4. Three-Axis, Eight-Zone Division Results and Analysis

Taking the median score of sustainable development of the systems for 221 cities, i.e., straight lines $x = 19.99$, $y = 26.83$, $z = 29.70$ as the baseline, sustainable development of the three-axis eight-zones of tourism cities in China was obtained, as shown in Table 2.

Table 2. Three-axis, eight-zone division of sustainable development of tourism cities.

Category	Number of Tourism Cities	Features (A-B-C)	Internal State
I	44	Low-low-low	Low
II	24	Low-low-high	Primary transformation
III	14	Low-high-low	Primary transformation
IV	28	Low-high-high	Advanced transformation
V	30	High-low-low	Primary transformation
VI	13	High-low-high	Advanced transformation
VII	22	High-high-low	Advanced transformation
VIII	46	High-high-high	High

To explore indicators affecting sustainable development, this paper defines the drivers as the five indicators with the highest sustainable development scores in the eight districts based on three-axis, eight-quadrant zoning, and the obstacles as the five indicators with the lowest scores, as shown in Figure 5. As can be seen from the figure, the main driving factors of and obstacles to sustainable development of tourism cities are different. Specifically, the main driving factors in the eight districts are proportion of safe treatment of wastewater (A34), rate of harmless treatment of municipal solid waste (A35), and greenhouse gas emission intensity (A36) in system A and water resources development and utilization rate (B41) and intensity of tourist space utilization (B42) in system B. Mortality due to road traffic injuries (C20) in system C is also one of the main driving factors. There are great differences among the obstacles to sustainable development: In districts I, II, III, IV, and VIII, system A is the main obstacle to increasing the level of sustainable development. In areas V and VII, systems C and B are the main obstacles, and in area VI, system B is the main hindrance.

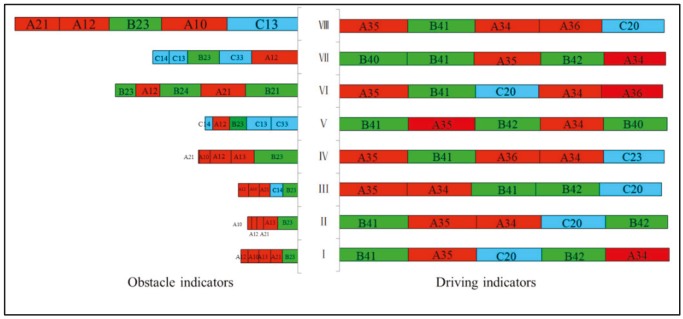


Figure 5. Obstacles to and drivers of sustainable development of tourism-oriented cities in three quadrants and eight districts. Note: (i) Red represents A, green represents B, blue represents C; (ii) value ranges of horizontal axis of drivers and obstacles are 0–4.80 and 0–0.93, respectively, which are not proportional to the plot.

3.5. Validation and Result Analysis of Multiple Linear Regression Model

It is proved that the values of all the explained variables analyzed in this paper show normal distribution. By setting the significance test level to 0.05 and using the method of stepwise regression analysis, the final model is formed after the following operations. The test indexes in the model are as follows: (1) The DW observation value of the final model is close to two, which reflects that the residual sequence has no autocorrelation, indicating that the regression equation can fully explain the changing law of the explained variables, and the selected regression model is more appropriate. (2) The tolerance of all variables in the final model is greater than 0.50, and the variance expansion factor is less than two, which indicates that the multicollinearity among multiple variables is weak. (3) In the significance test of the regression equation, the final probability *p*-value of the F test statistics of the final model is 0.000, which is less than the significance test level, indicating that the establishment of the linear regression model is appropriate, and the fitting effect of the model is better.

Using the above model verification method, the overall score and system score of sustainable development of tourism cities are taken as explained variables, and all specific indicators and corresponding specific indicators of each system are taken as explained variables. The stepwise screening strategy is used for multiple linear regression analysis, and the results are shown in Table 3.

Table 3. Results of multiple linear regression analysis.

Category	TOCSD-Specific Indicators	A-Specific Indicators	B-Specific Indicators	C-Specific Indicators
I	C22(0.489),A30(0.342), C25(0.310),C13(0.266)	A21(0.646),A10(0.552),A13(0.465), A20(0.465),A12(0.353)	B32(0.575),B10(0.567),B21(0.490), B30(0.487),B22(0.472)	C11(0.330)
II	A31(0.575)	A20(0.501),A36(0.362),A21(0.290), A11(0.289),A13(0.272)	B10(0.438),B23(0.223),B22(0.474), B24(0.360),B31(0.259)	C14(0.7878),C13(0.694),C33(0.344), C10(0.214),C22(0.092)
III	B24(0.553),C33(0.214), B32(0.168),A22(0.089)	A13(1.155),A31(0.920)	B10(0.607)	C11(0.546),C12(0.672),C25(0.387)
IV	A30(0.726),A13(0.543), A10(0.440),C22(0.237)	A12(0.689),A10(0.643),A30(0.415)	B24(0.994),B21(0.631),B10(0.419), B40(0.190),B23(0.439)	C14(0.486),C33(0.403),C10(0.187), C13(0.337),C22(0.176),C12(0.174)
V	A10(0.461),C14(0.415)	A12(0.458),A10(0.541),A21(0.478), A13(0.345),A35(0.245),A31(0.215)	B31(0.814),B22(0.745),B40(0.400), B32(0.390)	C13(0.852),C14(0.315),C25(0.276), C21(0.231)
VI	A30(1.001)	A10(0.833),A21(0.930),A12(0.279), A13(0.466),A20(0.277),A31(0.129)	B24(0.108)	C14(0.450),C21(0.225),C13(0.460), C33(0.357)
VII	A30(1.211),C20(0.818), B10(0.356)	A30(0.876)	B10(0.508)	C20(0.716),C23(0.550),C25(0.482)
VIII	B24(0.342),C22(0.326)	A21(0.643),A13(0.343),A12(0.363), A10(0.387),A20(0.147),A11(0.118)	B24(0.577),B23(0.267),B10(0.322), B32(0.124),B31(0.153)	C14(0.509),C33(0.426),C10(0.191), C13(0.213),C22(0.083),C24(0.087)

Taking the results of "TOCSD- Specific indicators" regression analysis in Category I as an example, the four indicators that have the greatest influence on the sustainable development level of tourism cities in Category I are C22, A24, C25, C13, and the standardized regression coefficient is in parentheses after the index, which means that if percentage of population covered by mobile network increases by one unit, the score of sustainable development will be increased by 0.489 points. It shows that the improvement of communication readiness can play a significant role in improving the level of sustainable development.

4. Discussion

4.1. Further Discussion

4.1.1. Comparative Analysis with SDG Index and Dashboards

The United Nations Network of Solutions for Sustainable Development (UNSDSN) and the Bertelsmann Foundation have issued five Sustainable Development Goals Index and Dashboard Reports since 2016, examining the extremes, data standardization, and weighted aggregation, and synthesizing countries' SDG index scores by calculating the average of each subdivision index and the 17 SDG overall goals [42]. The indices related to the SDGs in this paper are processed by equal weight arithmetic weighting to get the average score of each SDG of Chinese tourist cities, and according to the defined color ranking indicated on SDG Dashboards, the color of each SDG indicator of Chinese tourist cities is determined. A comparison between China's SDG dashboards (SDSN) and tourist city dashboards in 2018 is shown in Table 4.

Table 4. Comparison of Chinese (SDSN) and tourism city SDG dashboards.

SUSTAINABLE DEVELOPMENT GOALS	1 NO POVERTY	2 ZERO HUNGER	3 GOOD HEALTH AND WELL-BEING	4 QUALITY EDUCATION	5 GENDER EQUALITY	6 CLEAN WATER AND SANITATION	7 AFFORDABLE AND CLEAN ENERGY	8 DECENT WORK AND ECONOMIC GROWTH	9 INDUSTRY, INNOVATION AND INFRASTRUCTURE	10 REDUCED INEQUALITIES	11 SUSTAINABLE CITIES AND COMMUNITIES	12 RESPONSIBLE CONSUMPTION AND PRODUCTION	13 CLIMATE ACTION	14 LIFE BELOW WATER	15 LIFE ON LAND	16 PEACE, JUSTICE AND STRONG INSTITUTIONS	17 PARTNERSHIPS FOR THE GOALS
China national dashboard (SDSN)	99.70	71.50	80.00	73.80	75.60	89.90	69.10	83.10	58.70	59.60	69.20	73.20	69.30	33.50	58.60	72.50	53.60
Tourism city dashboard	57.36	-	61.10	-	-	86.62	-	48.19	48.30	52.37	51.97	44.62	81.44	-	46.10	-	15.31
		-	-	-	-		-							-		-	

Note: The SDG dashboard is represented by green, yellow, orange and red, respectively, indicating that the evaluation object is facing more and more serious challenges to achieve a SDG.

As can be seen from Table 4, the SDG scores of tourism cities are in the range of [15.31, 86.62], and the range of the SDG index is [33.50, 99.70]. The color of SDG6 on the Chinese SDG dashboard is the same as that of the dashboards in tourist cities, which is yellow, while the performance of SDG3, SDG10, and SDG13 in tourist cities as indicated by dashboard color is better than that of the Chinese dashboard. The performance of SDG1, SDG8, SDG9, SDG11, SDG12, SDG15, and SDG17 is worse than that of the Chinese dashboard. This is because there is no direct relationship between poverty level and tourism development, so SDG1 in tourism cities does not pay attention to indicators such as the incidence of poverty, but only focuses on the "proportion of expenditure on basic services in total government expenditure", which reflects social stability. Most of the rest are due to the addition of tourism-related indicators such as per capita tourism consumption expenditure, tourism space utilization intensity, and tourism infrastructure index to the sustainable development index of tourism-oriented cities. These indicators are more general than those in some foreign cities; for example, per capita tourism consumption expenditure reached EUR 2148 (equivalent to RMB 16338.33) in Paris in 2018, compared to RMB 1204 in China's tourism cities.

4.1.2. Comparative Analysis with the Travel and Tourism Competitiveness Index

The World Economic Forum (WEF) has released a Tourism Competitiveness Report every two years since 2007, which aims to measure the attractive factors and policies of the tourism industry in different countries, and to evaluate the competitiveness of the industry in major countries around the world by establishing a tourism competitiveness index. The Travel and Tourism Competitiveness Report 2019: Travel and Tourism at a Tipping Point covers 140 countries and regions around the world, with ranking by 14 metrics. The equal weight arithmetic average method is to calculate the total score, which ranges from one to seven, with one being the worst and seven the best [43]. The sustainable development index of tourism-oriented cities in this paper is calculated by the same method, and the score of the WEF China tourism competitiveness index is scaled 0–100, so as to facilitate a comparison between the two, as shown for 2019 in Table 5.

As can be seen from Table 5, the score range of sustainable development of the pillars of China's tourism cities in 2018 is [16.1, 81.54], while that of the tourism competitiveness index in 2019 is [44.29, 100.00]. The main reasons for the gap are as follows: (1) The index system constructed in this paper takes into account the differences in economies of scale and development levels, and adds indicators that reflect the economic and social basis. (2) It is expected that the original indicators of the tourism competitiveness index will have a different impact on competitiveness, and the pillar used by WEF consists of three to 12 indicators; this means that some indicators contribute more to the overall indicators than others. Therefore, this paper uses the entropy method of coefficient of variation to determine the weight of the index, rather than a simple equal weight method. (3) All indicators in this paper are treated on a per capita basis; for example, the tourism competitiveness index takes into account the total number of scenic spots and intangible cultural heritage, but this paper considers per capita number of scenic spots and per capita intangible cultural heritage, which can better reflect the background of natural and cultural resources in tourism cities.

4.2. Policy Implications

Government policies can promote sustainable development, but tourism cities need to explore various sustainable development paths to deal with the inherent differences between them and eliminate the negative impact of institutional mechanisms.

The development of tourism cities in China is uneven, and sustainable development shows obviously uneven spatial distribution. The balanced sustainability of tourism cities should be an important goal to narrow the overall gap between countries. A new mode of governance and participation should be implemented. In order to realize balanced development among tourism cities, regional cooperation must be further strengthened, as well as the substantive mechanism of cooperation.

The geographic locations of the eight comprehensive economic zones are similar, and the natural and cultural bases are also relatively similar, which can strengthen regional cooperation and exchanges on the whole, but the shortcomings and advantages of development in the economic zones are different. Specifically, the eastern and southern coastal economic zones should control the utilization rate of water and land resources within a reasonable range to enhance the sustainability of tourism development. The middle and northern coastal economic zones of the Yellow River should pay attention to the development and protection of natural and cultural resources, improve the development and utilization of natural and cultural resources, and increase the number of tourist associations and their overall planning capacity. The southwest and northwest economic zones should prioritize social and economic development, enhance the development and protection of heritage and scenic spots, improve social stability, and promote stable economic development. The economic zone in the middle reaches of the Yangtze River should further strengthen the construction of tourism infrastructure. The northeast economic zone should strengthen the governance of the tourism industry while excavating natural and cultural resources.

According to the characteristics, the drivers and obstacles in the eight districts are different, so the appropriate planning for a sustainable development path should be carried out. The sustainable development path planning and countermeasures of the eight tourism cities are shown in Table 6.

Table 5. Comparison of China's WEF tourism competitiveness index and level of sustainable development of tourism cities.

System	Enabling Environment					T&T Policy and Enabling Conditions				Infrastructure			Natural and Cultural Resources	
Pillar	Business Environment	Safety and Security	Health and Hygiene	Human Resources and Labor Market	ICT Readiness	Prioritization of Travel and Tourism	International Openness	Price Competitiveness	Environmental Sustainability	Air Transport Infrastructure	Ground and Port Infrastructure	Tourist Service Infrastructure	Natural Resources	Cultural Resources and Business Travel
China's tourism competitiveness (WEF)	67.14 (4.7/7)	80.00 (5.6/7)	80.00 (5.6/7)	74.29 (5.2/7)	71.43 (5.0/7)	68.57 (4.8/7)	44.29 (3.1/7)	81.43 (5.7/7)	54.29 (3.8/7)	61.43 (4.3/7)	55.71 (3.9/7)	50.00 (3.5/7)	72.86 (5.1/7)	100 (7.0/7)
Pillar	A1	A2	A3	B1	B2	B3	B4	C1	C2	C3	-	-	-	-
TOSDL	34.86	40.06	80.97	21.66	29.25	35.33	91.54	39.11	56.67	16.18	-	-	-	-

Table 6. Path planning and countermeasures for sustainable development in three quadrants and eight districts.

Category	Improvement Path and Suggestions
I	Consolidate foundation of economic and social development, prioritize construction of local cultural and sports infrastructure, and gradually improve speed and quality of tourism development.
II	Ensure macroeconomic stability, improve international openness, increase the rate of local financial self-sufficiency, improve local air quality, and promote the rapid development of tourism economy.
III	To enable the development of tourism economy to drive the development of natural and cultural resources and social and economic development, increase the rate of local financial self-sufficiency, and promote macroeconomic stability.
IV	Increase the development and utilization of natural cultural resources and the quality of environmental protection, reduce greenhouse gas emissions, increase the influence and popularity of cultural tourism resources, and further explore the development of urban smart tourism.
V	Consolidate the foundation of economic and social development, improve the development, utilization and protection of rich natural and cultural resources, improve the international openness of cities, and strengthen inter-regional exchanges and cooperation.
VI	Attach importance to the treatment and disposal of local water bodies and solid wastes, improve the level of ecological environment management, improve the preparation of resources and communications, and promote the coverage of mobile internet.
VII	With a better basis for development and conservation of natural resources and current situation of tourism economic development, steadily increase per capita GDP, support overall promotion of social and economic development.
VIII	Optimize the quality of tourism development. Increase publicity and the building of cultural tourism brands, enhance the visibility of the city, and increase investment in the construction of cultural and sports facilities and intelligent facilities while ensuring macroeconomic stability.

4.3. Limitations and Future Research Direction

This study explores the evaluation and analysis of the sustainable development level of tourism cities from the point of view of SDGs and tourism competitiveness index for the first time, which has a certain theoretical and practical value. However, the following limitations should be considered when interpreting this study.

First of all, the localization of urban SDGs is relatively weak and lacks a widely accepted theoretical system of SDGs localization methodology, so the construction method and logic of the evaluation index system of sustainable development of tourism cities in the context of SDGs need to be further clarified. Secondly, because the evaluation of sustainable development of tourism cities involves a wide range and the evaluation index system is complex, although a large number of data are used for evaluation and analysis, there are still some indicators that have not been quantified or deleted because of incomplete data and other problems; finally, due to the caliber of urban statistics and the limitation of time and energy, a large number of cities have not been studied for a long time, and time series comparison may be insufficient.

The research on the sustainable development of tourism cities is a complicated subject. How to implement SDGs in tourism cities also needs further research, and more in-depth and comprehensive work needs to be carried out in the future. The sustainable development of tourism cities involves many contexts. In the future, the sustainable development of tourism cities can be analyzed in more detail with SDGs, and the sustainable development indicator dashboard can be used to show the progress of tourism cities in implementing the 2030 sustainable development agenda, and to further explore the contribution of tourism cities in the process of achieving the 2030 Sustainable Development Goals. The index system established in this paper is generally applicable to domestic and foreign tourist cities, so in addition to evaluating as many tourism cities in China as possible, we can also select international well-known tourism cities to study together with Chinese tourist cities in the future. On the basis of discovering gaps and advantages, Chinese tourism cities can continue to give full attention to their strengths and learn from the relevant successful experiences of international tourism cities. In addition, the emergence of COVID-19 in December 2019 affected more than 200 countries and regions, and had an impact on industries such as health, biomedicine, environment, and tourism, among which hotels and tourist activities are productive sectors severely affected by the epidemic. The world's major tourism cities have been hit the hardest. Therefore, based on detailed data in the future, the impacts of COVID-19 on the sustainable development of tourism cities can be quantitatively analyzed, and how tourism cities should improve their crisis management ability and social governance level can be further discussed.

5. Conclusions

The research in this paper has theoretical and practical significance, which is mainly reflected in the establishment of a sustainable development evaluation framework for tourism cities that integrates SDGs and competitiveness indexes. This framework is generally applicable to the sustainable development evaluation of international tourism cities, complementing SDGs and the competitiveness evaluation model for the predicament of insufficient guidance for sustainable development evaluation of tourism cities, explores the SDGs-based sustainable development level evaluation technical methods for tourism cities, and takes 221 excellent tourism cities in China as an example. It is proved that the technical methods proposed in this paper are scientific and operable, and provide experience for the evaluation of sustainable development of other similar tourism cities in the world. The main conclusions are as follows.

On the whole, the sustainable development of tourism cities in China has not reached a high level, and there is a large gap in performance among the pillars, among which ecological environment protection (A3) and sustainability of tourism development (B4) perform better as a whole, while conservation of natural and cultural resources (A2) and tourism industry governance (C3) perform poorly. The results show that there is a gap between Chinese and international tourism cities. China also needs to strengthen the cultivation of high-quality tourism cities while expanding the scale of tourism.

From the weight results, the weight of system A is the largest among the three systems; the weights of heritage index (A1), degree of tourism infrastructure construction (B2), and economic support of natural and cultural resources (C1) are larger; and the weights of nature reserve coverage index (A21), network fever (A12), and heritage index (A10) are larger, indicating that tourism cities should pay attention to the exploration and protection of natural and cultural resources in order to improve the level of sustainable development. This is also consistent with the country's insistence that "history and culture are the soul of the city, and we should protect the city's historical and cultural heritage as well as our own life".

From the point of view of geographic divisions, there are obvious differences in the sustainable development level of tourism cities in China's eight major economic zones. Specifically, the eastern and southern coastal economic zones perform better, while the economic zones in the northwest and the middle reaches of the Yellow River perform poorly. The economic zones should strengthen cooperation and exchanges and pay more attention to their poor performance.

From the point of view of feature division, the main driving factors of tourism cities in the eight districts are proportion of safe treatment of waste water (A34), rate of harmless treatment of municipal solid waste (A35), greenhouse gas emission intensity (A36), and water resource development and utilization rate (B41), but the obstacle factors are different. According to the results of correlation analysis, the systems, pillars, and specific indicators most related to the level of sustainable development level are also different. From the point of view of the path of sustainable development, tourism cities in category I should first consolidate the foundation of economic and social development and gradually improve the speed and quality of tourism development; cities in category VIII should take the road of capacity expansion, quality improvement, and optimization, so as to further improve the level of sustainable development. Tourism cities in the transitional stage (categories II–VII) should expand the supportive and driving role of good system development to the development of other systems in order to ensure a better system. From the point of view of the comparative analysis of existing achievements, based on the unified calculation method, there is consistency between the sustainable development levels of Chinese tourism cities and the SDSN sustainable development index and tourism competitiveness index scores, which shows that the conclusion of this paper is scientific. There are also differences, and the main reason is that this paper focuses on the sustainable development of tourism cities and makes improvements in the design of an index system, specific index attributes, index standardization, and weight assignment.

Author Contributions: Conceptualization, C.S. and J.G.; Data curation, Z.W.; Methodology, C.S. and Z.W.; Software, J.G.; Supervision, C.S. and Z.W.; Validation, C.S.; Visualization, J.G. and S.C.; Writing—original draft, J.G. and S.C.; Writing—review & editing, C.S. All authors have read and agreed to the published version of the manuscript.

Funding: This work was supported by the National Key R&D Program of China (No.2019YFC0507505) and National Natural Science Foundation of China (No. 42071292).

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The data used to support the findings of this study will be available from the corresponding authors upon request.

Acknowledgments: The authors would like to thank the anonymous reviewers and the editor for their constructive comments and suggestions for this paper.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. China Environment News. *Towards the 21st World-A Literature Compilation of the United Nations Conference on Environment and Developmen*; China Environmental Science Press: Beijing, China, 1992; pp. 15–17.
2. United Nations. *SDG Indicators: Global indicator framework for the Sustainable Development Goals and targets of the 2030 Agenda for Sustainable Development*; United Nations: New York, NY, USA, 2018; pp. 3–15.
3. The Inter-Agency and Expert Group on SDG Indicators. Global Indicator Framework for the Sustainable Development Goals and Targets of the 2030 Agenda for Sustainable Development. Available online: https://unstats.un.org/sdgs/indicators/indicators-list/ (accessed on 1 February 2020).
4. UN General Assembly. Political Declaration of the High-Level Political Forum on Sustainable Development Convened under the Auspices of the General Assembly. Available online: https://undocs.org/en/A/RES/74/4 (accessed on 21 September 2019).
5. Satterthwaite, D. Successful, safe and sustainable cities: Towards a new urban agenda. *Commonw. J. Local Gov.* **2016**, *19*, 3–18. [CrossRef]
6. Global Taskforce of Local and Regional Governments. UN-Habitat, UNDP. Roadmap for Localizing the SDGs: Implementation and Monitoring at Subnational Level. Available online: https://www.uclg.org/sites/default/files/roadmap_for_localizing_the_sdgs_0.pdf (accessed on 20 July 2016).
7. Croese, S.; Green, C.; Morgan, G. Localizing the sustainable development goals through the lens of urban resilience: Lessons and learnings from 100 resilient cities and cape town. *Sustainability* **2020**, *12*, 550. [CrossRef]
8. International Council for Science. *A Guide to "SDG" Interactions: From Science to Implementation*; International Council for Science: Paris, France, 2017; pp. 16–25.
9. Liu, J.; Hull, V.; Godfray, H.C.J.; Tilman, D.; Gleick, P.; Hoff, H.; Pahl-Wostl, C.; Xu, Z.; Chung, M.G.; Sun, J.; et al. Nexus approaches to global sustainable development. *Sustainability* **2018**, *1*, 466–476. [CrossRef]
10. Tseng, M.-L.; Wu, K.-J.; Lee, C.-H.; Lim, M.K.; Bui, T.-D.; Chen, C.-C. Assessing sustainable tourism in Vietnam: A hierarchical structure approach. *J. Clean. Prod.* **2018**, *195*, 406–417. [CrossRef]
11. Savage, V.R.; Huang, S.; Chang, T.C. The Singapore river thematic zone: Sustainable tourism in an urban context. *J. Geogr. Sci.* **2004**, *170*, 212–225. [CrossRef]
12. Lee, C.-F.; Huang, H.-I.; Yeh, H.-R. Developing an evaluation model for destination attractiveness: Sustainable forest recreation tourism in Taiwan. *J. Sustain. Tour.* **2010**, *18*, 811–828. [CrossRef]
13. Wang, H. Study on the Sustainable Development of Small and Medium-Sized Tourism Cities. Ph.D. Thesis, Central China Normal University, Wuhan, China, 1 May 2014.
14. Li, Y.X. Sustainable Development and Image Perception Analysis of Lijiang Urban Tourism under the Goal of Ring Model. Ph.D. Thesis, Yunnan University, Kunming, China, 1 May 2017.
15. Yin, F.X. The construction of international tourist cities under the guidance of the concept of sustainable development. *Managers* **2009**, *17*, 358.
16. Pérez, V.; Hernández, A.; Guerrero, F.; León, M.A.; Da Silva, C.L.; Caballero, R. Sustainability ranking for Cuban tourist destinations based on composite indexes. *Soc. Indic. Res.* **2015**, *129*, 425–444. [CrossRef]
17. Blancas, F.; Lozano, M.G.; González, M.; Caballero, R. Sustainable tourism composite indicators: A dynamic evaluation to manage changes in sustainability. *J. Sustain. Tour.* **2016**, *24*, 1403–1424. [CrossRef]
18. Crouch, G.I. Destination competitiveness: An analysis of determinant attributes. *J. Travel Res.* **2010**, *50*, 27–45. [CrossRef]
19. Bornhorst, T.; Ritchie, J.B.; Sheehan, L. Determinants of tourism success for DMOs & destinations: An empirical examination of stakeholders' perspectives. *Tour. Manag.* **2010**, *31*, 572–589. [CrossRef]
20. Dwyer, L.; Cvelbar, L.K.; Edwards, D.; Mihalic, T. Fashioning a destination tourism future: The case of Slovenia. *Tour. Manag.* **2012**, *33*, 305–316. [CrossRef]
21. Sainaghi, R.; Phillips, P.; Zavarrone, E. Performance measurement in tourism firms: A content analytical meta-approach. *Tour. Manag.* **2017**, *59*, 36–56. [CrossRef]
22. Mendola, D.; Volo, S. Building composite indicators in tourism studies: Measurements and applications in tourism destination competitiveness. *Tour. Manag.* **2017**, *59*, 541–553. [CrossRef]
23. City Department of Los Angeles. *Sustainable Development Goals: A Local Review of Progress in 2019*; City Department of Los Angeles: Los Angeles, LA, USA, 2020; p. 58.
24. Organization for Economic Cooperation and Development. *Measuring Distance from Sustainable Development Goals: Assessment of the Process of Achieving SDGs in OECD Countries in 2019*; Organization for Economic Cooperation and Development: Paris, France, 2019; p. 58.
25. The Economic and Social Commission for Asia and the Pacific. *Asia and the Pacific SDG Progress Report 2019*; The Economic and Social Commission for Asia and the Pacific: New York, NY, USA, 2019; p. 67.
26. Statistical Office of the European Communities. *EU SDG Indicator set 2019: Result of the Review in Preparation of the 2019 Edition of the EU SDG Monitoring Report*; Statistical Office of the European Communities: Brussels, Belgium, 2019; pp. 17–19.
27. The Japanese Government. *Japan's Voluntary National Review Report on the Implementation of the Sustainable Development Goals*; The Japanese Government: Tokyo, Japan, 2017; p. 27.
28. Federal Government of Germany. *German Sustainable Development Strategy 2016*; Federal Government of Germany: Berlin, Germany, 2017; pp. 12–13.

29. Monash Sustainable Development Institute. *Transforming Australia SDG Progress Report: 2020 Update*; Monash Sustainable Development Institute: Monash, Australia, 2020; pp. 67–89.
30. SDSN; BERTELSMANNS. *The 2019 SDG Index and Dashboards Report for European Cities*; SDSN: New York, NY, USA, 2019; pp. 26–35.
31. SDSN; BERTELSMANNS. *The 2019 Italian Cities Sustainable Development Report*; SDSN: New York, NY, USA, 2019; pp. 15–20.
32. Institute for Global Environmental Strategies, City of Turku. *The Implementation of the 2030 Agenda for Sustainable Development in the City of Turku*; Institute for Global Environmental Strategies: Kanagawa, Japan, 2020; pp. 43–60.
33. City Department of Mannheim. *The Implementation of the UN SDGs in Mannheim*; City Department of Mannheim: Mannheim, Germany, 2019; pp. 16–18.
34. Sydney Government. *City of Sydney Community Wellbeing Indicators*; Sydney Government: Sydney, Australia, 2019; pp. 36–58.
35. Institute for Global Environmental Strategies. *Shimokawa the Sustainable Development goals Report 2018*; Institute for Global Environmental Strategies: Kanagawa, Japan, 2018; pp. 13–16.
36. SDSN; BERTELSMANNS. *2018 SDG Index and Dashboards Report*; SDSN: New York, NY, USA, 2018; p. 11.
37. Zhu, D.J. Pursue the goal of sustainable development within the "planetary boundary. *Econ. Guide Sustain. Dev.* **2019**, *7*, 53–56.
38. Pulido-Fernández, J.I.; Rodríguez-Díaz, B. Reinterpreting the World Economic Forum's global tourism competitiveness index. *Tour. Manag. Perspect.* **2016**, *20*, 131–140. [CrossRef]
39. Chen, H.G.; Li, X.N.; Li, C.Y. Evaluation of resilience of water resources system based on entropy method of coefficient of variation-A case study of water resources in Heilongjiang Province from 2007 to 2016. *Ecol. Econ.* **2021**, *37*, 179–184.
40. Gong, X.; Zheng, C.D.; Xiao, Y.R. A study on the income growth of farmers and herdsmen in Tibet from the perspective of green de-velopment– based on multiple linear regression analysis. *Tibet. Stud.* **2018**, *6*, 131–138.
41. Shi, H.J. Research on low-carbon consumption behaviors and influencing factors of urban residents: A case study of Fuzhou, Fujian Province. *Resour. Sci.* **2015**, *37*, 308–317.
42. Zhou, Q.; Wu, Y.H.; Dong, Z.F.; Li, H.X.; Ge, C.Z. Analysis and revelation of the 2017 global sustainable development goals index and dashboard report. *Environ. Prot.* **2018**, *46*, 63–69.
43. World Economic Forum. *The Travel & Tourism Competitiveness Report 2019-Travel and Tourism at Tipping Point*; World Economic Forum: Geneva, Switzerland, 2020; pp. 25–31.

sustainability

MDPI

Article

Impacts of Temperature Trends and SPEI on Yields of Major Cereal Crops in the Gambia

Fanta F. Jabbi [1], Yu'e Li [1,*], Tianyi Zhang [2], Wang Bin [1], Waseem Hassan [1] and You Songcai [1]

[1] Institute of Environment and Sustainable Development in Agriculture, Chinese Academy of Agricultural Sciences, Beijing 100081, China; jabbifanta1@gmail.com (F.F.J.); wangbin01@caas.cn (W.B.); waseem.hassan@caas.cn (W.H.); yousongcai@caas.cn (Y.S.)

[2] Institute of Atmospheric Physics, Chinese Academy of Sciences, Beijing 100029, China; zhangty@mail.iap.ac.cn

* Correspondence: liyue@caas.cn; Tel.: +86-13-9116-51365

Abstract: Variations in the climate constitute a significant threat to the productivity of food crops in the Gambia. A good understanding of the influence of climate variability on crop production is vital for climate resilience and improved food security. This study examined the trends, relationships, and the extent to which growing season temperatures and the SPEI (Standardized Precipitation and Evapotranspiration Index) impacted sorghum, millet, maize, and rice yields in three agro-ecological regions of the Gambia during 1990–2019. Mean temperatures and the SPEI exhibited increasing trends while observed yields showed a decline across all regions. The SPEI had a significant positive relationship with yields, and temperatures were negatively associated with yields. Though yield response to climate variability differs among regions, 20% to 62% of variations in the four crop yields were due to climate trends. The combined effect of the SPEI and temperatures decreased yields from 3.6 kg ha^{-1} year^{-1} to 29.4 kg ha^{-1} year^{-1}, with the most severe decline observed in rice and maize yields in the Sahelian zone. Although uncertainties might arise from not considering related extreme climate events, this study highlights how past climate trends affect cereal yields in the Gambia; thus, any unfavorable change in the local climate could have severe repercussions on the country's food security. There is a need for concerted efforts to increase investments in adaptation strategies to lessen the effects of the climate for improved crop productivity.

Keywords: climate variability; temperatures; SPEI; impacts; yields

Citation: Jabbi, F.F.; Li, Y.; Zhang, T.; Bin, W.; Hassan, W.; Songcai, Y. Impacts of Temperature Trends and SPEI on Yields of Major Cereal Crops in the Gambia. *Sustainability* **2021**, *13*, 12480. https://doi.org/10.3390/su132212480

Academic Editors: Ayyoob Sharifi, Baojie He, Chi Feng and Jun Yang

Received: 10 October 2021
Accepted: 3 November 2021
Published: 12 November 2021

1. Introduction

The productivity of global food crops has experienced changes driven by technological, infrastructural, and management practices [1]. However, this increase in crop production is a non-linear process due to crop yields' variability characterized by episodes of yield declines and crop failures [2]. Numerous factors such as management, pest and diseases, soil type, and socio-economic crises lead to variations and or decline in crop yields [3]. Nonetheless, anthropogenic greenhouse gas emissions from food production and energy consumption [4,5] are expected to cause an increase in temperatures, changes in precipitation patterns, and increased frequencies of extreme weather events such as droughts and floods [6]. Evidence from a series of empirical and statistical studies [7] indicates that agriculture is one of the most directly sensitive sectors affected by changes in climatic parameters because the weather is an essential input in crop production. Thus, the agricultural sector is projected to continue under severe threat, as droughts and rising temperatures induced by global warming will exert pressure on agricultural resources, consequently affecting the spatial and temporal distribution of crops and crop yields and global food security [8,9]. Considerable evidence regarding the potential impacts of historical and future climate change on yields has been reported [2,4,10]. These impacts are projected to be severe in developing countries where chronic hunger and malnutrition already persist and resources to cope with the effects of climate-induced yield losses and natural disasters are limited [11].

Sub-Saharan Africa, for instance, is considered one of the most susceptible, with 34 of the 50 most climate-vulnerable countries located within the region [12]. Studies by [12,13] indicate that the risk posed by climate change in this region is due to many factors, including the region's dependency on rain-fed agriculture, rapid population growth, weak institutions, and less economic capacity to adapt to the impacts of the climate. Many agricultural populations in this region are exposed to climate change-induced droughts and rising temperatures [14], exacerbating the already recurrent water scarcity, which will cause further pressure on the future of the African economies and livelihoods and increase food insecurity in the region [15]. The yields of sorghum, millet, and maize are projected to decline by −14.5%, −9.6%, and −5%, respectively, in this region by the end of the 21st century if no adaptation measures are taken [16]. Drought severity and frequency are expected to worsen with the advent of increased climate variability and change with significant impacts in arid and semi-arid regions [17,18].

Like many Sub-Saharan African countries, the Gambian agriculture depends heavily on rain-fed weather conditions, with only three percent of arable land under irrigation, mainly rice cultivation. Crop yields depend highly on the amount and distribution of seasonal rains, which makes the country most vulnerable to increased climate variability incidents [19]. The country is facing pronounced risks of higher temperatures, more erratic but lower rainfall of about a 400-mm decline compared to the 1961–1990 period, more frequent droughts and lengthened dry spells coupled with above-average rains resulting in a decrease in annual crop yield trends [20–22]. This situation adversely affects the country's food security and the livelihood of small-scale subsistence and semi-intensive farmers who form 70 percent of the country's population.

Before developing any climate-crop prediction model, there is a need to establish a proven relationship and the impacts of historical and current climate variability on crop yields to help design adaptation strategies for improving climate resilience [5,23]. Several studies using empirical models in recent and past decades have shown the significance of climate variability and change (especially precipitation and temperature) in explaining historical and future variations in crop yields at temporal and spatial scales [24–26]. Employing a statistical climate–crop yield relationship, the authors in [27] showed the significant impact of growing season temperature and precipitation on cereal crop production in Nepal. The authors of a study conducted in the United States and China [28] use an econometric model that incorporated climate, economic, and technology variables and concluded that climate change would not universally cause negative impacts on maize yields in the United States and China. Despite rapid progress in establishing the relationship and impacts of variations of these climatic variables on crop yields in different agro-ecological zones, a substantial gap exists due to climate dynamics and uncertainties under changing environments [18]. Most of these studies [29–32] at local and global scales only focused on basic climatic variables such as precipitation and temperatures. In addition to variations in mean climate variables, different studies have identified drought indices linked with prolonged effects and anomalous moisture deficit as recurrent climate hazards affecting crop production with severe societal and economic constraints [33–35]. The authors of [36,37] proposed that extreme climate events such as droughts and higher temperatures will significantly have adverse impacts on crop yields more than variations in mean precipitation and temperatures alone.

Studies by [38] revealed that cereal yields mostly have a positive response with increasing precipitation in rain-fed tropical regions like the Gambia, while the rise in temperatures and a decrease in the SPEI has a more adverse effect on yields [39]. A growing number of studies have used drought indices such as the Palmer Drought Severity Index (PDSI) [40], Standardized Precipitation Index (SPI) [41], and most recently, the Standardized Precipitation and Evapotranspiration Index (SPEI) [42] at different time scales to characterize drought events associated with crop yield anomalies and to develop statistical models to predict crop yields [43,44].The SPEI is considered more relevant to crop production because it combines the characteristics of PDSI (which uses temperature) and SPI (which uses precipitation) to assess droughts at multiple time scales [45].

Economic growth in the Gambia is highly correlated with its agricultural growth, owing to its contribution to national food security, about 75% of employment, 70% of its foreign exchange earnings, and 24% of GDP [46]. As reported by the authors of [21,47], variations in temperatures and recurring drought events cause a significant impact on yields and increase the poverty level of the country's larger population who depends on agriculture as a source of income. Similarly, studies by [48,49] evaluated farmers' perceptions and adaptations to climate change and variability in some specific regions within the country and indicated that farmers perceived a high increase of temperature and a decrease in rainfall, contributing to a decline in yields. However, studies investigating the impact of historical and/or current climatic trends alongside extreme climate events such as drought are limited, and no such study has been conducted on agro-regional scales in the Gambia so far. Hence, this study aims to establish the trends, relationships, and impacts of temperatures (minimum and maximum) and the SPEI on yields of major cereal crops in the three agro-ecological regions of the Gambia. A better understanding of these impacts is crucial for better decision-making at all levels to minimize climate-related yield losses and geared towards improving crop production and food security.

2. Materials and Methods

2.1. Study Area

The Gambia, located on latitude 13.28 N and 16.34 W, is the smallest country on the Atlantic coast of mainland Africa with a land area of 10,120 km^2. The country is divided into 6 administrative regions from east to west. Based on biophysical characteristics and rainfall patterns, these 6 administrative regions are further divided into three main agro-ecological zones (Figure 1), namely, the Sahelian (considered the smallest region located in the central river region north of the country, characterized by 70 days of active crop production during the raining season), the Sudan-Sahelian (considered the largest agro-ecological region comprising of four administrative regions with an active growing season length of 79–119 days), and the Sudano-Guinean zone (comprising of two administrative regions with a growing season length of 120–150 days) [50]. A semi-arid monomodal rainfall characterizes the three regions from June to October. This rainfall season is controlled by the movement of the tropical rain belt (also known as the Intertropical Conversion Zone, ITCZ), which oscillates between the northern and southern tropics over a year, affecting the Gambia when it is in its north position [51]. The total annual rainfall in the three study regions varies enormously, with average amounts ranging from about 700 mm to 920 mm (1975 to 2018 data). The wettest areas have been over the Sudano-Guinean and the driest regions have been the Sahelian zone [52]. Average temperatures in these regions range from 18 °C to 30 °C during the dry season and 23 °C to 33 °C during the wet season, with maximum temperatures in April and May exceeding 40 °C towards the eastern and inland areas of the country [46]. The Gambian primary sector has been (early millet, late millet, maize, sorghum, and rice), semi-intensive cash crop production (groundnuts, cotton, sesame, and horticulture), and traditional livestock rearing. The farming system in these regions is characterized by subsistence mix cropping comprising cereals such as sorghum (*Sorghum bicolour* (L.) Moench), pearl millet (*Pennisetum glaucum* (L.) R.Br.), maize (*Zea mays* L.), and rice (*Oryza sativa*) and semi-commercial production of legumes such as groundnut (*Arachis hypogaea* L.) and cowpea (*Vigna unguiculata* (L.) Walp.). This is alongside traditional livestock rearing, though crops account for a more significant portion of the production [53]. Soils in these regions (most especially the Sudano-Sahelian and Sahelian regions) have low inherent fertility characterized by low cation exchange capacity (CEC), which have over the years been subjected to various types of degradation attributed to soil erosion (wind and water), clearing by burning, and limited incorporation of green manure. Crop yields in these regions have declined drastically during the past decades due to many factors, including erratic and insufficient rainfall, and the low use of mineral and organic fertilizers in a context of decreasing soil fertility combined with soil salinization due to seawater intrusion [19].

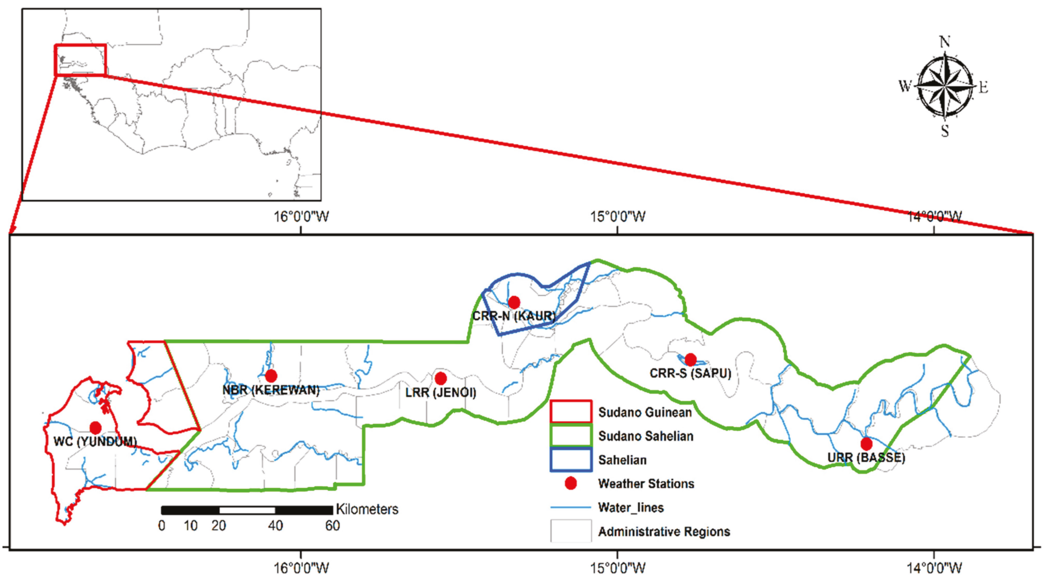


Figure 1. Agro-ecological regions and the spatial distribution of the weather stations used in the study.

2.2. Data Acquisition

The climate data (precipitation, maximum and minimum temperatures) from the 10 weather stations across the country were obtained from the Department of Water Resources from 1990 to 2019 (30 yrs. period). A quality control check was performed, and stations with more than 5% of missing data and outliers were removed. A homogeneity test was also carried out to test the fluctuations in the dataset using the RHtest software package [54]. After that, six synoptic stations with continuous data series representative of the 3 study regions were used for the analysis (Figure 1). Climate variables were used according to the crop growth season because non-growing season climate factors have no direct impacts on yields and may contribute to uncertainties in our study [55]. Annual records of the four cereal crop yields (sorghum, millet, maize, and rice) aggregated according to the agro-ecological regions were acquired from the Planning Service Unit (PSU) under the Ministry of Agriculture for the same period as of the climate record. Outliers were removed and replaced with the mean of the dataset during the study period for the analysis.

2.3. Trend Analysis

The Mann–Kendall test (a non-parametric test), adapted from [56], was used to examine crop yields' trends and significance level and changes in growing season temperatures and SPEI at one- and three-month timescales. The Mann–Kendall test was calculated using the modified Mk package in R software at a 95% ($p < 0.05$) significance level. Results indicate positive and negative values as increasing or decreasing monotonic trends, respectively. Sen's slope was used to quantify the magnitude of trends (temporal change per unit in climate and yield variables) using a simple non-parametric procedure developed by Sen.

2.4. Determination of Drought Severity Index

The widely used standardized precipitation evapotranspiration index (SPEI) was used to express the duration and magnitude of drought. SPEI is a multi-scalar index that uses the differences between precipitation (P) and potential evapotranspiration (PET), thus including the impact of temperature on soil moisture responsible for crop growth. There exist several methods of computing PET, from the simple Thornthwaite or Hargreaves [57,58] to the sophisticated FAO and WMO's standard accepted Penman–Monteith (PM) [59] method. Due to data limitations, this study used Hargreaves using minimum, maximum air temperature, and geographic coordinates of the stations [57]. This method has been used widely in similar studies performed in Africa and beyond and provides results similar to the complex methods [38,60]; hence this method is recommended in data-scarce regions [61]. The precipitation (P_i) and potential evapotranspiration (PET_i) were used to calculate the climatic water balance (D_i) at different timescales and for each region as:

$$D_i = P_i - PET_i \tag{1}$$

The D_i was standardized by the log-logistic distribution series to derive the SPEI values at 1- and 3-month timescales for meteorological (SPEI-1) and agricultural (SPEI-3) drought due to their significance to crop production [62]. Though the 30 years, monthly SPEIs were determined, but only the five month-growing seasons (June–October) was used in further analysis. The SPEI R package (http://cran.r-project.org/web/ (accessed on 20 October packages/SPEI) developed by [63] was used to calculate both the PET, D, and SPEI following previous studies such as [64,65]. The classification of the SPEI values ranging from ≥+2 (extreme wet) to ≤−2 (extreme drought) are presented in Table 1, and the greater the negative value, the more severe the drought condition and vice versa [66].

Table 1. SPEI classifications corresponding to wet and dry conditions used in this study [66].

SPEI Value	SPEI Classification
≥2.00	Extreme wet (EW)
1.50 to 1.99	Severe wet (SW)
1.49 to 1.00	Moderate wet (MW)
0.99 to −0.99	Normal (N)
−1.00 to −1.49	Moderate drought (MD)
−1.50 to −1.99	Severe drought (SD)
≤−2.00	Extreme drought (ED)

From the above classification, we determined the probability of wet or drought incidence of a given threshold as the frequency ratio of occurrence of the SPEI category to the total record of SPEIs for the study period.

2.5. Climate–Crop Yield Relationship and Impact Analysis

To determine the relationship and how much variation in crop yields was explained by climate variables, it was necessary to remove or minimize the trend effects of non-climatic factors such as cultivar, management, and technology to eliminate bias due to these trends. Anomalies were obtained by detrending time series in crop yields and climate (Tmin, Tmax, and SPEI), using the first differencing approach applied in many studies [11,67].

Associations between detrended yield and climate were explored through correlation analyses using the corrplot package in R. The correlation results provide initial information on the positive or negative associations, which help to understand the regression results. The SPEI was used instead of precipitation in this study since it produces similar qualitative results with precipitation, and it is more accurate in describing wetness and dryness than precipitation because it accounts for the varying rates of evapotranspiration [60]. Including the SPEI and precipitation in our model would induce collinearity since both were significantly correlated; thus, only the SPEI was used.

Finally, a multi-regression analysis of the detrended yield and climate was performed to quantify the percentage response (r^2) of yield variations achieved jointly by precipitation and temperatures. Though less complex than crop simulation models, this method gives the best linear and unbiased estimates among other estimators. It has been used in several studies in Africa [68,69] to study the impact of the climate on crop yields. The regression model adapted from [70] was applied for a single crop in each region as:

$$\Delta Y_{ij} = constant + \left(\alpha \times \Delta SPEI_{ij}\right) + \left(\beta \times \Delta Tmax_{ij}\right) + \left(c \times \Delta Tmin_{ij}\right) \quad (2)$$

where Y represents the change in the dependent variable (yield) in region i in year j; α, β and c, are the coefficients of SPEI, maximum and minimum temperatures during the study period. $\Delta SPEI$, $\Delta Tmax$, and $\Delta Tmin$ are the observed changes in independent variables (SPEI, maximum and minimum temperatures).

3. Results

3.1. Observed Trends of Tmin, Tmax, and SPEI

The long-term trends in growing season Tmin, Tmax, and SPEI at 1- and 3-month time scales were assessed for all the three study regions through the Kendall–Tau statistical tests at a 95% significance level and quantified by the Sen's slope, and are presented in (Table 2). A substantial positive (warming) trend has been observed across the three study regions for mean minimum and maximum air temperatures between 1990–2019. However, this warming trend was significant (($p < 0.05$) only for October Tmin in the Sudano-Guinean region and for August, September, and October Tmin in the Sudano-Sahelian region with the minimum average seasonal warming trend of 0.010 °C year $^{-1}$ observed in the Sahelian region and a maximum trend of 0.019 °C year $^{-1}$ observed in the Sudano-Sahelian region, respectively. Growing season monthly Tmin exhibited a more significant increasing trend than Tmax. However, a non-significant decreasing (cooling) trend was observed in the maximum air temperatures (Tmax) in August (0.023 °C) and September (0.018 °C) in the Sahelian region and in August Tmin in the Sudano-Sahelian region. The maximum and minimum temperatures patterns show well-defined coherent spatial and temporal characteristics characterized with year-to-year variability. The long-term trends show both below and above-average temperatures during the growing season (Figure 2).

Table 2. Annual trend slopes of Tmin, Tmax, and SPEIs in the growing season for the three agro-ecological regions from 1990 to 2019.

	Tmin						Tmax					
	Jun	**Jul**	**Aug.**	**Sep.**	**Oct.**	**Mean**	**Jun**	**Jul**	**Aug.**	**Sep.**	**Oct.**	**Mean**
S. Guinean	0.025	0.018	−0.006	0.018	0.029 *	0.017	0.003	0.027	0.006	0.005	0.010	0.014
S. Sahelian	0.00	0.00	0.018 **	0.015 *	0.038 **	0.019 *	0.033	0.00	0.011	−0.007	0.01	0.011
Sahelian	0.008	0.006	0.000	0.016	0.017	0.010	0.041	0.025	−0.023	−0.018	0.013	0.010
	SPEI-1						SPEI-3					
	Jun	Jul	Aug.	Sep.	Oct.	Mean	Jun	Jul	Aug.	Sep.	Oct.	Mean
S. Guinean	0.011	0.004	0.036	0.013	0.008	0.013	0.003	0.009	0.025	0.029	0.036	0.021
S. Sahelian	−0.003	0.029	0.049 **	0.061 **	0.006	0.029 *	−0.011	0.017	0.066 **	0.055 **	0.047	0.034 *
Sahelian	−0.015	0.021	0.032	0.038 *	−0.008	0.010	−0.016	0.016	0.037	0.042	0.034	0.021

** p-value ≤ 0.01, * p-value ≤ 0.05. The green and red colors represent positive and negative values, respectively. The different shades of green colors represent the significant and non-significant trends at the 95% confidence interval.

The mean seasonal SPEI-1 and SPEI-3 show an increasing trend over the years for all the regions. The magnitude of changes differed between regions with monthly upward trends varying from 0.04 in July to 0.061 in September for SPEI-1 and from 0.003 in June to 0.055 in September for SPEI-3, with a significant trend mainly found in the Sudano-Sahelian zone (Table 2). August and September, which correspond to the wettest months of the Gambia's growing season, had the highest monthly SPEI trends across the three regions, with increases in 1- and 3-month lags varying from 0.013 in the S. Guinean to 0.066 in the S. Sahelian.

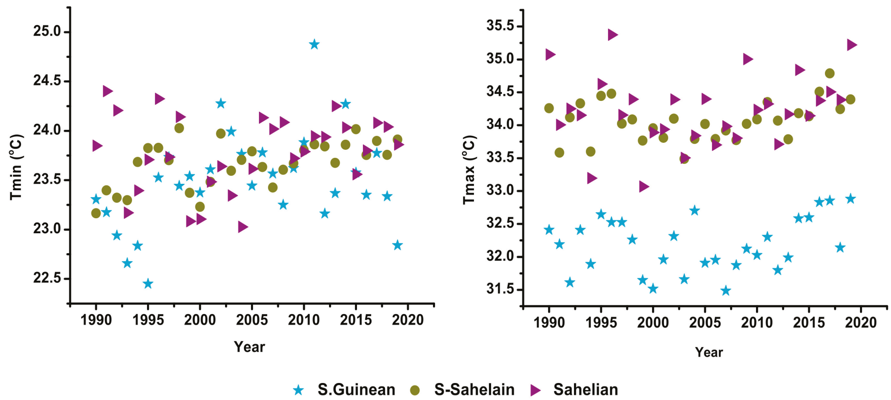


Figure 2. Spatial and temporal variability and distribution of Tmin and Tmax in the growing season of the three (3) agro-ecological regions.

Figure 3 shows the temporal evolutions of the regional averaged SPEI with 1- and 3-month time scales. The overall trends in the SPEI show variations towards positive and negative lags clustered together, indicating that both wet and dry conditions were observed over the past 30 years. All the regions were exposed to a range of drought conditions during the first 10 years of our study for both SPEI-1 and SPEI-3. The years 1990–1998 presented a period of drought, registering an index of −2.62 in 1991 in the Sudano-Sahelian zone (Figure 3b) and −2.98 in 1996 in the Sudano-Guinean area (Figure 3a). The 1999–2012 period experienced a remarkable shift towards an anomalous increase in wet conditions across all the three regions with a maximum SPEI index of up to 2.44 in 1999 and 2.45 in 2009 in the regions mentioned above, respectively. This situation indicates a favorable shift towards the increase of soil moisture during the period of the study.

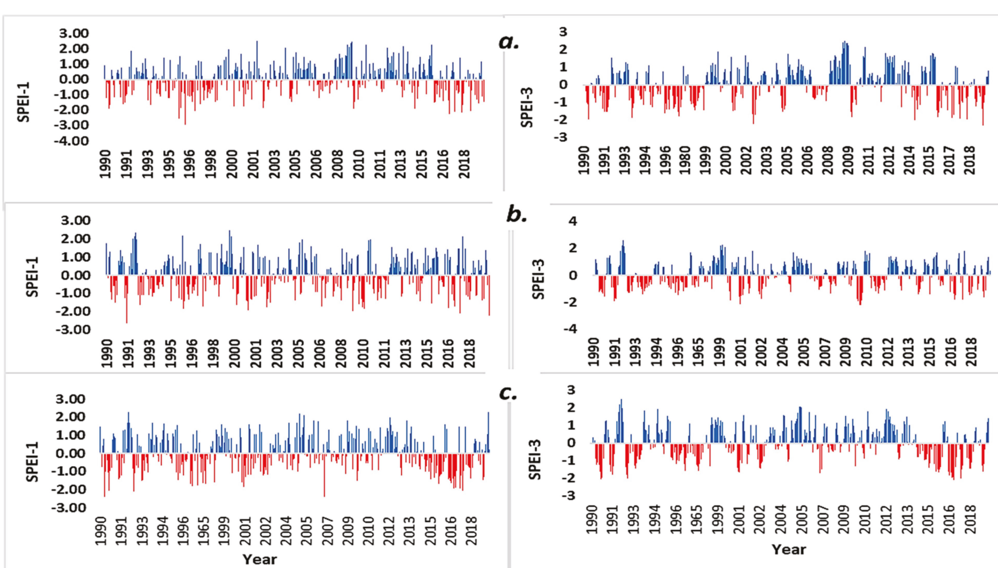


Figure 3. Temporal variations of SPEI-1 and SPEI-3 at the 3 study regions (**a**) Sudano-Guinean, (**b**) Sudano-Sahelian, (**c**) Sahelian.

To further understand the historical SPEI, drought and wetness severity levels (moderate, severe, and extreme) have been assessed (Figure 4). Our results show monthly droughts ranging from moderate to extreme droughts from 1990 to 1996 across the three regions and alternate drought and floods conditions captured from 1997 onwards with tendencies of monthly dry scenarios becoming frequent, particularly after 2012. The SPEI-1 exhibits a periodic change in the dry/wet conditions more than the SPEI-3; thus, values of the SPEI-1 (Figure 4 (left)) characterize individual monthly conditions and hence the effect of dry/wet conditions does not affect the following month. However, the absolute value of the wet or dry condition of the SPEI increased gradually when the SPEI series was calculated at 3month lags, indicating that previous moisture from the preceding 2 months could be integrated to latter months, thus, highlighting the persistence of alternate dry and wet months (Figure 4 (right)). The above result suggests that the length of extreme events as showed by the SPEI-3 might not be effectively detected with SPEI at a one-month lag; thus, the combination of SPEI-1 and SPEI-3 provide a better explanation of dry/wet conditions.

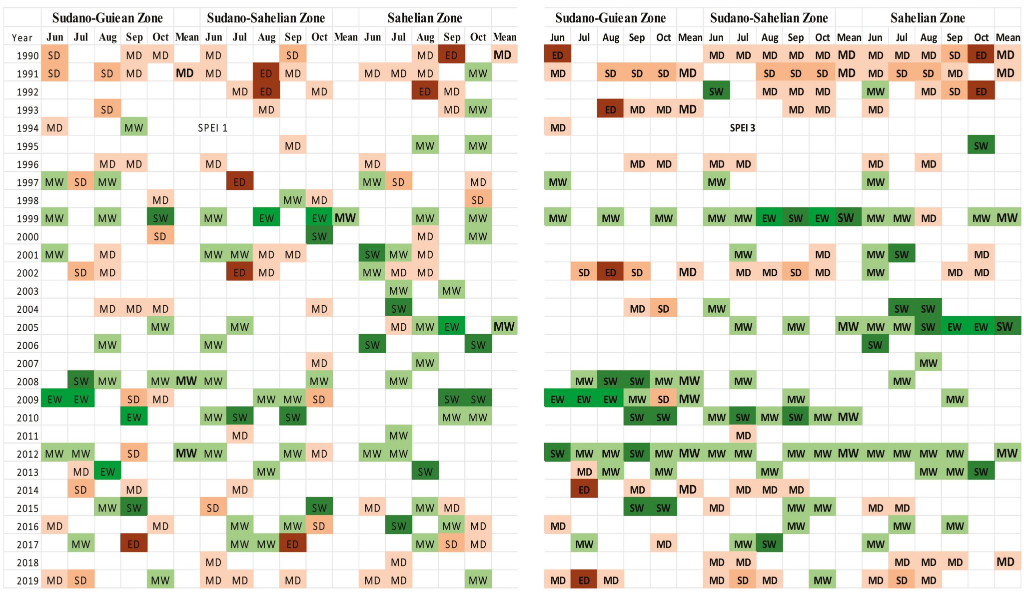


Figure 4. Temporal and spatial variation of wet and dry conditions from 1990–2019 based on SPEI-1(**left**) and SPEI-3 (**right**) values. The months June–October corresponds to the 5-month growing season. The climatic events are classified into two main groups: dryness (orange) and wetness (green). The color level displays the degrees of condition ranging from moderate to extreme. Adapted from the authors of [71].

Similarly, the frequency of probability of drought and wetness occurrence and intensity has been analyzed for each region (Table 3). Abnormal wet and dry conditions were seen in all three regions with a frequency probability from 35 to 39%. The evolution of SPEIs over the three regions was similar, though the Sudano-Sahelian region experienced a more frequent number of drought episodes for both SPEI-1 and 3 than the rest of the regions. The SPEI-1 revealed more dry months across the three regions while the number of wet months increased slightly in the SPEI-3, suggesting an increase of moisture with time scale. The probability of extreme, severe, and moderate drought combined for the two-time scales 18.3%, 20%, and 17.3%, while anomalous wet conditions combined ranges from 15.3%, 17.7, and 21% for the three regions, respectively. Extreme wet and dry conditions were rare compared to moderate drought and wetness, while near-normal conditions were more common with 66.3%, 62.0%, and 61.6% across the three regions for the SPEI-1 and SPEI-3 combined.

Table 3. Probabilities of experiencing anomalous dry and wet conditions in the 3 regions from 1990 to 2019.

Category	SPEI-1						SPEI-3					
	S. Guinean		S. Sahelian		Sahelian		S. Guinean		S. Sahelian		Sahelian	
	F	P	F	P	F	P	F	P	F	P	F	P
Extreme drought	1	0.006	5	0.033	2	0.013	5	0.033	0	0.00	2	0.013
Severe drought	11	0.073	4	0.026	3	0.02	7	0.047	5	0.033	5	0.033
Moderate drought	18	0.12	21	0.14	20	0.133	13	0.086	25	0.167	20	0.133
Extreme wet	4	0.026	2	0.013	1	0.006	3	0.02	2	0.013	2	0.013
Severe wet	3	0.020	4	0.026	8	0.053	8	0.053	5	0.033	7	0.047
Moderate wet	15	0.10	18	0.12	24	0.16	13	0.086	22	0.147	21	0.14
Normal	98	0.653	96	0.64	92	0.613	101	0.67	91	0.606	93	0.62

3.2. Crop Yield Trends

The country's average yields declined at an average rate of 13.4 kg $ha^{-1}yr^{-1}$ for millet, 19.6 kg $ha^{-1}yr^{-1}$ for maize, and 20 kg $ha^{-1}yr^{-1}$ for rice, while sorghum yields exhibited a slight increase of 2.5 kg $ha^{-1}yr^{-1}$ (Figure 5). Except for sorghum, the Mann–Kendall test revealed a significant decreasing trend on the regional average yields of all crops across the three regions. The most considerable yield decrease was observed in the Sahelian and Sudano-Sahelian region for maize (28.1 kg $ha^{-1}yr^{-1}$ and 19.1 $ha^{-1}yr^{-1}$) and rice (29 kg $ha^{-1}yr^{-1}$ and 19 $ha^{-1}yr^{-1}$), respectively. Average yields and yield trends differed across regions showing high inter-annual variability, with a standard deviation between 131 kg ha^{-1} for sorghum yields in the Sudano-Guinean region to 428 kg ha^{-1} for rice in the Sahelian region.

3.3. Climate–Crop Yield Correlation

The correlation analysis showed that maximum and minimum temperatures in the growing season had a generally negative association with detrended crop yield across all the regions, except for Tmin and millet in the S. Guinean zone (Figure 6). For the S. Guinean and Sahelian regions, the strongest (significant) negative correlation values were observed between Tmin and rice yields (0.45 & 0.50), while Tmax revealed a stronger negative relationship with sorghum and rice yields in the S. Sahelian region. The most significant (p-value ≤ 0.05) correlation value (r) between yields and temperatures for the three regions was observed between Tmax and sorghum yields (r = −0.53) in the S. Sahelian region, and the lowest correlation coefficient was observed for Tmin and millet yields (r = −0.03) in the Sahelian region. Conversely, a generally positive and significant correlation ($p \leq 0.05$) was observed between yields and SPEIs with detrended crop yields in all of the three regions (Figure 6). The mean SPEI-1 indicated a higher positive association with yields than the SPEI-3, with the maximum correlation recorded for maize yields (r = 0.73) in the Sahelian zone. However, the SPEI-3 exhibited more months with a significant correlation pattern than the SPEI-1.

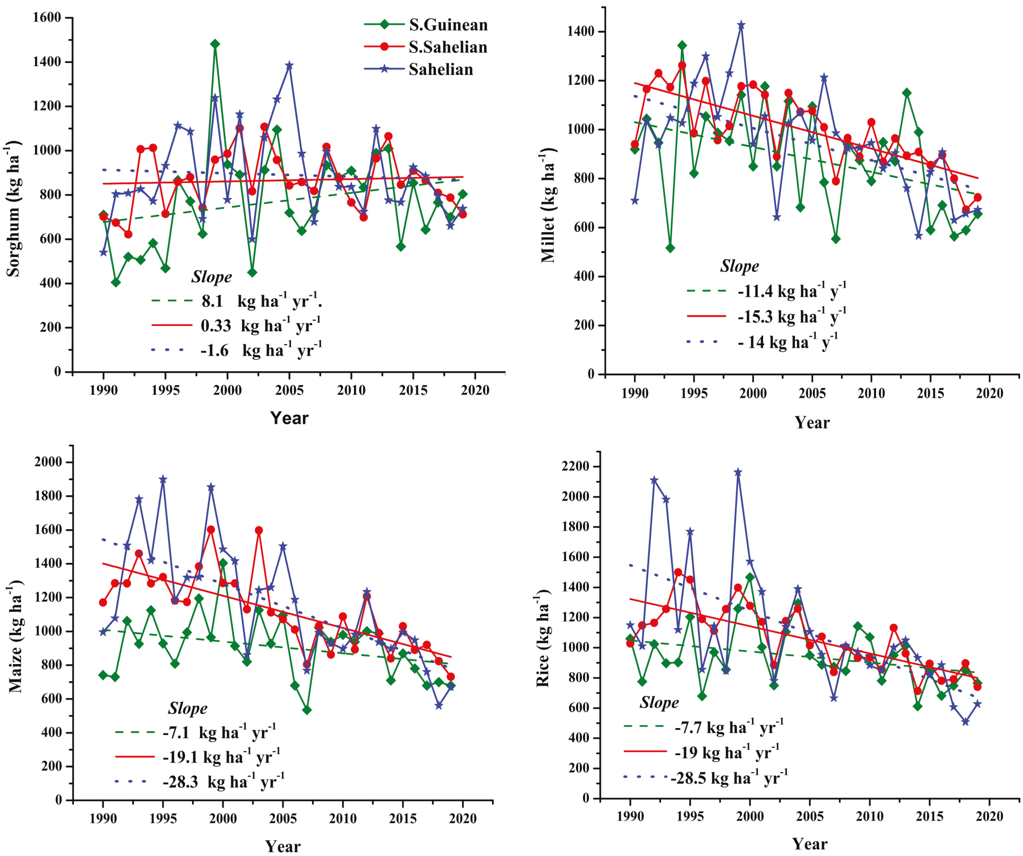


Figure 5. Time series of sorghum, millet, maize, and rice yields from 1990 to 2019.

3.4. Impact of Historical Climate Trends on Yields

The multi-linear regression model represented by the r^2 between detrended yields and the climate was used to indicate the degree of yield variation explained by changes in climate trends. Results from the analysis reveal that variations in mean predictors (SPEI-1, Tmin, Tmax) explained from R^2 = 0.20 to R^2 =0.62 of the year-to-year change in yields for all crops (Table 4). This means that 20% and 62% of the yearly variations in sorghum (kg ha^{-1}) and maize (kg ha^{-1}) yield in the Sudano-Guinean and Sahelian region for the past 30 years can be explained jointly by the variations in SPEI, Tmax, and Tmin. The remaining 80% and 38% can be attributed to other non-climate factors such as seed varieties, financial status, soil characteristics, planting dates, weeds, pests, diseases, etc., omitted in our analysis. As shown in Table 4, the magnitude of climate variability responsible for yield fluctuations was region and crop-specific and thus varied between crops and across regions. For example, climate variables accounted for only 32% of the changes in maize yields in the Sudano-Guinean zone, whereas 62% of the changes in the same crop were accounted for by climate in the Sahelian zone and vice versa.

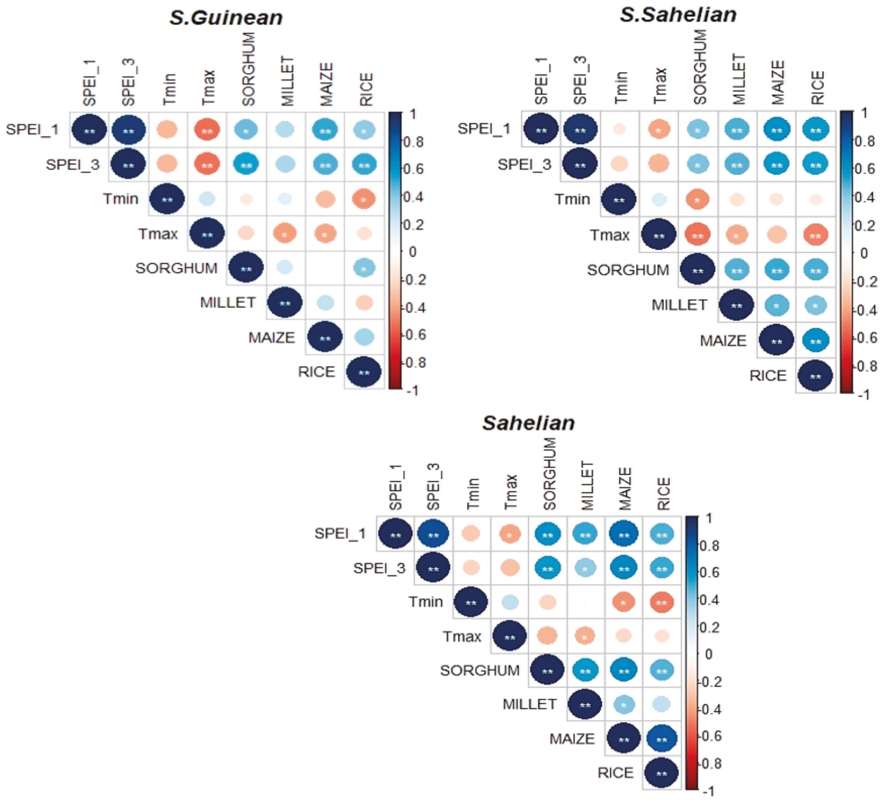


Figure 6. Pearson's correlation between crop yields, SPEIs, Tmin, and Tmax for 1990–2019. * p-value ≤ 0.05, ** p-value ≤ 0.01. The blue colors denote the positive values and the orange colors denote the negative values, respectively.

Table 4. Multiple linear regressions relating crop yields, SPEI-1, Tmin, and Tmax.

		Sorghum		Millet		Maize		Rice	
		Estimate	Sig.	Estimate	Sig.	Estimate	Sig.	Estimate	Sig.
S. Guinean	Intercept	1.57		−4.86		−2.843		−13.1	
	SPEI−1	168.25	**0.04 ***	72.88	0.38	108.52	0.08	93.8	0.18
	Tmin	6.35	0.95	162.26	0.11	−72.98	0.32	−168.98	0.06
	Tmax	16.37	0.89	−233.3	0.07	−74.148	0.42	28.6	0.78
	R^2	0.2		0.26		0.32		**0.27**	
	Sig.	0.13		**0.05 ***		**0.021 ***		**0.046 ***	
S. Sahelian	Intercept	6.763		−7.53		−17.6		−11.357	
	SPEI-1	44.9	0.21	72.32	**0.05 ***	155.5	**0.002 ****	96.67	**0.015 ***
	Tmin	−235.68	**0.027 ***	−48.05	0.63	−57.7	0.67	−8.85	0.93
	Tmax	−167.07	**0.03 ***	−89.54	0.23	−34.21	0.72	−142.97	0.07
	R^2	**0.44**		**0.29**		**0.38**		**0.41**	
	Sig.	**0.001 ****		**0.032 ***		**0.007 ****		**0.004 ****	
Sahelian	Intercept	−1.798		−6.68		−23.96		−29.3	
	SPEI-1	297.98	**0.004 ****	190.7	**0.016 ***	424.76	**0.00 ****	377.49	**0.03 ***
	Tmin	−37.338	0.73	80.517	0.34	−208.32	**0.03 ***	−456.92	**0.02 ***
	Tmax	−43.95	0.51	−65.1	0.22	58.91	0.31	59.06	0.61
	R^2	**0.39**		**0.32**		**0.62**		**0.38**	
	Sig.	**0.006 ****		**0.02 ***		**0.000 ****		**0.006 ****	

* $p < 0.05$, ** $p < 0.01$.

The regression coefficients indicate that the SPEI-1 index was a significant factor favoring crop yield increase across the three study regions. In contrast, inferred Tmin and Tmax sensitivities mostly impacted yields negatively, though positive effects due to temperatures were observed on some region-specific crops (Table 4).

The yield changes due to the combined impacts of the three climatic trends on crop yields presented in Table 4 were calculated using the equation below for a single crop (e.g., maize in the Sahelian zone) as:

$$\Delta M_{ij} = -23.96 + 424.8 * \Delta SPEI.1 - 208.32 * \Delta Tmin + 58.9 * \Delta Tmax \quad (3)$$

where ΔM_{ij} is the estimated yield change of maize in the Sahelian zone, $\Delta SPEI.1$, $\Delta Tmin$, and $\Delta Tmax$ are the changes in SPEI-1, minimum and maximum temperatures (°C), and the numbers correspond to the values of the estimated coefficients.

Substituting the trends of the three climate variables between 1990–2019 in Equation (3) implies that a unit change in growing season SPEI at 1-month will lead to an increase of 424.8 kg ha^{-1} year^{-1} of maize yield, a unit change in Tmin will lead to a yield decrease of 208.32 kg ha^{-1} year^{-1}, and a unit change in Tmax will increase yields by 58.9 kg ha^{-1} year^{-1}, respectively.

Applying the above equation for all crops revealed that the increase in the SPEI-1 trend significantly increased yields across all the study regions (Table 4). These impacts likely depend on the rainfall distribution during the growing season; thus, regular distribution of precipitation, especially during the early part of the rainy season, translated into higher yields than years with inconsistent distribution patterns. Conversely, increasing temperatures, especially Tmin, mostly suppressed yields, particularly in the Sahelian region with the most pronounced impact on rice yields. Nevertheless, warming trends in Tmin and Tmax also favored a yield increase on some region-specific crops, particularly sorghum and millet in the S. Guinean zone and maize and rice in the Sahelian region, respectively. In most instances, the yield impacts were determined by SPEI trends rather than temperatures except for sorghum and millet yields in the S. Sahelian and maize and rice in the Sahelian, where impacts were determined by both SPEI-1 and Tmin, respectively (Table 4).

The estimated impacts of yields due to growing season SPEI-1, Tmin, and Tmax trends across the three study regions are shown in Figure 7. Although varying from one region to the other, yields decreased consistently due to climate trends for all crops (3.6 kg ha^{-1} year^{-1} to 29.4 ha^{-1} year^{-1}) except for sorghum which showed yield gains across the three regions. Rice yields experienced the most significant decrease due to the combined effects of SPEI-1, Tmin, and Tmax in the Sahelian and Sudano-Sahelian regions. These regions are characterized as the most intensive agricultural areas with a higher risk of drought and warming in the Gambia.

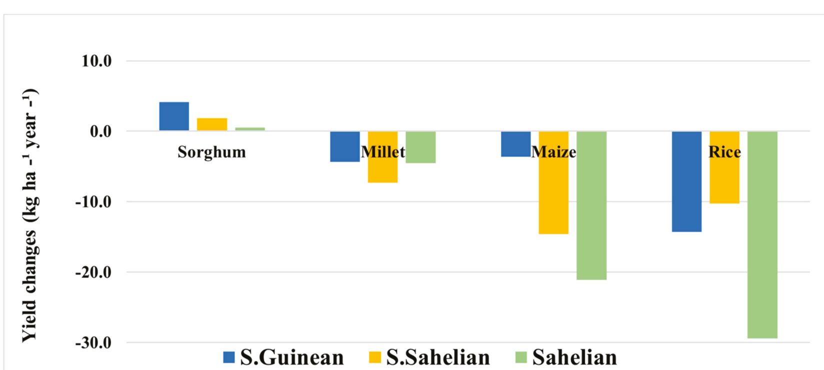


Figure 7. Estimated impacts of climate trends from the multiple linear regression for 1990–2019 on crop yields (kg ha^{-1} y^{-1}).

4. Discussion

Agriculture contributes 24% of the GDP and 75% of the household income in the Gambia [46]. As in in many parts of the globe [72–74], the agricultural sector in the Gambia is expected to be severely affected by climate change characterized by increasing temperatures and the spatio-temporal variation of precipitation patterns, favoring the formation of seasonal and annual droughts [75]. A likely increase in climate events is projected across the world, which will cause serious repercussions on crop yields, affecting the overall GDP of most developing countries and the livelihoods of people, especially those who depend on rainfed agricultural production systems. Hence, this study attempts to analyze the trends and impacts of mean temperatures (Tmin and Tmax) and the Standardized Precipitation Evapotranspiration Index (SPEI) on the four main cereal crops over the three agro-ecological regions in the Gambia 1990–2019, which could support effective agricultural adaptation practices under a changing climate.

Though several studies have been conducted globally and on regional scales relating historical climate impacts and yields, to the best of our knowledge, no such studies, particularly during cropping seasons, have been conducted in the Gambia. Some studies revealed an upward trend in temperature (representing climate warming), considered a major driver in drought frequency and severity across different regions [9,21,76], which aligns with the findings of this work. Tmin is rising faster than Tmax, consistent with studies such as [77,78] with more apparent warming observed in the S. Sahelian region. These warming trends also agree with the study in [79], which indicates an increase in global mean temperatures, likely to affect precipitation patterns, especially in tropical and subtropical regions like the Gambia. In the current context of global warming, this increasing trend in temperatures found in our study could likely exacerbate evapotranspiration, accelerate crop development, and reduce grain filling duration, thereby causing a reduction in grain yields and or seed number [80].

We consider that in the arid regions like the Gambia, where evaporation is large, the SPEI is more appropriate than total precipitation alone to characterize drought evolution because the SPEI captures the combined effects of temperatures and precipitation to assess the role global warming plays in drought evolution. Overall, the time series of the SPEIs at cropping season exhibited an increasing trend across the three regions (significant only in the S. Sahelian region), with alternate dry and wet conditions, at 1- and 3-month lags, representing drought characterization: severity, extent, and duration [81]. This observed increase in the SPEI trend over the three regions can be partially attributed to the partial recovery of recent precipitation patterns in most Sahelian countries [82]. Our assessment agreed with the finding reported by recent studies in Africa and beyond [83–85], indicating the variation of wet and drought episodes and more frequent extreme events based on observed long-term data. The frequency of severe and moderately dry conditions compared with wetness was more evident in the SPEI at a 1-month lag in the S. Guinean and S. Sahelian regions than in the Sahelian zone, whereas the percentage of wetness increased with the increase of the SPEI at a 3-months lag. This implies that the magnitude and level of dry and wet conditions increase with the 3-month SPEI time scale, as the SPEI-3 accumulates the impacts of soil moisture conditions from the previous two consecutive months. The alternate increase in dry and wet episodes, along with rising temperatures found in our study and consistent with [71], could likely cause increased soil evaporation and reduced soil moisture during the rainy season. Since trends in wetness/dryness are considered to be mainly determined by the water balance in a region [66], wherein the climate components of warming temperatures found in our study often play a big role, this could likely result in the consistent increase of potential evapotranspiration (PET), which is detrimental to crop growth. Previous studies [86,87] reported a considerable uncertainty related to the SPEI patterns in west African countries like the Gambia with linear trends towards decreases and increases associated with extreme rain events and intra-seasonal variations caused by the El Niño Southern Oscillation (ENSO) events. However, whether statistically significant or not, these climate trends can still have severe consequences for crop production through yield declines, reduced soil moisture, etc., and hence need appropriate attention while assessing the climate impacts on crop yields [88]. Using shorter time scale SPEIs of 1- and 3-months was useful to detect more dry and wet events in our study as both time scales consider only the current month (1-month scale) and the previous 2 months (3-month scale); hence, their responses to the change of climatic variables are more instant. However, a longer time scale is more appropriate to investigate the long-term changing pattern of drought conditions as they reveal a more intuitive presentation of the trend [60].

According to the World Food Program (WFP), cereals account for more than two-thirds of the Gambia's food energy intake, albeit with varying importance across regions [89]; thus, impacts of climate variability on these crops could have a severe effect on the larger majority of the country's population who depends on agriculture for livelihood. Consistent with the findings in [90], the yields of all crops in our study (except sorghum) exhibit a downward trend. This finding aligns with the authors of [7,91], who indicate a decline in cereal yields in France and most African sub-regions due to increasing climate variability and change. However, the difference and magnitude of yield reduction across the regions in this study could likely be driven by certain complex environmental, biological, and socio-economic factors that need further investigation.

A clear negative relationship was found between detrended yields, Tmin and Tmax, respectively. This suggests a decrease in crop yields due to heat stress and reductions in net photosynthetic rates [30]. The negative relationship between temperatures and yields can be associated with an increase in evapotranspiration, which reduces the soil moisture needed for optimum crop growth in arid and semi-arid regions like the Gambia, where irrigation is a limiting factor. Studies such as [26,67,92,93] also reported a negative correlation between temperatures and cereal crops. Correlations between yield and growing season mean SPEIs [94] were highly positively significant [38,65], suggesting that SPEI constantly influences crop yields. Significant correlations are more pronounced in the SPEI at 3-month lags than 1-month, with the former indicating the progress of crops' growth stages; hence, yields depend on all growth stages in a crop cycle, and the later growth stage reflects a long period of water deficit.

The regression model confirms the susceptibility of crop yields to increasing temperatures and mirrors the effect of positive gains from SPEI trends to help compensate for the adverse impact of temperatures. Hence, possible yield declines due to warming trends could, to some extent, be lessened by improved water deficiency through water management and irrigation measures. These findings align with studies such as [95–97]. Yield variability due to SPEIs reveals more explanatory power than temperatures, exhibiting the vulnerability of crop yields in these regions to drought events. Cereal yield variability has been linked to variation in precipitation-related droughts or wetness in rain-fed areas, while increased temperatures were associated with yield declines [98,99], similar to the findings of this study. Stress due to high temperatures and low humidity reduces pollen viability and silk receptivity due to desiccation, resulting in poor seed formation and low yield [62]. The regression coefficients revealed both the positive and negative impacts of individual climate trends on yields, though the combined effect of the three observed climate trends decreased yields for all crops except sorghum. Unless addressed through adaptation strategies, observed climate trends will suppress yields for millet, maize, and rice at varying rates across all regions, particularly in the Sahelian and Sudano-Sahelian regions which are considered the areas with the largest population of vulnerable subsistence farmers in the Gambia. Reduction rates per year across all regions were mainly attributed to Tmin and Tmax rather than the SPEI trends. Similar findings were also found in studies by [100,101].

5. Conclusions

Assessing the historical impacts of declining cereal yields in the Gambia, mostly attributed to variations in climatic parameters, is vital to address the various risks of projected climate change. This study gives an insight into the effects of the past 30 years (1990–2019) of mean temperatures (Tmin and Tmax) and the SPEI on major cereals (sorghum, millet, maize, and rice) over the three agro-ecological regions in the Gambia, where no such study has been carried out before. The quantification of the climate change impact on yields using a correlation and regression analysis will help address the core challenges of climate-related yields losses, based on which the influences of expected changes in future climate can be more realistically assessed at regional scales.

The trend analysis results show that during the last 30 years, all of the three agro-ecological zones underwent a region-wide increasing trend and variability in temperatures and the SPEI across all the study regions. SPEIs revealed that all the study regions experienced an alternate episode of droughts and wetness during the main crop growth stages, though near-normal conditions were more frequent than extreme, severe, and moderate drought or flood conditions. The correlation analysis shows that SPEI had a positive ($p < 0.05$) relationship with all four crops, while temperatures were negatively associated with yields. A unit increase in mean growing season temperatures intrinsically contributed to an estimated decline in yields for almost all crops ranging from an estimate or coefficient of -37.34 kg h^{-1} year $^{-1}$ for Tmin on sorghum yields in the Sahelian and -456.92 kg h^{-1} year $^{-1}$ for rice yields in the same region. Though the magnitude of these impacts varies among crops and across regions, our study revealed that the combined effect of Tmin, Tmax, and SPEI trends during the last three decades played a determining role in the percentage of yield variations from $r^2 = 0.20$ (20%) for sorghum in the Sudano-Guinean region to $r^2 = 0.62$ (62%) for maize in the Sahelian region, thus suggesting that climatic trends will continue to have a discernible negative impact on the country's cereal crop production if no adaptation measures are implemented.

Our analysis shows that of the four cereal crops studied, maize and rice yields were the most vulnerable to climate, with the Sahelian region experiencing the highest yield decline in rice (29. 4 kg ha^{-1} $year^{-1}$) and maize (21 kg ha^{-1} $year^{-1}$) yields. Thus, this heterogeneity of the impact of the climate between crops and across regions suggests that current policies promoting cereal cultivation in the Gambia need to consider each region and crops' relative vulnerability to the climate. This indicates that every region requires its adaptation strategy or tailor-made intervention action, which should be analyzed in a participative decision-making process. Policies and adaptation measures should include integrated approaches depending on each region's specific climate parameters, soil type, topography, technology availability, suitability, etc. However, in this study, we showed only the inferred impacts of the mean growing season temperatures (Tmin and Tmax) and the SPEI as influencing factors to yield variability and decline from 1990–2019. Hence, more insights related to the significant decline in yield trends within the study regions may be obtained by including the influence of other climate parameters and or non-climatic factors, such as agronomic practices, agricultural policies, market prices, cultivars, and fertilizers, which were not captured/included in our model.

Although the impact of climate trends on crop yields had mixed effects and involved greater uncertainties, most likely during certain growth stages of the crops studied, the results of this study provide an understanding of the significance of climate trends and set the bibliographic basis for projecting current and future climate impacts on yields in the Gambia. Policymakers can use this information for informed decision-making geared towards improving crop productivity.

Author Contributions: Conceptualization, F.F.J. and Y.L.; methodology, F.F.J. and Y.L.; data collection, F.F.J.; validation, F.F.J., Y.L. and T.Z.; formal analysis, F.F.J., Y.L. and T.Z.; investigation, F.F.J.; resources, Y.L.; data curation, F.F.J. and W.B.; writing—original draft preparation, F.F.J.; writing—review and editing, F.F.J., Y.L., T.Z. and W.H.; visualization, F.F.J., W.B., Y.S. and W.H.; supervision, F.F.J., Y.L. and T.Z.; funding acquisition, Y.L. and Y.S. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by China's National Key Research and Development Program (Grand No. 2017YFD0300400).

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The data that support the findings of this study are available upon reasonable request from the corresponding author and/or from the department of water resources and the planning service unit of the Gambia. The data are not yet publicly available due to efforts to publish it in a data journal.

Acknowledgments: We thank the National Key Research and Development Program of China for the financial support, the Department of Water Resources and the Planning Service Unit of the Gambia for their willingness to provide the necessary data for the research.

Conflicts of Interest: All authors declare that they have no financial or personal conflicts of interest that are relevant and/or could influence the content reported in this article.

References

1. Grassini, P.; Eskridge, K.M.; Cassman, K.G. Distinguishing between yield advances and yield plateaus in historical crop production trends. *Nat. Commun.* **2013**, *4*, 2918. [CrossRef] [PubMed]
2. Lobell, D.B.; Schlenker, W.; Costa-Roberts, J. Climate trends and global crop production since 1980. *Science* **2011**, *333*, 616–620. [CrossRef]
3. Peña-Gallardo, M.; Vicente-Serrano, S.M.; Quiring, S.; Svoboda, M.; Hannaford, J.; Tomas-Burguera, M.; Martín-Hernández, N.; Domínguez-Castro, F.; El Kenawy, A. Response of crop yield to different time-scales of drought in the United States: Spatio-temporal patterns and climatic and environmental drivers. *Agric. For. Meteorol.* **2019**, *264*, 40–55. [CrossRef]
4. Intergovernmental Panel on Climate Change (IPCC). Climate change 2007: The physical science basis. *S. Afr. Geogr. J.* **2013**, *92*, 86–87. [CrossRef]
5. Intergovernmental Panel on Climate Change (IPCC). *Climate Change 2014: Impacts, Adaptation, and Vulnerability; Impacts, Adaptation, and Vulnerability*; Part A: Global and Sectoral Aspects; Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change; Cambridge University Press: Cambridge, UK; New York, NY, USA, 2014; p. 1132.
6. Araya, A.; Hoogenboom, G.; Luedeling, E.; Hadgu, K.M.; Kisekka, I.; Martorano, L.G. Assessment of maize growth and yield using crop models under present and future climate in southwestern Ethiopia. *Agric. For. Meteorol.* **2015**, *214–215*, 252–265. [CrossRef]
7. Gammans, M.; Mérel, P.; Ortiz-Bobea, A. Negative impacts of climate change on cereal yields: Statistical evidence from France. *Environ. Res. Lett.* **2017**, *12*, 054007. [CrossRef]
8. Hansen, J.; Ruedy, R.; Sato, M.; Lo, K. Global surface temperature change. *Rev. Geophys.* **2010**, *48*, 1–29. [CrossRef]
9. Zewdie, A. Impacts of Climate Change on Food Security: A Literature Review in Sub Saharan Africa. *J. Earth Sci. Clim. Change* **2014**, *5*, 8–11. [CrossRef]
10. Mesike, C.S.; Esekhade, T.U. Rainfall variability and rubber production in Nigeria. *Afr. J. Environ. Sci. Technol.* **2014**, *8*, 54–57. [CrossRef]
11. Vogel, E.; Donat, M.G.; Alexander, L.V.; Meinshausen, M.; Ray, D.K.; Karoly, D.; Meinshausen, N.; Frieler, K. The effects of climate extremes on global agricultural yields. *Environ. Res. Lett.* **2019**, *14*, 054010. [CrossRef]
12. Nkemelang, T.; New, M.; Zaroug, M. Temperature and precipitation extremes under current, 1.5 °C and 2.0 °C global warming above pre-industrial levels over Botswana, and implications for climate change vulnerability. *Environ. Res. Lett.* **2018**, *13*, 065016. [CrossRef]
13. Adamgbe, E.M.; Ujoh, F. Effect of Variability in Rainfall Characteristics on Maize Yield in Gboko, Nigeria. *J. Environ. Prot.* **2013**, *04*, 881–887. [CrossRef]
14. Yamusa, A.M.; Abubakar, I.U.; Falaki, A.M. Rainfall variability and crop production in the North- western semi-arid zone of Nigeria. *J. Soil Sci. Environ. Manag.* **2015**, *6*, 125–131. [CrossRef]
15. Ahmed, M.; Hassan, F.U.; Aslam, M.A.; Akram, M.N.; Akmal, M. Regression model for the study of sole and cumulative effect of temperature and solar radiation on wheat yield. *Afr. J. Biotechnol.* **2011**, *10*, 9114–9121. [CrossRef]
16. Ramirez-Villegas, J.; Thornton, P.K. *Climate Change Impacts on African Crop Production*; CCAFS Working Paper No. 119; CGIAR Research Program on Climate Change, Agriculture and Food Security (CCAFS): Copenhagen, Denmark, 2015; pp. 1–27.
17. Cairns, J.E.; Sonder, K.; Zaidi, P.H.; Verhulst, N.; Mahuku, G.; Babu, R.; Nair, S.K.; Das, B.; Govaerts, B.; Vinayan, M.T.; et al. Maize production in a changing climate. impacts, adaptation, and mitigation strategies. *Adv. Agron.* **2012**, *114*, 1–58. [CrossRef]
18. Byakatonda, J.; Parida, B.P.; Kenabatho, P.K.; Moalafhi, D.B. Influence of climate variability and length of rainy season on crop yields in semiarid Botswana. *Agric. For. Meteorol.* **2018**, *248*, 130–144. [CrossRef]
19. World Bank. *The Gambia Agriculture Engagement Note: Fostering Agriculture-Led Inclusive Growth*; World Bank: Washington, DC, USA, 2019; pp. 1–51.
20. Sanneh, E.S.; Hu, A.H.; Hsu, C.W.; Njie, M. Prioritization of climate change adaptation approaches in the Gambia. *Mitig. Adapt. Strateg. Glob. Chang.* **2014**, *19*, 1163–1178. [CrossRef]

21. Jaiteh, M.S. *Climate Change and Development in the Gambia Challenges to Ecosystem Goods and Services*; Center for International Earth Science Information Network (CIESIN): Kanifing, Gambia, 2011; pp. 1–57.
22. Loum, A.; Fogarassy, C. The effects of climate change on cereals yield of production and food security in Gambia. *Appl. Stud. Agribus. Commer.* **2015**, *9*, 83–92. [CrossRef]
23. Serdeczny, O.; Adams, S.; Baarsch, F.; Coumou, D.; Robinson, A.; Hare, W.; Schaeffer, M.; Perrette, M.; Reinhardt, J. Climate change impacts in Sub-Saharan Africa: From physical changes to their social repercussions. *Reg. Environ. Chang.* **2017**, *17*, 1585–1600. [CrossRef]
24. Omoyo, N.N.; Wakhungu, J.; Oteng'i, S. Effects of climate variability on maize yield in the arid and semi arid lands of lower eastern Kenya. *Agric. Food Secur.* **2015**, 1–13. [CrossRef]
25. Xu, X.; Hu, H.; Tan, Y.; Yang, G.; Zhu, P.; Jiang, B. Quantifying the impacts of climate variability and human interventions on crop production and food security in the Yangtze River Basin, China, 1990–2015. *Sci. Total Environ.* **2019**, *665*, 379–389. [CrossRef] [PubMed]
26. Najafi, E.; Pal, I.; Khanbilvardi, R. Climate drives variability and joint variability of global crop yields. *Sci. Total Environ.* **2019**, *662*, 361–372. [CrossRef]
27. Bhatt, D.; Maskey, S.; Babel, M.S.; Uhlenbrook, S.; Prasad, K.C. Climate trends and impacts on crop production in the Koshi River basin of Nepal. *Reg. Environ. Chang.* **2014**, *14*, 1291–1301. [CrossRef]
28. Li, X.; Takahashi, T.; Suzuki, N.; Kaiser, H.M. The impact of climate change on maize yields in the United States and China. *Agric. Syst.* **2011**, *104*, 348–353. [CrossRef]
29. Nicholls, N. Increased Australian wheat yield due to recent climate trends. *Nature* **1997**, *387*, 484–485. [CrossRef]
30. Tao, F.; Yokozawa, M.; Liu, J.; Zhang, Z. Climate-crop yield relationships at provincial scales in China and the impacts of recent climate trends. *Clim. Res.* **2008**, *38*, 83–94. [CrossRef]
31. Lobell, D.B.; Bänziger, M.; Magorokosho, C.; Vivek, B. Nonlinear heat effects on African maize as evidenced by historical yield trials. *Nat. Clim. Chang.* **2011**, *1*, 42–45. [CrossRef]
32. Wei, T.; Cherry, T.L.; Glomrød, S.; Zhang, T. Climate change impacts on crop yield: Evidence from China. *Sci. Total Environ.* **2014**, *499*, 133–140. [CrossRef] [PubMed]
33. Intergovernmental Panel on Climate Change (IPCC). Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation; A Special Report of Working Groups I and II of the Intergovernmental Panel on Climate Change. Cambridge University Press: Cambridge, UK; New York, NY, USA, 2012; p. 582.
34. Leng, G.; Tang, Q.; Rayburg, S. Climate change impacts on meteorological, agricultural and hydrological droughts in China. *Glob. Planet. Change* **2015**, *126*, 23–34. [CrossRef]
35. Zampieri, M.; Ceglar, A.; Dentener, F.; Toreti, A. Wheat yield loss attributable to heat waves, drought and water excess at the global, national and subnational scales. *Environ. Res. Lett.* **2017**, *12*, 064008. [CrossRef]
36. Tubiello, F.N.; Soussana, J.-F.; Howden, S. Crop and pasture response to climate change. *Proc. Natl. Acad. Sci. USA* **2007**, *104*, 19686–19690. [CrossRef] [PubMed]
37. Rowhani, P.; Lobell, D.B.; Linderman, M.; Ramankutty, N. Climate variability and crop production in Tanzania. *Agric. For. Meteorol.* **2011**, *151*, 449–460. [CrossRef]
38. Shi, W.; Tao, F. Vulnerability of African maize yield to climate change and variability during 1961–2010. *Food Secur.* **2014**, *6*, 471–481. [CrossRef]
39. Miyan, M.A. Droughts in asian least developed countries: Vulnerability and sustainability. *Weather Clim. Extrem.* **2015**, *7*, 8–23. [CrossRef]
40. Palmer, W.C. Meteorological Drought. *U.S. Weather Bur. Res. Pap.* **1965**, *45*, 58.
41. McKee, T.B.; Doesken, N.J.; Kleist, J. The relationship of drought frequency and duration to time scales. In Proceedings of the 8th Conference on Applied Climatology, Boston, MA, USA, 17–22 January 1993; pp. 179–184.
42. Vicente-Serrano, S.M.; Beguería, S.; López-Moreno, J.I. A multiscalar drought index sensitive to global warming: The standardized precipitation evapotranspiration index. *J. Clim.* **2010**, *23*, 1696–1718. [CrossRef]
43. Potopová, V.; Štěpánek, P.; Možný, M.; Türkott, L.; Soukup, J. Performance of the standardised precipitation evapotranspiration index at various lags for agricultural drought risk assessment in the Czech Republic. *Agric. For. Meteorol.* **2015**, *202*, 26–38. [CrossRef]
44. Lu, J.; Carbone, G.J.; Gao, P. Detrending crop yield data for spatial visualization of drought impacts in the United States, 1895–2014. *Agric. For. Meteorol.* **2017**, *237–238*, 196–208. [CrossRef]
45. Wang, Q.; Wu, J.; Li, X.; Zhou, H.; Yang, J.; Geng, G.; An, X.; Liu, L.; Tang, Z. A comprehensively quantitative method of evaluating the impact of drought on crop yield using daily multi-scale SPEI and crop growth process model. *Int. J. Biometeorol.* **2017**, *61*, 685–699. [CrossRef]
46. International Fund for Agricultural Development (IFAD). *(The) Resilience of Organizations for Transformative Smallholder Agriculture Programme: Project Design Report*; International Fund for Agricultural Development (IFAD): Rome, Italy, 2019; pp. 1–377.
47. Yaffa, S. Loss and Damage from Drought in the North Bank Region of The Gambia. In *Loss and Damage in Vulnerable Countries Initiative, Case Study Report*; United Nations University Institute for Environment and Human Security: Bonn, Germany, 2013; pp. 1–44.

48. Kutir, C. Farmers Awareness and Response to Climate Change: A Case Study of the North Bank Region, The Gambia. *J. Econ. Sustain. Dev.* **2015**, *6*, 32–41.
49. Bagagnan, A.R.; Ouedraogo, I.; Fonta, W.M. Perceived climate variability and farm level adaptation in the Central River Region of The Gambia. *Atmosphere* **2019**, *10*, 423. [CrossRef]
50. Food and Agriculture Organization of the United Nations (FAO); International Crops Research Institute for the Semi-Arid Tropics (ICRISAT); International Center for Tropical Agriculture (CIAT). *Climate-Smart Agriculture in the Gambia*; CSA Country Profiles for Africa Series; International Center for Tropical Agriculture (CIAT): Rome, Italy; International Crops Research Institute for the Semi-Arid Tropics (ICRISAT): Hyderabad, India; Food and Agriculture Organization of the United Nations (FAO): Rome, Italy, 2018; pp. 1–26.
51. International Fund for Agricultural Development (IFAD). *Republic of The Gambia: Country Strategic Opportunities Programme 2019–2024*; Note to Executive Board Representatives Focal points: Executive Board-126th Session; International Fund for Agricultural Development (IFAD): Rome, Italy, 2019; pp. 1–66.
52. Government of The Gambia. *The Gambia Annual Climate Report*; Government of The Gambia: Banjul, Gambia, 2018; pp. 1–45.
53. Wagner, A.; Hermelin, B.; Bruyeron, O.; Alby-Flores, V.; Faivre-Dupaigre, B.; Kaboré, C.; Ficini, C. *Food Security Profile, The Gambia*; CSAO-CILSS: Banjul, Gambia, 2008.
54. R Core Team. *A Language and Environment for Statistical Computing*; R Foundation for Statistical Computing: Vienna, Austria, 2019.
55. Gourdji, S.; Läderach, P.; Valle, A.M.; Martinez, C.Z.; Lobell, D.B. Historical climate trends, deforestation, and maize and bean yields in Nicaragua. *Agric. For. Meteorol.* **2015**, *200*, 270–281. [CrossRef]
56. Etana, D.; Snelder, D.J.R.M.; van Wesenbeeck, C.F.A. Trends of Climate Change and Variability in Three Agro-Ecological Settings in Central Ethiopia: Contrasts of Meteorological Data and Farmers' Perceptions. *Climate* **2020**, *8*, 121. [CrossRef]
57. Hargreaves, B.G.H. Reference evapotranspiration. *J. Irrig. Drain. Eng.* **1994**, *120*, 1132–1139. [CrossRef]
58. Venkataraman, K.; Nelson, M.; Frandsen, C. Comparison of Two Temperature-Based Methods of Estimating Potential Evapotranspiration (PET) in Texas. In Proceedings of the World Environmental and Water Resources Congress 2016: Hydraulics and Waterways and Hydro-Climate/Climate Change, West Palm Beach, FL, USA, 22–26 May 2016; pp. 699–708. [CrossRef]
59. Allen, R.G.; Pereira, L.S.; Raes, D.; Smith, M. *Crop Evapotraspiration Guidelines for Computing Crop Water Requirements*; Food and Agriculture Organization of the United Nations: Rome, Italy, 1998; ISBN 9251042195.
60. Fu, J.; Niu, J.; Kang, S.; Adeloye, A.J.; Du, T. Crop production in the Hexi Corridor challenged by future climate change. *J. Hydrol.* **2019**, *579*, 124197. [CrossRef]
61. Beguería, S.; Vicente-Serrano, S.M.; Reig, F.; Latorre, B. Standardized Precipitation Evapotranspiration Index (SPEI) revisited: Parameter fitting, evapotranspiration models, tools, datasets and drought monitoring. *Int. J. Climatol.* **2014**, *34*, 1–48. [CrossRef]
62. Potopová, V.; Boroneanţ, C.; Boincean, B.; Soukup, J. Impact of agricultural drought on main crop yields in the Republic of Moldova. *Int. J. Climatol.* **2016**, *36*, 2063–2082. [CrossRef]
63. Begueria, S.; Serrano, V.; Sawasawa, H. SPEI: Calculation of Standardised Precipitation-Evapotranspiration index. *R Package Version 1.7.* **2017**, *16*. [CrossRef]
64. Masupha, T.E.; Moeletsi, M.E. Use of standardized precipitation evapotranspiration index to investigate drought relative to maize, in the Luvuvhu River catchment area, South Africa. *Phys. Chem. Earth* **2017**, *102*, 1–9. [CrossRef]
65. Tian, L.; Yuan, S.; Quiring, S.M. Evaluation of six indices for monitoring agricultural drought in the south-central United States. *Agric. For. Meteorol.* **2018**, *249*, 107–119. [CrossRef]
66. Tan, C.; Yang, J.; Li, M. Temporal-spatial variation of drought indicated by SPI and SPEI in Ningxia Hui Autonomous Region, China. *Atmosphere* **2015**, *6*, 1399–1421. [CrossRef]
67. Karunaratne, A.S.; Wheeler, T. Observed relationships between maize yield and climate in Sri Lanka. *Agron. J.* **2015**, *107*, 395–405. [CrossRef]
68. Tunde, A.M.; Usman, B.A.; Olawepo, V.O. Effects of climatic variables on crop production in Patigi L. G. A., Kwara State, Nigeria. *J. Geogr. Reg. Plan.* **2011**, *4*, 695–700.
69. Alemayehu, A.; Bewket, W. Local climate variability and crop production in the central highlands of Ethiopia. *Environ. Dev.* **2016**, *19*, 36–48. [CrossRef]
70. Poudel, S.; Shaw, R. The relationships between climate variability and crop yield in a mountainous environment: A case study in Lamjung District, Nepal. *Climate* **2016**, *4*. [CrossRef]
71. Prabnakorn, S.; Maskey, S.; Suryadi, F.X.; de Fraiture, C. Rice yield in response to climate trends and drought index in the Mun River Basin, Thailand. *Sci. Total Environ.* **2018**, *621*, 108–119. [CrossRef]
72. Shiru, M.S.; Shahid, S.; Dewan, A.; Chung, E.S.; Alias, N.; Ahmed, K.; Hassan, Q.K. Projection of meteorological droughts in Nigeria during growing seasons under climate change scenarios. *Sci. Rep.* **2020**, *10*, 1–18. [CrossRef]
73. Ahammed, S.J.; Homsi, R.; Khan, N.; Shahid, S.; Shiru, M.S.; Mohsenipour, M.; Ahmed, K.; Nawaz, N.; Alias, N.E.; Yuzir, A. Assessment of changing pattern of crop water stress in Bangladesh. *Environ. Dev. Sustain.* **2020**, *22*, 4619–4637. [CrossRef]
74. Sediqi, M.N.; Shiru, M.S.; Nashwan, M.S.; Ali, R.; Abubaker, S.; Wang, X.; Ahmed, K.; Shahid, S.; Asaduzzaman, M.; Manawi, S.M.A. Spatio-temporal pattern in the changes in availability and sustainability ofwater resources in Afghanistan. *Sustainability* **2019**, *11*, 5836. [CrossRef]
75. Cao, Y.; Chen, S.; Wang, L.; Zhu, B.; Lu, T.; Yu, Y. An agricultural drought index for assessing droughts using awater balance method: A case study in Jilin Province, Northeast China. *Remote Sens.* **2019**, *11*, 66. [CrossRef]

76. Adhikari, U.; Nejadhashemi, A.P.; Woznicki, S. Climate change and eastern Africa: A review of impact on major crops. *Food Energy Secur.* **2015**, *4*, 110–132. [CrossRef]
77. Zhou, L.; Dickinson, R.E.; Tian, Y.; Fang, J.; Li, Q.; Kaufmann, R.K.; Tucker, C.J.; Myneni, R.B. Evidence for a significant urbanization effect on climate in China. *Proc. Natl. Acad. Sci. USA* **2004**, *101*, 9540–9544. [CrossRef] [PubMed]
78. Padma Kumari, B.; Londhe, A.L.; Daniel, S.; Jadhav, D.B. Observational evidence of solar dimming: Offsetting surface warming over India. *Geophys. Res. Lett.* **2007**, *34*, 1–5. [CrossRef]
79. Yaro, J.A.; Hesselberg, J. *Adaptation to Climate Change and Variability in Rural West Africa*; Yaro, J.A., Hesselberg, J., Eds.; Springer International Publishing: Cham, Switzerland, 2016; ISBN 978-3-319-31497-6.
80. Roudier, P.; Sultan, B.; Quirion, P.; Berg, A. The impact of future climate change on West African crop yields: What does the recent literature say? *Glob. Environ. Chang.* **2011**, *21*, 1073–1083. [CrossRef]
81. Lloyd-Hughes, B. A spatio-temporal structure-based approach to drought characterisation. *Int. J. Climatol.* **2012**, *32*, 406–418. [CrossRef]
82. Vondou, D.A.; Guenang, G.M.; Djiotang, T.L.A.; Kamsu-Tamo, P.H. Article trends and interannual variability of extreme rainfall indices over Cameroon. *Sustainability* **2021**, *13*, 1–12. [CrossRef]
83. Hamal, K.; Sharma, S.; Khadka, N.; Haile, G.G.; Joshi, B.B.; Xu, T.; Dawadi, B. Assessment of drought impacts on crop yields across Nepal during 1987–2017. *Meteorol. Appl.* **2020**, *27*, 1–18. [CrossRef]
84. Tao, H.; Borth, H.; Fraedrich, K.; Su, B.; Zhu, X. Drought and wetness variability in the Tarim River Basin and connection to large-scale atmospheric circulation. *Int. J. Climatol.* **2014**, *34*, 2678–2684. [CrossRef]
85. Haile, G.G.; Tang, Q.; Leng, G.; Jia, G.; Wang, J.; Cai, D.; Sun, S.; Baniya, B.; Zhang, Q. Long-term spatiotemporal variation of drought patterns over the Greater Horn of Africa. *Sci. Total Environ.* **2020**, *704*, 135299. [CrossRef]
86. Panthou, G.; Vischel, T.; Lebel, T. Recent trends in the regime of extreme rainfall in the Central Sahel. *Int. J. Climatol.* **2014**, *34*, 3998–4006. [CrossRef]
87. Reay, D.; Sabine, C.; Smith, P.; Hymus, G. Spring-time for sinks. *Nature* **2007**, *446*, 727–728. [CrossRef]
88. Kukal, M.S.; Irmak, S. Climate-Driven Crop Yield and Yield Variability and Climate Change Impacts on the U.S. Great Plains Agricultural Production. *Sci. Rep.* **2018**, *8*, 3450. [CrossRef] [PubMed]
89. Urban Market Assessment in The Gambia A feasibility study on cash and vouchers September 2011 Table of Contents List of Acronyms Acknowledgments. 2011. Available online: https://reliefweb.int/report/gambia/urban-market-assessment-gambia-feasibility-study-cash-and-vouchers (accessed on 20 October 2021).
90. Gibba, A. The Competitiveness of Gambia's Agricultural Products in International Trade: An Incentive for Economic Progress. Ph.D. Thesis, Doctoral School of Management and Business Administration Sciences, Szent Istvan University, Godollo, Hungary, 2017.
91. Niang, I.; Ruppel, O.C.; Abdrabo, M.A.; Essel, A.; Lennard, C.; Padgham, J.; Urquhart, P. Africa. *Climate Change 2014 Impacts, Adaptation and Vulnerability*; Part B Reg. Asp. Work. Gr. II Contrib. to Fifth Assess. Rep. Intergov. Panel Clim. Chang.: Cambridge University Press: Cambridge, UK, 2015; pp. 1199–1266. [CrossRef]
92. Traore, B.; Corbeels, M.; van Wijk, M.T.; Rufino, M.C.; Giller, K.E. Effects of climate variability and climate change on crop production in southern Mali. *Eur. J. Agron.* **2013**, *49*, 115–125. [CrossRef]
93. Mumo, L.; Yu, J.; Fang, K. Assessing Impacts of Seasonal Climate Variability on Maize Yield in Kenya. *Int. J. Plant Prod.* **2018**, *12*, 297–307. [CrossRef]
94. Liu, X.; Pan, Y.; Zhu, X.; Yang, T.; Bai, J.; Sun, Z. Drought evolution and its impact on the crop yield in the North China Plain. *J. Hydrol.* **2018**, *564*, 984–996. [CrossRef]
95. Leng, G.; Huang, M. Crop yield response to climate change varies with crop spatial distribution pattern. *Sci. Rep.* **2017**, *7*, 1463. [CrossRef] [PubMed]
96. Kotir, J.H. Climate change and variability in Sub-Saharan Africa: A review of current and future trends and impacts on agriculture and food security. *Environ. Dev. Sustain.* **2011**, *13*, 587–605. [CrossRef]
97. Lobell, D.B.; Field, C.B. Global scale climate-crop yield relationships and the impacts of recent warming. *Environ. Res. Lett.* **2007**, *2*, 2. [CrossRef]
98. Matiu, M.; Ankerst, D.; Menzel, A. Interactions between temperature and drought in global and regional crop yield variability during 1961–2014. *PLoS ONE* **2017**, *12*, e0178339. [CrossRef] [PubMed]
99. Bapuji Rao, B.; Santhibhushan Chowdary, P.; Sandeep, V.M.; Rao, V.U.M.; Venkateswarlu, B. Rising minimum temperature trends over India in recent decades: Implications for agricultural production. *Glob. Planet. Chang.* **2014**, *117*, 1–8. [CrossRef]
100. Waha, K.; Müller, C.; Rolinski, S. Separate and combined effects of temperature and precipitation change on maize yields in sub-Saharan Africa for mid- to late-21st century. *Glob. Planet. Chang.* **2013**, *106*, 1–12. [CrossRef]
101. Ahmed, K.F.; Wang, G.; Yu, M.; Koo, J.; You, L. Potential impact of climate change on cereal crop yield in West Africa. *Clim. Chang.* **2015**, *133*, 321–334. [CrossRef]

sustainability

MDPI

Article

The Impact of the COVID-19 Pandemic on the Global Value Chain of the Manufacturing Industry

Jiaze Sun [1], Huijuan Lee [2] and Jun Yang [1,*]

1 School of International Trade and Economics, University of International Business and Economics, Beijing 100029, China; sunjiaze91@gmail.com
2 School of Economics and Management, Beijing Forestry University, Beijing 100083, China; lihuijuan40@gmail.com
* Correspondence: yjydy.ccap@igsnrr.ac.cn

Abstract: This paper adopts the GDYN model to estimate the dynamic impact of the COVID-19 pandemic on global manufacturing industry and the value chain. Our simulation finds that (1) In the short run, the low-tech manufacturing industries will suffer greater shocks, with a decline of output growth in 2021 by 6.0%. The growth rate of the high-tech manufacturing industry showed an increasing trend of 3.7% in 2021. (2) In the post-epidemic period, the total manufacturing output will return to the baseline level, from which the growth rate of low-tech manufacturing will rebound, demonstrating a V-shaped development trajectory. (3) From the perspective of Global Value Chain (GVC), the participation in GVCs of manufacturers in countries along the Belt and Road, the European Union and the United States will weaken, while China's manufacturing industry has witnessed an obvious improvement in export competitiveness. The import added value of China has decreased, which shows that its ability to meet domestic demand has been improving. This indicates that the COVID-19 pandemic is providing a crucial opportunity for China to upgrade its manufacturing value chain, which contributes to the accelerated construction of a new dual-cycle development pattern.

Keywords: global value chain; manufacturing; COVID-19; global trade analysis project

Citation: Sun, J.; Lee, H.; Yang, J. The Impact of the COVID-19 Pandemic on the Global Value Chain of the Manufacturing Industry. *Sustainability* **2021**, *13*, 12370. https://doi.org/10.3390/su132212370

Academic Editors: Baojie He, Ayyoob Sharifi, Chi Feng, Jun Yang and Vincenzo Torretta

Received: 16 September 2021
Accepted: 29 October 2021
Published: 9 November 2021

1. Introduction

The COVID-19 epidemic continues to rage, putting humanity through a public health and economic crisis with far-reaching implications. Preliminary evidence shows that the COVID-19 crisis is considerably more profound than the 2008 Global Financial Crisis [1,2]. According to official data released by the countries, the GDP of the United States, Japan, Germany and the United Kingdom contracted by 3.5%, 4.4%, 4.9%, and 9.9% in 2020 [3–6]. COVID-19 is already having far-ranging economic consequences, and the end is not yet in sight. Although recent vaccine approvals have raised hopes of a turnaround in the pandemic later this year, renewed waves and new variants of the virus pose concerns for the outlook [7]. The cross-border flow of products and components is still greatly restricted worldwide, signifying a pessimistic outlook on the development trend of the global manufacturing value chain. Comprehensively measuring and predicting the impact of the COVID-19 epidemic on the global manufacturing industry and its Value Chain is an important prerequisite for accurately dealing with the impact of the epidemic and building a new dual-cycle development pattern in the context of globalization.

The Global Value Chain (GVC) theory originated from the value chain theory proposed and developed by international commercial researchers in the 1980s [8,9]. The global value chain trade accounting method can be traced back to the discussion of quantitative vertical specialization in Hummels et al. [10]. They defined a country's import intermediate input for production and export as vertical specialization. After that, scholars continued to relax the strict assumption of Hummels et al. along this logic and gradually constructed a general accounting formula for value-added trade) [10–12]. In particular, Koopman et al. and Wang et al. divided gross exports into four categories: domestic added value eventually absorbed abroad, domestic added value converted back to home after export, foreign added value and pure double counting items, and incorporated relevant indicators such as gross trade, value-added trade, and trade-added value into a unified accounting framework [13–15]. On this basis Wang et al. the global value chain indicators are further divided into forward participation and backward participation. From the perspective of forward and backward decomposition, the added value and final products are divided into pure domestic use, traditional trade, simple GVC and complex GVC, and the forward and backward participation are calculated respectively, GVC activities and non GVC activities are distinguished, and the forward and backward participation of GVC activities are calculated [16]. Over the past three decades, the division of labor in the GVC has led to unprecedented rapid growth in the world economy and international trade. At present, the virus continues to mutate, and the development of the new coronavirus epidemic is highly uncertain, causing great concerns about the GVC and the process of economic globalization. Verikios links epidemiological and economic models to capture the transmission from regional populations to regional economies, finding that COVID-19 is likely to be of longer duration and more severe in its economic effects than previous pandemics [17]. Islam and Muyeed use Meta-Analysis approach, exhibiting that this crisis could cost 2.7 trillion U.S. dollars, which is about 3.06% of the global GDP [18]. Guan et al. study the impact of COVID-19 on Global Supply Chain using CGE model based on GTAP framework, finding that regardless of the strategy, the complexity of global supply chains will magnify losses beyond the direct effects of COVID-19 [19]. Li and Chen points out that some countries represented by the United States and Japan will further upgrade the plan to return to domestic manufacturing, with more government subsidies to the regression of manufacturing, and the impact on manufacturing supply chains cannot be ignored [20]. Rajak S., Mathiyazhagan K. et al. summarized the requirements of current supply chain stakeholders and used the CSF method to identify 16 key factors. The study found that during the COVID-19 pandemic, social distance, emergency response to the logistics system, and emergency backup facilities are the three most important factors to stabilize the supply chain [21].

Some studies focused on the impact of COVID-19 on specific countries and industries. Walmsley et al. use CGE model to estimate the macroeconomic impacts of mandatory business closures in the U.S. in order to control the spread of the COVID-19, finding that for the three-month scenario, there will be a 20.3% decline in GDP and a decline of 22.4% in the employment of the U.S [22]. Duan et al., evaluate the economic impacts of COVID-19 outbreak on both national and industrial levels by employing quarterly CGE model, revealing that the epidemic may lower China's economic growth in 2021 by 1.2–2.7% [23]. Zhao and Yang use GDYN model and find that the real GDP of China will increase by 0.9%. To be specific, the added value of textile and clothing, papermaking and printing products, chemical and pharmaceutical products and metal products will rise by 1.2%, 1.8%, 2.2%, and 2.0%. The added value of high-end manufacturing, such as machinery and transportation equipment industries will rise 0.8% and 1.4% respectively [24]. Shen and Xu suggest that the epidemic has led to a large upstream supply shortage in China. Moreover, the energy industry and the electronic information industry are facing high downstream demand [25]. Zhu et al. find that textile clothing, electrical, metal, metal smelting and other industries may have a higher risk of a shift in internal-to-external industry in China [26]. Under the influence of this global public health crisis, many questions arise: What challenges are the global manufacturing industries facing? How will the manufacturing GVC structure change? What role will China play in the GVC in the future?

To date, there have been few quantitative studies on the impact of the epidemic on the global manufacturing value chain. In addition, most of the GTAP model methods used to measure the economic impact of COVID-19 are relatively static or adopt the Chinese CGE model for the 2017 domestic input-output table, which cannot accurately describe the impact of the epidemic on the global manufacturing value chain. Based on the OECD international input-output table, this study expands the GTAP database, adopts the modified GDYN model to measure the dynamic impact of the epidemic on the global high-tech, medium-tech and low-tech manufacturing industries, and analyzes the evolution of the global manufacturing value chain structure from the perspective of value added.

2. Materials and Methods

2.1. Data Sources and Processing

This study adjusts the GTAP10 dynamic database and constructs a standard international input-output table based on GTAP data. For industries, the 65 industries in the GTAP database match 34 industries in the OECD database, and ultimately, 23 manufacturing related categories are retained in this study. The database is summarized according to the national and regional division, and the manufacturing industry in China, the United States, Japan, South Korea, ASEAN nations and the region are analyzed (Table 1). In terms of trade flow, the flow of goods in the GTAP10 database are divided to distinguish commodity flow and distribution, and the import share in the database is adjusted based on the 2014 OECD International Input Output Table.

Table 1. Country (or region) Division.

Country Division	GTAP Primitive Country Division
Country	Australia (AUS), China (CHN), Japan (JPN), South Korea (KOR), India (IND), United State of America (USA), Germany (DEU), Brazil (RUS), Russia (RUS), South Africa (ZAF), United Kingdom (UK)
Region	ASEAN, Latin America (except Brazil, LAM), European Union (except France and Germany, EU), Belt and Road Initiative (TBTR), other countries in the world (ROW)

Note: Detailed national name in the region; see Schedule 1.

According to the European Union's statistical office, the manufacturing sector is divided into high technology, medium to high technology, medium to low technology and low technology manufacturing. In this paper, according to the existing classification of industries, the medium and high technology manufacturing industry and the medium and low technology manufacturing industry are merged into the medium technology manufacturing industry, so the manufacturing industry is divided into high technology, medium technology and low technology three categories as in Table 2.

Table 2. Industry division.

Industry Division	
Low tech	Textile and clothing; Leather products industry; Wood processing; Papermaking and printing, other manufacturing industries
Medium tech	Petroleum and coal processing; Rubber and plastic manufacturing; Ferrous metal smelting and processing; Non-ferrous metal smelting and processing; Metal products industry; Other fuel processing industries;
High tech	Chemical fiber manufacturing industry; Medical manufacturing industry; Automobile manufacturing; Transportation equipment manufacturing; Computer, communications and other electronic equipment manufacturing (referred to as electronic equipment manufacturing); Electrical equipment; Instrument manufacturing; General and special equipment manufacturing (mechanical equipment manufacturing for short)

To ensure that the total input equals the total output in the global and national levels, we adjusted the tax. Equation, in which all income taxes are removed from intermediate input and final demand. In addition, income is divided into income for each component to ensure that the total investment is equal in the three levels of the industry, the country, and the total output. $VIMS\_N_{i,r,s}$ represents the total amount of goods imported by country s from country r, $VIGM_{i,s}$ is the total amount of final consumer goods imported by the government of country s, $VIPM_{i,s}$ is the total amount of final consumer goods imported by households in country s, and $VIFM_{i.r.s}$ is the total amount of intermediate products imported from r by manufacturers in country s. $shr\_F_{t,r,s,\text{"Government"}}$, $shr\_F_{t,r,s,\text{"private"}}$ and $shr\_I_{i.r.j.s}$ are the share of a country's government's source of final consumer products, the share of household consumption's source of final products, and the flow of imported intermediate products among different industries in the country calculated using the 2014 OCED Inter-Country Input-Output Table. (Equation (1)).

$$\begin{aligned} VIMS\_N_{i,r,s} &= VIGM_{i,s} \times shr\_F_{t,r,s,\text{"Government"}} \\ &+ VIPM_{i,s} \times shr\_F_{t,r,s,\text{"private"}} \\ &+ \sum_{jj} VIFM_{i.r.s} \times shr\_I_{i.r.jj.s} \end{aligned} \tag{1}$$

The data of consumption, unemployment and investment used in the simulation are all from the annual data of major economies in the wind database. and HP filtering is used to remove the cycle term for the consumption, unemployment, and investment data, and strive to obtain the true impact of the COVID-19 decrease trend, and then find the rate of decline caused by the COVID-19.

The equivalent tariff data is calculated based on Minor and customs clearance time data on the World Bank's doing business website [27].

2.2. GYDN Model Improvements

2.2.1. GYDN Model

This study is based on the application of a Computable General Equilibrium (CGE) model, which has been applied successfully to examine economic impacts of health threats [28]. Global Trade Model (GTAP) is one of the most widely used CGE models. This model is a global static equilibrium model developed by Professor Hertel Thomas from Purdue University and has the extended capability for examining employment and supply chain impacts linked to economic activity and policies [29].

In particular, we use the Global Dynamic General Equilibrium Model (GDYN) is a dynamic extended version of the GTAP model, developed by Ianchovichina and Walmsley [30]. The GDYN model has two outstanding advantages: first, it introduces a dynamic mechanism of investment and capital accumulation, allowing investment to be allocated on a global scale according to the difference in the rate of return of various countries, thus having an impact on the total capital of each country. It also allows fierce competition. Second, asset income is distributed globally according to the relationship of asset ownership, which accurately matches the relationship between capital ownership and the corresponding income; that is, assets in a country are not entirely owned by residents of that country, making the model analysis more accurate.

Based on the database's dimension setting, the framework of the original GYDN model is modified, and the GYDN model is connected to the GVC decomposition model. In addition, the front and rear indicators of the GVC model are expanded, and the source of the added value is defined. The specific improvement is as follows.

As shown in Figure 1, first, the GYDN model framework is improved. The dimensions of the partial coefficient are extended, and variables and related formulas are added based on the original model. In addition, the elastic coefficients in the model are adjusted to portray the elasticity difference between the intermediate components and the final product. New variables are defined, the CES demand function is used to define new variables to describe the source and distribution of imports. Specifically, it includes the consumption variables of enterprises ($qfms_{i,r,j,s}$ and $pfms_{i,r,j,s}$), households ($qpms_{i,r,s}$ and $ppms_{i,r,s}$) and governments ($qgms_{i,r,s}$ and $pgms_{i,r,s}$), as well as the relationship between import and export trade volume. See Equations (2)–(5).

$$qfms_{i,r,j,s} = \frac{qfm_{i,j,s}}{ams_{i,r,s}} \times \left[\frac{1}{ams_{i,r,s}} \times \frac{pfms_{i,r,j,s}}{pfm_i} \right]^{-ESUBNf_{j,s,i}} \tag{2}$$

$$qpms_{i,r,s} = \frac{qpm_{i,s}}{ams_{i,r,s}} \times \left[\frac{1}{ams_{i,r,s}} \times \frac{ppms_{i,r,s}}{ppm_{i,s}} \right]^{-ESUBMh_{s,i}} \quad (3)$$

$$qgms_{i,r,s} = \frac{qgm_{i,s}}{ams_{i,r,s}} \times \left[\frac{1}{ams_{i,r,s}} \times \frac{pgms_{i,r,s}}{pgm_{i,s}} \right]^{-ESUBMh_{s,i}} \quad (4)$$

$$qxs_{i,r,s} = qim_{i,r,s} \quad (5)$$

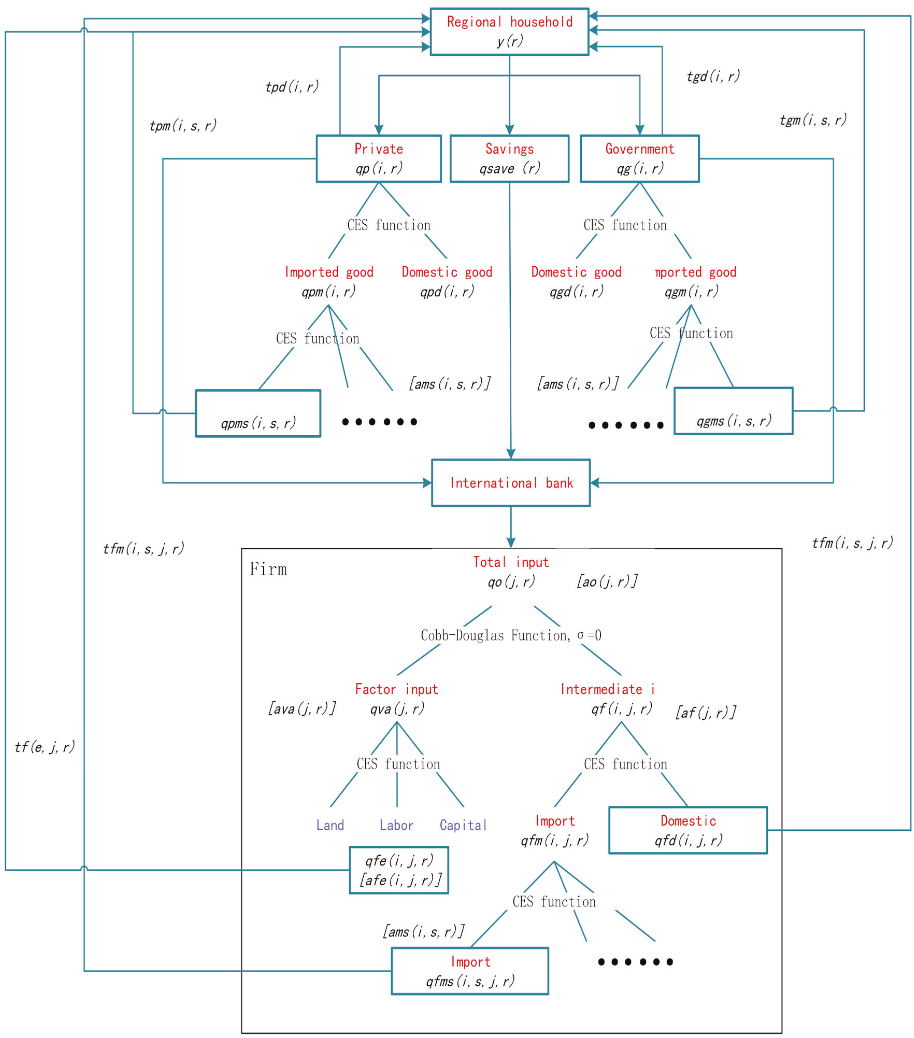


Figure 1. Frame diagram of the modified GYDN model in this paper.

The second improvement is redefine some of the equations and use the weighted average method to link the original variable with the new variable. Among them, the prices of enterprises ($pfm_{i,j,s}$), households ($ppm_{i,s}$) and the government ($pgm_{i,s}$), as well as the prices ($pim_{i,s}$) and quantity ($qim_{i,r,s}$) of imports are redefined, see Equations (6)–(10) for details;

$$pfm_{i,j,s} = \sum_{r}\left[\frac{VIFA_{i,r,j,s}}{\sum_{r} VIFA_{i,rr,j,s}} \times \left(\frac{pfms_{i,r,j,s}}{ams_{i,r,s}}\right)\right] \tag{6}$$

$$\sum_{r} VIPA_{i,r,s} \times ppm_{i,s} = \sum_{r} VIPA_{i,r,s} \times \frac{ppms_{i,r,s}}{ams_{i,r,s}} \tag{7}$$

$$\sum_{r} VIGA_{i,r,s} \times pgm_{i,s} = \sum_{r} VIGA_{i,r,s} \times \frac{pgms_{i,r,s}}{ams_{i,r,s}} \tag{8}$$

$$pim_{i,s} = \sum_{r}\left(\frac{VIMS_{i,r,s}}{\sum_{k} VIMS_{i,k,s}} \times \frac{pms_{i,k,s}}{ams_{i,k,s}}\right) \tag{9}$$

$$qim_{i,r,s} = \left[\sum_{j}\left(\frac{VIFM_{i,r,j,s}}{VIM_{i,r,s}} \times qfms_{i,r,j,s}\right)\right] + \left(\frac{VIPM_{i,r,j,s}}{VIM_{i,r,s}} \times qpms_{i,r,s}\right) + \left(\frac{VIGM_{i,r,j,s}}{VIM_{i,r,s}} \times qgms_{i,r,s}\right) \tag{10}$$

The third improvement the link between the GYDN model and the GVC model. The front and rear decomposition formulas are expanded on the basis of Koopman et al. (2014) and Wang Zhi et al. (2017b), value-added trade is transferred to value-added income (GVC income), the source of the value added is defined, and the front and rear summed results are calculated in Equations (11) and (12).

$$\begin{aligned}(Va^s)' &= \hat{V}^s \times L^{ss} \times Y^{ss} + \hat{V}^{ss} \times L^{ss} \times \sum_{r \neq s}^{G} Y^{sr} \\ &+ \hat{V}^{ss} \times L^{ss} \times \sum_{r \neq s}^{G} A^{sr} \times L^{rr} \times Y^{rr} + \hat{V}^s \times L^{ss} \times \sum_{r \neq s}^{G} A^{sr} \times \sum_{u}^{G} B^{ru} \times Y^{us} \\ &+ \hat{V}^s \times L^{ss} \times \left(\sum_{r \neq s}^{G}\sum_{t \neq s}^{G} A^{st}\sum_{u}^{G} B^{tu} Y^{ur} - \sum_{r \neq s}^{G} A^{sr} \times L^{rr} \times Y^{rr}\right)\end{aligned} \tag{11}$$

$$\begin{aligned}Y' &= V^s \times L^{ss} \times \hat{Y}^{ss} + V^{ss} \times L^{ss} \times \sum_{r \neq s}^{G} \hat{Y}^{sr} \\ &+ V^{ss} \times L^{ss} \times \sum_{r \neq s}^{G} A^{sr} \times L^{rr} \times \hat{Y}^{rr} + V^s \times L^{ss} \times \sum_{r \neq s}^{G} A^{sr} \times \sum_{u}^{G} B^{ru} \times \hat{Y}^{us} \\ &+ V^s \times L^{ss} \times \left(\sum_{r \neq s}^{G}\sum_{t \neq s}^{G} A^{st}\sum_{u}^{G} B^{tu} \hat{Y}^{ur} - \sum_{r \neq s}^{G} A^{sr} \times L^{rr} \times \hat{Y}^{rr}\right)\end{aligned} \tag{12}$$

L is the local Leontief inverse matrix, B is the global Leontief inverse matrix, A is the direct consumption coefficient matrix, V is the value added coefficient matrix, and Y is the final demand matrix. Taking Equation (11) as an example, $\hat{V}^s \times L^{ss} \times Y^{ss}$ represents the domestic production and consumption of a country, $\hat{V}^{ss} \times L^{ss} \times \sum_{r \neq s}^{G} Y^{sr}$ indicates the value-added flow of a country's traditional trade, $\hat{V}^{ss} \times L^{ss} \times \sum_{r \neq s}^{G} A^{sr} \times L^{rr} \times Y^{rr}$ indicates the flow direction of added value of a country's simple GVC and $\hat{V}^s \times L^{ss} \times \sum_{r \neq s}^{G} A^{sr} \times \sum_{u}^{G} B^{ru} \times Y^{us} + \hat{V}^s \times L^{ss} \times \left(\sum_{r \neq s}^{G}\sum_{t \neq s}^{G} A^{st}\sum_{u}^{G} B^{tu} Y^{ur} - \sum_{r \neq s}^{G} A^{sr} \times L^{rr} \times Y^{rr}\right)$ represents flow direction of added value of a country's complex GVC.

In Equation (12), $V^s \times L^{ss} \times \hat{Y}^{ss}$ represents the part of domestic production and domestic consumption of a country, $V^{ss} \times L^{ss} \times \sum_{r \neq s}^{G} \hat{Y}^{sr}$ represents the source of value added in a country's traditional trade, $V^{ss} \times L^{ss} \times \sum_{r \neq s}^{G} A^{sr} \times L^{rr} \times \hat{Y}^{rr}$ represents the source of value added in a country's simple GVC, and $\hat{V}^{s} \times L^{ss} \times \sum_{r \neq s}^{G} A^{sr} \times \sum_{u}^{G} B^{ru} \times Y^{us} + \hat{V}^{s} \times L^{ss} \times \left(\sum_{r \neq s}^{G} \sum_{t \neq s}^{G} A^{st} \sum_{u}^{G} B^{tu} Y^{ur} - \sum_{r \neq s}^{G} A^{sr} \times L^{rr} \times Y^{rr} \right)$ represents the source of value added in a country's complex GVC.

The third improvement is the benchmark scenario for building a dynamic model. Referring to the recursive dynamic method of Chappuis [31] and using the forecast data of international authoritative institutions such as CEPII, IMF and the World Bank, the benchmark scenario for the endogenous GDP growth rate is obtained (2015–2035), ensuring that there is no difference between the endogenous GDP growth rate and the previous exogenous GDP growth rate.

2.2.2. Method of Social Network Analysis

Based on Meng Bo's method [32], the demand centers and supply centers of the global manufacturing trade are identified using the increased value of imports and exports. From the supply perspective, a country is a value-added supply center if the increased value imports in most countries in the region come from that particular country. In terms of demand, a country is a regional value-added demand center if the value-added exports of most countries in the region flow to that particular country.

2.2.3. Scenario Setting

The decrease of GDP in 2020 reflected the decreases in personal consumption expenditures, exports, private inventory investment, nonresidential fixed investment, and government expenditures [33]. By early May in 2020, the total volume of online job vacancies had fallen by over 50% in five OECD countries (Australia, Canada, New Zealand, the United Kingdom, and the United States) with respect to the beginning of the year, with even larger declines in some sectors [2]. As the limits to personnel flow and travel restrictions directly lead to a decrease in consumption demand and labor supply, the labor-intensive industry is impacted from both the supply and demand sides. Dunn et al. (2020) evaluate the economic effects of the COVID-19 pandemic on consumer spending using daily card transaction data and estimate an aggregate effect of −27.8% on consumer spending after mitigation measures have had time to take hold [34].

From the perspective of international trade, governments have implemented restrictions, closed ports, and strengthened inspections and quarantines, and the epidemic is mainly influencing import demand. In addition, trade facilitation affects the goods trade and manufacturing value chain structure. When the financial section of the chain is impacted, the economic downtown is expected to increase, the trend in domestic international investment slows down, and effective capital stock and capital prices both decline due to the impacts on the international supply chain.

Based on the research and analysis above, this study selects employment, consumption, trade facilitation and capital stock as proxy variables for shock.

Employment Rate

We remove the trend in the unemployment rate of countries with HP filtering for nearly 10 years and retain the cycle costs. The unemployment data are converted into labor data for each year of employment data. On this basis, the employment losses of various countries in the context of the epidemic are calculated to obtain the 2020 employment rate by country. It is expected that the epidemic will continue to affect the employment rate in 2021, which maintained a level approximately 2/3 of the previous average in 2020. Projections are that the epidemic will be controlled in 2022, and the labor supply will gradually be restored to the steady state of the economy.

Consumption

With HP filtering, the trend item is removed; the 2020 consumption growth rates for countries are used to reduce their 2019 consumption growth rate by selecting the most recently published consumption expenditure growth rate of the various countries. Based on this, the decline in consumption is obtained under the influence of COVID-19. In the GTAP model, the relationship between personal private consumption demand, the price of different consumer products and personal private consumption expenditures is as follows in Equation (13):

$$\frac{qp_{i,r}}{pop_r} = \left(\sum_k pp_{k,r}{}^{EP_{i,k,r}}\right) \times \left(\frac{yp_r}{pop_r}\right)^{EY_{i,r}} + f\_qp_r \tag{13}$$

In the above formula, f_qp_r is the mobile variable for the consumption of region r. The changes in the preference for private consumption demand caused by impact f_qp_r and the preference for private consumption demand by household are obtained. This study expects to find a long-term impact from the epidemic through final consumption. It is expected that the final consumption at the family level in 2021 will remain at 2/3 of the level in 2020. On this basis, the rebound mechanism is set, assuming the model will return to a steady level in 2025.

Trade Facilitation

According to Minor P and Tsigas M's GTAP database-based association of different types of imports and exports to the imports and exports of different industries and considering the effects of the epidemic over Time multiplied, equivalent tariffs are determined in various industries [27]. According to the import and export trade volume as a weight, the equivalent tariff results are matched with merged countries and industries. Equivalent tariffs in different industries in two countries are determined by adding import and export equivalent tariffs [35]. This study assumes that the flight restrictions following the epidemic have restricted transportation capacity, countries have increased efforts to review immigration products, enhance inspection and quarantine standards, etc., causing import customs transfer time to increase to 14 days, while export customs transfer time does not change.

Investment Level

The annual investment data comes from IMF. To accurately show the investment changes, we remove the trend items with the method of HP filter. The investment data adjusted by HP filter are matched with the country and region categories in this paper. Investment is assumed to rebound to a steady level after 2022.

2.3. Global Value Chain Participation Index

Global value chain participation indexes the connotation of global value chain participation is the proportion of a country or region's participation in the global value chain in its added value. The greater the value of the index, the stronger the participation of the country/region in the global value chain; the smaller the value of the index, the weaker the participation of the country/region in the global value chain. Equation (14) VAS_GVC represents the global value chain participation index based on forward decomposition. Equation (15) VAS_GVC_S represents the activity participation index of simple value chain based on forward decomposition. Equation (16) VAS_ GVC_C represents the complex participation index of complex value chain based on forward decomposition. Equation (17) FGYS_ GVC represents the global value chain participation index based on backward decomposition. Equation (18) FGYS_ GVC_ S represents the activity participation index of simple value chain based on backward decomposition. Equation (19) FGYS_ GVC_ C represents the complex participation index of complex value chain based on backward decomposition. The global value chain forward participation index aims to answer the question "what proportion of production factors are used by countries/sectors for global value chain production"; The global value chain backward participation index aims to answer "what proportion of national/sectoral production inputs for final products are based on global value chain production activities". Compared with the traditional global value chain participation index, the GVC participation index of Wang et al. (2017) perfectly deconstructs the GVC participation at the national and departmental levels, effectively makes up for the shortcomings of the traditional global value chain participation index system, and clarifies the source and destination of added value at different levels from the perspective of global value chain.

$$VAs\_GVC = \frac{VA\_GVC}{Va'} = \frac{VA\_GVC\_S}{Va'} + \frac{VA\_GVC\_C}{Va'} \tag{14}$$

$$VAs\_GVC\_S = \frac{VA\_GVC\_S}{Va'} \tag{15}$$

$$VAs\_GVC\_C = \frac{VA\_GVC\_C}{Va'} \tag{16}$$

$$FGYs\_GVC = \frac{FGY\_GVC}{Y'} = \frac{FGY\_GVC\_S}{Y'} + \frac{FGY\_GVC\_C}{Y'} \tag{17}$$

$$FGYs\_GVC\_S = \frac{FGY\_GVC\_S}{Y'} \tag{18}$$

$$FGYs\_GVC\_C = \frac{FGY\_GVC\_C}{Y'} \tag{19}$$

3. Results and Analysis

Based on the general law of the development of infectious diseases, this study assumes that the development of the epidemic will undergo three stages: Peak period, effective control period, and recession period. In addition, the changes in all periods will affect factors such as employment, consumption, trade facilitation, and capital stocks. (1) In the peak period of the COVID-19 epidemic (2020–2021), businesses face declines in short-term consumption demand, employment and investment and challenges in trade. (2) Once the epidemic is under effective control, the previously suppressed consumer demand, employment and investment will gradually rebound after the epidemic is effectively controlled (2022–2025). (3) In the third stage, various types of elements will gradually return to their normal level, and supply and demand present a stable situation after the epidemic recedes (2026–2035).

In order to further analyze specific industries, this study will carry out analysis on a few representative industries from the three categories. The detailed simulation results and analysis are as follows.

3.1. The Impact on the Output of Global Manufacturing

The simulation results show that by 2035, the prices of production factors, manufacturing output, and total imports and exports of most countries and regions will generally show a downward trend. Due to the large decline in labor wages, the decrease in primary factor prices in countries such as France, the United Kingdom, and South Africa will be significantly affected. The wages of unskilled labor in the above three countries will fall by 21.19%, 16.61%, and 14.96%, and the wages of skilled labor fall by 20.5%, 17.81%, and 15.39%. The wages of skilled labor, wages of unskilled labor, and capital prices in traditional manufacturing countries such as China, Japan, South Korea, and Germany will all declined, resulting in a relatively large negative impact on the prices of primary factors. From the perspective of import and export, India, South Africa, France, the United Kingdom, and Brazil have the largest decline in exports, with 0.55%, 0.50%, 0.44%, 0.42%, and 0.40% respectively. China's manufacturing imports will fall the most, reaching 0.42%, but the decline in China's manufacturing exports was limited, only 0.24%. However, the decline in exports in the United States, India, Japan, the United Kingdom, France, Europe, and the United States and other countries/regions is greater than the decline in imports. This indicates that after the epidemic, China's import dependence on the international market will decrease. Affected by factors such as factor prices, demand, and customs clearance time, the manufacturing output of South Africa, India, and France has dropped significantly, by 0.48%, 0.43%, and 0.39%, respectively.

Due to the length of the value chain and the degree of globalization varies in different industries, the impact of epidemic shows great differences (Figure 2). Global low-end manufacturing industry was largely negatively impacted in the short term compared to the baseline scenario. Its growth rate of output will decrease by 4.2% in 2021 and will gradually return to normal levels after the epidemic is effectively controlled. On the whole, it exhibits a V-type development path, with an output of 1% in 2030. On the other hand, the high-end manufacturing industry will grow rapidly in the short term, with an increasing of output growth rate by 2.15% in 2021, which in turn will drive global manufacturing growth. The overall development trend of the manufacturing industry will gradually return to the benchmark level after the epidemic recedes. We choose a few representative industries for further analysis as in Figure 3.

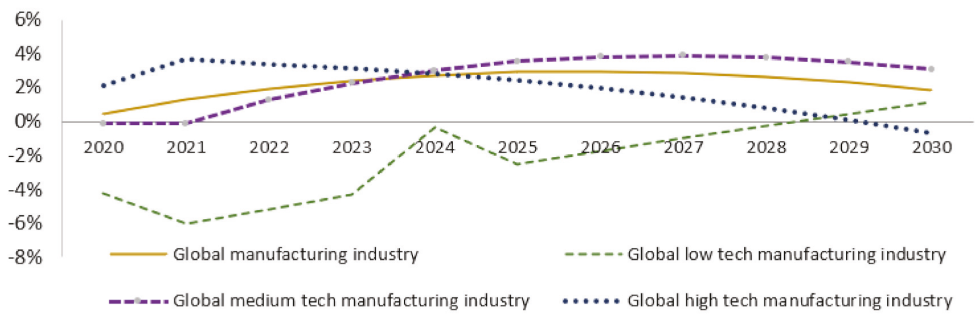


Figure 2. Growth Rate of Global Manufacturing Output (2020–2030).

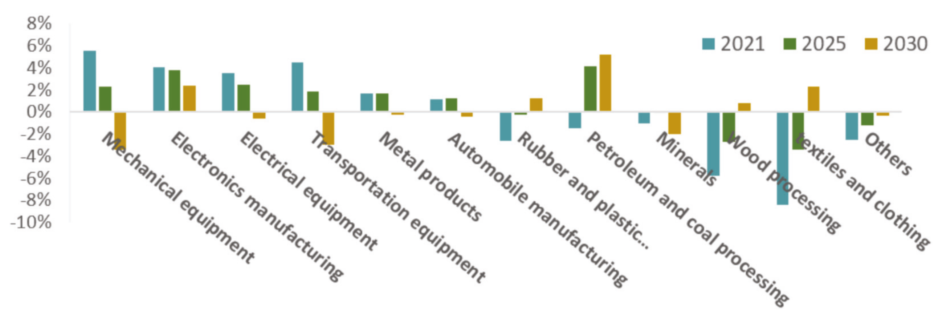


Figure 3. Changes in Output Growth in Various Industries.

The medium and low-tech manufacturing industries suffer large impact, especially for textiles and clothing, forest products, papermaking, and printing, with the outputs dropped by 8.4%, 5.8%, and 5.4% in 2021. The main reason for the decline is that most of these industries are labor-intensive. As the epidemic spreads, unemployment keeps rising, and the production cost of those labor-intensive industries greatly increases, resulting in a decline in output. On the other hand, these industries provide a large number of final products (to the consumer). They are affected by declines in consumption and residents' income, and the output of traditional manufacturing will further decline. In addition, international demand is reduced due to the challenges in transport logistics during the epidemic and the reduced facility of trade. Most manufacturing will gradually return to normal levels after the epidemic recedes, which will further promote industrial output growth for textiles and clothing, forest products, and petrochemical products, which will experience a pulling effect from the rebound of consumption rebound and return of capital flows.

The high-tech manufacturing industries experience relatively small effects from the epidemic in the short term, and some industrial output has increased significantly. The industrial output of mechanical equipment, electronic products, transportation equipment, and electrical appliances grows faster in 2021, with growth rates of 5.5%, 4.5%, 4.0%, and 3.5% compared with the benchmark scenario. The main driver of this growth is that these industries belong to technically intensive industries, with high levels of production automation and digital technology leading to relatively small impacts from unemployment. For example, China's steel industry has built a "black light factory" that requires little labor; thus, it can easily ensure virus prevention and control during the epidemic while maintaining efficient production operation. The second driver is the importance of investment capital in the above industries. Because the epidemic leads to a large decline in capital, the production cost of these capital-intensive industries is significantly reduced, but demand remains for the output. Third, these industries are far down the chain from final consumption, and so the demand side impact is smaller during the short term. Finally, high-tech manufacturing is situated in the middle of the chain from the perspective of investment; for example, it receives investment in electronic information manufacturing from automotive and parts industries, mechanical equipment, automobiles, and the component industry. As a consequence, the epidemic has a small influence in the short term.

3.2. Impact on the GVC of the Global Manufacturing Industry

After the epidemic, how will the GVC structure of global manufacturing industry change in the long run? Will the changes be different for specific industries? As the world's largest manufacturing center, what role will China play in the GVC trade? This study identifies the trade relationships between countries according to the source and destination of the value added trade and analyzes the trade between major countries/regions in the world after the epidemic subsides by constructing a social network structure diagram.

First, the former and latter term are decomposed from the perspective of added value trade, and the source and orientation of added value are identified to build trade relationships among countries. The output of an industry can be divided into four parts: pure domestic production, traditional trade, the simple GVC trade, and the complex GVC trade. "Pure domestic production" refers to the added value of a final product produced to be absorbed by the domestic market; "traditional trade" refers to the added value of a final product for trade; "simple GVC" refers to an intermediate input product that is used for local production or for export, which is a single product cross-border export or import; "complex GVC" is two or more cross-border exports or imports of intermediate products in trade. The flow of GVC can be divided considering forward and backward decomposition; forward decomposition adopts the perspective of added value production, see Equation (5) for details, while backward decomposition takes the perspective of added value demand, see Equation (6) for details.

Second, a social network structure diagram is built to show the trade share between trading partners and analyze the changes in the value chain structure. In the social network structure diagram, the size of each node indicates the forward and backward added value of a country, the thickness of the line between countries/regions reflects the share of the forward and backward added value between trading partners in the forward and backward added value of each country, and the arrow represents the direction of flow. What should be noted is that the presence of a relationship between two countries/regions in the social network structure diagram is determined by two conditions. Take forward participation as an example: first, if country A's share of the value added of country B's imports is larger, there is an association between country A and country B; second, if country A's share of the value added of country B's imports is greater than 25%, country A and country B have an association. Backward participation considers the share of the value added of country A's exports to country B.

3.2.1. Impact of Novel Coronavirus Pneumonia on the Participation of Global Value Chains at the National Level

As can be seen from Table 3, by 2035, COVID-19 had a strong impact on the forward and backward manufacturing industries of the world's major economies. From a forward-looking perspective, in terms of traditional trade, India, the United States, France, and Canada suffered the most serious impact, with a decrease of 0.35%, 0.21%, 0.19%, and 0.18%, respectively, compared with the benchmark scenario. In terms of GVC, South Africa, Latin America, India, and the United States experienced the largest decline, with a decrease of 0.47%, 0.30%, 0.30%, and 0.22% respectively. In terms of complex GVC, South Africa, Brazil, the United Kingdom, India, and other countries were most affected, with a decrease of 0.67%, 0.47%, 0.46%, and 0.44% respectively. In contrast, the forward participation of China's GVC has also decreased, but the decline is far lower than the global average, which makes the production capacity of GVC products in China's manufacturing industry relatively sufficient. From a backward perspective, in terms of GVC, China, ASEAN and South Africa decreased the most, by 0.32%, 0.28%, and 0.19% respectively. Among them, China's complex GVC decreased by 0.24%, and ASEAN and South Africa's complex GVC decreased by 0.14%. Different from the forward participation, the countries with a large decline in backward GVC participation are those that were good at processing trade before the epidemic, which shows that COVID-19 may provide an opportunity for the industrial upgrading of the above countries to reduce the dependence of manufacturing intermediates on foreign countries, especially China and ASEAN, and their manufacturing value chain has shown an upward trend.

Table 3. Impact of novel coronavirus pneumonia on the participation of global value chains at the national level (Cumulative impact of 2020–2035 relative baseline scenario).

	Forward					Backwards				
	VA_D (%)	VA_RT (%)	VA_GVC (%)	VA_GVC_S (%)	VA_GVC_C (%)	FGY_D (%)	FDY_RT (%)	FGY_GVC (%)	FGY_GVC_S (%)	FGY_GVC_C (%)
AUS	−0.01	−0.07	−0.01	0.05	−0.20	−0.01	−0.07	−0.11	−0.05	−0.26
NZL	0.00	−0.05	−0.17	−0.11	−0.34	0.00	−0.05	−0.11	−0.05	−0.21
CHN	−0.03	−0.07	−0.18	−0.07	−0.36	−0.03	−0.07	−0.32	−0.24	−0.47
CAN	0.02	−0.18	−0.08	0.02	−0.29	0.02	−0.18	−0.04	0.05	−0.23
JPN	−0.06	−0.02	−0.19	−0.11	−0.34	−0.06	−0.02	−0.14	−0.08	−0.28
KOR	−0.12	0.04	−0.13	−0.01	−0.31	−0.12	0.04	−0.14	−0.10	−0.22
IND	0.08	−0.35	−0.30	−0.24	−0.44	0.08	−0.35	−0.10	0.02	−0.45
USA	0.05	−0.21	−0.22	−0.14	−0.37	0.05	−0.21	−0.13	−0.04	−0.31
DEU	−0.06	−0.06	−0.12	−0.02	−0.32	−0.06	−0.06	−0.10	−0.04	−0.19
GBR	−0.16	−0.17	−0.25	−0.11	−0.46	−0.16	−0.17	−0.18	−0.08	−0.25
FRA	−0.18	−0.19	−0.18	−0.07	−0.38	−0.18	−0.19	−0.17	−0.08	−0.23
BRA	0.03	−0.16	−0.30	−0.24	−0.47	0.03	−0.16	−0.13	−0.06	−0.33
RUS	0.04	−0.15	−0.14	−0.01	−0.33	0.04	−0.15	−0.07	0.00	−0.28
ZAF	−0.09	−0.04	−0.47	−0.36	−0.67	−0.09	−0.04	−0.20	−0.14	−0.34
ROEP	0.02	−0.12	−0.21	−0.13	−0.40	0.02	−0.12	−0.16	−0.06	−0.33
TBTR	0.03	−0.09	−0.20	−0.11	−0.38	0.03	−0.09	−0.19	−0.10	−0.37
LAM	0.10	−0.26	−0.30	−0.23	−0.46	0.10	−0.26	−0.15	−0.06	−0.37
AssAN	0.02	−0.21	−0.22	−0.15	−0.39	0.02	−0.21	−0.28	−0.14	−0.47
AFR	0.04	−0.17	1.00	−0.04	−0.36	0.04	−0.17	1.00	−0.10	−0.35
ROW	−0.29	0.04	1.00	0.06	−0.29	−0.29	0.04	1.00	−0.24	−0.31

Data source: The GDYN simulation results. Note: the EU region refers to other EU countries except Britain, Germany and France.

3.2.2. Structural Changes in the GVC of Traditional Manufacturing

As seen in Figure 4, the simulation results reveal that after the pandemic, the final product trade among the world's major economies will be relatively stable compared to the base scenario in 2035, and there will be no major change in the value chain structure. From the perspective of export added value, except for the Asia-Pacific region, China's finished products mainly flow to the United States and countries along the "Belt and Road"; from the perspective of import added value, the United States and the countries along the "Belt and Road" represent the essential sources of China's final product imports. In 2035, China represents the core of the finished product supply and demand system of manufacturing in the Asia-Pacific region, and there is a close trade relationship among EU countries.

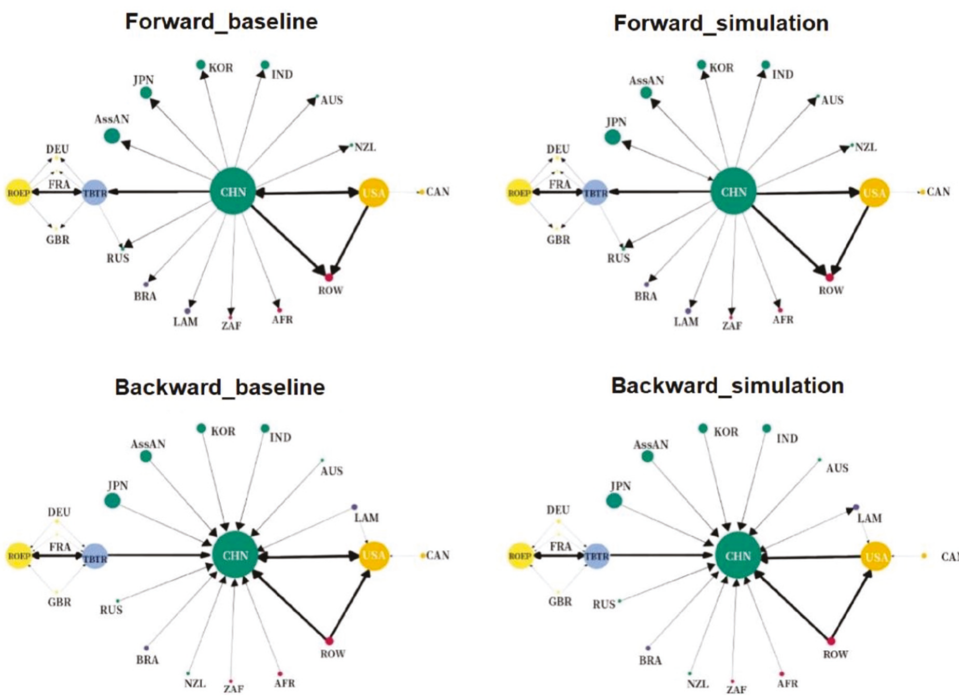


Figure 4. Changes in the manufacturing industry from the perspective of traditional trade (2035).

3.2.3. Structural Changes in the Manufacturing GVC from the Angle of Simple GVC

As seen in Figure 5, after the pandemic, the global simple GVC will see a regional development trend. The demand for simple GVC worldwide falls into two main sectors: one is the supply and demand network of the European Union and the countries along the "Belt and Road", and the other is the "Asia Pacific-North America" GVC trade network with China as the core. There is closer cooperation within the sectors. For instance, the simple GVC trade between China and the major economies in the Asia-Pacific region will be further strengthened, as it will no longer rely on the markets of countries along the "Belt and Road", and exports and imports of intermediate products to the United States will decrease.

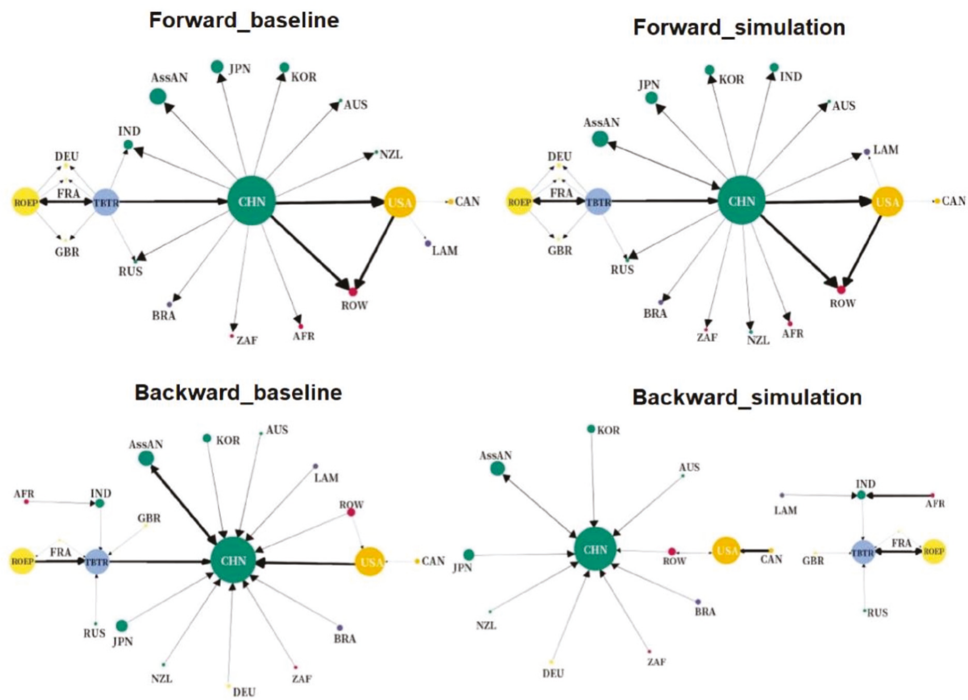


Figure 5. Changes in the manufacturing industry from the perspective of simple GVC (2035).

Examining export added value, compared with the baseline scenario, China's supply scale and status in the Asia-Pacific manufacturing value chain will have improved by 2035, and it will see heightened trade with the United States. It will rely less on the GVC markets of the countries along the "Belt and Road", and India will be included in its supply network. These changes indicate that the international competitiveness of simple GVC products is increasing. The added value of exports of countries along the "Belt and Road" will show a downward trend; they are closer to the European Union and will exchange less in trade with India. From the perspective of import added value, there will be less import added value for China from the United States, ASEAN countries, Latin America, and countries along the "Belt and Road", which indicates that China's domestic products will be beginning to replace imported intermediate products and that China's ability to meet domestic demand will be strengthened.

3.2.4. Structural Changes in Complex GVC of Manufacturing Industries

In the post-pandemic period, there will be an obvious trend of centralization in the complex GVC of manufacturing industries. The pandemic has offered an opportunity for the transformation and upgrading of China's manufacturing industry. China will become the largest supply center and demand market in the world, and its core position in the GVC will improve. The main reason behind this change is the deep integration of the industrial chain among China, the United States, the European Union, Japan, and South Korea [36]. In the medium and long term, the decrease in the export supply of the United States, the European Union, Japan, South Korea, and the countries along the Belt and Road has provided an opportunity to fill the global industry gap and transform and upgrade the industrial chain for China.

In general, the global manufacturing value chain will still mainly be represented as two supply and demand networks: one is the complex GVC supply and demand network of the European Union and the countries along the "Belt and Road", while the other is the complex GVC supply and demand network of Asia Pacific-North America, with China as the core. In terms of export added value, China will step forward to become the core of the global manufacturing complex GVC supply network based on its complete industrial chain and manufacturing cost advantages. The major global economies will all be taken into the supply network of China's manufacturing complex GVC. From the perspective of import value added, China's import demand will show a significant decrease, especially for imports from ASEAN countries and the United States. This shows that China's manufacturing capacity for high-tech products has strengthened, the export competitiveness and ability to meet domestic demand have improved, and China will be striding forward to the high end of the value chain. Although the pandemic will have some implications for the United States, its complex GVC activities and main trading partners change little. The main reasons for this are that, first, the complex GVC production procedures in the United States are principally implemented in China, second, its GVC activities are mainly concentrated at the two ends of the value chain (R&D and consumer demand). Hence, the impact of the pandemic on the status and activities of US manufacturing in the complex GVC is not significant. What is worth noting is that China's import demand for complex GVC products from the United States will remain relatively large.

4. Discussion

4.1. Modification of the GDYN Model and the Data Base

The application of the traditional CGE model is mostly concentrated in the environment and energy fields. Fujimori et al. used CGE model to study the impact of Japan's environmental policies on the Japanese economy, and Kapitza et al. quantified the impact of biophysical and socio-economic intermediaries on Vietnam [37,38]. Li et al. use a global adaptive multiregional input–output model and scenarios of lockdown and fiscal counter measures, showing that compared with a no-pandemic baseline scenario, global emissions from economic sectors will decrease by 3.9 to 5.6% in 5 years due to COVID-19 [39]. Till now, there are few studies on the impact of COVID-19 under CGE model. Some scholars have begun to use the GTAP model to study the economic impact of COVID -19 and GVC related problems which are referable for this study [38–42]. However, there is still room for improvement in existing researches. First, the GTAP database has issues when setting the flow direction of products. Since the flow direction of imported intermediates is not explained in GTAP data, previous studies have generally assumed that the flow direction of imported intermediates is represented by the proportion of domestic intermediates in one flow direction, which is obviously inconsistent with actual product flow direction. As a result, this strong assumption leads to two serious concerns: one is that segmentation after the GTAP database is constructed will be carried out in accordance with the input and output table after the merger. After the synthesis, if the input and output portions of the industry's total output and the total are not equal, if the inverse matrix and local Lyon initial inverse matrix show significant deviation when calculating the global Lyon, the GVC decomposition may lead to incorrect results. Second, there is a forced assumption in the information on the product flow, which makes it difficult to truly reflect the status of intermediate goods trade among countries globally, and the GTAP database cannot depict the dependence of upstream and downstream industries among countries. Any simulation results based on these assumptions will be far from the real results.

To solve the above problems, this study links the GDYN model and WWYZ model to estimate the impact of COVID-19 on the GVC of manufacturing industry. And the world input-output table structure is embedded into the GTAP 10 dynamic database. In the GDYN model and GTAP database, the import source country and domestic flow direction of products are divided. This approach can not only more accurately reflect the status of intermediate goods trade among countries worldwide but also more clearly and carefully depict the dependence of upstream and downstream industries among countries, and the simulation results are more accurate. At the same time, it ensures that the database results will balance global inputs and outputs when summed; that is, the total input and total output of any country and industry are equal, the global and local Leontief inverse matrices obtained are both real and valid, and the GVC decomposition results based on this approach are valid and credible.

4.2. The Impact of Epidemics on Specific Manufacturing Industries

Due to the different industrial chain positions, production characteristics and factor densities of different industries, the structure of the GVC of various industries and the position of countries in the industrial value chain vary. This paper finds that in the post-epidemic period, the importance of China's manufacturing industry in different types of trade activities will increase—in particular, the export value added of China's simple GVC products and complex GVC products will increase significantly—and most of the world's major economies will be included in the supply network of China's manufacturing complex GVC. The results show that industries with more cross-border intermediate products and higher technical complexity will be "made in China" in the long run. To verify this conclusion, this paper selected the high-tech manufacturing industry and its internal industry, the electronics industry, to conduct a further analysis of the complex GVC product trade.

As seen in Figures 6–8 on the supply side (export added value), the complex GVC structure of the high-tech manufacturing industry and electronics industry is basically the same as that of the manufacturing industry. However, it is worth noting that from the perspective of imported added value, China will become the core of the imported added value supply of the electronics industry, indicating that there are certain differences in the structural changes in the complex GVC in the electronics industry and those in the manufacturing industry and high-tech manufacturing industry. This finding shows that with the gradual rise of technical barriers, China's influence in the GVC will gradually increase, and China's core position will become more prominent. The overall trend of the impact of the epidemic on the manufacturing industry is consistent, but there will be a certain degree of industry heterogeneity. In general, COVID-19 does provide an opportunity for China's manufacturing industry, especially high-end manufacturing, to move up the GVC.

4.3. Limitations

As with most studies, the design of the current study is subject to limitations. (1) Therefore, this study may have allocated insufficient time in its design to the development stage of the epidemic. (2) The study focused on the GVC and trade relationships, but it does not incorporate the complex and changeable international economic situation into the simulation scenario. For example, it does not reflect the trade cooperation framework between China, the "Belt and Road" countries and RCEP; at the same time, how China participates in the GVC and its competitive strength need to be further strengthened. (3) The third limitation is that nonmarket factors such as Sino-U.S. trade frictions and Sino-European trade frictions are not fully considered in the simulation mechanism. Therefore, in the context of anti-globalization, China's participation in GVCs and its competitiveness need to be further studied. In future studies, we will further improve the model structure, the design of simulation scenarios, and the overall international situation as much as possible in the model to make the analysis more accurate.

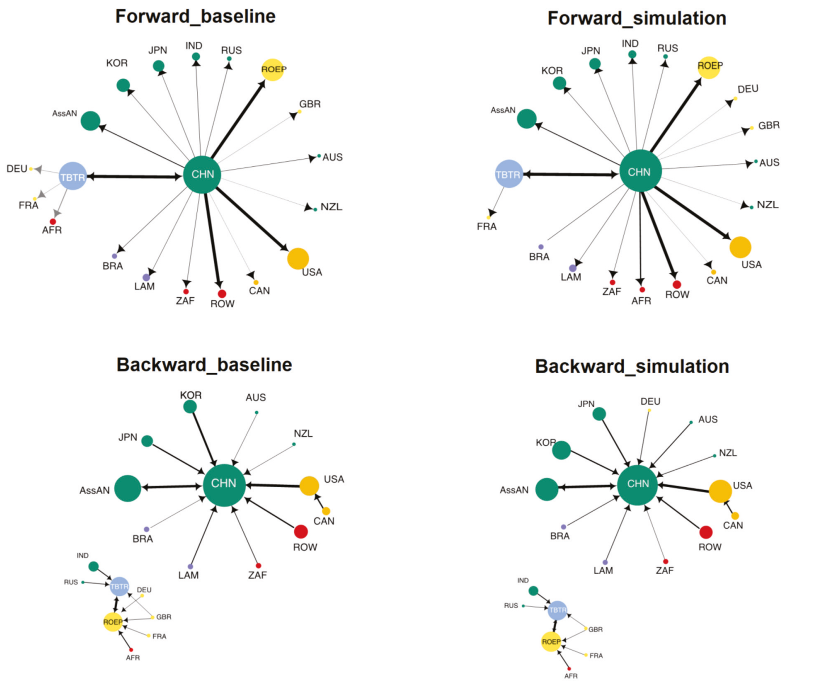


Figure 6. Changes in the manufacturing industry from the perspective of complex GVC (2035).

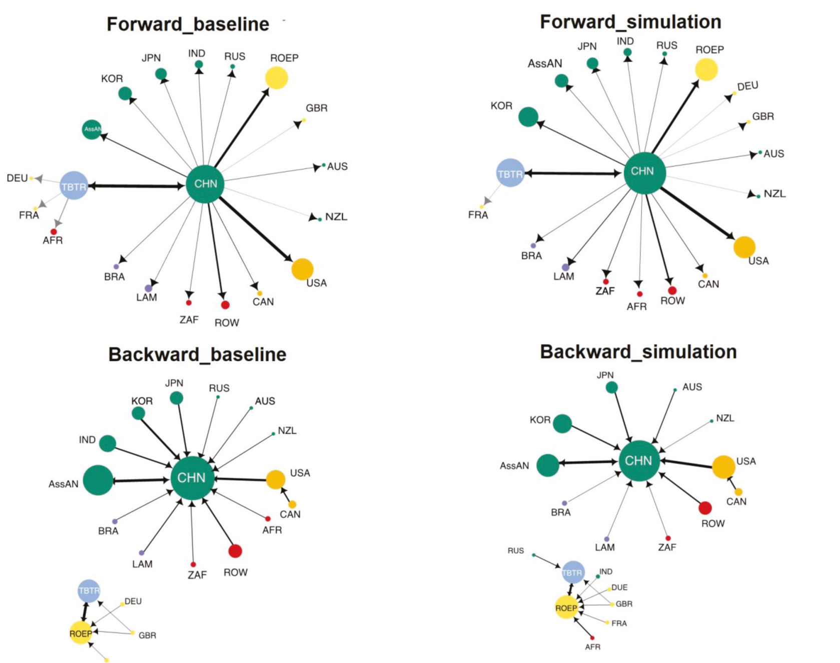


Figure 7. Changes in the high-tech manufacturing industry from the perspective of complex GVC (2035).

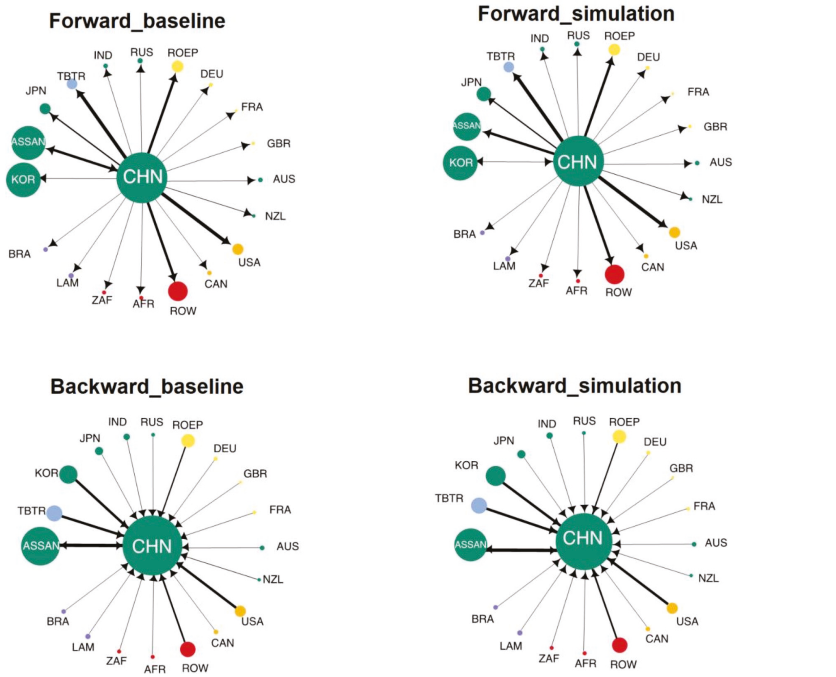


Figure 8. Changes in the computer global value chain from the perspective of complex GVC (2035).

5. Conclusions

This paper chooses employment, consumption, trade facilitation, and capital as simulation shock variables and adopts the GDYN model to simulate and analyze the dynamic impact of the COVID-19 pandemic on the output and GVC of the manufacturing industry. The main conclusions are as follows:

(1) The extent of the impact is projected to vary significantly across industries. In the short term, the low-tech manufacturing sector will be greatly affected by the epidemic, while the output of some high-tech manufacturing sectors will see a growth trend. Compared with the baseline scenario, the global output of low-tech manufacturing for textile and clothing, forest products, paper and printing, will decline by 8.4%, 5.8%, and 5.4%, respectively, in 2021, due to factors such as reduced labor supply and weak consumer demand. High-tech industries such as mechanical equipment, electronic and optical products, transportation equipment, and electrical equipment will grow by 5.5%, 4.5%, 4.0%, and 3.5%, respectively, in 2021, due to their relatively stable output, which stems from their distance from final consumption and their high digitization.

(2) After COVID-19 subsides, the overall trend of manufacturing output will return to the baseline level. Post-COVID-19 recovery will improve the output of the affected medium- and low-tech manufacturing industries for textiles and clothing, Petroleum and coal processing, and Rubber and plastic manufacturing, which will be 2.3%, 5.2%, and 1.2% higher than the baseline scenario in 2030, showing a V-shaped development path. The output of most high-tech manufacturing industries in 2030 will be lower than that in the baseline scenario. For example, machinery and transportation equipment will decline by 3.4% and 3.0% by 2030, but this trend will slow.

(3) From the perspective of GVCs, the influence of China's manufacturing industry in GVCs will increase once the COVID-19 pandemic fades, while the participation in GVCs of manufacturers in countries along the Belt and Road, the European Union and the United States will weaken. In 2035, China will become the country with the fastest growth in

value-added exports in the GVC, especially in the export of complex GVC products, and Imports will decrease significantly, indicating that the epidemic represents an important opportunity for China to accelerate its move toward the higher end of the value chain. China will continue to rely heavily on complex GVC products from the United States, indicating that the United States will continue to have a certain influence on China's high-end manufacturing industry in the long term.

Author Contributions: J.S.: methodology and writing; H.L.: visualization and data curation; J.Y.: methodology and funding acquisition. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by Major projects of National Natural Science Foundation of China "Research on "global value chain" and China's industrial upgrading" (71733002), the National Natural Science Foundation of China" Research and development of China Global Agricultural impact simulation model of major shocks and changes" (71761147004) and Major projects of China Social Science Foundation "Research on American problems under the new situation" (20VMG020).

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Gtap10 database and WIND databases are commercial databases, and readers need to purchase corresponding licenses by themselves. The input-output data of OCED can be obtained by logging in https://www.oecd.org/sti/ind/input-outputtables.htm, and the CEPII data can be obtained by logging in http://www.cepii.fr/CEPII/en/bdd_modele/presentation.asp?id=11.

Acknowledgments: We appreciate the journal reviewers' feedbacks and Shuzhou Liu's help in visualization.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. OECD. *OECD Employment Outlook 2020: Worker Security and the COVID-19 Crisis*; OECD Publishing: Paris, France, 2020.
2. OECD. OECD Policy Responses to Coronavirus (COVID-19): An Assessment of the Impact of COVID-19 on Job and Skills Demand Using Online Job Vacancy Data. 2021. Available online: https://www.oecd.org/coronavirus/policy-responses/an-assessment-of-the-impact-of-covid-19-on-job-and-skills-demand-using-online-job-vacancy-data-20fff09e/ (accessed on 1 February 2021).
3. World Economic Look January 2021. Available online: https://www.imf.org/en/Publications/WEO?page=1 (accessed on 21 January 2021).
4. German Federal Statistical Office (destatis.de): Gross Domestic Product (GDP). Available online: https://www.destatis.de/EN/Themes/Economy/National-Accounts-Domestic-Product/Tables/gdp-bubbles.html;jsessionid=1853BA9C044EE3164A33400145E67EFD.live722 (accessed on 11 September 2021).
5. The Cabinet Office: National Economic Statistics. Available online: https://www.esri.cao.go.jp/jp/sna/menu.html (accessed on 11 September 2021).
6. The Guardian: UK Economy Shrinks Record 9.9% in 2020 on Virus. Available online: https://guardian.ng/news/uk-economy-shrinks-record-9-9-in-2020-on-virus (accessed on 11 September 2021).
7. IMF. Policy Responses to COVID-19. 2020. Available online: https://www.imf.org/en/Topics/imf-and-covid19/Policy-Responses-to-COVID-19 (accessed on 21 January 2021).
8. Porter, M. *Competitive Advantage: Creating and Sustaining Superior Performance*; The Free Press: New York, NY, USA, 1985.
9. Kogut, B. Designing Global Strategies: Comparative and Competitie Value-added Chains. *Sloan Manag. Rev.* **1985**, *26*, 15.
10. Hummels, D.; Ishii, J.; Yi, K.-M. The nature and growth of vertical specialization in world trade. *J. Int. Econ.* **2001**, *54*, 75–96. [CrossRef]
11. Daudin, G.; Rifflart, C.; Schweisguth, D. Who produces for whom in the world economy? *Can. J. Econ. Rev. Can. Déconomique* **2011**, *44*, 1403–1437. [CrossRef]
12. Johnson, R.C.; Noguera, G. Accounting for intermediates: Production sharing and trade in value added. *J. Int. Econ.* **2012**, *86*, 224–236. [CrossRef]
13. Koopman, R.; Wang, Z.; Wei, S.-J. Tracing Value-added and Double Counting in Gross Exports. *Am. Econ. Rev.* **2012**, *104*, 459–494. [CrossRef]
14. Wang, Z.; Wei, S.-J.; Zhu, K. Quantifying International Production Sharing at the Bilateral and Sector Levels. NBER Working Paper. 2013. Available online: https://www.nber.org/papers/w19677 (accessed on 18 May 2021).

15. Wang, Z.; Wei, S.J.; Zhu, K.F. Gross Trade Accounting Method: Offical Trade Statistics and Measurement of the Global Value Chain. *Soc. Sci. China* **2015**, *9*, 108–127.
16. Wang, Z.; Wei, S.-J.; Yu, X.; Zhu, K. Measures of Participation in Global Value Chains and Global Business Cycles. NBER Working Paper. 2017. Available online: https://www.nber.org/papers/w23222 (accessed on 18 May 2021).
17. Verikios, G. The dynamic effects of infectious disease outbreaks: The case of pandemic influenza and human coronavirus. *Socio-Econ. Plan. Sci.* **2020**, *71*, 100898. [CrossRef] [PubMed]
18. Islam, M.R.; Muyeed, A. Impacts of COVID-19 pandemic on global economy: A meta-analysis approach. *Int. J. Tech. Res. Sci.* **2020**, *5*, 8–19. [CrossRef]
19. Guan, D.; Wang, D.; Hallegatte, S.; Davis, S.J.; Huo, J.; Li, S.; Gong, P. Global supply-chain effects of COVID-19 control measures. *Nat. Hum. Behav.* **2020**, *4*, 577–587. [CrossRef] [PubMed]
20. Li, H.l.; Chen, W.H. COVID-19 Epidemic Impact on the Global Manufacturing Supply Chain and my country's strategy. *Price Theory Pract.* **2020**, *5*, 9–12.
21. Rajak, S.; Mathiyazhagan, K.; Agarwal, V.; Sivakumar, K.; Kumar, V.; Appolloni, A. Issues and analysis of critical success factors for the sustainable initiatives in the supply chain during COVID- 19 pandemic outbreak in India: A case study. *Res. Transp. Econ.* **2021**, 101114. [CrossRef]
22. Walmsley, T.L.; Rose, A.; Wei, D. Impacts on the U.S. macroeconomy of mandatory business closures in response to the COVID-19 Pandemic. *Appl. Econ. Lett.* **2021**, *28*, 1293–1300. [CrossRef]
23. Duan, H.; Bao, Q.; Tian, K.; Wang, S.; Yang, C.; Cai, Z. The hit of the novel coronavirus outbreak to China's economy. *China Econ. Rev.* **2021**, *67*, 101606. [CrossRef]
24. Zhao, Z.X.; Yang, J. The Impact of COVID—19 on Shandong's Economyand Industry Chain and Its Countermeasures. *Rev. Econ. Manag.* **2020**, *3*, 5–10.
25. Shen, G.B.; Xu, Y.H. The Impacts of Global Spread of COVID—19 Pandemic on China's Export, Import and Global Industrial Chain and Related Countermeasures. *J. Sichuan Univ.* **2020**, *4*, 75–90.
26. Zhu, K.F.; Gao, X.; Yang, C.H.; Wang, S.Y. The COVID-19 Shock on Global Production Chains and Risk of Accelerated China's Industrial Chains Outflow. *Bull. Chin. Acad. Sci.* **2020**, *35*, 283–288.
27. Minor, P.; Tsigas, M. *Impacts of Better Trade Facilitation in Developing Countries: Analysis with a New GTAP Database for the Value of Time in Trade*; Global Trade Analysis Project, Working Paper; Purdue University: West Lafayette, IN, USA, 2008.
28. Dixon, P.; Rimmer, M.; Lee, B.; Rose, A.; Rose, A.; Verikios, G. Effects on the U.S. Of an H1N1 Epidemic: Analysis with a Quarterly CGE Model. *J. Homel. Secur. Emerg. Manag.* **2010**, *7*, 7. [CrossRef]
29. Hertel, T.D.; Tsigas, M.E. Structure of GTAP. In *Global Trade Analysis: Modeling and Applications*; Hertel, T.W., Ed.; Cambridge: New York, NY, USA, 1997; pp. 13–73.
30. Ianchovichina, E.; Walmsley, T.L. *Dynamic Modeling and Applications for Global Economic Analysis*; Cambridge University Press: Cambridge, UK, 2012.
31. Chappuis, T.; Walmsley, T. *Projections for World CGE Model Baselines*; GTAP Research Memoranda 3728, Center for Global Trade Analysis; Working Paper; Department of Agricultural Economics, Purdue University: West Lafayette, IN, USA, 2011.
32. Meng, B.; Xiao, H.; Ye, J.; Li, S. *Are Global Value Chains Truly Global? A New Perspective Based on the Measure of Trade in Value-Added*; Institute of Developing Economies, Japan External Trade Organization (JETRO): Tokyo, Japan, 2019.
33. U.S. Bureau of Economic Analysis (BEA): Gross Domestic Product, (Third Estimate), GDP by Industry, and Corporate Profits, Fourth Quarter and Year 2020. Available online: https://www.bea.gov/index.php/news/2021/gross-domestic-product-third-estimate-gdp-industry-and-corporate-profits-4th-quarter-and (accessed on 18 May 2021).
34. Dunn, A.C.; Hood, K.K.; Driessen, A. Measuring the Effects of the COVID-19 Pandemic on Consumer Spending Using Card Transaction Data. BEA Working Paper Series 2020-5. 2020. Available online: https://www.bea.gov/system/files/papers/BEA-WP2020-5_0.pdf (accessed on 11 March 2021).
35. Yang, J.; Huang, J.; Hong, J.J.; Dong, W.L. Analysis of Impacts of Trade Facilitation on China's Economy. *J. Int. Trade* **2015**, *9*, 156–166.
36. Zhao, J.L.; Xiao, W. The Influence of COVID-19 Epidemic on the Global Value Chain of China. *China Econ. Trade Guide.* **2020**, *6*, 15–16.
37. Fujimori, S.; Oshiro, K.; Shiraki, H.; Hasegawa, T. Energy transformation cost for the Japanese mid-century strategy. *Nat. Commun.* **2019**, *10*, 4737.
38. Kapitza, S.; Van Ha, P.; Kompas, T.; Golding, N.; Cadenhead, N.C.R.; Bal, P.; Wintle, B.A. Assessing biophysical and socio-economic impacts of climate change on regional avian biodiversity. *Sci. Rep.* **2021**, *11*, 3304.
39. Li, X.; Ghadami, A.; Drake, J.M.; Rohani, P.; Epureanu, B.I. Mathematical model of the feedback between global supply chain disruption and COVID-19 dynamics. *Sci. Rep.* **2021**, *11*, 15450.
40. Zhou, L.L.; Zhang, K.Y. Study of Reconstruction of Chinese Global Value Chains Participation on COVID-19. *Rev. Ind. Econ.* **2020**, *25*, 5–15.
41. McKibbin, W.; Fernando, R. The Global Macroeconomic Impacts of COVID-19: Seven Scenarios. *Asian Econ. Pap.* **2021**, *20*, 1–30. [CrossRef]
42. Walmsley, T.; Minor, P. *ImpactECON Global Supply Chain Model: Documentation of Model Changes*; Working Paper No. 06; ImpactECON: Boulder, CO, USA, 2016.

sustainability

Communication

Is Soil Bonitet an Adequate Indicator for Agricultural Land Appraisal in Ukraine?

Leonid Shumilo [1,2,*], Mykola Lavreniuk [3], Sergii Skakun [1,4] and Nataliia Kussul [2,3]

1 Department of Geographical Sciences, University of Maryland, College Park, MD 20742, USA; skakun@umd.edu
2 Department of Mathematical Modelling and Data Analysis, National Technical University of Ukraine 'Igor Sikorsky Kyiv Polytechnic Institute', 03056 Kyiv, Ukraine; nataliia.kussul@lll.kpi.ua
3 Department of Space Information Technologies and Systems, Space Research Institute NAS Ukraine & SSA Ukraine, 03680 Kyiv, Ukraine; lavreniuk@ikd.kiev.ua
4 NASA Goddard Space Flight Center Code 619, Greenbelt, MD 20771, USA
* Correspondence: lshumilo@umd.edu

Abstract: Agriculture land appraisal analysis is an important component of the land market. This task is especially essential for Ukraine, which plans to lift the moratorium on land transactions and legalize farmland sales in 2021. Most post-Soviet countries adopted the notion of a soil bonitet—a quantitative score representing natural soil fertility. This score is also proposed in Ukraine to perform agricultural land appraisals. However, this is a static parameter and does not account for the dynamics of actual crop production on the agricultural lands. Moreover, the bonitet score is not crop-specific. Therefore, in this study, we use maps of bonitet based on the soil map and natural-agricultural districts of Ukraine and crop yields at the village scale to explore the relationships between bonitet values and actual crop production in Ukraine. We found that land appraisal is not correlated with the actual soil bonitet.

Keywords: bonitet; agricultural land appraisal; soil quality; yield assessment

Citation: Shumilo, L.; Lavreniuk, M.; Skakun, S.; Kussul, N. Is Soil Bonitet an Adequate Indicator for Agricultural Land Appraisal in Ukraine? *Sustainability* **2021**, *13*, 12096. https://doi.org/10.3390/su132112096

Academic Editors: Baojie He, Ayyoob Sharifi, Chi Feng and Jun Yang

Received: 17 September 2021
Accepted: 25 October 2021
Published: 2 November 2021

Publisher's Note: MDPI stays neutral with regard to jurisdictional claims in published maps and institutional affiliations.

1. Introduction

Since the breakup of the Soviet Union in 1991, Ukraine has been experienced major changes in land cover and land use (LCLUC) [1]. The major drivers for these changes have been continuous economical and policy changes as well as climate variability. Since approximately 70% of land in Ukraine is devoted to agriculture (cropland, pasture, meadow), the changes were especially profound in the agricultural sector. In the past 5–10 years, these changes were particularly magnified due to: (i) the military conflict in the Eastern Ukraine [2], (ii) the conversion to double-cropping due to temperature increase [3] and a sharp increase in the production of industrial crops [4], (iii) the continuous practice of burning agricultural fields, and (iv) the preparation of the policy to open the land market [5]. The latter is directed to lift the moratorium on land transactions and legalize farmland sales. By the World Bank's estimates [5], establishing a transparent and efficient land market would boost economic growth by an estimated 0.5 to 1.5 percent per year over a 5-year period, depending on the reform design and complementary policies.

Within the open land market, land appraisal becomes one of the most important variables. Specifically, for agricultural lands, variables influencing land productivity would increase or decrease the value of the land parcel. In order to assess the value of agricultural land, many post-Soviet countries adopted the concept of a soil bonitet score [6–8]. Soil bonitet (B) is a quantitative assessment of its natural fertility and is expressed as a score in the range from 0 to 100. It is a component in the land appraisal technique that is officially used in Ukraine.

Within this assessment, bonitet is the only variable that is related to potential land productivity. The bonitet strongly depends on the soil type and bio-chemical characteristics of the soil. While bonitet represents a potential value of the land in terms of productivity, it does not directly relate to the real (factual) land productivity and potential economical revenues. The former depends on multiple factors, including crop type and seeds, agricultural practices, meteorological conditions, and soil properties. Previous studies utilising remote sensing-based and bio-physical models [9–12] addressed the issues related to crop yield assessment in Ukraine.

Therefore, there can be a gap between the potential productivity and the real productivity of agricultural lands, which could alter the land appraisal value. While the soil bonitet can be considered as an integrated value, crop yields represent factual values, though they depend not only on the land properties itself. Therefore, there is an open question of how soil bonitet in Ukraine relates to specific crop yields in terms of agricultural productivity and land appraisal. In order to perform such an analysis, one has to incorporate crop maps, so crop-dependent relationships can be explored, as well as yields and bonitet scores at a finer-resolution scale.

The aim of this study is to show the real relationships between the actual economical capacity of the agricultural land represented in the yield on the village level and the main indicator of economic capacity of fields—the bonitet. The use of the bonitet indicator is widely discussed in the Ukrainian agricultural sector, so we have to provide essential decision-making information about the adequacy of its economic representation to support the reformation of the Ukrainian agrarian sector and opening of land market.

2. Materials and Methods

The present study takes advantage of multi-year, satellite-derived crop maps developed in 2016–2018 (Figure 1) [13] and village-level crop yields and bonitet values derived from soil maps to explore the crop-specific relationships between bonitet scores and crop yields in Ukraine. The results would give an insight if incorporating a bonitet score only into the land appraisal would provide an adequate metric of agricultural land value. Some recent studies proposed to use for this purpose additional information, such as crop rotation history [14], that can be obtained with use of available products.

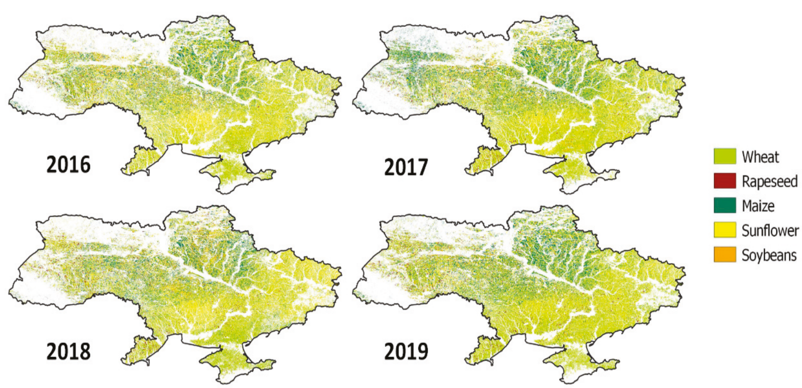


Figure 1. Crop type maps for Ukraine with majoritarian crop types for 2016–2018.

The analysis between crop yield and soil bonitet scores was performed using three major sources of data. The first one is official statistics on crop yields provided by the State Statistics Service of Ukraine for 2016–2018 at the village scale. The second data source is geospatial soil map for Ukraine, which is based on the national soil atlas data of Ukraine. The third source is natural-agricultural rayon's map. Using these maps with known bonitet values for each soil type and district, we generate a bonitet maps for Ukraine. Further analysis of these products was conducted using regression analysis and correlational analysis statistical techniques.

2.1. Yield Maps

Ukrainian governments provide yield statistics at the country and regional level. Since 2020, State Statistics Service of Ukraine provide statistics on the village level. This change provides new possibilities for yield assessment and analysis. The statistics are available for 2016–2018 years and cover all major crops: wheat, maize, soybean, and sunflower. These statistics available for all regions except Luhansk and Donets oblast that are under military conflict in the south of Ukraine and annexed by Russia Crimea. For further geospatial analysis, these data were aggregated using official village borders of Ukraine to obtain geospatial vector layers with the yield for each crop. Figure 2 shows an example of such geospatial layer for the sunflower yield statistics. The missing values are related to the areas without human settlements or cultivated fields by specific crop. The measurement unit for these statistics is the centner per hectare.

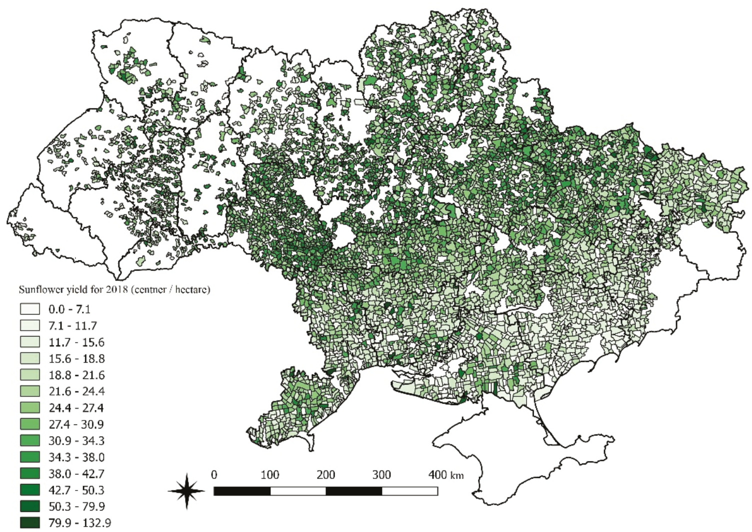


Figure 2. Geospatial layer with the sunflower yield statistics for 2018 aggregated with use of official village borders.

2.2. Bonitet Maps

Bonitet is the main soil quality characteristic used for the land appraisal. The estimation of field-level bonitet requires ground measurements and laboratory analysis of soil properties. As the result, not every field still has measured bonitet value and the aggregation of such data in the geospatial form for further analysis is not possible today, due to the limitation in the data availability. These limitations are related to the fact that as of now, bonitet data for Ukraine can be obtained only on the pages of official land auctions, they are not in digitized form. Due to the absence of convenient interface or instrument for the data access, it is not possible to automate the data collection process. In addition, for many fields, bonitet does not exist at all. Therefore, we used two sources of bonitet geospatial information. The first one is the official soil map of Ukraine, and the second one is a natural-agricultural map rayon's map of Ukraine. The second map is used as official reference data for estimation of B_m coefficient in the state land appraisal laws of Ukraine.

To validate the obtained maps, we prepared ground truth data by digitizing bonitet documents for agricultural fields. The territory of Ukraine was covered by 79 ground samples for the validation.

2.2.1. Bonitet Map Production Based on the Soil Map

To produce soil bonitet map for Ukraine we assumed that soil bonitet depends on the soil type. Thus, the soil type map can be used as reference data for bonitet map. To produce the bonitet map shown in Figure 3, we assigned the standard soil type's bonitet values and corresponding soil types on the soil type map.

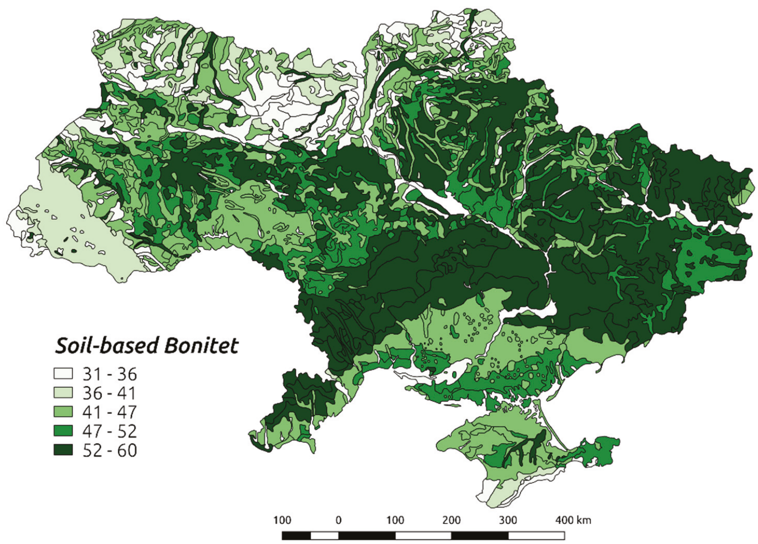


Figure 3. The bonitet map for Ukraine based on the soil atlas map.

This bonitet map contain 1200 units. The smallest unit has area of 349 th. ha, while the largest has area 2,721,723 th. ha. The average area of unit is 49,274 th. ha. Each unit has the bonitet value from 31 to 58. The average bonitet value for this map is 45.4, while the coefficient of variation is 15%. Therefore, this map has moderate variation of bonitet coefficient.

2.2.2. Bonitet Map Based on the Natural-Agricultural Rayon's Map

According to the Law of Ukraine "On Approval of the Methodology of Normative Monetary Valuation of Agricultural Lands", № 831, adopted by the Verkhovna Rada, formula (1) is used for agricultural land appraisal, where the coefficient B_m is determined in the annexes for all natural-agricultural rayon's of Ukraine. This coefficient is considered to be the average bonitet score for each zone and was obtained during ground measurements. To conduct our experiments, we made a georeference and vectorization of natural-agricultural rayon's map of Ukraine to produce the bonitet map shown in Figure 4.

This bonitet map contain 205 units. The smallest unit has area of 8494 th. ha, while the largest has area 988,588 th. ha. The average area of unit is 291,481 th. ha. Each unit has the bonitet value from 10 to 71. The average bonitet value for this map is 37.28, while the coefficient of variation is 0.35. Therefore, this map has significant variation of bonitet coefficient.

2.3. Methods

In this study, we used two statistical methods to obtain analysis of dependences between yield and bonitet and to understand sufficiency of bonitet use in the land appraisal methodology. In addition, these methods were used to validate yield statistics data and soil-based bonitet map.

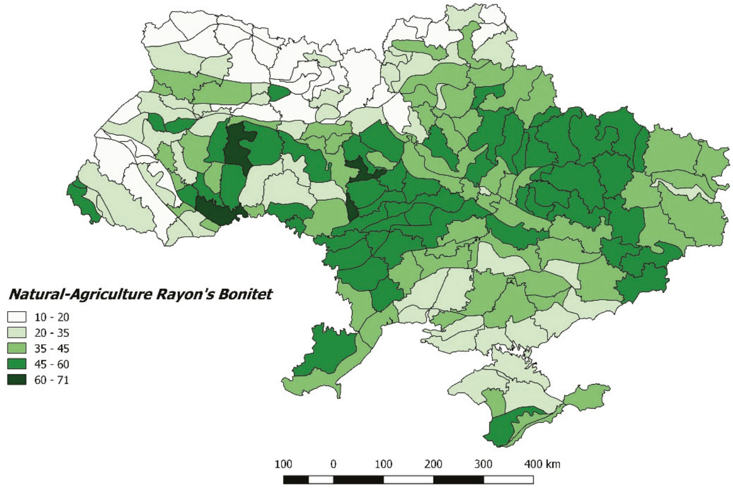


Figure 4. The bonitet map for Ukraine based on the natural-agricultural rayon's map.

2.3.1. Land Appraisal Methodology in Ukraine

Agricultural Land appraisal methodology in Ukraine consist in the use of multiple coefficients that reflect the distances between the field and some essential infrastructure objects or the location of the field relatively to the cities or recreational zones. The only economic variables that represent the quality of soil in terms of agricultural capacity or possible yield is the bonitet. The land appraisal in Ukraine can be represented by formula:

$$L_p = A * CRI * MC * \frac{B}{B_m}, \tag{1}$$

where A is the area of agricultural land; CRI is the standardized capitalized rental income per unit area, which is determined by special tabulated tables; MC is the multiplication of coefficients, which considers location relatively to the settlements, resort and recreational areas, zones of radiation pollution, zonal factors of land location, and other coefficient related to the specification of land use and indexation of regulatory monetary valuation; B is the soil bonitet; and B_m is the mean soil bonitet for the natural and agricultural area.

2.3.2. Regression Analysis

Regression analysis is the technique for data analysis that can be used for dependencies studies between two or more variables. It is common technique in the environmental and economy science. It based on the linear regression model, which was demonstrated in Equation (1), fitting with use of least square error method. Using this approach, it is possible to estimate a_1 and a_0 coefficients of the linear regression for further analysis:

$$Y = a_1 B + a_0, \text{ where :} \tag{2}$$

- Y—yield on the village level;
- B—mean village bonitet;
- a_1, a_0—regression coefficients, obtained by use of mean square error (MSE) method

The angular coefficient a_1 obtained by regression model fitting can be used for the hypothesis of the bonitet and yield dependence type selection. If the coefficient takes values very small or equal to 0, the hypothesis of lack of interdependence will be correct. In that case, when the modulus of the coefficient is much greater than 1, the interdependence is present, the function grows faster than the other. When the modulus of the coefficient is equal or close to 1, the model is close to the ideal and greatly describes the dependence between these variables. In addition, the sign of the coefficient indicates if the relationship is direct or inverse.

2.3.3. Correlation Analysis

The second data analysis technique, which was used in this research, is the correlation analysis based on the Pearson coefficient. This statistical coefficient evaluates the linear dependence between two values and equal to multiplication of two vales covariations:

$$r(B,Y) = \frac{\sum_{i=1}^{m}\left(B_i - \overline{B}\right)\left(Y_i - \overline{Y}\right)}{\sum_{i=1}^{m}\left(B_i - \overline{B}\right)\sum_{i=1}^{m}\left(Y_i - Y\right)}, \quad (3)$$

The correlation coefficient takes values between −1 and 1. If the coefficient takes value close to 0, the variables do not have any dependencies. If the absolute value is close to 1, the data dependence can be fully described using linear function. As well as for regression a_1 coefficient, the sign of the correlation coefficient indicates if the dependence is direct or inverse.

3. Results

3.1. Yield Data Validation

We have investigated the concordance of the crop yield data collected at the village council level for different years. For this purpose, we selected the yield data for each one of two years in a row and for each major crop. After this, we used regression and correlation analysis techniques to estimate the dependencies between yields for different years in the same villages. The results in terms of the visual dependency, the Pearson correlation coefficient, and two linear regression coefficients are shown in the Figure 5.

It is shown that the yield data for each crop has strong correlation for two years in a row (Pearson correlation coefficient is between 0.44 and 0.68). It means that there are no rapid or abrupt changes in the statistic data from year to year. The conclusion is that the statistical data are consistent and accurately collected. The differences and variations in yields for specific crop from year to year can be explained by different weather conditions (temperature and precipitation amount and distribution over the vegetation periods), mainly.

3.2. Impact of Bonitet Estimated from Soil Map on the Yield

For the first conducted experiment, we validated available soil-based bonitet map using collected ground-truth samples. The mean absolute error between ground-truth data and soil-based map is equal 8.39. To estimate more approximated accuracy, for each soil type, the mean ground truth bonitet was calculated. It was performed for comparison between ground truth bonitet and soil-based bonitet. In this case, the mean absolute error is equal to 6.32, and the Pearson coefficient is equal to 0.67.

To evaluate the impact of soil bonitet on the yield we explored dependence between these variables through the regression analysis and the correlation analysis. The results in terms of the visual dependency, the Pearson correlation coefficient, and two linear regression coefficients are shown in the Figure 6.

It is shown that the yield data for each crop do not have strong correlation with the soil bonitet index. In every case, we have found that the Pearson coefficients are very small and close to zero. So, we can conclude that there is no correlation between these values. Furthermore, the dependencies are also negative. Thus, we can assume that the soil-based bonitet value affects the fertility of the soil much less than other essential agricultural variables (agro-climatology, agricultural practices, and the history of crop rotations).

Such absence of dependencies between the yield data and soil bonitet shows that the soil quality indicator used for the agriculture land appraisal in Ukraine, namely, bonitet, does not meets with the land productivity capacity. So, other essential characteristics of location, such as agro-climatology, land use history, crop rotations, and agro-management have much higher influence on the yield data. The field located in the area vulnerable to the droughts can have the same bonitet and price as the field in more sustainable areas for agriculture. Therefore, this bonitet information has no value for the land owner.

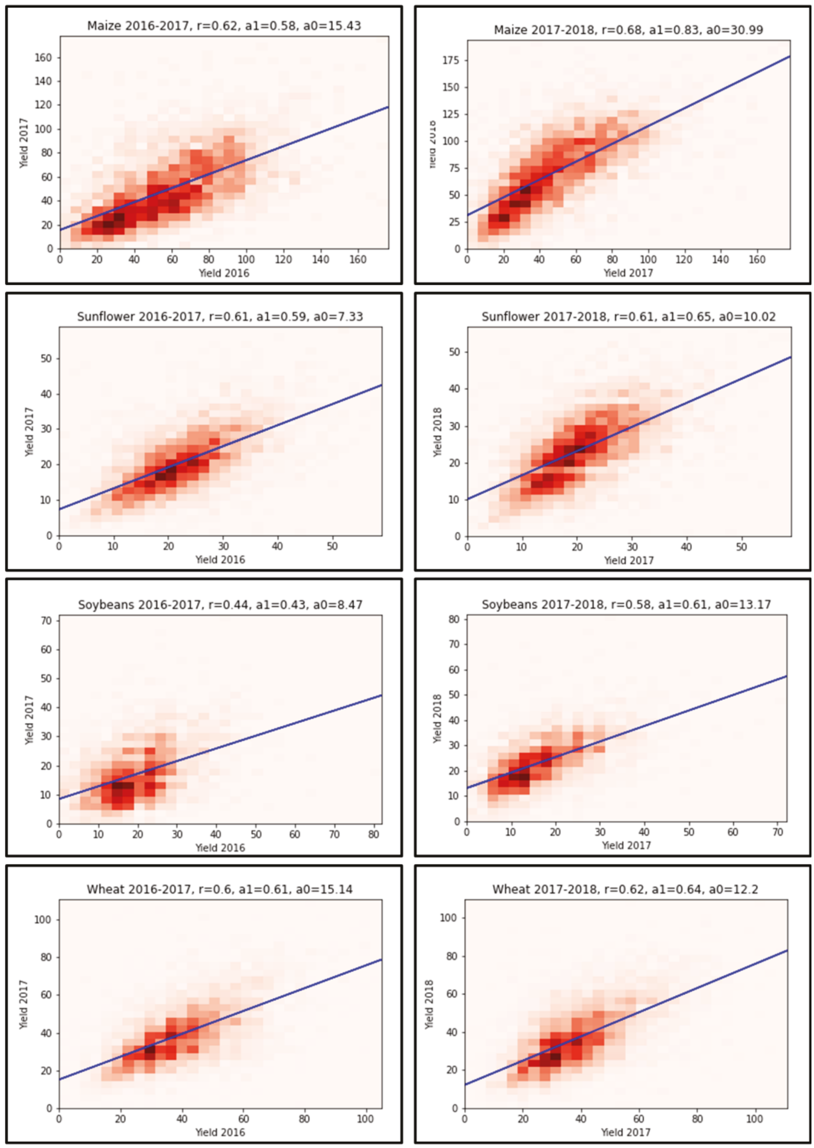


Figure 5. Dependency of the yield for the same crop and the same village councils within two consequent years. The background is a 2D histogram for two years yields, blue line is the regression function fitted on these values, r is Pearson coefficient, a_1 and a_0 are regression coefficients.

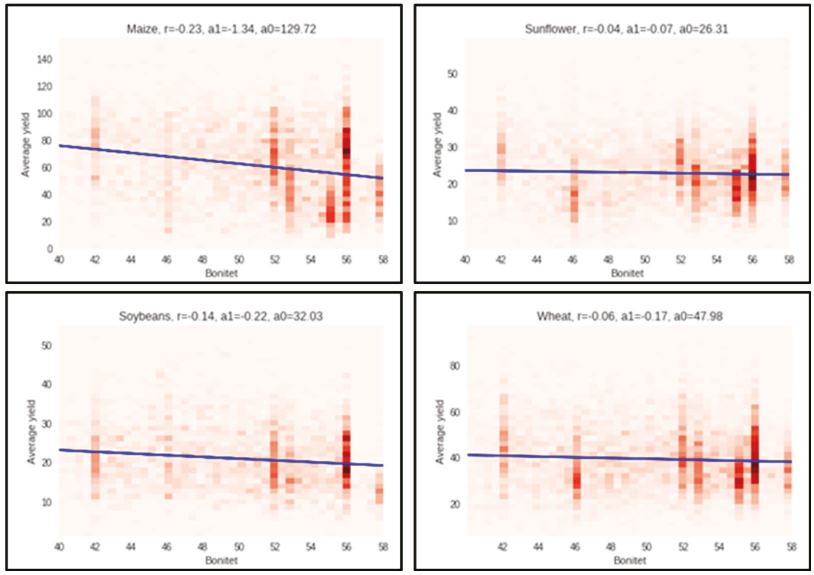


Figure 6. Dependence between average 3 years yield and soil-based bonitet on the village level. The background is 2d histogram for yield and bonitet values, blue line is the regression function fitted on these values, r is Pearson coefficient, a_1 and a_0 are regression coefficients.

3.3. Impact of Bonitet Estimated from the Natural-Agricultural Rayon's Map on the Yield

To conduct the second experiment, we validated the natural-agricultural rayon's based bonitet map using the same ground-truth samples. The mean absolute error between the ground-truth data and the soil-based map is equal to 10.33, and the Pearson coefficient equal to 0.36. Such a weak correlation and large error can be explained by the large average sizes of bonitet map units and significant variation coefficient. Thus, this map on the field level aggregation is not accurate. However, it still can be used for the village level analysis.

The experiment of the impact evaluation of natural-agricultural rayon's bonitet on the yield was conducted in the same way as at the 4.2 (Figure 7). The obtained results, as in the first case, indicate the absence of dependencies between bonitet and yield. Now, coefficients are small and two of four are negative. Thus, we can summarize that natural-agricultural zoning cannot be used as the reference data for land appraisal, because it cannot express the fertility of the soil. By the land appraisal logic, the B_m value is used as a norm for the districts. It is an average bonitet value for it, so if the field bonitet in the district is higher than average, the land should have a higher price. In the opposite way, it works the same—if the land has lower bonitet, it should be cheaper. However, this experiment consumed that land with a higher bonitet value can have the same fertility as the land with a lower bonitet.

This experiment showed the same result as the previous one, so we have the same conclusion about the representation quality of the bonitet of natural-agricultural rayon's map as about the bonitet obtained from the soil map. However, if in the first case it was the approximate estimation of the bonitet values, now, it is the values that are used as B_m in the official land appraisal methodology.

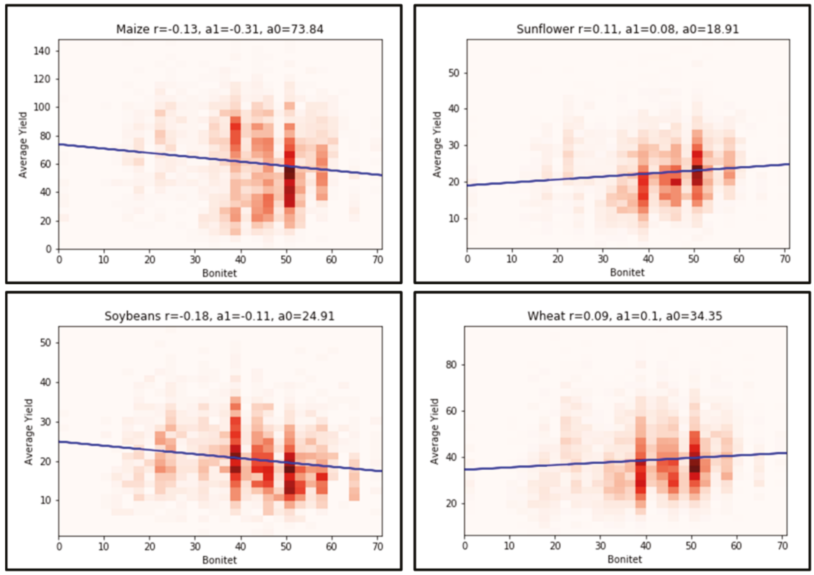


Figure 7. Dependency between average 3 year yield and natural-agricultural rayon's map bonitet on the village level. The background is 2D histogram for yield and bonitet values, blue line is the regression function fitted on these values, *r* is Pearson coefficient, a_1 and a_0 are regression coefficients.

4. Discussion

Using this obtained knowledge, Ukrainian policy makers could analyze how provided reforms for land market and in particular for land appraisal technique can be improved. The results provided by this research indicate that it is better to replace soil bonitet by more representative indicators. It is an important task because Ukraine is one of the biggest agri-food exporters in the Europe, and the land market opening will strongly affect Ukrainian economy. In addition, for the successful reform completion, laws governing the relations between landowners and land purchasers must comply with European standards.

The first way of land appraisal technique improvement may be the implementation of widely used land productivity sub-indicators. The historical biophysical information can be used to define if the land has signs of degradation or if it is sustainable or productive. In this case, when there are no available in situ information about historical biophysical characteristics, it is possible to use remote sensing data. The technology for the SDG 15.3.1 "Proportion of land that is degraded over total land area" assessment [15] can be very useful for this purpose. The main product used for the land degradation assessment is the land productivity map based on the vegetation indices' trends. Such a map can help to classify each land unit in one out of five classes: increasing productivity, stable not stressed, stable but stressed, early signs of decline, and declining productivity [16]. After, these classes can be used as the coefficients for the land appraisal. Instead of the use of static coefficients related to the field's location, this coefficient can be changed through the time by farmer's activities. These possible changes can stimulate the farmer to use more sustainable and environmentally friendly agrarian practices to increase the price of the land. From the other side, this coefficient can work as penalty for the use of unsustainable practices. In general, the implementation of the sustainable development goals' assessment practices can decrease the trend of desertification in the Ukraine and force agrarians to modernize their production by implementing more sustainable practices that can bring increase in the economy development [17]. Such an implementation of UN practices in Ukrainian agriculture is also consistent with the direction of Ukraine in the digitalization and the implementation of smart farming practices that can significantly boost the potential of

Ukrainian agricultural sector [18]. The only problem that makes it hard to implement such evaluation on the country level is the spatial resolution of satellite data. However, today's studies on the harmonization of Landsat-8 and Sentinel-2 [19] data are very promising, and today, it is already possible to build a land productivity map on the country level with 30 m spatial resolution [20].

The second way of land appraisal technique improvement may be the implementation of agro-climatic data. Ukrainian agrarians are still using old, out of date information about the agcro-climatic zoning of Ukraine, while the climatic conditions in the region has changed significantly in last decades. Such implementation requires the harmonization of official agro-climatic zoning and recent European research on the climatic zones [21]. The climatic variables are very important characteristics that can contain information about the probabilities of extreme weather events occurrence, such as droughts, floods, and high wind speed. Such events are very dangerous for the yield, so the agricultural land appraisal also should contain risk assessment component. Using these data, it is possible to obtain the crop yield potential of land [22] that can be used as an additional coefficient of land appraisal.

The last, but not least, possible way to improve the land appraisal technique in Ukraine is implementation of crop rotation history. The recent article of Deininger et al. [23] provide an analysis of dependence between crop yield and crop rotations on the village levels. This study shows that the violation of crop rotation rules has significant negative effect on the further yields, meanwhile, the use of good practices of crop rotations can provide sustainability of land or even slightly increase the productivity of land. The most common crop rotation violations in Ukraine are related to the plantation of technical crops that have negative effects on the land's biochemical characteristics, with higher frequencies then is allowed by the law [24]. As an example, sunflower planting is allowed only once per seven years. However, a lot of farmers are planting sunflowers every two or three years and sometimes even each year. The implementation of a crop history as a coefficient can solve many problems in Ukrainian agricultural regulation. If this coefficient will be based on the evaluation of the crop rotation history, then the effect can be similar to the implementation of SDG-based coefficient. It can decrease trends of desertification of land by stimulating farmers to use sustainable crop rotation schemes. In addition, this coefficient can act as a penalty for the farmers for the violation of crop rotation rules. After the implementation of this coefficient, all farmers are going to think twice when choosing between quick economic benefits that can be provided by monocropping and long-term benefits by saving or increasing land price, yield, and soil quality.

The further reformation and integration of more suitable indicators for the land appraisal should be completed to support the opening of Ukrainian land market. Right now, there is a lack of instruments to ensure the food security, land sustainability, and land appraisal probity. One of the main tasks of Ukrainian governances should be the protection of soils fertility and land productivity. The fines for the improper land use and crop rotation violation are too small and cannot avoid illegal actions that are leading to the land degradation. The absence of governmental control allows farmers to violate crop rotation rules and common agricultural practices. The benefits that can provide remote sensing information in the terms of land appraisal are related to the impossibility to hide or change information that is open and public. So, the satellite-based coefficients that are changing by the farmers actions are a good way to save the productivity of land. The violation of sustainable agricultural practices will bring long-term economic losses to the farmers, so they will be interested in the modernization of their food production.

5. Future Work

The further research of this problem requires significant changes in data availability policies. As it was mentioned in the article, bonitet data collection on the field level or village level require a lot of work, due to the data providers technical limitations. Thus, this procedure cannot be automated and require a lot of human work for data collection and parsing. In addition, these data are available for a very limited number of fields and cover a very small territory. Therefore, we had to create geospatial bonitet layers based on the available for Ukraine soil map and natural-agricultural rayon's map. This approach is not so accurate, because the soil characteristics could be changed by years, while both maps are static for many years. This approach is the only way to currently conduct such research today.

6. Conclusions

Bonitet in Ukrainian law is an important characteristic of the soil quality that measure suitability of soils for growing crops. The agricultural land appraisal technique in Ukraine avoids the usage of important features, which are common for the crop yield assessment, such as agroclimatic conditions or agro-practices. The only variable that describes the yield potential of the agriculture land is the soil bonitet. In this article we analyzed how well this variable meets actual yield for croplands. This research is interesting from the geographical side because it shows a good example for the fusion of multi-scale maps and statistical data. From the economy side, it is also interesting, because the bonitet-based land appraisal technique is widely used in Eastern Europe and Asia, and it is the first analysis of bonitet metrics and yield dependencies on the village level. This research is unique because it was not possible to conduct bonitet sufficiency analysis for the full territory of Ukraine before, due to the bonitet and village-level statistical data availability problem. To conduct this research, we had to build geospatial bonitet maps based on the available soil map and natural-agricultural rayon's map for Ukraine. Based on these data, we calculated the mean bonitet values for each village and conducted correlational and regression analyses between village bonitet and yield for the majoritarian crops: wheat, maize, sunflower, and soybean. The analysis showed that the bonitet maps have very small correlation with actual yield. It means that bonitet does not meet the actual yield and food production potential for agricultural fields. Using these analytical results, policy makers in Ukraine have a scientific basis for the reforms implementation in the agriculture land market that meets European standards and have positive impact on the Ukraine economy. Ukrainian stakeholders and policy makers should consider more attention to the field's characteristics related to economic potential during land appraisal. At the same time, Ukrainian farmers and other land users should implement more sustainable agricultural practices to save the fertility of soil, to not lose the economic potential of owned land, and to meet the requirements of European agricultural policies. The main problem of this research is that field-level bonitet has much higher variability in comparison with the village level values. A more accurate analysis of the bonitet requires field-level bonitet data and yield data. However, due to the fact that correlation between village-level bonitet and village-level yield is very weak, we can assume that on the field level, it will not be much higher, especially when considering that other agro-management factors, such as fertilization or irrigation, have a very significant impact on the yield.

Author Contributions: Conceptualization, N.K. and S.S.; methodology, N.K., S.S., L.S. and M.L.; validation, L.S.; investigation, L.S. and M.L.; data curation, N.K., L.S., S.S. and M.L.; writing—original draft preparation, L.S., S.S., N.K. and M.L.; writing—review and editing, L.S.; visualization, L.S.; supervision, N.K. and S.S. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded within the NASA Land-Cover/Land-Use Change (LCLUC) Program, Grant Number 80NSSC21K0314. The authors acknowledge the funding received by the National Research Foundation of Ukraine from the state budget 2020/01.0273 "Intelligent models and methods for determining land degradation indicators based on satellite data" (NRFU Competition "Science for human security and society").

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Not applicable.

Conflicts of Interest: The authors declare no conflict of interest. The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript, or in the decision to publish the results.

References

1. Gutman, G.; Radeloff, V. (Eds.) *Land-Cover and Land-Use Changes in Eastern Europe after the Collapse of the Soviet Union in 1991*; Springer: Berlin/Heidelberg, Germany, 2016.
2. Skakun, S.; Justice, C.O.; Kussul, N.; Shelestov, A.; Lavreniuk, M. Satellite data reveal cropland losses in South-Eastern Ukraine under military conflict. *Front. Earth Sci.* **2019**, *7*, 305. [CrossRef]
3. Kogan, F.; Adamenko, T.; Guo, W. Global and regional drought dynamics in the climate warming era. *Remote Sens. Lett.* **2013**, *4*, 364–372. [CrossRef]
4. Sobolev, D.O. Products Annual. *USDA FAS*, Kyiv, Ukraine. 2019. Available online: https://apps.fas.usda.gov/newgainapi/api/Report/DownloadReportByFileName?fileName=Oilseeds%20and%20Products%20Annual_Kyiv_Ukraine_04-15-2020 (accessed on 10 October 2021).
5. World Bank. Ukraine, Special Focus Note: Land Market for Agricultural Growth. 2019. Available online: http://pubdocs.worldbank.org/en/204821574084103184/Ukraine-special-focus-note-Fall-2019-en.pdf (accessed on 10 October 2021).
6. Mamedov, G.S.; Shabanov, J.A.; Kholina, T.A. Ecological assessment of soils in high-mountain landscapes of northeastern part of the Greater Caucasus (Azerbaijan). *Eurasian Soil Sci.* **2017**, *50*, 630–635. [CrossRef]
7. Huseynova, S.V. Drawing up of the open and total bonitet scales in the Mugan plain soils from Azerbaijan. *Ann. Agrar. Sci.* **2016**, *14*, 205–211. [CrossRef]
8. Akramkhanov, A.; Kuziev, R.; Sommer, R.; Martius, C.; Forkutsa, O.; Massucati, L. Soils and soil ecology in Khorezm. In *Cotton, Water, Salts and Soums*; Springer: Berlin/Heidelberg, Germany, 2012; pp. 37–58.
9. Kogan, F. Winter wheat yield forecasting in Ukraine based on Earth observation, meteorological data and biophysical models. *Int. J. Appl. Earth Obs. Geoinf.* **2013**, *23*, 192–203. [CrossRef]
10. Becker-Reshef, I.; Vermote, E.; Lindeman, M.; Justice, C. A generalized regression-based model for forecasting winter wheat yields in Kansas and Ukraine using MODIS data. *Remote Sens. Environ.* **2010**, *114*, 1312–1323. [CrossRef]
11. Kolotii, A. Comparison of Biophysical and Satellite Predictors for Wheat Yield Forecasting in Ukraine. *Int. Arch. Photogramm. Remote Sens. Spat. Inf. Sci.* **2015**, *12*, 145. [CrossRef]
12. Adamenko, T.; Prokopenko, A. Monitoring droughts and impacts on crop yield in Ukraine from weather and satellite data. In Use of satellite and in-situ data to improve sustainability. *Dordrecht* **2011**, *11*, 3–9.
13. Shelestov, A. Cloud Approach to Automated Crop Classification Using Sentinel-1 Imagery. *IEEE Trans. Big Data* **2020**, *6*, 527–582. [CrossRef]
14. Zhichkin, K.; Nosov, V.; Zhichkina, L.; Zhenzebir, V.; Sagina, O. Cadastral appraisal of lands: Agricultural aspect. *IOP Conf. Ser. Earth Environ. Sci.* **2020**, *421*, 022066. [CrossRef]
15. UN Sustainable Development Goals–Metadata Repository for the Goal 15. Available online: https://unstats.un.org/sdgs/metadata/files/Metadata-15-03-01.pdf (accessed on 10 October 2021).
16. Ivits, E.; Cherlet, M. Land-Productivity Dynamics: Towards integrated assessment of land degradation at global scales. *Jt. Res. Cent. Eur. Comm.* **2013**, *10*, 59315.
17. Kharas, H.; McArthur, J. Building the SDG economy. Needs, spending, and financing for universal achievement of the Sustainable Development Goals, Global Economy & Development. *Brook. Work. Pap.* **2019**, *131*, 21.
18. Goel, R.K.; Yadav, C.S.; Vishnoi, S.; Rastogi, R. Smart agriculture–Urgent need of the day in developing countries. *Sustain. Comput. Inform. Syst.* **2021**, *30*, 100512.
19. Claverie, M.; Ju, J.; Masek, J.G.; Dungan, J.L.; Vermote, E.F.; Roger, J.C.; Justice, C. The Harmonized Landsat and Sentinel-2 surface reflectance data set. *Remote Sens. Environ.* **2018**, *219*, 145–161. [CrossRef]
20. Kussul, N.; Lavreniuk, M.; Kolotii, A.; Skakun, S.; Rakoid, O.; Shumilo, L. A workflow for Sustainable Development Goals indicators assessment based on high-resolution satellite data. *Int. J. Digit. Earth* **2019**, *14*, 745. [CrossRef]
21. EEA Report No 4/2019—Climate Change Adaptation in the Agriculture Sector in Europe. Available online: https://www.eea.europa.eu/publications/cc-adaptation-agriculture (accessed on 10 October 2021).
22. Van Wart, J.; van Bussel, L.G.; Wolf, J.; Licker, R.; Grassini, P.; Nelson, A.; Cassman, K.G. Use of agro-climatic zones to upscale simulated crop yield potential. *Field Crop. Res.* **2013**, *143*, 44–55. [CrossRef]
23. Deininger, K.; Ali, D.A.; Kussul, N.; Lavreniuk, M.; Nivievskyi, O. Using Machine Learning to Assess Yield Impacts of Crop Rotation. *World Bank Policy Res. Work. Pap.* **2020**, *44*, 456.
24. Resolution of the Cabinet of Ministers of Ukraine, 11 February 2010, Nr 164, "Approval of Standards for Optimal Balance of Crop Types in Crop Rotation in Different Natural and Agricultural Regions.". Available online: https://zakon.rada.gov.ua/laws/show/164-2010-%D0%BF#Text (accessed on 10 October 2021).

sustainability

MDPI

Review

Disaster Risk Mapping: A Desk Review of Global Best Practices and Evidence for South Asia

Giriraj Amarnath *, Upali A. Amarasinghe and Niranga Alahacoon

International Water Management Institute (IWMI), 127 Sunil Mawatha, Battaramulla, Colombo 10120, Sri Lanka; u.amarasinghe@cgiar.org (U.A.A.); n.alahacoon@cgiar.org (N.A.)
* Correspondence: a.giriraj@cgiar.org; Tel.: +94-11-2880000

Abstract: The frequency, intensity, and variability of natural hazards are increasing with climate change. Detailed sub-national information on disaster risks associated with individual and multi-hazards enables better spatial targeting of adaptation and mitigation measures. This paper reviews the global best practices of disaster risk mapping (DRM) to assess the nature and magnitude of disasters, and the vulnerability and risks at the sub-national level in South Asian countries. While some global DRMs focus on vulnerability, others assess risks. Most DRMs focus on national-level vulnerability and risks. Those which focus on the sub-national risks have a limited scope and different methodologies for evaluating risks, mainly in relation to the population. Climate change exposes not only people but also many infrastructures, assets and their impacts to disaster risk. For DRMs to be useful tools for sub-national planning, they require a coherent methodology and a high-resolution spatial focus. The vulnerability and risk assessments should focus on different aspects, including population, infrastructure, and assets in various economic sectors of agriculture, industry, and services.

Keywords: disaster risk mapping; climate hazards; vulnerability; agriculture; South Asia

Citation: Amarnath, G.; Amarasinghe, U.A.; Alahacoon, N. Disaster Risk Mapping: A Desk Review of Global Best Practices and Evidence for South Asia. *Sustainability* **2021**, *13*, 12779. https://doi.org/10.3390/su132212779

Academic Editors: Baojie He, Ayyoob Sharifi, Chi Feng and Jun Yang

Received: 12 October 2021
Accepted: 15 November 2021
Published: 18 November 2021

1. Introduction

Population growth and rapid urbanization are driving the increase in disaster risks. The Bank's Aftershocks report explains that these trends could put 1.3 billion people and USD 158 trillion in assets at risk from river and coastal floods alone [1]. Disaster risks are increasing the world over [2], with major concerns being the increasing frequency, intensity, spatial variability, and unpredictability of natural hazards and their impacts [3]. In South Asia (SA), the incidence of natural hazards increased from about 14 per year in the 1970s to 24, 36, and 47 per year in the 1980s, 1990s, and 2000s, respectively [4], including losses and damages due to natural disasters. Consequently, the number of people affected, the loss of lives, and the costs to economies associated with disasters are also increasing rapidly. The economic losses triggered by natural hazards at present are over USD four billion per year in SA [5].

With rapidly changing demographics, growing economies, and interactions between different sectors, more people, businesses, infrastructure, assets, and economic activities are exposed to disaster risks from natural hazards [6,7]. Often, the most affected people are disadvantaged groups, including women, children, the elderly, disabled people, displaced populations, and religious and ethnic minorities [8,9]. The small- and medium-scale enterprises are among the hardest-hit businesses. Furthermore, the losses to ecosystems and their subsequent impacts often go unnoticed. Therefore, detailed risk assessments are essential to safeguard investments in all sectors and value chains of economic activities [10–15].

The South Asian countries, with 1.5 billion people, have one of the largest populations exposed to natural hazards [16]. A majority of the people in SA still live in rural areas and depend upon agriculture for their livelihoods [17]. The industrial and service sectors, mostly concentrated in urban areas, increasingly contribute to a substantial part of the gross domestic product. Indeed, all economic sectors face high risks with increasing natural hazards [18]. Understanding the nature and magnitudes of risks of disaster associated with natural hazards is critical to enhancing resilience to the impacts of climate change and accelerating socio-economic development [19,20].

Flood and droughts are recurrent and simultaneously occur in different parts in small to large countries. In SA, the northern and southern parts of India, the Indian state of Bihar, or the small islands such as Sri Lanka are examples [21–24]. Floods create havoc in some regions, while droughts destroy agricultural production and livelihoods within the other areas. Extreme rainfall, temperature, cold- or heatwaves, storms, and cyclones can exacerbate the situation [25].

Investigations of the risks of multiple hazards are also urgently needed since the occurrence of some hazards can exacerbate or even reduce the probability of secondary hazards [26]. Therefore, a risk assessment should account for the potential interactions between multiple hazards, such as precipitation with landslides or fires with drought or earthquakes, etc. [27]. Moreover, risk assessments and management must account for the upstream and downstream effects in river basins. High amounts of rainfall upstream can create flooding downstream [28]. Conversely, substantial water storage upstream to mitigate climate change impacts can contribute to droughts downstream [29]. Such up- and down-stream interactions are especially true in South Asia due to the transboundary nature of many large river basins.

Transboundary river basins, such as the Indus, Ganges, and Brahmaputra cover a large part of SA. These river basins are already under extreme pressure, on the one hand, due to recurrent natural hazards especially floods and droughts and on the other hand due to the over-exploitation of water resources, especially for agriculture [16,30,31]. The other big river basins such as Krishna, Godavari, Mahanadi, Cauvery, and Narmada in peninsular India that flow through several states also have similar issues with disaster risks. Increasing disaster risks only aggravate the conflicts of water sharing and allocation and constrain regional economic growth in transboundary river basins.

Disaster risk mapping (DRM) is gaining substantial attention lately due to climate change [32]. Yet, many disaster risk management activities do not use sub-national risk maps due to a lack of sufficiently high-resolution information [33]. Historical data estimate and/or model the frequency of occurrence of hazards; however, high-resolution maps tend to reduce the disaster risk from natural hazards by overlooking exposure, vulnerability, and coping capacity. The profiling of disaster risks requires detailed information on the causes, losses, damages, and coping capacity of people and infrastructure [34]. Yet, because of the considerable spatial variation of incidence and frequency of disasters, the sub-national DRMs are critical for regions such as SA [35,36].

The main purpose of this study is to review the best practices available globally for disaster risk mapping (DRM) including the methods and tools for (sub) national risk as-assessment in South Asian countries. The outline of the DRM review in this paper follows Section 2 of the paper, and reviews existing practices in disaster risk mapping. The next section illustrates various approaches to single and multiple hazard maps as well as exposure and vulnerability/capacity maps. Finally, the paper concludes with recommendations for future DRMs.

Review of Existing Disaster Risk Mapping Tools

The report only considers open-source and publicly available DRM tools and assessments (Table 1). The geographical focus of these tools varies from most countries in the world to a few countries in a region. The geographic scale of assessment ranges from global and national to the sub-national level. The tools have played an essential role in improving the risk mapping methodology and/or providing geo-spatial information to governments, development organizations, or disaster risk management practitioners.

Table 1. Introduction to the analyzed disaster risk tools and assessments.

No.	Name and Abbreviation (If Commonly Used)	Agency and Year (Updates If Available)	Publicly Accessible Tool	Publicly Available Assessment	Geographical Focus	Geographical Scale of Analysis
1	Natural Disaster Hotspot: A Global Risk Analysis (Hotspot s Study)	WB 2005 [37]	No	Yes	The world	Global to sub-national levels
2	Open Data for Resilience Initiative (Open DRI)	WB/GFDRR 2011 (Continuous updates by countries) [38]	No	Yes	All countries	Global to sub-national levels
3	Global Risk Data Platform (GRDP)	UNEP/UNISDR 2013 [39]	Yes	No	The world	Global to sub-national levels
4	Child-centered Risk Assessment: Regional Synthesis of UNICEF Assessments in Asia	UNICEF 2014 (continuous updates by country offices) [40]	No	Yes	Six countries in the Asia-Pacific including Nepal and India in South Asia	National to sub-national levels
5	South Asia Women's Resilience Index (WRI)	Action Aid 2014 [41]	No	Yes	Countries in South Asia and Japan	National level only
6	Index for Risk Management (INFORM)	IASC/EC 2015 (updated every half year, last updates from mid-2018) [42]	No	Yes	All countries	Global to the national level (and sub-national levels for individual countries outside South Asia)
7	The World Risk Index (WRI) (For more information see: http://www.uni-stuttgart.de/ireus/Internationales/WorldRiskIndex/ (accessed on 11 June 2021))	University of Stuttgart 2015 (updated annually) [43]	No	Yes	All countries	Global to national levels
8	The GAR Atlas: Unveiling Global Disaster Risk (GAR Atlas)	UNISDR 2017 (updated biennially) [15]	No	Yes	The world	Global to sub-national levels
9	Atlas of the Human Planet: Global Exposure to Natural Hazards	European Commission 2017 [44]	No	Yes	All countries	Global to national levels
10	Mapping Multiple Climate-related Hazards in South Asia	IWMI 2017 [16]	No	Yes	South Asia only	Regional to sub-national levels

Table A1 provides the list of various disaster risk mapping tools and their application. The synthesis following this section compares and contrasts the methodologies of risk assessment, spatial scope, results, and the inclusion of social development in disaster risk mapping.

Conventionally, hazards take two forms: natural or human-induced hazards, although this distinction is increasingly becoming blurred due to the impacts of human activities, e.g., climate change and fracking. Most DRMs reviewed below have focused on natural hazards (Table 2). Only a few have considered risks induced by climate change such as the sea-level rise and by humans such as conflicts, industrial accidents, etc.

Table 2. Types of hazards and analyzed tools and assessments.

No.	Name and Abbreviation	Geo-Physical Hazards				Hydro-Meteorological Hazards						Climate Change	Human-Made Hazards	
		Volcanos	Earthquakes	Tsunamis	Landslides (Seismic)	Floods	Cyclones	Landslides (Precipitation)	Drought	Heat Waves and Cold Spells/Wind	Wildfires	Sea Level Rise/Storm Surge	Conflict	Industrial Accidents
1	WB 2005	Y	Y	Y	N	Y	Y	Y	Y	N	Y	N	N	N
2	WB/GFDRR 2011	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	N	N	N
3	UNEP/UNISDR 2013	Y	Y	Y	N	Y	Y	N	N	N	N	N	N	N
4	UNICEF 2014	Y	Y	Y	Y	Y	Y	Y	Y	N	N	N	N	N
5	Action Aid 2014	N	N	N	N	N	N	N	N	N	N	N	N	N
6	IASC/EC 2015	N	Y	Y	N	Y	Y	N	Y	N	N	N	Y	N
7	University of Stuttgart 2015	N	Y	N	N	Y	Y	N	Y	N	N	Y	N	N
8	UNISDR 2017	Y	Y	Y	N	Y	Y	N	N	Y	N	Y	N	N
9	EC 2017	Y	Y	Y	N	Y	Y	N	N	N	N	Y	N	N
10	IWMI 2017	N	N	Y	N	Y	Y	N	Y	Y	N	N	N	N

Note: Yes and No referred as "Y" and"N".

The natural hazards in this review include:

- Geophysical hazards such as earthquakes, tsunamis, volcanoes, and landslides (seismic induced);
- Hydro-meteorological hazards such as cyclones, floods, droughts, landslides (caused by precipitation), extreme rainfall events or heatwaves, and wildfires.

2. Materials and Methods

The Methodology of Risk Assessment

The core of disaster risk assessments has three components: hazard (H), exposure (E), and vulnerability (V). The hazard component focuses on the probability of occurrence, intensity, and spatial coverage of hazards (Schneiderbauer 2004). Exposure is hazard dependent. It combines the likelihood of an event and the exposure to the danger of various elements and assets such as population, buildings, economic value, GDP, etc. Vulnerability includes both physical and socio-economic vulnerability and varies from hazards to aspects of exposure. The disaster risk is generally a function of the three components H, E, and V [45].

However, the approaches to risk assessments vary. Some use an entirely probabilistic approach, which includes historical data to assess the likelihood of hazards with different return periods, and the vulnerability to disasters with vulnerability curves [46]. The vulnerability curves show the probability of the exceedance of losses of various magnitudes. Others use both probabilistic and deterministic approaches for risk assessments. Here the exposure and vulnerability are based on a composite index of various demographic, social, economic, and environmental factors (IASC/EC 2015; University of Stuttgart 2015; IWMI 2017).

The geometric mean of H, E, and V is the risk function in some assessments, while others use the arithmetic mean. The geometric mean gives low prominence to low values of risk of E or V (and in cases with adaptive capacity). The arithmetic means have equal prominence to each component.

The review in this paper contrasts and compares various types of DRM methodologies (Table 3). The risk assessments in the WB 2005, UNEP/UNISDR 2013, UNISDR 2017, and EC 2017 were entirely probabilistic. IASC/EC 2015 and University of Stuttgart 2015 used probabilistic approaches to assess the exposure to hazards and a deterministic approach to assess vulnerability and adaptive capacity. IWMI used a deterministic approach to determine exposure and susceptibility. UNICEF 2014 focused on only child-centered vulnerability in a few Asian countries. Action Aid 2014 assessed the capacity of disaster-risk management with a specific focus on women's needs using various indicators of economic, infrastructure, social, and institutions of the countries. While most DRMs have conducted multi-hazard analyses, only a few have focused on the impacts of climate change [47]. A majority of the DRMs have assessed the exposure of people and assets to disaster risks.

Table 3. Disaster risk components in the analyzed tools and assessments.

No.	Organization and Year	Geo-Physical Hazards	Hydro-Meteorological Hazards	Probabilistic or Deterministic	Multi-hazard Analysis	Climate Change	Exposure to Assets	Exposure to People	Gender and Age	Vulnerability	Social Development	Capacity
1	WB 2005	Y	Y	Prob	Y	N	Y	Y	N	Y	N	N
2	WB/GFDRR 2011	Y	Y	Det	Y	Y	Y	Y	Y	Y	Y	Y
3	UNEP/UNISDR 2013	Y	Y	Prob	Y	N	Y	Y	N	Y	N	N
4	UNICEF 2014	Y	Y	Both	Y	Y	Y	Y	Y	Y	Y	Y
5	Action Aid 2014	N	N	Det	N	N	N	Y	Y	Y	Y	Y
6	IASC/EC 2015	Y	Y	Both	Y	N	Y	Y	N	Y	Y	Y
7	University of Stuttgart 2015	Y	Y	Both	Y	N	Y	Y	N	Y	Y	Y
8	UNISDR 2017	Y	Y	Prob	Y	Y	Y	N	N	Y	N	N
9	EC 2017	Y	Y	Prob	N	N	Y	Y	N	N	N	N
10	IWMI 2017	Y	Y	Det	Y	Y	Y	Y	N	Y	N	N

Notes: Yes and No referred as "Y" and"N", Prob—Probabilistics, Det—Deterministic.

First, the hazard information of population grids is calculated using the area-weighted sum of hazard information of grids that lie entirely or partially in the population grid. The product of the estimated hazard value and the total population is the exposed population to hazard. The assessment includes collecting data for developing hazards exposure, vulnerability profiles, and estimating risk at the sub-national level. This initiative supports 31 countries, with 4 in South Asia, including Bangladesh, Nepal, Pakistan, and Sri Lanka at present for sharing, collecting, or/and processing data for different components.

- In South Asia, OpenDRI supports the uploading of hazards and exposure data collected from various government departments and other sources onto open data sharing disaster-risk-information platform.

- At present, the risk platforms are available at http://geodash.gov.bd/ (accessed on 20 April 2021) in Bangladesh, http://drm.moha.gov.np/ (accessed on 1 March 2021) in Nepal, www.disasterinfo.gov.pk (accessed on 20 April 2021) in Pakistan, and http://riskinfo.lk/ (accessed on 20 April 2021) in Sri Lanka.
- Pakistan, Nepal, and Sri Lanka use open access Geonode (GeoNode, which is a web-based platform for developing geospatial information systems. It facilitates the uploading of spatial data and infrastructure http://geonode.org/ (accessed on 20 April 2021), while Bangladesh has created its own information platform.
- OpenDRI supports data collection by mapping buildings and roadways on crowd-sourced OpenStreetMap database. So far, it has mapped 8500 buildings, 93 km of roads, and 50 km of drainage canals in Bangladesh; 2250 schools and 350 health facilities in Nepal; and 130,564 buildings and more than 1000 km of road in Sri Lanka. In Pakistan, it has trained people to use open access Geonode and OpenStreetMap.
- In Sri Lanka, assessments of the impacts of recent floods and the required risk mitigation response in the Gampaha district in the Western province used OpenStreetMap.
- UNEP/UNISDR 2013, UNISDR 2017, and EC 2017 estimate sub-national risk maps using an entirely probabilistic approach. The latter two mainly use the data generated in UNEP/UNISDR 2013.
- IWMI 2017 is a regional assessment and focused on climate-related hazards at the sub-national level in South Asia. It combined the disaster exposure maps estimated at the grid level and the human development index (HDI) available at the district level to assess sub-national level vulnerability in SA. The HDI [48] is based mainly on socio-economic indicators of education, gross national income, and life expectancy at birth. The accuracy of this estimate depends on how far HDI accurately represents the vulnerability to hazards at the sub-national level.
- UNICEF 2014 and Action Aid 2014 focus on disaster risk management of different population segments, in particular women and children. They only have a regional focus—the former on Asia and the Pacific and the latter on the South Asian countries.

3. Results

3.1. Individual Hazard Maps

Hazards maps show the frequency (number of occurrences), intensity (return periods), or actual exposure of the area to different hazards (Table 4).

- The national-level hazard maps (IASC/EC 2015, University of Stuttgart 2015) are sufficient for comparisons across countries. The primary purpose of these maps is for the use of donors and funding agencies to prioritize support to states for disaster risk management.
- However, the higher resolution hazard maps (UNEP/UNISDR 2013, UNISDR 2017, EC 2017) show considerable details of hazard exposure by combing the frequency and intensity of hazards in a probabilistic framework. They provide useful information for intensive hazards (Figure 1).
- IWMI 2017 exposure maps show the actual exposure regardless of the intensity of hazards. They use remote sensing images to identify the exposed pixels to disasters. The sub-national estimates derived from these are essential for local-level disaster-risk management planning.
- While most risk maps use similar hazard data, the disaster maps, assessed either with probabilistic or deterministic methods, generate different risk profiles for some regions. IASC/EC 2015 shows an extensive earthquake profile for India, but the UNEP/UNISDR 2013 and UNISDR 2017 display large parts which are free of seismic hazards.
- The hazard maps with more extended return periods show the exposure due to intensive hazards (i.e., frequent or short return periods with low intensity). However, with monsoonal and El Niño/Southern Oscillation (ENSO) dominated weather patterns, many locations in South Asia are exposed to recurrent or shorter (4–6 years) return

period floods and droughts. The aggregate losses are generally more substantial due to extensive rather than intensive hazards (UNISDR 2015).

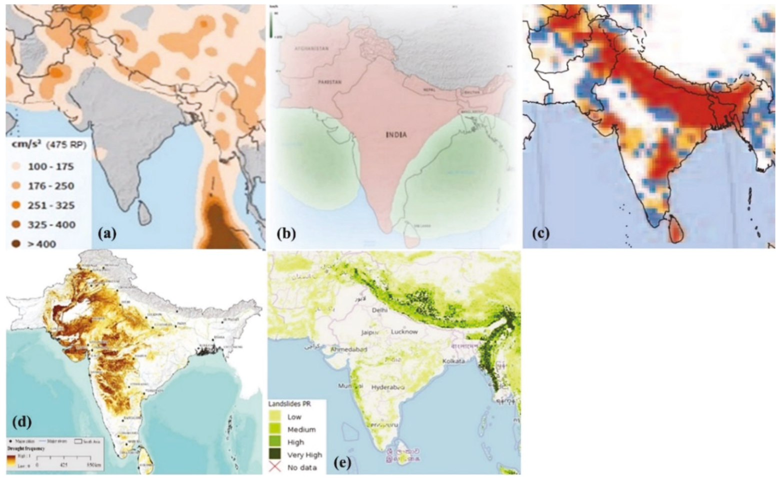


Figure 1. High-resolution exposure hazard maps of different DRMs: (**a**) Physical exposure to earthquakes, (**b**) physical exposure to cyclones, (**c**) physical exposure to riverine floods, (**d**) physical exposure to drought, and (**e**) physical exposure to landslides. (Sources: World Bank 2005 [37], UNEP/UNISDR 2013 [39], IASC/EC 2015 [42], UNISDR 2017 [15], IWMI 2017 [16]).

3.2. Multi-Hazard Maps

Multi-hazard maps (Figure 2) are useful for identifying locations with an elevated risk due to multiple hazards such as cyclones, droughts, floods, landslides and earthquakes. They show:

- Areas that are most likely to be exposed by multiple disasters;
- Disasters that occur immediately after the others, such as fires or landslides after earthquakes or cyclonic storms;
- Disasters that occur independently of each other with a considerable time lag, such as floods and droughts.

Disasters emanating from multiple hazards are frequent in South Asia. In the agricultural landscape, thousands of small tanks that are scattered everywhere provide relief from both floods and droughts to rural populations. However, extreme rainfall events and flash floods often damage many poorly maintained small tanks and reservoir storages, which reduces the resilience of communities against recurrent floods and droughts [49]. Urban centers have a high population density and infrastructure assets, and the industrial and service sectors there contribute substantially to economic growth. Floods and water scarcities associated with droughts are a substantial threat to the economic activities in urban centers.

Detailed multi-hazard maps are useful for the efficient planning of interventions. These are especially important for big countries such as India to identify the locations of multiple threats for risk management. Planning spatially targeted interventions for risk management is essential for the population facing numerous hazards to reduce exposure and vulnerability, or to improve the adaptive capacity. However, methodological differences contribute to the differences in risks between multi-hazard risk maps (Figure 2).

- WB 2005 and IWMI 2017 provide sub-national multi-hazard risk maps. WB 2005 has considered six hazards, while IWMI 2017 has considered five hazards. Only four hazards, tsunamis, floods, cyclones, and droughts, are common to both. Moreover, in WB 2005, the sum of the individual risk values of the top three deciles (in 8th–10th deciles) is the multi-hazard index, where higher values indicate high-intensity multiple hazards. In IWMI 2017, a multi-hazard index (between 1 and 5) shows only the number of hazard occurrences in a pixel. Because some disasters have more prominence in the indicator value such as earthquakes in Nepal these two maps, to some extent, are not even comparable.

- IASC/EC 2015 and the University of Stuttgart 2015 show the aggregated risk of multi-hazards at the national level. They are thus adequate only for inter-country comparisons. They use a different number of hazards, indicators, and weights to aggregate indicators to assess risk components (exposure, vulnerability, and capacity). Moreover, the University of Stuttgart 2015 uses the arithmetic average, giving equal prominence to all risk components. However, IASC/EC utilizes the geometric average, giving differential prominence to different risk components. As a result, the risk pictures of some countries (Sri Lanka, Bhutan) show an opposite view.

Although there are differences, combining the information of multi-hazards and risks with local knowledge provides opportunities for designing efficient interventions to mitigate impacts (UNICEF 2014, WB/GFDRR 2011).

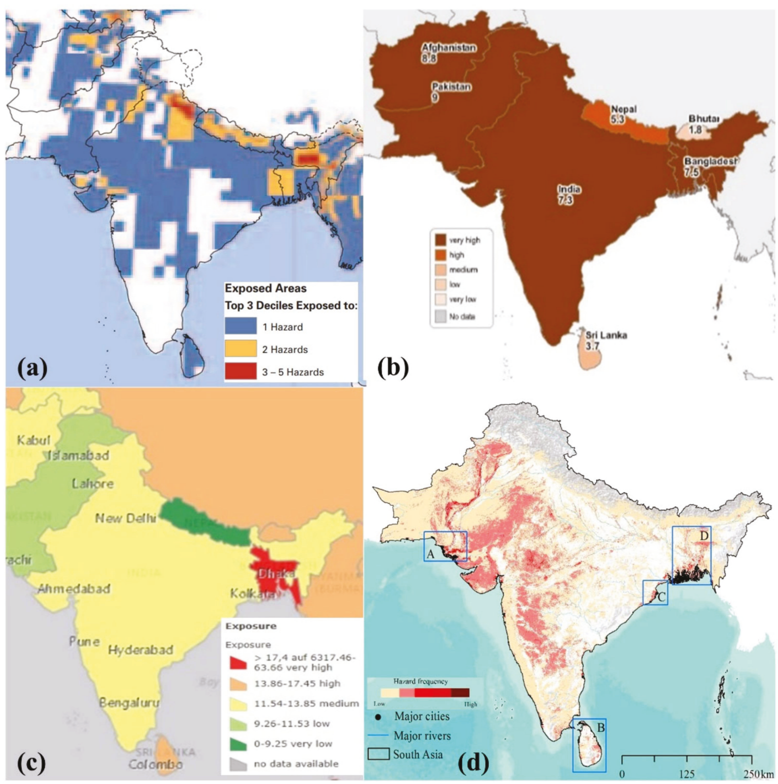


Figure 2. Physical exposure to multi-hazards. (Sources: (**a**) World Bank 2005 [37], (**b**) IASC/EC 2015 [42], (**c**) University of Stuttgart 2015 [43], (**d**) IWMI 2017 [16]).

Table 4. Details of data sources, spatial resolution, and intensity of hazard maps.

Figures		Assessment	Data Source	Pixel/Temporal Resolution	Return Period
Earthquakes	i	WB 2005	Global Seismic Hazard Program (GSHAP)	2.5′	475
	ii	UNEP/UNISDR 2013	UNEP/GRID-Geneva preview/GSHAP	2.5′	475
	iii	IASC/EC 2015	GSHAP Seismic hazard map	2.5′	475
	iv	UNISDR 2017	UNEP/UNISDR 2013	2.5′	475
	v	University Stuttgart 2015	UNEP/UNISDR 2013	2.5′	475
	vi	EC 2017	EMMI-GSHAP hazard map	2.5′	475
Cyclones	i	WB 2005	UNEP/GRID-Geneva Preview	30″	250
	ii	UNEP/UNISDR 2013	UNEP/GRID-Geneva preview	30″	250
	iii	IASC/EC 2015	Annual physical exposure 1969–2009	30″	250
	iv	UNISDR 2017	UNEP/UNISDR 2013	30″	250
	V	University Stuttgart 2015	UNEP/UNISDR 2013	30″	250
	vi	EC 2017	UNEP/UNISDR 2013	30″	250
Floods	i	WB 2005	Dartmouth Flood Observatory, World Atlas of Large Flood Events	1°	200
	ii	UNEP/UNISDR 2013	UNEP/GRID-Geneva preview	1°	200
	iii	IASC/EC 2015	Annual physical exposure 1999–2007		
	iv	UNISDR 2017	UNEP/UNISDR 2013		
	v	University Stuttgart 2015	UNEP/UNISDR 2013		
	vi	EC 2017	Flood map, JRC GloFAS	Raster/1 km	100
	vii	IWMI 2017	MODIS	500 m/8 days	-
Droughts	i	WB 2005	IRI (International Research Institute for Climate Prediction Climate Data) Library	2.5°	8 days
	ii	UNEP/UNISDR 2013	IRI Climate Data Library		
	iii	IASC/EC 2015	Not available		
	iv	UNISDR 2017	UNEP/UNISDR 2013		
	v	University Stuttgart 2015	UNEP/UNISDR 2013		
	vi	IWMI 2017	MODIS	500 m/8 days	-
Landslides	i	WB 2005	Not available		
	ii	UNEP/UNISDR 2013	Norwegian Geotechnical Institute (NGI)	30″	
	iii	IASC/EC 2017	Not available		
	iv	UNISDR 2017	Not available		

Sources: WB 2005 [37], UNISDR 2015 [14], UNISDR 2017 [15], EC 2017 [44], IWMI 2017 [16] Notes: GSHAP—Global Seismic Hazard Program; IRI—International Research Institute for Climate Prediction; NGI—Norwegian Geotechnical Institute.

3.3. Exposure Maps

Exposure to hazards is hazard dependent. It is a function of the probability of the occurrence of hazards with different intensities and the elements of actual exposure to disasters that follow. Some of the common aspects exposed are the disaster-affected:

- Population (humans or livestock) and/or their mortality;
- Infrastructure or businesses and their value and output;
- Economic activities and their losses;
- Ecosystems and their services.

Assessment of the probability of hazard occurrence is dependent upon the availability of historical data, the period used for the analysis, and their spatial coverage. Therefore, exposure depends on the spatial coverage of selected hazards and exposed elements. Thus, multi-hazard exposure estimates of the population (Figure 3, Table 5) may provide different exposure profiles.

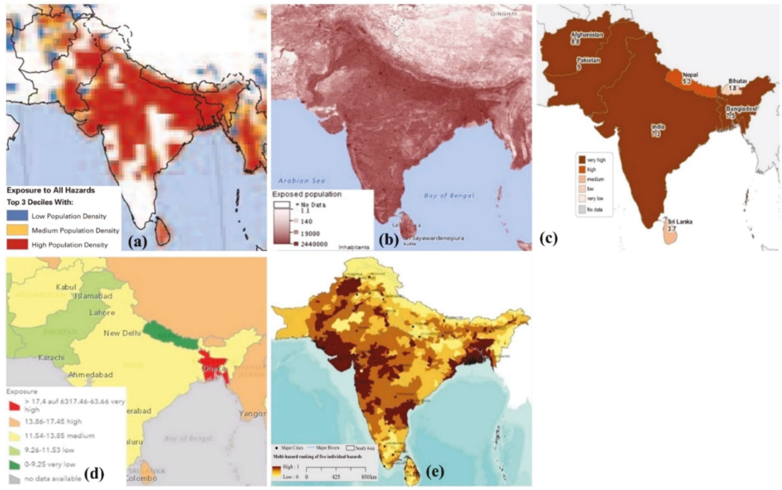


Figure 3. Population exposure to multi-hazards. (Sources: (**a**) World Bank 2005 [37], (**b**,**c**) IASC/EC 2015 [42], (**d**) University of Stuttgart 2015 [43], (**e**) IWMI 2017 [16]).

Table 5. Population exposed to disasters—% of the total population. (Sources: WB 2005 [37], IWMI 2017 [16], Pesaresi et al., 2017 [44]).

Hazard	Assessment	% Population [1] Exposed to Disasters					
		India	Pakistan	Bangladesh	Nepal	Sri Lanka	Bhutan
3+ hazards [2]	WB 2005						
	IWMI 2017	1%	2%	2%	0%	1%	0%
2+ hazards [2]	WB 2005	11	18	33	51	na	29
	IWMI 2017	11	15	20	2	12	14
Floods	IWMI 2017	8	8	34	6	5	0
	EC 2017	18	35	46	na	na	na
Droughts	IWMI 2017	19	30	1	2	10	28

Notes: [1] Percentage relative to total populations in 2005 in WB 2005, and 2015 in IWMI 2017 and E 2017. [2] Only floods, droughts, extreme temperature are common to WB 2005 and IWMI 2017.

Regarding the exposure of the population exposure to multi-hazards:

- The IASC/EC 2015 and University of Stuttgart 2015 assess the exposure to similar hazards. The former shows high to very high exposure to multi-hazards for all countries except Sri Lanka and Bhutan, and for them, the exposure varies from medium to low. The University of Stuttgart 2015 depicts a substantially different exposure profile for the SA countries.
- The sub-national exposure estimates for multi-hazards in WB 2005, UNEP/UNISDR 2013, and IWMI 2017 also vary. The number and the intensity of hazard treatment in the risk analyzed area are also significant factors in these differences.
- The WB 2005 study shows that 33% of the population (in 2005) were exposed to three or more hazards in Bangladesh, and about 33%, 18%, and 11% of the total population in Bangladesh, Pakistan, and India, respectively were exposed to two or more hazards. A detailed higher spatial resolution risk study of Sri Lanka showed not only vast spatial variation but also a distinct seasonal variation of exposure to multi-hazard risks.
- The IWMI 2017 with a higher spatial resolution shows that two or more hazards affect about 20% of the population in Bangladesh and only 11% of the population in India. A substantially lower exposure in Nepal in IWMI 2017 was observed, due to the

non-inclusion of earthquakes in the assessment. IWMI 2017 study shows that about 750 million people in South Asia are affected by one or more natural hazards. Of these, 72% are in India, and 14% are in Bangladesh and Pakistan.

The WB 2005 reveals that natural hazards expose more than two-thirds of the GDP in SA countries (Figure 4). In the UNEP/UNISDR 2013, the GDP exposed to disasters ranges from USD 1.5 to 3 billion, which is substantially less than that estimated by WB 2005.

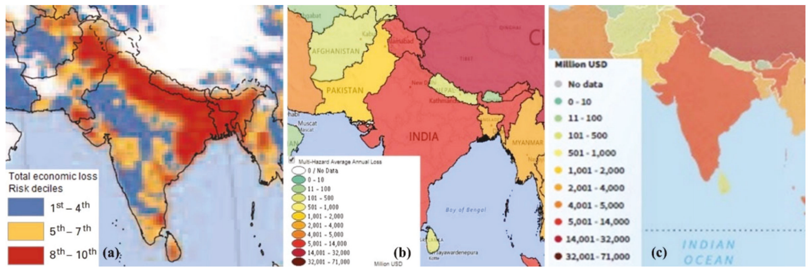


Figure 4. GDP exposed to multi-hazards. (Sources: (**a**) World Bank 2005 [37], (**b**) UNEP/UNISDR 2013 [39], (**c**) UNISDR 2017 [15]).

Despite these marked differences, global studies are still useful for prioritizing donor assistance for disaster risk reduction across countries. INFORM provides scientific support to a wide array of EU disaster risk assistance policy initiatives [50]. GRDP-UNISDR is the primary source of background information for policy dialogues at the biennial global gathering of member countries organized by the UNISDR. The exposure of the economy and GDP to multiple disasters is a valuable source for policymakers to take urgent action.

The individual disaster risk maps show the vast spatial spread of floods (Figure 5), droughts (Figure 6), and landslides (Figure 7) in most SA countries. However, the low spatial resolution in some studies (WB 2005, IASC/EC 2015) either masks or exposes more areas to floods and droughts. Table 6 shows that:

- IWMI 2017 estimated that floods affected 170 million people in SA. Of this, 101 and 53 million are in India and Bangladesh, respectively. However, according to EC 2017, the flood-affected populations in India and Bangladesh are 220 and 71 million, respectively.
- Estimates of the drought-affected population also vary. Figure 6 shows a different picture of drought exposure as depicted by the WB 20105 and UNEP/UNISDR 2013. IWMI 2017 estimated that droughts affected 293 million people in South Asia. Of this, 233 and 54 million are in India and Pakistan.

Table 6. Mortality and economic loss-related vulnerability coefficients of South Asia. (Source: World Bank 2005 [37]).

Factor	Income Status	Cyclones	Droughts	Earthquakes	Floods	Landslides
Economic loss	Low	26.64	0.18	1.33	7.00	0.07
	Lower middle	0	0	0	5.26	0
	Upper middle	0	0	0	0	0
	Upper	0	0	0	0	0
Mortality	Low	64.52	0.04	8.04	3.90	7.04
	Lower middle	0	0	0	0	0
	Upper middle	0	0	0	0	0
	Upper	0	0	0	0	0

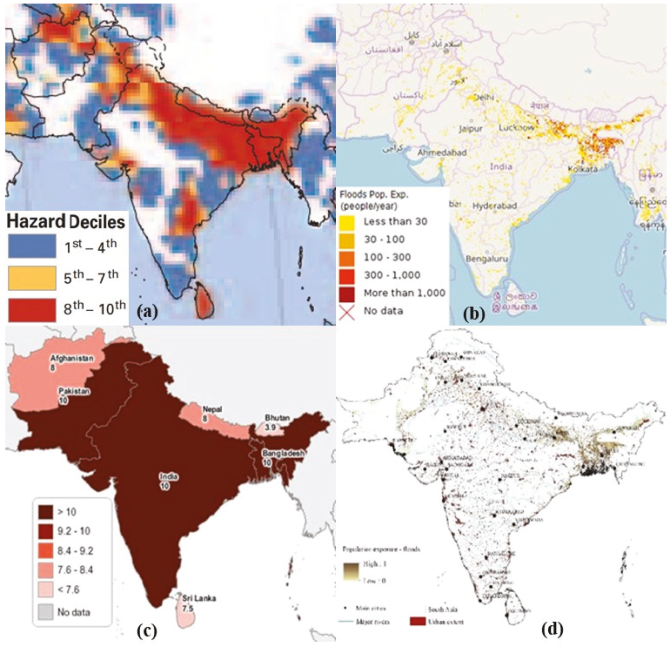


Figure 5. Population exposure to floods. (Sources: (**a**) World Bank 2005 [37], (**b**) UNEP/UNISDR 2013 [39], (**c**) IASC/EC 2015 [42], (**d**) IWMI 2017 [16]).

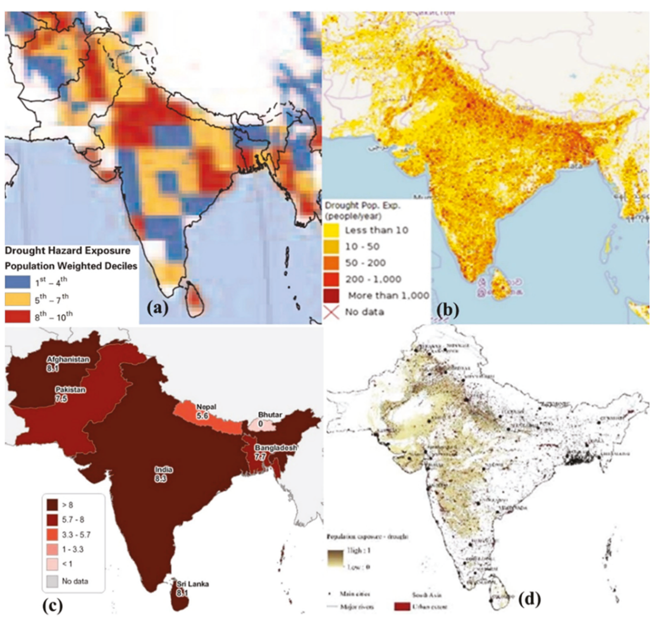


Figure 6. Population exposure to drought. (Sources: (**a**) World Bank 2005 [37], (**b**) UNEP/UNISDR 2013 [39], (**c**) IASC/EC 2015 [42], UNISDR 2017 [15], (**d**) IWMI 2017 [16]).

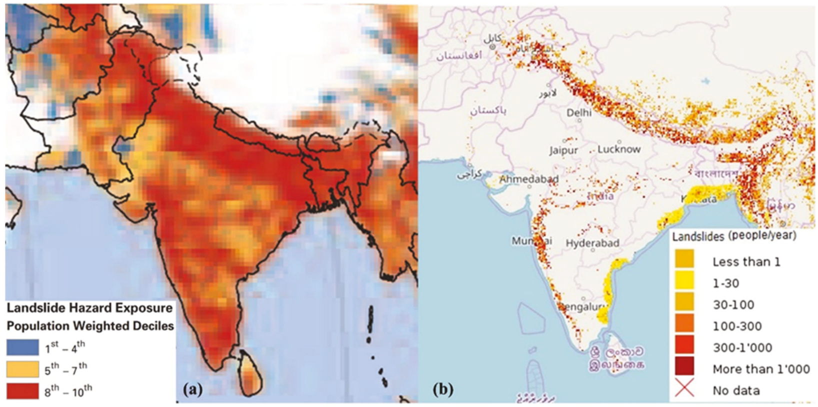


Figure 7. Population exposure to landslides. (**a**) World Bank 2005 [37], (**b**) UNEP/UNISDR 2013 [39].

3.4. Vulnerability Maps

Vulnerability includes both physical and social vulnerability. Often, physical vulnerability is hazard dependent. It assesses the vulnerability of infrastructure such as buildings, roads, bridges through vulnerability (or fragility) curves (World Bank 2015, UNISDR 2015). Social vulnerability is generally independent of hazards. It assesses the vulnerability of people, communities, and institutions by combining socio-economic, political, cultural indicators (IASC/EC 2015, University of Stuttgart, World Bank 2005, IWMI 2017). In addition to vulnerability, some studies assess coping capacity, which is independent of hazards. It measures the ability of people to cope with disasters. The latter includes two streams: institutional capacity and infrastructure capacity.

The comparison of assessments shows a lack of a coherent methodology underpinning the estimation of vulnerability. The vulnerability assessments of IASC/EC 2015 and the University of Stuttgart 2015 are deterministic, where the indices are from socio-economic, health, institutional, and infrastructure. However, there are substantial differences in the vulnerability estimates of these two assessments because they used different sub-indicators for the evaluation (Figure 8). On the other hand, IWMI 2017 used only HDI for the vulnerability assessment, where the HDI values are the vulnerability coefficients.

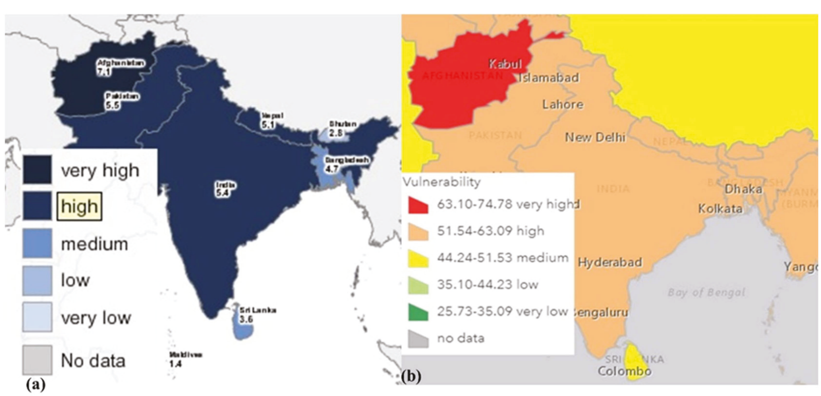


Figure 8. Vulnerability to multi-hazards. (**a**) IASC/EC 2015 [42], (**b**) University of Stuttgart 2015 [43].

The WB 2005, UNEP/UNISDR 2013, and UNISDR 2017 used a probabilistic approach using the historical data of mortality and economic losses to estimate vulnerability weights.

The WB 2005 estimated the vulnerability coefficients of mortality and losses using historical data for countries in the World Bank geographical region and income status. The estimated weights for the South Asia region in Table 6 are the economic loss per USD 100,000 of GDP and persons killed through 1981 and 2001 per 100,000 people in 2000. These estimates show that the low-income South Asian population has the highest vulnerability to death and economic losses due to cyclones.

The UNISDR-GRDP used historical data to assess vulnerability to hazards in different countries. This estimate includes vulnerability curves developed for each risk indicating mortality and potential losses concerning the intensity of hazards with varying periods of return. It is not possible to compare the vulnerability estimates of UNEP/UNISDR with those of IASC/EC 2015, University of Stuttgart 2015, and IWMI 2017, which used a deterministic approach through socio-economic details. Indirect comparison is possible through disaster risk maps, which are products of exposure and vulnerability.

3.5. Disaster Risks Maps

Two popular risk estimates are the risks to population and GDP. These are easy to estimate because the gridded population and GDP [51] estimates are available now. Still, there are substantial differences in calculated risks, especially the multi-hazard risks of various assessments. All assessments, except IWMI 2017, gave national level multi-hazard risks to GDP (Figure 9).

- WB 2005 shows high to medium risks for Sri Lanka, Bhutan, and Nepal, whereas UNEP/UNISDR 2013 shows low to substantially low risk for Sri Lanka, Nepal, and Bhutan. This variation may be due to the different spatial resolutions of hazard maps and different methods used for vulnerability estimation.
- The IASC/EC 2015 and University of Stuttgart 2015, which used a deterministic approach to vulnerability estimation, show a completely different risk picture. This difference may be due to various socio-economic development indicators and methods utilized for vulnerability estimation. For example, IASC/EC 2015 used a substantial number of socio-economic indicators for assessing vulnerability and coping capacity as compared to the University of Stuttgart 2015. Furthermore, the weights used for developing indexes are different. Moreover, IASC/EC 2015 used an arithmetic mean, while the University of Stuttgart 2015 used the geometric mean for estimating risk.

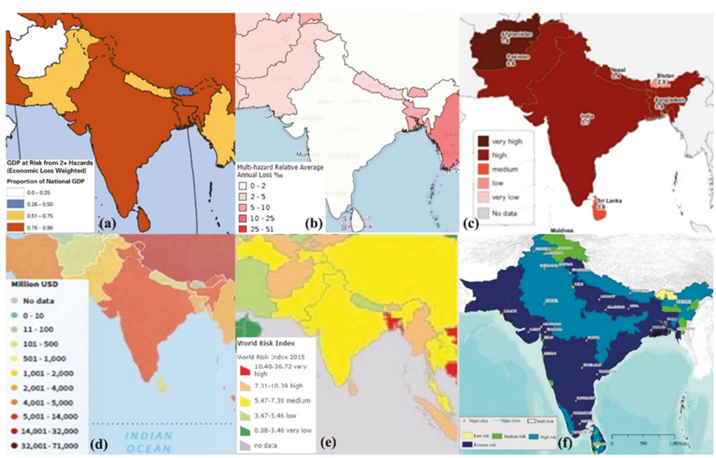


Figure 9. Spatial variation of multi-hazard risk. (**a**) World Bank 2005 [37], (**b**) UNEP/UNISDR 2013 [39], (**c**) University Stuttgart 2015 [43], (**d**) UNEP/UNISDR 2017 [15], (**e**) IASC/EC 2015 [42], (**f**) IWMI 2017 [16].

The sub-national multi-hazard disaster risk map of IWMI 2017 shows that a large swath of India has a very high risk of economic losses. This risk indicator, however, is different from others in that it used a sub-national HDI indicator, which included GDP, to assess risk. It provides useful information about sub-national risk, although it is not clear whether the exposure or vulnerability indicators dominated the risk assessment. Further analysis of the contribution of exposure and vulnerability to the final risk indicators could offer useful information to design appropriate risk management strategies.

3.6. Social Development Indicators in Risk Maps

The disaster risk maps show only a few social development indicators—mainly population, agriculture area, and GDP at risk. Many of the other social development indicators enter the risk analysis through the vulnerability component.

The selection of social development indicators shows a lack of a coherent methodology underpinning the estimation of vulnerability. The vulnerability assessments of IASC/EC 2015 and the University of Stuttgart 2015 are deterministic and used socio-economic indices on health, institution, and infrastructure. However, there are substantial differences in vulnerability values due to different sub-indicators used in the vulnerability assessments. On the other hand, IWMI 2017 combined HDI and hazard-affected populations for vulnerability assessment, where the HDI values are the vulnerability coefficients.

The gender inequality and age dimensions are only used in the risk assessments in IASC/EC 2015, ACTION Aid 2014, UNICEF 2014, and University of Stuttgart 2015. However, except in ACTION Aid 2014, gender-related indicators are subsumed under a host of other indices used for assessing vulnerability. Therefore, it is not clear how gender inequality and age dimensions influence the disaster risks of these two assessments.

Many national databases provide gender/age group-specific data such as population and employment at the sub-national level. Such estimates can provide gender and age group-specific exposure to hazards. The probabilistic assessment of gender and age-group vulnerability is still not possible due to a lack of information on gender/age group-specific mortality or economic losses. However, the method employed by IWMI 2017, which used HDI to assess vulnerability, can overcome this deficiency. By combining HDI with other social development indicators that represent gender-related issues, the vulnerability assessments of gender can be ameliorated. The Women Resilient Index of Action Aid 2014 incorporated many such gender-related matters.

The WRI-EIU used 68 indicators (Table A2) on social, economic, institutional, and infrastructure aspects to analyze the ability of South Asian countries with respect to disaster risk reduction (DRR) and women's roles in DRR [52]. Of these, 40% are gender-disaggregated indicators. Hazard exposure and vulnerability assessments can use those gender-related indicators where data are available at the sub-national level. Some of these include gender-disaggregated data on

- Access to financial institutions;
- Access to micro-finance;
- Access to loans;
- Access to land;
- Unemployment rate;
- The number employed in the police force;
- Enrolment in primary-secondary schooling;
- Literacy rate, etc.

4. Discussion

4.1. An Example of Disaster Risk Assessments from the Asian Development Bank's (ADB) Risk Strategies

The ADB proposes a disaster risk assessment (DRA) for countries with medium- to high-risk [53]. The high-risk countries are those with absolute Average Annual Losses (AAL) due to multi-hazards above 2% of the total GDP. The medium-risk countries are considered to be those with AAL between 0.8% and 2.0% of GDP. However, the DRAs should include low-risk countries with a large geographical area—such as India, which has pockets of high-risk regions—or those prone to hazards such as drought or insignificant earthquake zones, where the impacts of drought are often not included in AAL estimation. Earthquakes have long return periods, but when they do occur, they cause substantial damage.

Among the developing member countries (DMCs), high-risk members are often low- to middle-income countries [54]. In South Asia, Bangladesh and Bhutan are in the high-risk category with AALs of more than 2% of the GDP. India has the third largest AAL in Asia and the Pacific, but it is only 0.5% of the total GDP. All other DMCs in South Asia, except Sri Lanka and the Maldives, have a medium risk, where the expected AAL is between 0.8% and 2.0% of the total GDP. With a significant spatial and temporal variation in climate, large countries such as India or even island nations such as Sri Lanka can also have areas with significantly higher risks to disasters.

Because of the increasing incidence and increasing losses, the ADB proposes that DRAs should be part of the development policy and planning within countries [55]. The DRAs not only help in the planning of sustainable development projects, they also assist in enhancing resilience against disasters. Those, in turn, contribute to achieving sustainable development goals. Therefore, to discuss DRA and risk management strategies along with development projects with the relevant government officials, ADB proposes to include DRA as part of the country partnership strategies (CPS). The CPS is the springboard for the ADB to initiate discussions with the local governments on disaster risk management in development assistance.

In developing projects, the ADB project teams conduct a preliminary climate risk screening. They use a variety of methods, including the analysis of secondary data, a review of the published documents, and an assessment of risks using the online tool AWARE for such projects. Preliminary climate risk screening with AWARE was utilized in the Earthquake Emergency Assistance Project in Nepal, Thimpu Road development project in Bhutan, Dhaka Water Supply Network Improvement Project in Bangladesh, etc. While the preliminary risk screening of the ADB generally has a low spatial resolution (e.g., districts of Nepal in Figure 10), in project locations in high-risk areas, detailed localized risk assessments are conducted.

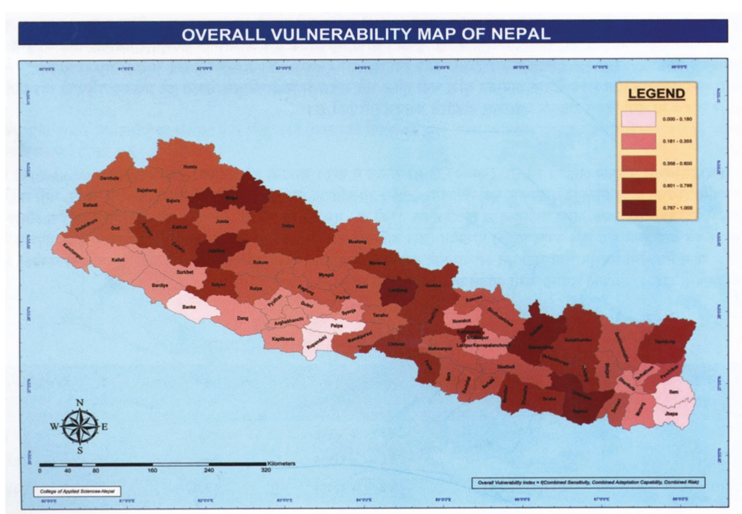


Figure 10. AWARE generated risk map.

4.2. Modeling and Future Applications

It is evident from the desk review that in order to manage natural disasters, mapping hazards and identifying areas for risk prioritization and planning are crucial. Most natural hazards studies as of now have focused on single hazards. However, there should be greater emphasis on the relationships between multiple hazards to collectively quantify risks and their impacts for medium- to long-term resilience strategies. Given the complexity of hazards and their exposure and vulnerability indicators, it is vital to integrate a machine learning framework for multi-hazard modeling and mapping to help understand the complex relationships. Various methods exist—namely, support vector machine (SVM), analytical hierarchy process (AHP), decision trees, and multivariate statistical analysis to combine hazards with the use of multiple variables with statistical weighing—for mapping multi-hazards risks. In addition to modeling, there is a need for expert opinion, the use of remote sensing information, and policy consultation to provide stakeholders with robust information for proactive climate adaptation strategies.

Innovations created through technological advancement are more effective in assisting disaster risk management, resilience, and response processes, as well as providing new dimensions for data analysis. Innovations in areas such as Artificial Intelligence (AI), Internet of Things (IoT), 4G-5G wireless network, and Machine Learning (ML) have overturned pre-existing methods in many areas, including disaster risk reduction and management. Furthermore, the past few decades have seen significant technological advances in areas such as remote sensing and information technology, resulting in the increasing use of satellite and drone data, smartphones, and social media, as well as the Internet. Moreover, technological advancements, as well as the use of data and tools, has led to a proliferation of Big Data platforms that provide additional information on disaster risks and impact. IoT, Big Data, ML, and AI are currently at the forefront of digital transformation around the world and will play a significant role in the development of comprehensive disaster risk management and resilience strategies with a high degree of efficiency [56].

Disaster/risk models are currently being used for a variety of stages throughout the DRM cycle, making them more useful for infrastructure planning, insurance products, and early warnings. Such risk models are primarily designed by integrating hazards, vulnerability, exposure elements, risk indicators, and historical impact data. As the amount of data retrieved increases day by day, there is a high potential to change the way disaster risk modeling and management is undertaken by combining it with artificial intelligence (AI). AI uses include real-time analysis of seismic data for forecasting and detection models, the identification of data communication patterns through social media in the event of disasters, and the generation of flood forecasting models.

5. Conclusions

Global DRMs mainly assess national-level disaster risks and provide broader climate adaptation strategies. The core of all global DRMs includes the assessment of single or multiple hazards, exposure, and vulnerability. However, the risk profiles of countries are mostly not comparable across assessments due to inconsistent approaches and methodologies used for the quantification of exposure, susceptibility, and risks. Moreover, many of the global DRMs do not provide detailed sub-national maps, which are critical for local-level development and disaster risk management planning. Therefore, regional studies with sub-national entities acting as the analytical units to support data sharing and evaluation with multi-institutions might be the best way forward in the generation of better disaster risk maps for South Asia.

At present, the gridded risk is mainly available for population and GDP. However, detailed production data on agriculture, water scarcity or security, and other sectors are available at the district level in South Asia in national/province/state-level databases. These databases also compile many other socio-economic development indicators. These can generate sub-national administrative boundary level risk estimates for population, agriculture and different sectoral outputs, and GDP. These need to be extended to other social development and demographic indicators, including gender and other vulnerable groups.

Risk assessments at the gender and age dimensions are rare. However, in some global DRMs, gender inequality and age dimensions are combined in risk estimation through a vulnerability assessment. However, their influence on risk estimates is not apparent due to the large number of indicators that are used for vulnerability assessments. Yet, there is potential to estimate gender and age division risk profiles by using sub-national data collected by the various census. A deterministic vulnerability assessment can use detailed census data to assess risks at a sub-national or project level aided with a machine learning framework to produce reliable multi-hazard risk maps. It is important to identify a set of consistent indicators where data are available from the population and another census, to use in vulnerability and risk assessments [57].

In this respect, establishing a robust evidence base through the collection of data on current and projections of future hazards and disasters is crucial to disaster risk assessment, financing, and management. The information base requires (sub)national, regional, and global databases capable of pooling data from diverse sources. It enriches risk assessment and enables the development of more cost-effective, innovative disaster risk financing tools and insurance products such as Index-Based Flood Insurance [58] and the Parametric product for Storm, Cyclone or Hailstorm [59].

The use of remote sensing and GIS to assess and integrate hazard, exposure, and risk indicators with higher spatial resolutions to sub-national risk maps is preferable because existing global DRMs do not provide a sectoral-wide risk. These estimates are essential given the increasing influence of disaster risk on industrial and service sectors involved in economic growth. In order to improve the accuracy and rapid mapping of multi-hazard risks, it is important to use advance models such as the machine learning approach to guide policymakers for timely hazard mitigation measures. Such assessments allow the policymakers, development practitioners, and the private sector including the insurance industry to manage current and future risks through risk reduction, risk transfer, and risk management instruments. High-precision multi-hazard risk maps should also be part of the global, regional, national, and sub-national implementation plans to strengthen the Sustainable Development Goals (SDG), the Paris Climate Change Agreement, and the Sendai Framework for Disaster Risk Reduction towards building resilience among vulnerable communities in South Asia.

Author Contributions: G.A. and U.A.A. conceptualized the study. U.A.A., G.A. and N.A. performed the review and written the paper. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the CGIARs (Consultative Group of International Agricultural Research Program (CRP) on Climate Change, Agriculture and Food Security (CCAFS), Asian Development Bank (ADB) and CGIAR Research Program (CRP) on Water, Land and Ecosystems (WLE).

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Not applicable.

Acknowledgments: The authors would like to acknowledge and thank the funding and data-providing organizations. We are grateful to three anonymous reviewers and the editors for their comments, which greatly improved the manuscript.

Conflicts of Interest: The authors declare no conflict of interest.

Appendix A

Table A1. List of various disaster risk mapping tools and their application.

No.	Name and Abbreviation	Agency and Year (Updates If Available)	Objectives (Link to Risk Maps or Mapping Tools)
1	Natural Disaster Hotspot: A Global Risk Analysis (Hotspot Study)	WB 2005	The project enhances the knowledge of global risks of natural disasters by conducting an assessment with global datasets but taking into account the spatial variation of hazards, exposure, and vulnerabilities of six natural hazards. http://documents.worldbank.org/curated/en/621711468175150317/pdf/344230PAPER0Na101official0use0only1.pdf (accessed on 18 April 2021)
2	Open Data for Resilience Initiative (Open DRI)	WB/GFDRR 2011	OpenDRI provides information about the rapidly changing dynamics of the risks and impacts due to population growth, economic expansion, and climate change. OpenDRI promotes spatially targeted investments, policy, or technical interventions that enhance the resilience of people and communities TABLEagainst climate change impacts. https://opendri.org/ (accessed on 18 April 2021)
3	Global Risk Data Platform (GRDP)	UNEP/UNISDR 2013	The UNISDR organizes a biennial global gathering of member countries on reducing disaster risk and enhancing the resilience of communities and nations. The *Global Assessment Reports* (*GARs*) are UNISDRs flagship publications of Global Platform meetings. The GRDP is the warehouse of spatial information of exposure and risks generated by stakeholders for the biennial gatherings. http://preview.grid.unep.ch/index.php?preview=home&lang=eng (accessed on 18 April 2021)
4	Child-centered Risk Assessment: Regional Synthesis of UNICEF Assessments in Asia	UNICEF 2014	UNICEF, with a mandate for humanitarian relief and development, especially for children, promotes child-centered disaster risk assessment. It informs the governments, the UNICEF country offices, and partner organizations on assessments of disaster risks for the survival and development of children. The evaluation explores ways to reduce vulnerability and build capacity to enhance resilience against disaster risks. https://www.preventionweb.net/publications/view/36688 (accessed on 12 April 2021)
5	South Asia Women's Resilience Index (WRI)	Action Aid 2014	The WRI-EIU shows the extent to which the disaster risk reduction and building national resilience initiatives in the South Asian counties incorporated gender inequality in risk estimation. http://www.actionaid.org/australia/digital-tool-womens-resilience-index-wri (accessed on 12 May 2021)
6	Index for Risk Management (INFORM)	IASC/EC 2015	INFORM's objective is to assess countries that are at a potentially high risk of hazards and inform the world and donors for prioritizing for international humanitarian assistance. http://www.inform-index.org/ (accessed on 14 Apr 2021)
7	The World Risk Index (WRI)	University Stuttgart 2015	The World Risk Index combines physical hazard information with vulnerability (susceptibility, coping, and adaptive capacity) to assess the risk of people exposed to disasters. It provides the likelihood of natural hazards affecting people and their vulnerability to hazards. http://www.uni-stuttgart.de/ireus/Internationales/WorldRiskIndex/ (accessed on 11 June 2021)
8	The GAR Atlas: Unveiling Global Disaster Risk (GAR Atlas)	UNISDR 2017	The GAR Atlas presents the results of the Global Risk Model, which uses a state-of-the-art probabilistic approach to assess hazards, exposure, and vulnerability. The UNISDRs GAR report [15] previewed the initial results of the Global Risk Model. https://www.preventionweb.net/english/hyogo/gar/atlas/ https://www.unisdr.org/we/inform/publications/42809 (accessed on 11 April 2021)
9	Atlas of the Human Planet: Global Exposure to Natural Hazards	EC 2017	The Atlas shows the spatial patterns and temporal trends of exposure of human settlements to disaster risk and their relation to socio-economic vulnerability. They draw attention to geographical hotspots for a comprehensive understanding of disaster risks. https://ec.europa.eu/jrc/en/publication/eur-scientific-and-technical-research-reports/atlas-human-planet-2017-global-exposure-natural-hazards (accessed on 19 May 2021)
10	Mapping Multiple Climate-related Hazards in South Asia	IWMI 2017	This study develops a high spatial resolution mapping of areas exposed to multi-climatic hazards and estimates exposure and vulnerability of population and agriculture to multi-hazard disaster risks. http://www.iwmi.cgiar.org/publications/iwmi-research-reports/iwmi-research-report-170/ (accessed on 28 May 2021)

Appendix B

Table A2. Indicators used for vulnerability assessment.

	Indicators in Different Risk Assessments	WB 2005	UNEP/UNISDR 2013	WB/GFDRR 2011	UNICEF 2014	ACTION Aid 2014	IASC/EC 2015	University of Stuttgart 2015	EC 2017	UNISDR 2017	IWMI 2017
1	GDP per capita	x			x						
2	Human development index						x		x		x
3	Human poverty index				x		x				
4	Extreme poverty										
5	GINI index						x				
6	Adult literacy rates					x	x	x			
7	Gender inequality index						x	x			
8	Public aid received (total and % of GDP)				x		x				
9	Displaced people (total and % of the total population)					x	x				
10	Dependency ratio					x	x				
11	Prevalence of TBC						x				
12	Malaria mortality						x				
14	Adult HIV cases						x				
15	Children underweight						x				
16	Children morality rate						x				
17	Health expenditure per capita						x	x			
18	1-year old fully immunized against						x				
19	Prevalence of undernourishment						x				
20	Average dietary energy supply adequacy						x				
21	Life expectancy at birth							x			
22	The domestic food price index						x				
24	Domestic food price volatility index						x				
25	Number of physicians per 10,000 inhabitants					x	x	x			
26	Governance ineffective index						x	x			
27	Corruption perceptions index						x	x			
28	Access to electricity				x	x	x				
29	Number of women in the police force					x					
30	Internet users						x				
31	Mobile phone subscriptions						x				
32	Road density						x				
33	Access to improved water supply					x	x				
34	Access to clean sanitation					x	x				
35	Number of hospital beds 10,000 inhabitants					x		x			
36	Insurance availability							x			
37	Share of females in the national parliament							x			
38	Water resources (Envir. security index)							x			
39	Biodiversity and habitat productions							x			
40	Forest management							x			
41	Agriculture management							x			
42	Government funding for disaster relief				x						
43	Country-level economic strength				x						
44	Personal finance of women				x						
45	Labor environment of women				x						
46	Communication				x						
47	Quality of power supply				x						
48	Environmental sanitation				x						

Source: World Bank 2005 [37].

References

1. The World Bank. *Aftershocks: Remodeling the Past for a Resilient Future*; Global Facility for Disaster Reduction and Recovery, The World Bank: Washington, DC, USA, 2018; p. 68.
2. Sarker, M.N.I.; Peng, Y.; Yiran, C.; Shouse, R.C. Disaster resilience through big data: Way to environmental sustainability. *Int. J. Disaster Risk Reduct.* **2020**, *51*, 101769. [CrossRef]
3. Tabari, H. Climate change impact on flood and extreme precipitation increases with water availability. *Sci. Rep.* **2020**, *10*, 13768. [CrossRef]
4. The World Bank. *Disaster Risk Management in South Asia: A Regional Review*; The World Bank: Washington, DC, USA, 2012; pp. 1–166. Available online: https://openknowledge.worldbank.org/handle/10986/13218 (accessed on 15 July 2021).
5. UN Office for Disaster Risk Reduction (UNDRR); Centre for Research on the Epidemiology of Disasters (CRED). *The Human Cost of Disasters: An Overview of the Last 20 Years 2000–2019*; UNDRR: Geneva, Switzerland; CRED: Brussels, Belgium, 2020; pp. 1–30.
6. Alexander, D. Cascading Disasters: Multiple Risk Reduction and Resilience. In *Handbook of Disaster Risk Reduction for Resilience: New Frameworks for Building Resilience to Disasters*; Eslamian, S., Eslamian, F., Eds.; Springer: Cham, Switzerland, 2021; pp. 187–201.
7. Zuccaro, G.; Leone, M.F.; Martucci, C. Future research and innovation priorities in the field of natural hazards, disaster risk reduction, disaster risk management and climate change adaptation: A shared vision from the ESPREssO project. *Int. J. Disaster Risk Reduct.* **2020**, *51*, 101783. [CrossRef]
8. Lwanga-Ntale, C.; Owino, B.O. Understanding vulnerability and resilience in Somalia. *Jàmbá* **2020**, *12*, 856. [CrossRef]
9. Chowdhury, R.I. Humanitarian Response for Improving Quality of Life of Persons with Disabilities: A study on Rohingya Camps of Cox's Bazar, Bangladesh. *J. Hum. Rights Peace Stud.* **2020**, *6*, 60–88. Available online: https://so03.tci-thaijo.org/index.php/HRPS/article/view/241771 (accessed on 22 July 2021).
10. Breiling, M. Global rural value chains and the role of natural disasters in their transformation. *J. Soc. Econ. Dev.* **2021**, *23*, 540–567. [CrossRef]
11. United Nations International Strategy for Disaster Reduction (UNISDR). *2009 Global Assessment Report on Disaster Risk Reduction: Risk and Poverty in a Changing Climate-Invest Today for a Safer Tomorrow*; UNISDR: Geneva, Switzerland, 2009.
12. United Nations International Strategy for Disaster Reduction (UNISDR). *Global Assessment Report on Disaster Risk Reduction: Revealing Risk, Redefining Development*; UNISDR: Geneva, Switzerland, 2011.
13. United Nations International Strategy for Disaster Reduction (UNISDR). *Global Assessment Report on Disaster Risk Reduction: From Shared Risk to Shared Value: The Business Case for Disaster Risk Reduction*; UNISDR: Geneva, Switzerland, 2013.
14. United Nations Office for Disaster Risk Reduction (UNISDR). Making Development Sustainable: The Future of Disaster Risk Management. In *Making Development Sustainable: The Future of Disaster Risk Management. Global Assessment Report on Disaster Risk Reduction*; UNISDR: Geneva, Switzerland, 2015.
15. United Nations Office for Disaster Risk Reduction (UNISDR). *The GAR Atlas: Unveiling the Global Disaster Risk*; UNISDR: Geneva, Switzerland, 2017.
16. Amarnath, G.; Alahacoon, N.; Smakhtin, V.; Aggarwal, P. *IWMI Research Report-170: Mapping Multiple Climate-Related Hazards in South Asia*; International Water Management Institute (IWMI): Colombo, Sri Lanka, 2017; p. 41.
17. Kumar, K.K.; Karunagoda, K.; Haque, E.; Venkatachelam, L.; Bahal, G.N. Addressing Long-term Challenges to Food Security and Rural Livelihoods in South Asia. *Gates Open Res.* **2019**, *3*, 721.
18. Moşteanu, N.R.; Faccia, A.; Cavaliere, L.P.L. Disaster Management, Digitalization and Financial Resources: Key factors to keep the organization ongoing. In Proceedings of the 2020 4th International Conference on Cloud and Big Data Computing, New York, NY, USA, 26 August 2020; pp. 118–122.
19. Kumar, A.; Pandey, A.C.; Khan, M.L. Urban Risk and Resilience to Climate Change and Natural Hazards: A Perspective from Million-Plus Cities on the Indian Subcontinent. In *Techniques for Disaster Risk Management and Mitigation*; Srivastava, P.K., Singh, S.S., Mohanty, U.C., Murty, T., Eds.; John Wiley & Sons, Inc.: Hoboken, NJ, USA, 2020; pp. 33–46.
20. Govindan, R.; Al-Ansari, T. Computational decision framework for enhancing resilience of the energy, water and food nexus in risky environments. *Renew. Sustain. Energy Rev.* **2019**, *112*, 653–668. [CrossRef]
21. Amarnath, G.; Matheswaran, K.; Pandey, P.; Alahacoon, N.; Yoshimoto, S. Flood mapping tools for disaster preparedness and emergency response using satellite data and hydrodynamic models: A case study of Bagmathi Basin, India. *Proc. Natl. Acad. Sci. India Sect. A Phys. Sci.* **2017**, *87*, 941–950. [CrossRef]
22. Amarasinghe, U.A.; Amarnath, G.; Alahacoon, N. Vulnerable hotspots to water and agricultural risks in Sri Lanka. *NeelaHaritha Clim. Chang. Mag. Sri Lanka* **2020**, *3*, 1–11, ISSN 2536-8591.
23. Alahacoon, N.; Matheswaran, K.; Pani, P.; Amarnath, G. A Decadal Historical Satellite Data and Rainfall Trend Analysis (2001–2016) for Flood Hazard Mapping in Sri Lanka. *Remote Sens.* **2018**, *10*, 448. [CrossRef]
24. Amarnath, G.; Umer, Y.M.; Alahacoon, N.; Inada, Y. Modelling the flood-risk extent using LISFLOOD-FP in a complex watershed: Case study of Mundeni Aru River Basin, Sri Lanka. *Proc. Int. Ass. Hydrol. Sci.* **2015**, *370*, 131–138. [CrossRef]
25. Urama, K.C.; Ozor, N. Impacts of climate change on water resources in Africa: The role of adaptation. *Afr. Tech. Pol. Stud. Netw.* **2010**, *29*, 1–29, Corpus ID: 130792900.
26. Gill, J.C.; Malamud, B.D. Reviewing and visualizing the interactions of natural hazards. *Rev. Geophys.* **2014**, *52*, 680–722. [CrossRef]

27. Van Westen, C.J.; Kappes, M.S.; Luna, B.Q.; Frigerio, S.; Glade, T.; Malet, J.P. Medium-scale multi-hazard risk assessment of gravitational processes. In *Mountain Risks: From Prediction to Management and Governance*; Asch, T.V., Corominas, J., Greiving, S., Malet, J.P., Sterlacchini, S., Eds.; Springer: New York, NY, USA, 2014; pp. 1–23.
28. Van Westen, C.J.; Alkema, D.; Damen, M.C.J.; Kerle, N.; Kingma, N.C. Multi-hazard risk assessment. In *Distance Education Course*; United Nations University, ITC School on Disaster Geoinformation Management (UNU-ITC DGIM): Enschede, The Netherlands, 2011.
29. Mix, K.; Groeger, A.W.; Lopes, V.L. Impacts of dam construction on streamflows during drought periods in the Upper Colorado River Basin, Texas. *Lakes Reserv. Res. Manag.* **2016**, *21*, 329–337. [CrossRef]
30. Amarasinghe, U.A.; Sharma, B.R. *Water Productivity and Poverty in the Transboundary River Basin of India and Bangladesh: A Situation Analysis. Project Report Submitted to IUCN under the Project "Water Productivity, Poverty and Food Security*; International Water Management Institute (IWMI): New Delhi, India, 2011; p. 24.
31. Sharma, B.; Amarasinghe, U.A.; Cai, X.; de Condappa, D.; Shah, T.; Mukherji, A.; Bharati, L.; Ambili, G.K.; Qureshi, A.S.; Pant, D.; et al. The Indus and the Ganges: River basins under extreme pressure. In *Water, Food, and Poverty in River Basins: Defining the Limits*; Fisher, M., Cook, S., Eds.; Routledge: London, UK, 2012; pp. 30–58.
32. Ntajal, J.; Lamptey, B.L.; Mahamadou, I.B.; Nyarko, B.K. Flood disaster risk mapping in the lower Mono river basin in Togo, West Africa. *Int. J. Disaster Risk Reduc.* **2017**, *23*, 93–103. [CrossRef]
33. Parker, L.; Bourgoin, C.; Martinez-Valle, A.; Läderach, P. Vulnerability of the agricultural sector to climate change: The development of a pan-tropical Climate Risk Vulnerability Assessment to inform sub-national decision making. *PLoS ONE* **2019**, *14*, e0213641. [CrossRef]
34. Birkmann, J.; Welle, T. Assessing the risk of loss and damage: Exposure, vulnerability and risk to climate-related hazards for different country classifications. *Int. J. Glob. Warm.* **2015**, *8*, 191–212. [CrossRef]
35. Seidler, R.; Dietrich, K.; Schweizer, S.; Bawa, K.S.; Chopde, S.; Zaman, F.; Khaling, S. Progress on integrating climate change adaptation and disaster risk reduction for sustainable development pathways in South Asia: Evidence from six research projects. *Int. J. Disaster Risk Reduc.* **2018**, *31*, 92–101. [CrossRef]
36. Amarasinghe, U.; Amarnath, G.; Alahacoon, N.; Ghosh, S. How Do Floods and Drought Impact Economic Growth and Human Development at the Sub-National Level in India? *Climate* **2020**, *8*, 123. [CrossRef]
37. The World Bank. *Natural Disaster Hotspots: A Global Risk Analysis*; Disaster Management Series No. 5; The World Bank, Hazard Management Unit: Washington, DC, USA, 2005.
38. The World Bank. *Vulnerability, Risk Reduction and Adaptation to Climate Change-Philippines*; The World Bank Group, Global Facility for Disaster Risk Reduction (WB-GFDRR): Washington, DC, USA, 2011.
39. United Nations Environment Programme (UNEP); The United Nations Office for Disaster Risk Reduction (UNISDR). *Multiple Risk-Mortality Risk Index*; The United Nations Office for Disaster Risk Reduction: Geneva, Switzerland, 2013.
40. United Nations Children's Fund (UNICEF). *Child-Centered Risk Assessment: Regional Synthesis of UNICEF Assessments in Asia*; UNICEF Regional Office for South Asia (ROSA): Kathmandu, Nepal, 2014.
41. Economist Intelligence Unit (EIU). *The South Asia Women's Resilience Index: Examining the Role of Women in Preparing for and Recovering from Disasters*; Economist Intelligence Unit: London, UK, 2014.
42. De Groeve, T.; Poljansek, K.; Vernaccini, L. *Index for Risk Management-INFORM: Concept and Methodology-Version 2015*; Joint Research Centre, Institute for the Protection and the Security of the Citizen, Publications Office of the European Union: Luxembourg, 2015.
43. Institute of Spatial and Regional Planning (IREUS). The World Risk Index. University of Stuttgart. 2015. Available online: https://www.ireus.uni-stuttgart.de/en/International/WorldRiskIndex/ (accessed on 20 June 2021).
44. Pesaresi, M.; Ehrlich, D.; Kemper, T.; Siragusa, A.; Florczyk, A.J.; Freire, S.; Corban, C. *Atlas of the Human Planet 2017: Global Exposure to Natural Hazards*; EUR 28556 EN; Joint Research Centre, Publications Office of the European Union: Luxembourg, 2017.
45. Lei, Y.; Wang, J.A.; Yue, Y.; Zhou, H.; Yin, W. Rethinking the relationships of vulnerability, resilience, and adaptation from a disaster risk perspective. *Nat. Hazards* **2014**, *70*, 609–627. [CrossRef]
46. Ward, P.J.; Blauhut, V.; Bloemendaal, N.; Daniell, J.E.; Ruiter, M.C.; Duncan, M.J.; Emberson, R.; Jenkins, S.F.; Kirschbaum, D.; Kunz, M.; et al. Natural hazard risk assessments at the global scale. *Nat. Hazards Earth Syst. Sci.* **2020**, *20*, 1069–1096. [CrossRef]
47. Mehryar, S.; Surminski, S. National laws for enhancing flood resilience in the context of climate change: Potential and shortcomings. *Clim. Pol.* **2020**, *21*, 133–151. [CrossRef]
48. Roser, M. Human Development Index (HDI). Our World in Data. 2017. Available online: https://ourworldindata.org/human-development-index (accessed on 11 May 2021).
49. Mirza, M.M. Climate change, flooding in South Asia and implications. *Reg. Environ. Change* **2011**, *11*, 95–107. [CrossRef]
50. De Groeve, T.; Vernaccini, L.; Poljansek, K. *Index for Risk Management-INFORM: Concept and Methodology-Version 2016*; Joint Research Centre, Institute for the Protection and the Security of the Citizen, Publications Office of the European Union: Luxembourg, 2016.
51. Kummu, M.; Taka, M.; Guillaume, J.H. Gridded global datasets for Gross Domestic Product and Human Development Index over 1990–2015. *Sci. Data* **2018**, *5*, 1–15. [CrossRef] [PubMed]
52. Bhatt, M.R.; Durrani, K.K.; Wisner, B.; Bhatti, A.; Taher, M.; Fernando, K. *Are We Building Back Better? Lessons from South Asia*; Duryog Nivaran Secretariat: Colombo, Sri Lanka, 2016.

53. *ADB Disaster Risk Management and Country Partnership Strategies: A Practical Guide*; Asian Development Bank: Manila, Philippines, 2017.
54. *ADB Disaster Risk Assessment for Project Preparation: A Practical Guide*; Asian Development Bank: Manila, Philippines, 2017.
55. *ADB Natural Hazard Data: A Practical Guide*; Asian Development Bank: Manila, Philippines, 2017.
56. Minges, M. *Disruptive Technologies and Their Use in Disaster Risk Reduction and Management*; International Telecommunication Union (ITU): Geneva, Switzerland, 2019.
57. United Nations International Strategy for Disaster Reduction (UNISDR). *National Disaster Risk Assessment–Governance System, Methodologies, and Use of Results*; The United Nations Office for Disaster Risk Reduction: Geneva, Switzerland, 2017.
58. Amarnath, G.; Malik, R.P.S.; Taron, A. *Scaling Up Index-Based Flood Insurance (IBFI) for Agricultural Resilience and Flood-Proofing Livelihoods in Developing Countries*; International Water Management Institute (IWMI): Colombo, Sri Lanka, 2021.
59. Nyagadza, B.; Nyauswa, T. Parametric insurance applicability in Zimbabwe: A disaster risk management perspective from selected practicing companies. *Insur. Mark. Co.* **2019**, *10*, 36–48. [CrossRef]

sustainability

MDPI

Article

The Influence of Environment Factors on Chronic Non-Communicable Diseases in a Heavy Industry City—A Case of Xigu District of Lanzhou City

Haili Zhao, Yuhan Du *, Jialiang Li, Minghui Wu and Fang Zhang

College of Geography and Environmental Science, Northwest Normal University, Lanzhou 730070, China; zhaohl@nwnu.edu.cn (H.Z.); 18851253591@163.com (J.L.); wmh17865575597@163.com (M.W.); zf20211101@163.com (F.Z.)

* Correspondence: dyh2021nwnu@163.com

Abstract: Taking Xigu District of Lanzhou City as an example, this paper systematically analyzes the spatio-temporal distribution characteristics of patients with chronic non-communicable diseases (NCD) and compares the differences between heating period and non-heating period. Furthermore, the impact paths of natural environmental factors and built-up environmental factors on NCD are probed with the help of the geographic detector. The results are as follows: In time, the incidence of NCD in Xigu district fluctuated from 2012 to 2019. In space, there was an overall declining trend in high incidence rate from the central area to the surrounding areas, among which Xigucheng street was the high-risk area. The incidence of NCD in heating period was higher than that of in non-heating period, and the number of H-H cluster areas was witnessed an obviously increasing growth in Sijiqing Street. There are significant differences in the explanatory power of different factors (if any) for NCD. The explanatory power of each index in Xigu District is as follows: Facility > SO_2 > NO_2 > PM2.5 > food > Beverage Service > Green Facilities > Traffic Regulations > medical facilities. The interaction between plant facilities and SO_2 has the strongest effect on NCD. Except for the negative correlation between greening and medical facilities and the incidence of NCD, all the influencing factors were positively correlated with NCD.

Keywords: noninfectious chronic disease; heavy industry city; factors of environment; geographic detector; Xigu district

Citation: Zhao, H.; Du, Y.; Li, J.; Wu, M.; Zhang, F. The Influence of Environment Factors on Chronic Non-Communicable Diseases in a Heavy Industry City—A Case of Xigu District of Lanzhou City. *Sustainability* **2021**, *13*, 12636. https://doi.org/10.3390/su132212636

Academic Editors: Baojie He, Ayyoob Sharifi, Chi Feng and Jun Yang

Received: 9 October 2021
Accepted: 10 November 2021
Published: 16 November 2021

1. Introduction

"Chronic disease" is short for noninfectious chronic disease (NCD) which refers to sort of complex non-communicable disease caused by genetic and environmental factors as well as by lifestyle [1]. Since the WHO (World Health Organization) released the report of "Preventing Chronic Diseases: A Vital Investment" in 2006, chronic diseases have arisen more and more regard of countries all over the world [2]. Statistics show that 40 million people die of chronic diseases each year since the year of 2015. In China, there currently exist more than 200 million patients with hypertension and 90 million ones with diabetics. The fatality resulted from chronic ailments account for 75% of the overall death rate and has become one major bane for the loss of population [3,4]. In view of the detrimental impacts of chronic diseases to our people's health, *Healthy China 2030* Planproposed the goal: compared with 2015, China's chronic disease mortality rate to reduce 30% [5]. With people putting more focus on health issue, many fields ramp up investments on related research and what factors are running behind chronic diseases also has become a hot topic for scholars.

Scholars at home and abroad have long started to study the factors influencing NCD from a medical point of view and have verified the relationship between NCD and patients' dietary structure, age, marriage, culture, smoking and drinking habit, overweight and obesity, sitting time and other personal behavior habits and individually social characteristics [6–11]. With the development of medical geography, the discipline has turned to study the distribution of diseases and health status among population and the influencing factors. Some scholars put an eye on the impact of the environment on NCD and have discovered that a link existed between the growth of NCD and patients' social factors, such as, occupation, family background, income in the economic environment; and green land area in the natural environment and air quality [12–17]. Domestic and foreign scholars make their study with the help of many methods such as the kernel density analysis [18], Moran index spatial autocorrelation [19], logistic regression model, ordinary least squares (OLS), and ordinary linear regression model, [20–24] etc. Existing research can be generally categorized as the one between NCD and environment (natural environment, built environment, social environment) [25–29]. In heavy industrial areas, compared to the social environment, the natural environment and built environment play a particularly important role in the health of urban residents, and they can easily induce diseases such as high blood pressure, heart trouble, and chronic obstructive pneumonia [28,29]. At the present stage, the influence path of natural and built environments on the health of urban residents urgently needs to be further revealed.

As far as the impact of the environment on NCD is concerned, scholars at home and abroad have carried out many empirical studies, but in the existing research, when exploring the impact mechanism of air pollution on NCD, they often use months and years as time scales to study its seasonal changes while in heavy industrial areas or other special regions, other time scales have not been considered yet [30–34]. Meanwhile, most studies only consider the impact of the natural environment or the built environment on the NCD unilaterally, and there are few studies that combine the two together. Concurrently, there also exist some problems, such as, the data sources that fail to be updated in time, the unreasonable questionnaire design and some individual data with less explanatory power. Based on this, taking account of the incompleteness of the existing research, this paper selects Xigu District, Lanzhou City, a heavy industry region, as the research area and collects the NCD outpatient data from Xigu District Hospital as the research object to make its spatio-temporal pattern clear. Furthermore, by comparing the data in the heating period with the non-heating period, and by the technology of geo-detector tech, natural environment and built environment factors that affect the NCD are analyzed. Compared with other studies, this paper has the advantage of data acquisition. Meanwhile, the selected heavy industry area can discuss the different research results of the special area and enrich the special case of the existing research, research into the built environment and natural environmental factors of chronic diseases can provide references for the prevention and control of NCD and the improvement of the health status of local residents.

2. Materials and Methods

2.1. Overview of the Study Area

Located at 36 degrees 05 min 18 s north latitude and at longitude of 103 degrees 37 min 40.70 s east, Xigu District of Lanzhou City covers a total area of 385 km^2 with a population of 369,000 (2019), and there are 5 towns, 1 township, 40 administrative villages and 8 subdistricts and 70 communities under its jurisdiction. As a core manufacturing area in Lanzhou City and the largest petrochemical base in west China, it has formed an industrial system propped up with three sectors: petrochemicals, energy, equipment manufacturing and new materials. Most large state-owned enterprises in Xigu were founded during the "First Five-Year Plan" and "Three-line" construction periods which implied a special economic and national defense background; as a result, a typical job-residential integration pattern was formed. Due to an adjoining location between the industrial zone and dwellings (Figure 1). The paper selects the central downtown where distributes dense heavy chemical industry in Xigu District as the study area which includes: Lintao Street, Xigucheng Street, Sijiqing Street, Fulilu Street, Xianfenglu Street, Chenping Street, and Xiliugou Street.

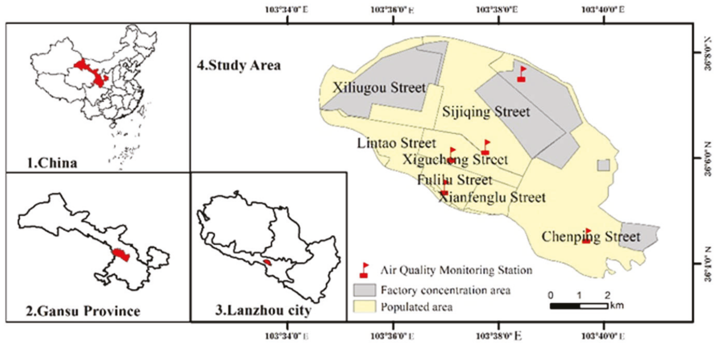


Figure 1. Overview of the study area.

2.2. Data Sources

The data of NCD comes from in-patients of a hospital in Xigu District, Lanzhou City from 2012 to 2019 and there are 15,819 in total covering: hypertension (1388 cases), diabetes (3007 cases), chronic obstructive pneumonia (7556 cases), heart disease (683 cases), and others (3185 cases). The above data is only used for this study and patients' privacy has been handled properly. POI data (2012–2019), obtained after crawling and cleaning through Baidu Point of Interest websites, is filtered based on the actual situation in Xigu District, and five types of built environment are picked out: greening, medical treatment, factory, transportation, and catering after unwanted data are removed (Table 1). Air quality data (2012–2019) is sourced from China National Environmental Monitoring Center (http:/www.cnemc.cn/ accessed date: 10 December 2020). As the study area has the characteristics of a heavy industry area, three indicators are used for description: PM2.5 is selected to represent the concentration of fine particles, and SO_2 and NO_2 are used to reflect the pollution level of industrial emissions.

Table 1. Statistics of natural environment and built environment factors in Xigu district of Lanzhou City.

Factors	Top Order	Secondary Order	Expected Direction	Amount
Air pollution	SO_2		Positive	2920
	PM2.5		Positive	2920
	NO_2		Positive	2920
Greening rate	Greening facilities	Road greening, greenbelts in neighborhood, parks, etc.	Negative	316
Medical resources	Medical facilities	Hospitals, clinics, health centers, etc.	Negative	1533
Industrialization level	Factory facilities	Chemical plants, oil refineries, mechanical processing plants, cotton mills, power plants, etc.	Positive	840
Traffic network	Traffic facilities	Bus stations, train stations, toll stations, parking lots, etc.	Positive	3542
Dietary habits	Catering service	Chinese restaurants, foreign-style restaurants, casual dining restaurants, coffee houses, etc.	Positive	3725

2.3. Research Methods

2.3.1. Moran Index

Moran Index is applied in this paper to evaluate the spatial autocorrelation of NCD in Xigu District. Its ultimate principle runs as follows:

$$I = \frac{n \sum_{i=1}^{n} \sum_{j=1}^{n} w_{i,j} z_i z_j}{s_0 \sum_{i=1}^{n} z_i^2} \quad (1)$$

where I is Moran's I index, and the value of I goes between -1–1. A positive value is a positive correlation, and vice versa. The positive correlation is positive, and vice versa. The higher the value, the stronger the spatial autocorrelation of NCD incidence. Z_i refers to the deviation of the attribute of the element i from the average value $(X_i - \overline{X})$, and $W_{i,j}$ means the spatial weight between the element i and j. n is equal to the total number of elements, and S_0 is the aggregation of all the spatial weights.

$$s_0 = \sum_{i=1}^{n} \sum_{j=1}^{n} w_{i,j} \quad (2)$$

$$E(I) = \frac{-1}{n+1} \quad (3)$$

And when Moran's $I < E(I)$, it means negative spatial correlation while Moran's $I > E(I)$, it means positive spatial correlation, and when Moran's $I = E(I)$, it means zero spatial correlation. Firstly, we created a fishnet of 30 × 30 in Xigu District, then counted the number of NCD in each fishnet, and analyzed the spatial autocorrelation of NCD in Xigu District with a single fishnet as the smallest unit. This method not only meets the basic data requirements of Moran index analysis but conforms to the first law of geography as well. It can take into account the continuity of space, and what's more, can be in line with the spatial distribution characteristics of geographical things.

2.3.2. Geographic Detector

The paper adopts the interaction detection in the geographic detector, which is commonly used to detect the spatial distribution of Y and to find how much the detection factor X explains the spatial distribution of the attribute Y. By comparing the values of $X1$ and $X2$ with the interacted value, whether the two independent variables work together on the dependent variable Y can be judged.

$$q = 1 - \frac{\sum_{h=1}^{n} N_h \sigma_h^2}{N\sigma^2} = 1 - \frac{SSW}{SST} \quad (4)$$

$$SSW = \sum_{h=1}^{L} N_h \sigma_h^2, SST = N\sigma^2 \quad (5)$$

where the value of q measures the spatial distribution, the value range of q goes between [0, 1]; As h = 1, 2..., L is the stratification of variable Y or the factor X; In the formula, N_h and N refer to the number of h and that of units in the whole area, respectively; σ_h^2 and σ^2 refer to the variance of h and that of Y in the whole area, respectively; SSW and SST are the sums of the intra-stratal variance and the total variance of the whole area separately.

It can be seen from Table 2 that the eight probe factors selected in this paper are composed of natural environment and built environment factors. The value of q calculated by the geographic detector is used to evaluate the influence of this factor on the NCD. That is to say, the larger the value is, the higher the influence of the factor has, and vice versa.

Table 2. Statistics of probe factors.

No.	Probe Factors	Indexes
X1	SO_2	Industrial emission concentration
X2	PM2.5	Concentration of fine particles
X3	NO_2	Industrial emission concentration
X4	Catering facilities	Amount
X5	Factory facilities	Amount
X6	Traffic facilities	Amount
X7	Greening facilities	Amount
X8	Medical facilities	Amount

3. Results

3.1. Significant Change Characters in the Time Series of NCD in Xigu District

It can be seen from Figure 2 that the incidence rates of NCD from 2012 to 2019 were 13.03%, 12.37%, 9.64%, 10.95%, 11.85%, 13.70%, 14.85%, and 13.67%. In terms of years, the rate of NCD presented a trend with fluctuation within the given time from 2012 to 2019 and the average incidence rate reached 12.51%. In view of the actual situation, Lanzhou provides heating on a regular basis every year from 1 November to 31 March of the following year. By comparing the average rates of NCD between the heating period from 2012–2019 and the non-heating period, it is found that the number of patients during the heating period (spring and winter season) was relatively high, accounting for 50.01% of the total patients; while non-heating period (summer and autumn season) witnessed a lower rate making up 49.99% in all the patients. The average incidence of NCD in each month during the heating period increased by 41.86% compared to that of in the non-heating period. In terms of months, the incidence of NCD fluctuated greatly in a year. December was the month with the highest average value of NCD having an incidence rate of 1.30% and accounting for 10.37% of the annual average; while June was the lowest one with an incidence rate of 0.83%, accounting for 6.65% of the annual average.

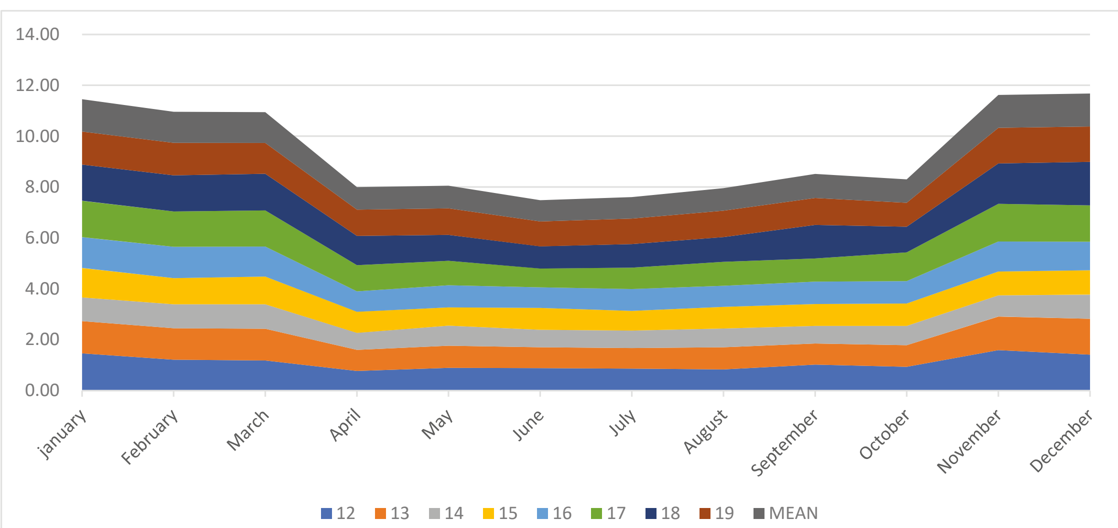


Figure 2. NCD incidence statistics from 2012 to 2019 (%).

Figure 3 depicts the time series characters between NCD and the monthly average concentrations of PM2.5, of SO_2 and of NO_2 from 2012 to 2019. The specific changes are shown as follows: the peak number of NCD patients and the peak concentration values of the three variables were all fastened on the heating period in a year (spring and winter season) rather than the non-heating period (summer and autumn season, and October) in which each variable had a decline to a varying degree. The number of NCD patients in the non-heating period was witnessed a larger fall than that of in the heating period, accompanying an overall large fluctuation, with a variance of 1356.59. In the meantime, the concentration of the other three variables in the non-heating period and the heating period experienced a small decrease with a slight overall fluctuation. The variances of the PM2.5 concentration, SO_2 concentration and NO_2 concentration were 249.69, 111.59 and 128.01, respectively. When the concentrations of PM2.5, SO_2 and NO_2 rose, the number of patients with NCD went up accordingly, and vice versa indicating that there might be a positive correlation between NCD and these three variables.

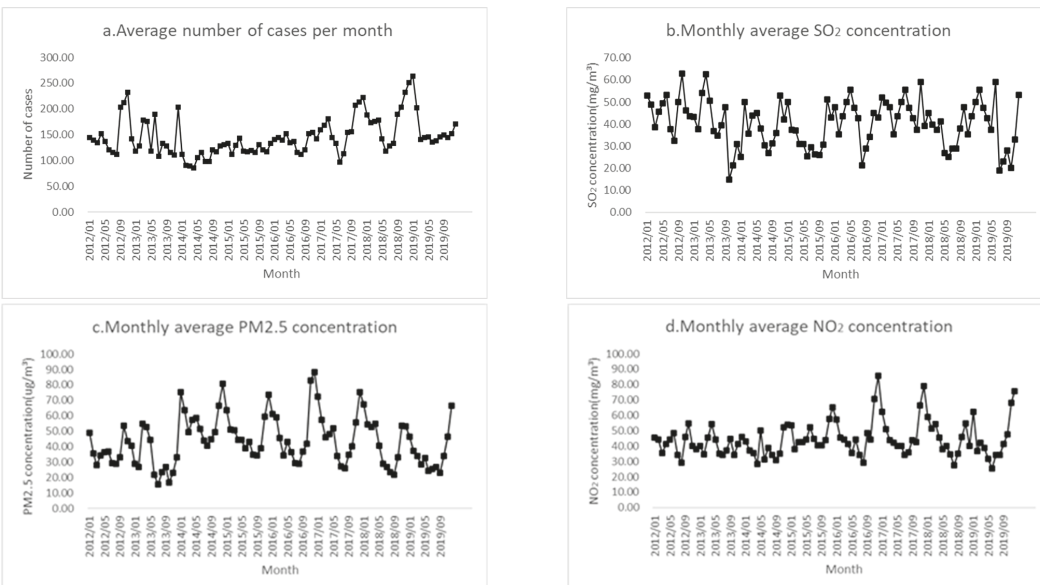


Figure 3. Time series analysis of natural environmental factors and NCD.

3.2. Spatial Distribution Characteristics of NCD in Xigu District

The spatial distribution of NCD over time is illustrated in Figure 4, The average values of NCD incidence from 2012 to 2019 revealed that NCD in Xigu District showed a decreasing trend from the high incidence in the central area to the surrounding areas, which was shown as follows: Xigucheng Street (22.71%) > Fulilu Street (18.46%) > Sijiqing Street (14.47%) > Xianfenglu Street (13.26%) > Lintao Street (12.05%) > Chenping Street (10.715%) > Xiliugou Street (8.34%).

Taken Figure 4 and Table 3 for reference, in terms of time, the incidence in Lintao street increased by 39.70% in 2012 and 2013 while the changes in other streets were relatively small. In 2014 and 2015, the incidence in Sijiqing Street decreased by 68.10%, while the incidence in Chenping Street and Fulilu Street showed an upward trend, increasing by 5.89% and 23.32%, respectively. In 2016 and 2017, the NCD high-incidence areas gradually shifted from the east of Xigu District to the north. The incidence of Sijiqing Street soared sharply (102.54%), while the incidence in Xianfenglu decreased by 28.57%, and the rest of the streets had a small drop. In 2018 and 2019, the incidence of Xiliugou Street increased by 116.03%, while the incidence of Sijiqing Street decreased by 17.93%, and the remaining streets changed little. In terms of all these streets, from 2012 to 2019, Xigucheng Street had always been a high-risk area with an average incidence rate of 22.71%, much higher than others. Xiliugou Street, however, was a low incidence area for NCD, with an average incidence of 8.34%.

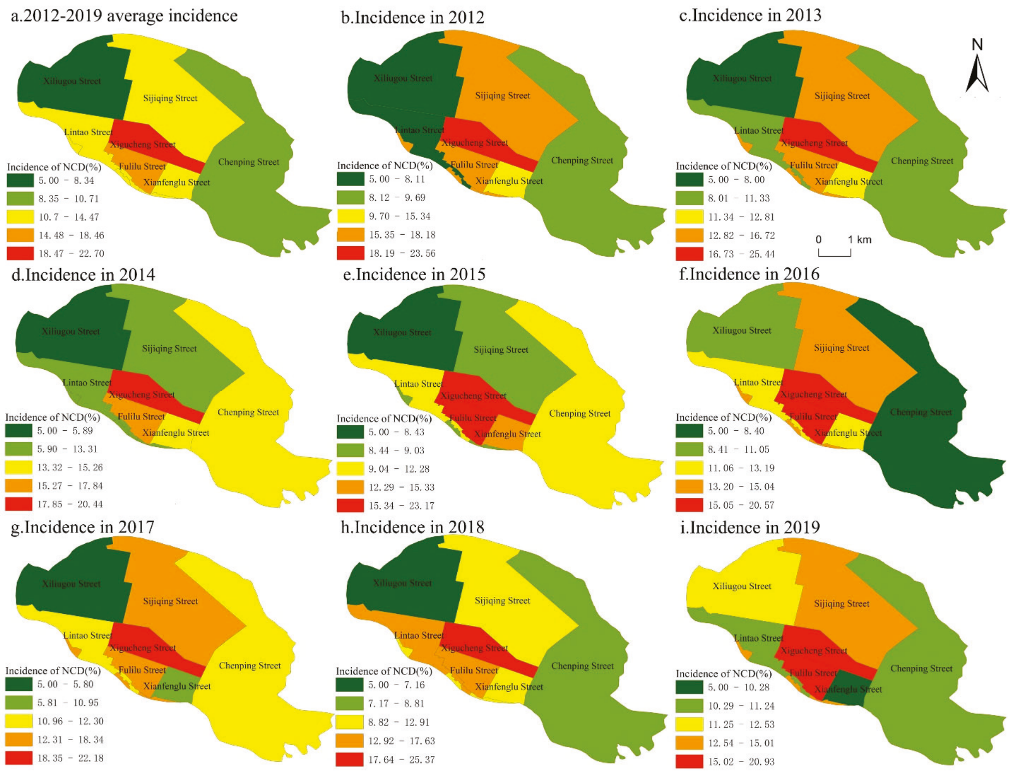


Figure 4. NCD incidence distribution in Xigu district, 2012–2019.

Table 3. Annual variation of NCD prevalence in streets of Xigu District, 2012–2019(%).

Year	2012	2013	2014	2015	2016	2017	2018	2019	Average Value
Xigucheng Street	0.85	2.73	−2.27	0.46	−2.14	−0.53	2.66	−1.78	22.71
Fulilu Street	−0.28	−1.74	−0.62	2.16	0.65	−0.12	−0.83	0.79	18.46
Xianfenglu Street	2.08	−0.45	2	2.07	−0.07	−2.31	−0.35	−2.98	13.26
Lintaojie Street	−3.94	−0.72	1.13	0.23	0.59	0.09	3.39	−0.81	12.05
Sijiqing Street	2.78	0.71	−1.16	−5.44	0.57	3.82	−1.79	0.54	14.47
Chenping Street	−1.02	−0.19	3.37	0.43	−2.31	1.59	−1.9	0.05	10.71
Xiliugou Street	−0.47	−0.34	−2.45	0.09	2.71	−2.54	−1.18	4.19	8.34

3.3. Obvious High Cluster of NCD during the Heating Period and the Non-Heating Period

Taking the incidence of NCD in Xigu District in 2019 as an example, the paper used the local Moran index to study the spatial heterogeneity of NCD in each month, as shown in Figure 4: during the heating period (spring and winter season), there were a large number of high-high cluster areas (Figure 5a–c,k,l), mainly concentrated in the Center of Xigu District. In the non-heating period (summer and autumn season), high-high cluster area was in the Center of Xigu District (Figure 5d–j). This finding shows that: the spatial distribution of NCD in the Center of Xigu District changed accordingly due to heating, and the number of NCD cases in the streets adjacent to the industrial zone increased significantly during the heating period while that of in the streets farther from the industrial zone did not vary greatly; The spatial distribution changes of NCD in these streets during the non-heating period were relatively small. However, The Center of Xigu District was always the area with high incidence of NCD before or after the heating period.

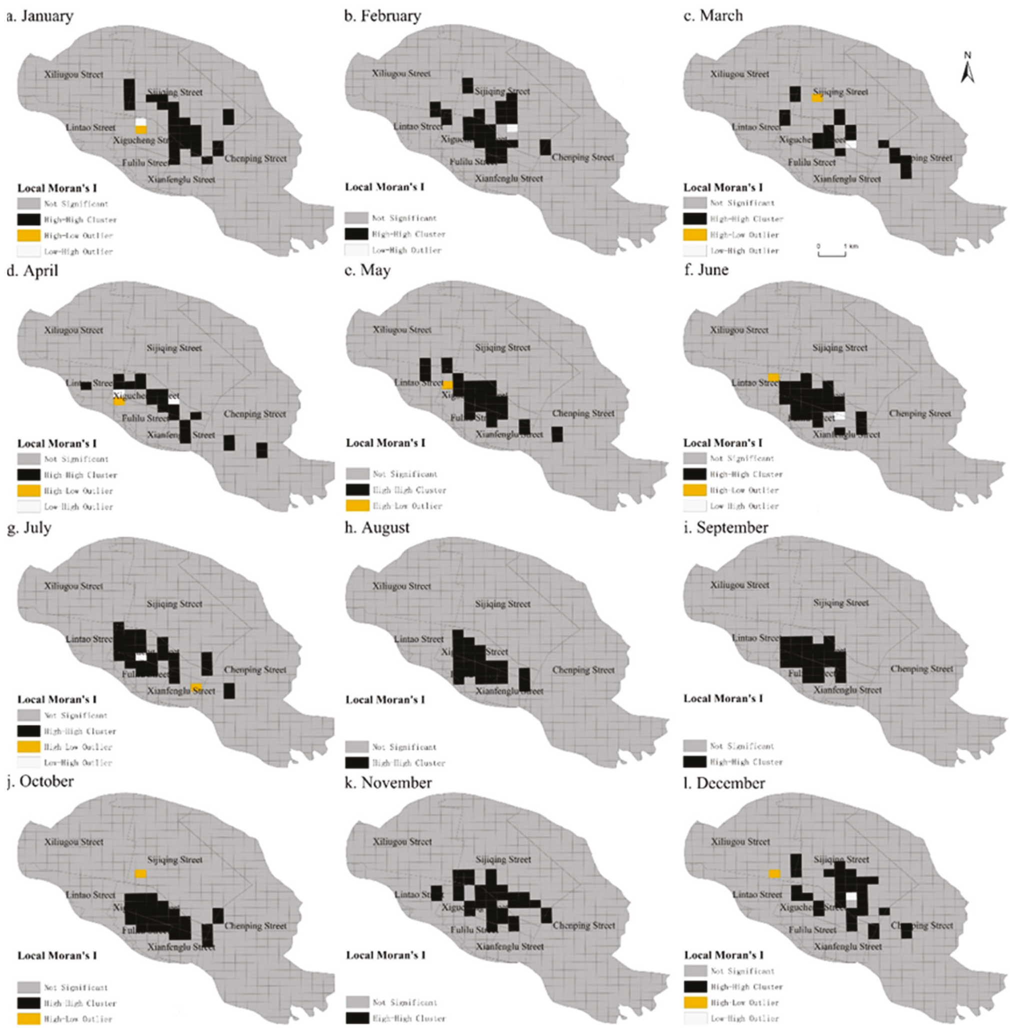


Figure 5. NCD mean local spatial autocorrelation for each month of 2019.

3.4. Natural Environment and Built Environment Factors Applied Significantly Different Acting Force on NCD

According to the results of the geo-detector (Table 4), the acting force of each factor on the NCD distribution went downwards all the way such as this: factory facilities (q = 0.7483) > SO_2 (q = 0.7230) > NO_2 (q = 0.6993) > PM2.5 (q = 0.6845) > catering services (q = 0.6620) > greening facilities (q = 0.6420) > traffic facilities (q = 0.5797) > medical facilities (q = 0.2744).

Table 4. Differentiation and factor detection results.

	SO_2	PM2.5	NO_2	Catering Service	Factory Facilities	Traffic Facilities	Greening Facilities	Medical Facilities
q	0.7230	0.6845	0.6993	0.6620	0.7483	0.5797	0.6420	0.2744
p	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000

In the natural environment, the concentration of PM2.5 and SO_2 had a heavy toll on the incidence of NCD, and the three factors all presented a positive correlation with the incidence of NCD. Air pollutants themselves, as the inducing factors of NCD, affected the incidence of NCD. Taking the characteristics of Xigu District into consideration, industrial production emitted a large amount of air pollutants, resulting in the air quality level in heavy industry areas being far worse than other areas, which in turn, further deepened the impact of natural environmental factors on the incidence of NCD.

In the built environment, the factory facilities had the strongest explanatory power of NCD. Xigu District, as a heavy industry base, hosts a large number of petrochemical companies whose industrial production brings negative sides to the environment, resulting in the number and distance of factory facilities greatly affect the incidence of NCD in Xigu District. In view of this, Xigu District should reasonably program the location of residential areas and control the distance between factory facilities and residential areas to alleviate the impact of factories on the incidence of NCD in the area. The explanatory power of catering services for NCD shows that: the growth of catering service facilities would affect the diet structure and eating habits of surrounding residents to a certain extent, and then would affect the incidence of hypertension, diabetes and other diseases; that is to say, the distribution of catering service facilities had a positive correlation with NCD in Xigu District. However, that as it may, it is an indispensable existence that catering services are. Only when residents adjust their own eating habits can the impact of catering services on NCD be fundamentally lessened. The explanatory power of transportation facilities for NCD indicated that the incidence of NCD in residential areas with dense traffic facilities was showing an upward trend. Greening facilities' explanation for NCD told us that the higher the greening rate in residential areas was, the lower the incidence of NCD had. In other words, the incidence of NCD can be effectively reduced by increasing the number of greening facilities around residential areas. As for the explanatory power of medical facilities on NCD, it showed that the number of medical facilities had a slight influence on the incidence of NCD. Chronic diseases are seen as non-communicable diseases. There is little effect in reducing the incidence of NCD by increasing the number of medical facilities, which again confirms the fact that prevention and control is the most effective way for the reduction of the incidence of NCD. From now on, we should publicize more about the prevention and control of chronic diseases, raise residents' awareness and improve the natural environment and built environment, which as a whole can achieve the goal of reducing the incidence of NCD.

It can be seen from Figures 6 and 7 that the interaction between factory facilities and SO_2 had the strongest explanatory power (q = 0.98862), which almost determined the distribution of NCD. The explanatory power of the interaction was greater than the explanatory power of single factor on NCD, for the type was classified as the two-factor enhanced one. The number of factories in the streets of Xigu District was directly proportional to the incidence of NCD. Factory facilities, as a static built environment factor, exerted an impact on the health of surrounding residents with the characteristics of long duration and small changes in the effecting degree, especially in Xigu District where such features were more obvious under the job-residential integration pattern. Combining the conclusions obtained in Figure 3, the impact of air pollutants (being viewed as a dynamically changing natural environmental factor) on the residents' health varied with the time sequence, which verified the hypothesis proposed in this paper that the natural environmental factors and built environmental factors acted on NCD together. Among them, air pollutants were seen as the direct path of influence, while factory facilities as the indirect path. That is to say, the emission of air pollutants from the factory facilities led to a decline in air quality, which affected the incidence of NCD in Xigu District. All types of factors interacting ones belonged to the two-factor enhanced types whose explanatory power was larger than the power by a single factor, indicating that the pathogenic process of NCD was a comprehensive process, determined by the interaction between the natural environment and the built environment factors.

	SO_2	PM2.5	NO_2	Catering services	Factory facilities	Traffic facilities	Greening facilities
PM2.5	0.79421						
NO_2	0.78213	0.71059					
Catering services	0.93995	0.93547	0.93988				
Factory facilities	0.98862	0.96941	0.96773	0.94358			
Traffic facilities	0.92908	0.91013	0.93997	0.95038	0.92745		
Greening facilities	0.9289	0.91949	0.90949	0.91953	0.95385	0.68222	
Medical facilities	0.61104	0.56633	0.5723	0.56173	0.59255	0.6888	0.59459

Figure 6. Interaction detector results.

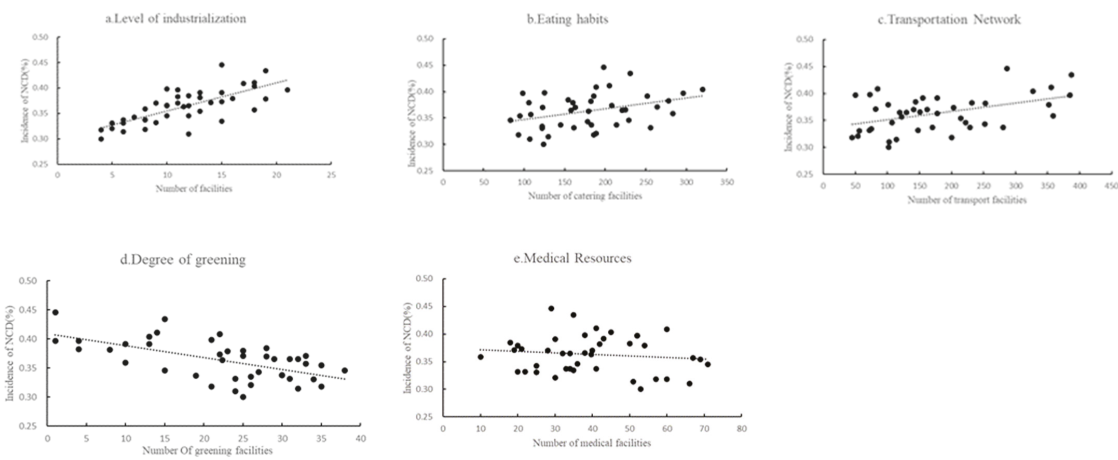


Figure 7. Correlation analysis between environmental factors and incidence of NCD.

4. Discussion and Outlook

4.1. Main Findings

Some scholars found time series changes between ambient air pollution and hypertension [35–37]. T The study found that the incidence of chronic non-communicable disease fluctuates over time and increases slowly. The conclusions of this study are similar to those of other cross-sectional studies or group studies. Most of the existing studies discuss the seasonal characteristics of the incidence of NCD, the research has found that the incidence in summer and autumn is higher than that in spring and winter [38–41]. But this paper, based on the characteristics of the study area, compares the incidence of NCD during the heating period and the non-heating period for the first time, and finds that the incidence of NCD during the heating period was greater than that in the non-heating period, As a control group before and after heating period, the study of the difference in the incidence of chronic Non-communicable disease is closer to the actual life of residents, which can be seen that there are variations in the incidence of NCD in different study areas.

Mainstream research has discussed the relationship between infrastructure, Transportation Planning, air pollutants and green space, and access to health care resources and the incidence of chronic diseases such as hypertension, heart disease and Obstructive lung disease [42–47]. These studies have shown that chronic diseases are affected by many factors and have shown that chronic diseases are affected by a single factor, but little has been carried out about the interaction of these two or more factors with NCD. This study examines the interaction of the natural and built environment with NCD, it is found that SO_2, PM2.5, NO_2, diet, traffic, greening and medical treatment in natural and built environment are the key factors affecting NCD in Xigu district, the incidence and spatial distribution of chronic non-communicable disease are almost entirely determined by factory facilities and air quality. The reason for this difference lies in the characteristics of heavy industry in the study area. The advantage is that it can well represent the heavy industry area, but the disadvantage lies in the lack of control group experiments, which cannot be well applied to other areas.

4.2. Strengths and Limitations

Selecting Xigu District of Lanzhou City as the research area, based on its own characteristics as a heavy industrial area, the paper takes fully consideration of the interaction between natural environment and built environment factors on NCD, but we've to say there are still a few weaknesses: (1). This paper collects 2012–2019 annual data in Xigu District on various types of chronic diseases. However, chronic diseases actually cover a variety of diseases whose characteristics and impact factors are not the same. In our research, all these diseases are generalized as chronic diseases to explore the relationship between NCD and the natural environment and built environment. Whether the results are convincing enough still needs further verification, and the POI data does not fully represent the built environment factors. In future studies, more comprehensive data will continue to be collected for a strong support. (2). The terrain of Xigu District is complex, and the distribution of residential areas and population activities are relatively clustered. This paper takes this area as an example to describe the temporal and spatial distribution of NCD in all heavy industrial areas and its influencing factors, which obviously lacks explanation for the distribution of NCD in other cities with different location characteristics. Since the research cannot be compared with other areas, it appears to be one-sided, leading to a narrow range of detection results. In the future, more comparisons with other research areas should be made to improve the accuracy of the results and the scope of application also can be expanded. (3). This paper only studies the impact of natural environment and built environment factors on chronic diseases and does not consider factors such as social environment and individual behavior and fails to take the active choices of individual behavior into consideration. In future, more impact factors should be supplemented into the research to improve the scientificity and accuracy of this paper.

4.3. Recommendations and Prospects

In summary, the spatio-temporal distribution of NCD presents obvious characteristics, and there are evident differences before and after the heating duration. The impact of various natural environment and built environment factors on NCD is varied. It is properly meaningful to start with improving the natural environment and built environment as a way of controlling and preventing NCD. Under the unique job-residential integration pattern of Xigu District, the service facilities around the residential areas should be reasonably configured, such as controlling the number of factory facilities around the residential areas, increasing the number of greening facilities, and considering the establishment of detecting points for air quality in industrial areas and residential areas. In this way, air pollutants will be detected in real time, and quantitative evaluation standards also will be established to reduce industrial emissions. Furthermore, for the sake of disease prevention and control, the publicity work on the prevention of NCD shall be strengthened, which will help reveal the main causes of disease (industrial facilities, air pollution), and develop a healthy lifestyle. In doing so, the incidence of NCD will be dropped and the health of residents will be ensured as well.

5. Conclusions

By collecting data on NCD patients in Xigu District, Lanzhou City from 2012 to 2019, this paper applies statistical methods and local Moran index into use to analyze the time sequence and spatial distribution of NCD. What's more, by comparing the space-time characteristics during the heating period and during the non-heating period with consideration of the actual situation, and by using the geographic detector to study the relationship between NCD and natural environment and built environment factors, the paper sums up following conclusions:

NCD in Xigu District presented obvious temporal and spatial characteristics. In terms of time, the incidence of NCD in Xigu District from 2012 to 2019 fluctuated over time. In terms of space, the NCD in Xigu District generally showed a downward trend from the high incidence in the central area to the surroundings. There was a clear contrast between the heating period and the non-heating period. In terms of time, the incidence of NCD was greatly affected by the heating period. In the heating period (spring and winter season), the incidence was higher than that of the non-heating period (summer and autumn season). In terms of space, there were quite a few H-H cluster areas during the heating period, mostly locating in Xigucheng Street and Sijiqing Street while H-H areas in the non-heating period were mainly concentrated in Xigucheng Street.

Natural environment and built environment factors had different paths of action on NCD. The explanatory power of the interaction between natural environment and built environment factors was stronger than that of any single one. All the interactions among impact factors fell into a two-factor enhanced relationship. The paths of the two factors on NCD went similar to this: Path 1, the natural environment and built environment directly affected the incidence of NCD. Path 2: The built environment treated the natural environment as an intermediary variable to indirectly affect NCD. Industrial production in factories caused an increase in the concentration of air pollutants, which not only affected air quality but triggered changes in the incidence of NCD.

Author Contributions: Conceptualization, H.Z. and Y.D.; methodology, J.L.; software, M.W.; validation, Y.D., F.Z. and M.W.; formal analysis, J.L.; investigation, H.Z.; resources, H.Z.; data curation, Y.D.; writing—original draft preparation, Y.D.; writing—review and editing, H.Z. and Y.D.; visualization, Y.D.; supervision, H.Z.; project administration, H.Z.; funding acquisition, Y.D. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by THE PROJECT OF NATIONAL SOCIAL SCIENCE FOUNDATION OF CHINA (NO. 41971268).

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Not applicable.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Yun, J.; Xiangyu, T. The current situation and countermeasures of the health education of self-management for diabetes patients. *J. Nurs. Adm.* **2005**, *2*, 29–30.
2. Wei, M. The report of preventing chronic diseases released by WHO. *Chin. Med. J.* **2005**, *45*, 72.
3. Evans, J.; Allan, N.; Cantle, N. A New Insight into the World Economic Forum Global Risks. *Econ. Pap. A J. Appl. Econ. Policy* **2017**, *36*, 185–197. [CrossRef]
4. Cherian, V.; Oyere, O.; Walter, J. Organizational Update: World Health Organization. *Stroke* **2017**, *48*, 341–342.
5. Jian, L.; Miaomiao, A.; Ying, X.; Jin, L.; Shuang, Y. The association between dietary fiber intake and the risk of chronic non-communicable diseases. *Prog. Mod. Biomed.* **2018**, *18*, 4194–4197.
6. Cai, Q.; Dekker, H.L.; Vinke, P.C.; Corpeleijn, V.E.; Stephan, J.L.; Borst, B.; Navis, G.J. Diet quality and incident chronic kidney disease in the general population: The Lifelines Cohort Study. *Clin. Nutr.* **2021**, *40*, 5099–5105. [CrossRef]

7. Yufeng, G.; Ying, L.; Xiaojie, L.; Yousheng, Q. Investigation and analysis of the epidemiology and influencing factors of chronic diseases among adults in Huairou District. *J. Cardiovasc. Pulm. Dis.* **2020**, *39*, 885–889.
8. Lei, C.; Xiaofei, H.; Jiali, Y.; Lin, H. Investigation and analysis of influencing factors on chronic disease prevention of urban residents in Wenzhou. *Chin. Rural. Health Serv. Adm.* **2017**, *37*, 436–439.
9. Lari, A.; Sohouli, M.H.; Fatahi, S.; Cerqueira, H.S.; Santos, O.; Pourrajab, B.; Rezaei, M.; Saneie, S.; Rahideh, S.R. The effects of the Dietary Approaches to Stop Hypertension (DASH) diet on metabolic risk factors in patients with chronic disease: A systematic review and meta-analysis of randomized controlled trials. *Nutr. Metab. Cardiovasc. Dis.* **2021**, *31*, 2766–2778. [CrossRef]
10. Gylling, A.T.; Eriksen, C.S.; Garde, E.; Wimmelmann, C.L.; Reislev, N.L.; Bieler, T.; Ziegler, A.K.; Andersen, K.W.; Bauer, C.; Dideriksen, K.; et al. The influence of prolonged strength training upon muscle and fat in healthy and chronically diseased older adults. *Exp. Gerontol.* **2020**, *136*, 110939. [CrossRef]
11. Wei, S.; Wenling, L.; Xuejing, Y.; Wenhui, L. Investigation and analysis of chronic diseases and their influencing factors in Heping District, Tianjin. *Pract. Prev. Med.* **2016**, *23*, 726–727.
12. Mendis, S.; Davis, S.; Norrving, B. Organizational Update: The world health organization global status report on noncommunicable diseases 2014.one more landmark step in the combat against stroke and vascular disease. *Stroke* **2015**, *46*, 121–122. [CrossRef]
13. Astell-Burt, T.; Feng, X. Urban green space, tree canopy, and prevention of heart disease, hypertension, and diabetes: A longitudinal study. *Lancet Planet. Health* **2019**, *3*, 16. [CrossRef]
14. Jung, J.; Park, J.Y.; Kim, Y.C.; Lee, H.; Kim, E.; Kim, Y.S.; Lee, J.P.; Kim, H. Effects of air pollution on mortality of patients with chronic kidney disease: A large observational cohort study. *Sci. Total Environ.* **2021**, *786*, 147471. [CrossRef]
15. Liang, Z.; Wang, W.; Yang, C.; Wang, Y.Y.; Shen, J.S.; Li, P.F.; Ma, L.; Wei, F.; Chen, R.; Liang, C. Residential greenness and prevalence of chronic kidney disease: Findings from the China National Survey of Chronic Kidney Disease. *Sci. Total Environ.* **2021**, *806*, 150628. [CrossRef]
16. Yao, Y.; Xi, C.; Wu, C.; Han, Y.Q.; Xue, T.; Wang, J.X.; Qiu, X.H.; Que, C.L.; Zheng, M.; Zhu, T. Differences in transcriptome response to air pollution exposure between adult residents with and without chronic obstructive pulmonary disease in Beijing: A panel study. *J. Hazard. Mater.* **2021**, *416*, 125790. [CrossRef]
17. Yu, W.H.; Ai, Y.H.; Yang, M.; Liu, J.P. Detecting "Hot spots" of facility POIs based on kernel density estimation and spatial autocorrelation technique. *Geomat. Inf. Sci. Wuhan Univ.* **2016**, *41*, 221–227.
18. Rouli, D.; Xin, L. Multivariate logistic analysis of risk factors for the onset and prognosis of patients with different types of coronary heart disease in Jiangsu Province. *Pharm. Clin. Res.* **2020**, *28*, 353–358.
19. Shi, Y.N.; Shi, Y.; Fan, C.S. Associating factors of hypoglycemic drug adjustment during hospitalization among diabetic population: A logistic regression analysis based on 130 hospital-data of US. *Hainan Med. J.* **2020**, *31*, 2594–2597.
20. Juan, L. Analysis of global distribution mode of theft crime rate based on Moran Index. *Police Technol.* **2014**, *1*, 45–46.
21. Guihong, L.; Fang, W.; Qian, W. Influence of chronic disease resource utilization on medication adherence among elder patients with primary hypertension in minority areas. *Chin. J. Mod. Nurs.* **2017**, *23*, 4072–4075.
22. Chen, Z.; Liu, J.; Wei, C.; Li, J.; Pan, J.J. Incidence of chronic diseases, medical care-seeking intention and its influencing factors among the community-dwelling elderly in Changsha city. *Pract. Prev. Med.* **2020**, *27*, 270–273.
23. Hao, L.; Mingxin, Z.; Ran, W. The effects of regional geographical factors on children's respiratory diseases in Jingyuan, Ningxia. *Geogr. Res.* **2019**, *38*, 5–10.
24. Hosseini, Z.; Safari, A.; Khan, N.A.; Veenstra, G.; Conklin, A.I. Gender differences in the role of social support for hypertension prevention in Canada: A population-based cross-sectional study of the CLSA cohort. *CJC Open* **2021**, *9*, 45–46. [CrossRef]
25. Gu, J.; Yang, C.; Zhang, K.; Zhang, Q. Mediating role of psychological capital in the relationship between social support and treatment burden among older patients with chronic obstructive pulmonary disease. *Geriatr. Nurs.* **2021**, *42*, 1172–1177. [CrossRef]
26. Fatimah, D.; Rachmi, S.F.; Indracahyani, A. The relationship between social support and emotional status among patients with chronic obstructive pulmonary disease. *Enferm. Clín.* **2019**, *29*, 134–138. [CrossRef]
27. Patino, J.E.; Hong, A.; Duque, J.C.; Rahimi, K.; Zapata, S.; Lopera, V.M. Built environment and mortality risk from cardiovascular disease and diabetes in Medellín, Colombia: An ecological study. *Landsc. Urban Plan.* **2021**, *213*, 104126. [CrossRef]
28. Kim, H.; Na, G.; Park, S.; Ra, S.W.; Kang, S.Y.; Kim, H.C.; Lee, S.W. The impact of life behavior and environment on particulate matter in chronic obstructive pulmonary disease. *Environ. Res.* **2021**, *198*, 111265. [CrossRef]
29. Jian, X.; Lingzhi, K. Focusing on chronic diseases to promote aging healthily. *Chin. J. Prev. Control. Chronic Non-Commun. Dis.* **2020**, *28*, 641–644.
30. Çapraz, Ö.; Deniz, A. Assessment of hospitalizations from asthma, chronic obstructive pulmonary disease and acute bronchitis in relation to air pollution in İstanbul, Turkey. *Sustain. Cities Soc.* **2021**, *72*, 103040. [CrossRef]
31. Seposo, X.; Arcilla, A.L.A.; de Guzman, J.G.N.; Dizon, E.M.S.; Figuracion, A.N.R.; Morales, C.M.M.; Tugonon, P.K.A.; Apostol, G.L.C. Ambient air quality and the risk for chronic obstructive pulmonary disease among metro manila development authority traffic enforcers in metro manila: An exploratory study. *Chronic Dis. Transl. Med.* **2021**, *7*, 117–124. [CrossRef]
32. Bo, Y.; Chang, L.; Guo, C.; Lin, C.Q.; Lau, A.K.H.; Tam, T.; Lao, X.Q. Reduced ambient PM2.5, better lung function, and decreased risk of chronic obstructive pulmonary disease. *Environ. Int.* **2021**, *156*, 106706. [CrossRef]

33. Wang, Z.; Zhou, Y.; Zhang, Y.; Huang, X.L.; Duan, X.Z.; Chen, D.H.; Ou, Y.B.; Tang, L.H.; Liu, S.L.; Hu, W. Association of change in air quality with hospital admission for acute exacerbation of chronic obstructive pulmonary disease in Guangdong, China: A province-wide ecological study. *Ecotoxicol. Environ. Saf.* **2021**, *208*, 111590. [CrossRef]
34. Qin, P.; Luo, X.; Zeng, Y.; Zhang, Y.Y.; Li, Y.; Wu, Y.Y.; Han, M.H.; Qie, R.R.; Wu, X.Y.; Liu, D. Long-term association of ambient air pollution and hypertension in adults and in children: A systematic review and meta-analysis. *Sci. Total Environ.* **2021**, *796*, 148620. [CrossRef]
35. Huang, B.; Xiao, T.; Grekousis, G.; Zhao, H.S.; He, J.R.; Dong, J.H.; Liu, Y. Greenness-air pollution-physical activity-hypertension association among middle-aged and older adults: Evidence from urban and rural China. *Environ. Res.* **2021**, *195*, 110836. [CrossRef]
36. Lin, X.; Du, Z.; Liu, Y.; Hao, Y.T. The short-term association of ambient fine particulate air pollution with hypertension clinic visits: A multi-community study in Guangzhou, China. *Sci. Total Environ.* **2021**, *774*, 145707. [CrossRef]
37. Guo, B.; Wang, Y.; Pei, L.; Yu, Y.; Liu, F.; Zhang, D.H.; Wang, X.X.; Su, Y.; Zhang, D.M.; Zhang, B.; et al. Determining the effects of socioeconomic and environmental determinants on chronic obstructive pulmonary disease (COPD) mortality using geographically and temporally weighted regression model across Xi'an during 2014. *Sci. Total Environ.* **2016**, *756*, 143869. [CrossRef]
38. Pan, S.C.; Huang, C.C.; Chin, W.S.; Chen, B.Y.; Chan, C.C.; Guo, Y.L. Association between air pollution exposure and diabetic retinopathy among diabetics. *Environ. Res.* **2020**, *181*, 108960. [CrossRef]
39. Liu, C.; Chen, R.; Zhao, Y.; Ma, Z.W.; Bi, J.; Liu, Y.; Meng, X.; Wang, Y.F.; Chen, X.X.; Li, W.H.; et al. Associations between ambient fine particulate air pollution and hypertension: A nationwide cross-sectional study in China. *Sci. Total Environ.* **2017**, *584–585*, 869–874. [CrossRef]
40. Sanidas, E.; Papadopoulos, D.P.; Grassos, H.; Velliou, M.; Tsioufis, K.; Barbetseas, J.; Papademetriou, V. Air pollution and arterial hypertension. A new risk factor is in the air. *J. Am. Soc. Hypertens.* **2017**, *11*, 709–715. [CrossRef]
41. Fan, L.; Ding, X.; Liu, S.; Zhang, Z.Z.; Liu, J.Y.; Wang, C.J.; Mo, Y.J. Impact of traffic noise exposure on blood pressure of bus drivers in Qinhuangdao region. *Pract. Prev. Med.* **2016**, *23*, 1074–1077.
42. Xi, C. *Spatial Association between the Characteristics of Urban Park Green Space and the Health of Residents Blood Pressure*; Harbin Institute of Technology: Harbin, China, 2019; pp. 45–60.
43. Zhao, F.; Wang, X. Research progress on the relationship between air pollution and chronic obstructive pulmonary disease. *Med. Recapitul.* **2018**, *24*, 3868–3872.
44. Yang, C.; Cheng, T. A Study on the influencing factors of the choice of patients with chronic diseases in Gaoyou. *City Med. Soc.* **2020**, *33*, 37–43.
45. Thomsen, M.N.; Skytte, M.J.; Astrup, A.; Deacon, C.F.; Holst, J.; Madsbad, T.; Krarup, H.; Haugaard, T.B.; Samkani, I. The clinical effects of acarbohydrate-reduced high-protein diet on glycaemic variability in metformin-treated patients with type 2 diabetes mellitus: A randomised controlled study. *Clin. Nutr. ESPEN* **2020**, *39*, 46–52. [CrossRef]
46. Yanhong, N.; Zhe, L.; Xu, J. Impact of reduced salt intake on the incidence of cardiovascular disease in patients with hypertension and diabetes mellitus. *China Prev. Med.* **2020**, *12*, 1–3.
47. Xi, C.; Teng, W.; Qiu, X.; Que, C.G.; Zhang, H.X.; Zhang, L.; Zhu, T. Susceptibility of individuals with chronic obstructive pulmonary disease to air pollution exposure in Beijing, China: A case-control panel study (COPDB). *Sci. Total. Environ.* **2020**, *717*, 137285.

MDPI
St. Alban-Anlage 66
4052 Basel
Switzerland
Tel. +41 61 683 77 34
Fax +41 61 302 89 18
www.mdpi.com

Sustainability Editorial Office
E-mail: sustainability@mdpi.com
www.mdpi.com/journal/sustainability

MDPI
St. Alban-Anlage 66
4052 Basel
Switzerland

Tel: +41 61 683 77 34

www.mdpi.com

ISBN 978-3-0365-4540-0