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Sustainable Governance in Northeast Asia:
Challenges for Sustainable Frontier

Edited by
Yongrok Choi, Malin Song and Seunghwan Myeong

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About the Special Issue Editors

Yongrok Choi is a distinguished research professor (Inha Fellow Professor) of the Inha University. He is the president of the Asia Business Forum and the organizer of the Sustainable Asia Conference (SAC). He has published more than 100 papers, including many SCI and SSCI level of journals such as *Energy Economics, Energy Policy, Tech. For. & Social Change*, etc. He also managed more than 10 special editions of the SCI level of journals such as *Energy Policy, Tech. For. & Social Change, Sustainability*, etc. His research focuses are on energy and environmental policy analyses, green IT applications and sustainable management.

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Preface to "Sustainable Governance in Northeast Asia: Challenges for Sustainable Frontier"

This Special Issue consists of selected papers from the Sustainable Asia Conference 2016, an annual international conference held on Jeju Island, South Korea, from 28 June to 2 July. SAC 2016 is one of the leading international conferences for presenting novel and fundamental advances in sustainable development issues for Asia. The purpose of the conference is for scientists, scholars, engineers, and students from universities and research institutes around the world to present ongoing research activities so as to promote global research networking in the area of sustainable development. This conference provides opportunities for the delegates to exchange new ideas and application experiences, face-to-face, to establish research or business relations, and to find global partners for future collaborations. The scope of this Special Issue encompasses topics related to sustainable development and management at both the macro- and micro-levels in Northeast Asian countries.

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Special Issue Editors

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Editorial

Sustainable Governance in Northeast Asia: Challenges for the Sustainable Frontier

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Abstract: This Special Issue consists of selected papers from the annual international Sustainable Asia Conference (SAC) 2016, held on Jeju Island, South Korea, from 28 June to 2 July 2016. SAC 2016 is one of the leading international conferences for presenting novel and fundamental advances in sustainable development issues for Asia. In this special issue, most of the papers emphasize the importance of sustainable governance in harmonizing economic development with a healthier life, while enhancing the quality of all economic activities. The majority of papers in this special issue also deal with problems of urbanization, because the Northeast Asian countries are experiencing the transformation of their economic structure from quantitatively oriented development to the qualitative, highlighting socioeconomic performance. There has been a vast amount of discussion and many ideas put forward on sustainable development, but as the Marrakech Proclamation of COP 22 concluded in November 2016, it is now time to meet the practical challenges of sustainable development. This special edition will shed light on the action plan against global warming and environmental degradation.

Keywords: Sustainable Asia Conference (SAC); Post-2020 climate regime; green growth; sustainable governance

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1. Background of the Special Issue

The Sustainable Asia Conference (SAC) is an academic network for Northeast Asian professors and researchers to share ideas and cooperate in facing new challenges in the field of sustainable development, green growth, and green IT. SAC has been based on its annual international conference since its inaugural event in 2009 at Incheon, Korea. Since then, there have been more than 100 papers published through the conference, and this Special Issue documents one of these annual conferences—SAC 2016, held on Jeju Island, Korea, during 28–29 June 2016. This conference provides opportunities for researchers, experts, and practitioners to exchange new ideas and experiences to find global partners for future collaborations. The scope of this special issue encompasses topics related to sustainable governance in Northeast Asia with challenges for the sustainable frontier.

Northeast Asian countries have witnessed the world's most rapid economic growth, as well as the resulting pollution, such as carbon dioxide (CO_2) emissions. To cope with these undesirable outcomes, all of the governments in the region have shifted their policy paradigms to place much more emphasis on environmental issues [1]. Due to the ever-increasing complexity of the issues in this field of sustainable development or green growth, there were many diverse views and suggestions put forward in SAC 2016, with most of them focused on matters of governance or the determining factors of various governance mechanisms. The Chinese government is facing severe environmental problems—especially in the winter season every year—due to the ever-increasing smog of particulate matter known as PM 2.5. Thousands of people are suffering from this toxic air pollution, and it has become much more severe over time. In particular, this air pollution easily reaches Korea and Japan during the winter due to the cold seasonal northwest wind in the region. This is why international cooperation to overcome this environmental disaster is so crucial in the region.

Korea has also experienced an annual temperature increase higher than any other country in the world, due to its specific environmental situation as a peninsula, resulting in the nation's highest temperature record being surpassed almost every year. Through the strong support of ex-president Lee, Korea hosted the Green Climate Fund, and has strongly promoted green growth policies, including the historical inauguration of its nationwide emission-trading scheme (ETS) in 2015. As the successful host of the Kyoto Protocol, Japan has been strongly prompted to mitigate its greenhouse gas (GHG) emission levels. Unfortunately, other leading countries such as the United States and China did not participate in the Kyoto Protocol, and thus it could not be fully implemented and sustained. Nonetheless, the Kyoto Protocol provided a great platform to deal with environmental issues via sustainable market-oriented solutions with flexible mechanisms, such as ETS, the Clean Development Mechanism, and Joint Implementation. The flexibility of the Kyoto Protocol's mechanisms opened a new frontier in sustainable development, because air pollution at least became measurable, reportable, and verifiable in order to mitigate its undesirable effects on the global economy.

All these Northeast Asian countries share the common goal of green growth. Environmental protection is important, but at the same time, economic development is crucial in a region that has become the engine of global economic growth. Fortunately, green growth policies could create a decoupling of economic development from environmental issues. In particular, the Paris Agreement in 2015 at the COP 21 meeting put in place an important cornerstone to promote the better performance of green growth policies for all these countries from a governance perspective.

Many of the papers presented in SAC 2016 are relevant to this new frontier of the Paris Agreement, and thus this special issue with selected papers from the conference could provide a new platform to implement sustainable governance in the region.

2. Fresh Challenges under the New 2020 Climate Regime

While the Kyoto Protocol regime provided a very important stepping-stone toward the marketability of air pollution issues, it lacked governance authority due to the presence of too many passive participants in the mitigation of GHG emissions. Only 38 Annex I developed countries and the European Union committed to mitigate six GHG emissions. This ambitious commitment, however, covered only 22 percent of global emissions, and most countries participating in the protocol are just passive members aiming only to get benefits from this protocol. This certainly resulted in only partially successful operation for the first round of five years from 2008 until 2012. The United States could not ratify the Kyoto protocol due to its market-oriented policy paradigm, and thus many other countries did not participate in the second round of the Kyoto Protocol. In order to mitigate the worsening conditions of the regime, 197 member countries of the UN Framework Convention on Climate Change held their 21st Conference of the Parties (COP 21) in Paris, and agreed to inaugurate the new 2020 climate regime.

Without global efforts, GHG emission levels may reach up to 700 ppm by 2030 with the business as usual (BAU) trajectory shown in Figure 1. At the COP 21 meeting at Paris, the member countries agreed that global warming is not a special issue for some countries, but is the responsibility of all; and that there should be no exceptions among nations in taking steps to mitigate GHG emissions worldwide to achieve below 2 °C (3.8 °F) from BAU. In order to decrease the average temperature of the Earth, all countries should make efforts to decrease overall emissions by at least 38 gigatons carbon dioxide equivalent (Gt CO_2e) per year by the target year of 2030. COP 21 agreed that—based on all possible technical measures up to 2030—we could and should make our best efforts to decrease emissions by 38 Gt CO_2e. However, it is never easy and effective to use all these potential technical measures, due to the budgets needed to develop and utilize them [2]. These potential technical measures are shown in Figure 2. In this figure, the height of the bar indicating each new technology represents the cost or budget for the research and development of this technology, while the width of the bar for each individual technology indicates the effect of GHG emission mitigation [2]. As shown in Figure 2, all these technological measures combined may contribute up to the 38 Gt CO_2e mitigation of GHG emissions.

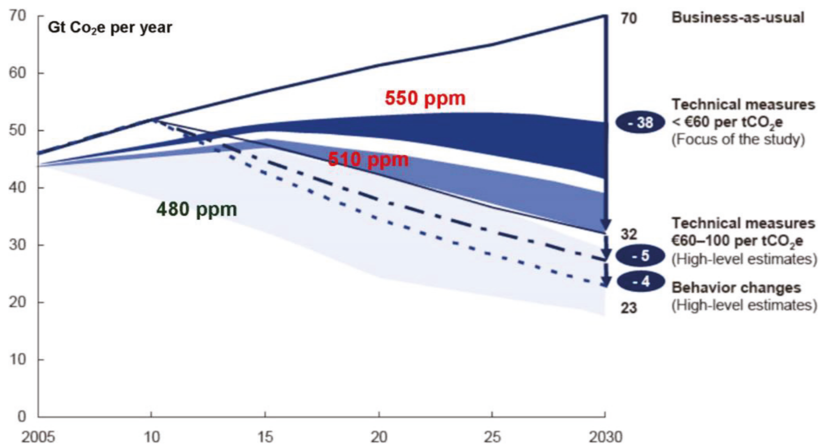

Figure 1. Global greenhouse gas (GHG) Emission Pathways. Source: Global GHG Cost Curve V2.0 (McKinsey & Co. 2009, [2]); IEA; IPCC; OECD; US EPA.

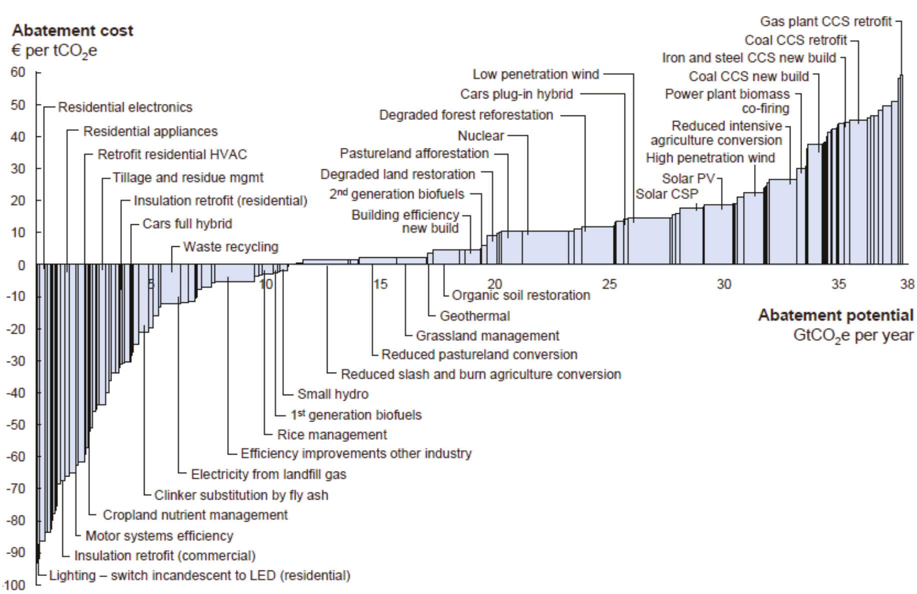

Figure 2. Greenhouse Gas Abatement Opportunities. Source: Global GHG Cost Curve V2.0 (McKinsey & Co. 2009, [2]). CCS: carbon capture and storage.

Some technologies—such as LED lights in residential areas—may not incur any cost to utilize; over time, they may give additional benefits (negative costs) to households. These technologies could be utilized easily and effectively if governments provided subsidies and/or other incentives to develop them, while some more advanced technologies, such as those for carbon capture and storage (CCS), are too risky in their utilization budgets, and thus strong support from public–private partnerships is desperately needed. With all these technological measures, it is not easy to decrease by 38 Gt CO_2e. In order to decrease by 1 Gt CO_2e, for example, all the vehicles in the EU would have to be kept from driving for a year [2]. All of these optimal controls on the GHG emission pathways are based on an estimated global GHG emissions peak of 480 ppm by the year 2015 and decreasing thereafter. Unfortunately, time really does matter for this emission pathway, because the optimal path is already mission impossible due to the late response from the COP member countries; thus, we may not have this pathway anymore, and to get the same result for the global temperature, we may need an additional 9 Gt CO_2e reduction through behavioral changes in people. Therefore, the member countries at the COP 22 meeting of 2016 emphasized the gap in the global goal between its mission and the possible efforts of the Marrakech Proclamation. The question is how we are going to fill this gap or missing link in terms of governance and workable mechanisms for sustainable performance [3]. At SAC 2016, many papers addressed the new challenges of governance raised by the 2020 climate regime, and we shall introduce selected papers on this theme from SAC 2016 in this special issue.

3. Governance Issues for the Sustainability of Asia

All the papers in this special issue are based on the common paradigm of governance aimed toward green growth. In particular, many papers argue that urbanization is a crucial dimension of policies for green growth, because urbanization was the one of the key successful phenomena in the rapidly growing Northeast Asian countries, although urbanization may face its limits for inclusive, harmonized, and sustainable development. Therefore, appropriate approaches to overcoming the diverse issues of urbanization could provide very basic stepping-stones for governments in implementing the new 2020 climate regime.

Urbanization could be considered as a primary source of the degradation of natural, open ecosystems, and unfortunately, most of this conversion from open land to built-up areas results in significant and irreversible natural habitat loss. To evaluate the ecological changes appropriate to Jiangsu's coastal wetland, Caiyao Xu et al. analyzed ecological security and ecosystem services in the region by using remote sensing and spatial analyses for the period from 1977 to 2014 [4]. They found that the total ecosystem service value decreased significantly from \$2.98 billion per year to \$2.31 billion per year over the study period due to this transformation from open to built-up land. Moreover, it will take 34 years for landscape ecological security and 39 years for ecosystem services to regain their original state of equilibrium. Nonetheless, food production was the only ecosystem service function that consistently increased, mainly because of government policy, implying that government regulation or incentives regarding the transformation and/or utilization of the land could be the best solution for green growth in the region [4].

Of course, rapid urbanization stimulated the expansion of industrial production and increased industrial pollutant emissions—especially in China and other developing countries. However, urbanization results in undesirable drawbacks, not only through environmental degradation, but also in unavoidable industrial structure. To remedy this drawback, Jin Guo et al. analyzed the influence of urbanization impacts on industrial pollutant emissions, looking at scale effects, intensive effects, and structural effects, using the Kaya Identity and the Log Mean Divisia Index (LMDI) method based on a spatial panel model [5]. Using data from 282 prefecture-level cities in China from 2003 to 2014, they found a significant inverse U-shape between China's urbanization rate and environmental degradation indicators such as the volume of industrial wastewater discharge and emissions of sulfur dioxide and PM (dust). With the consistent rise in the urbanization rate, the volume of industrial wastewater discharges increased steadily, and reached its peak in 2007. After that, the volume of industrial wastewater discharge showed a downward trend. This clearly shows that the paradigm shift of the Chinese government from the year 2005—with a greater focus on environmental regulations and promotion incentives—could effectively impede the rate of environmental degradation. Moreover, it is noteworthy from the findings that diverse surrounding suburban areas of China's cities may not serve as sponge belts absorbing industrial pollutants, because the spatial spillover effect from the central cities to these suburban areas is non-existent or non-significant, implying that a selective concentration on environmental regulation could be much more effective than a wide range of universal treatment [5].

As one of issues related to urbanization, more attention needs to be paid to the efficient use of forested land; thus, Yafen He et al. analyzed the forested land use efficiency (FLUE) and its spatiotemporal differences in China during the period from 1999 to 2010, using a global generalized directional distance function and global Malmquist–Luenberger index models [6]. They found obvious spatial differences in forested land use efficiency among 31 provinces, with Shanghai the best and Tibet, Inner Mongolia, and Qinghai the worst. Since this difference comes from a very complicated mixture of urbanization, economic development contexts, and population density (as shown in the model), it is not easy and effective for the central government to mitigate these differences. To mitigate this gap, Yafen He et al. tried to examine the dynamic changes in the FLUE, and found that the productivity of forested land was always increasing, and that changes in the productivity of forested land in the eastern region derived mostly from technological advances [6]. For the central region, the progress in forested land productivity derived mostly from improvements in efficiency. The change in the productivity of forested land in the western region resulted from the interactive effect of these two decompositions [6]. These findings imply that environmentally friendly green growth policies should be managed differently depending on the unique conditions of regional economic activities and their environmental settings.

As shown in Figures 1 and 2, the mitigation of GHG emissions is a truly important mission for all humankind. However, the Paris Agreement also emphasizes the importance of supportive efforts to enhance eco-efficiency. In this perspective, Shujing Yue et al. analyzed the total-factor ecological efficiency (TFEcE) of G20 countries during the period 1999–2013 using the slack-based Data Envelope Analysis (DEA) model [7]. In contrast with the traditional approach, they used the ecological footprint as one of the inputs, this being a simple assessment for an aggregate area of the productive lands and water required to generate the region's GDP. They found that the average TFEcE of the G20 nations is at a low level of about 0.54, which definitely needs to be enhanced. This finding provides background support for the new 2020 climate regime for all countries. In particular, China improved throughout the experimental period from 0.238 to 0.285, with much potential enhancement ahead. Korea shows a value of about 0.7—much smaller than its potential increase, but with an aggravating trend in efficiency; this also definitely needs to be improved. In contrast with these two countries, Japan is shown to be the best on its productivity frontier for the whole experimental period, indicating the most effective results of the Kyoto Protocol on its economic performance [7]. From these findings, it is extremely noteworthy that technological measures are important in mitigating GHG emissions, while the emphasis on ecological efficiency should not be discounted, because there is huge potential to enhance eco-friendly efficiency.

There are also some conflicts between the higher productivity of agricultural production and the higher quality of its products in terms of organic eco-production systems. Unfortunately, most Chinese farmers tend to use excessive pesticides for higher production, causing moral hazard behavior on food health. Zhang and Li examined how Chinese farmers' moral hazard behavior in crop production is influenced by their traditional culture using a semi-parametric logistic model, and found that Chinese traditional culture has a positive effect on restricting the farmers' excessive use of pesticides in crop production [8]. The probability of moral hazard could decrease by 17% if farmers become aware of traditional culture as providing a restraint on the use of pesticides. It is noteworthy that even if traditional culture is important to deal with moral hazard on the excessive use of pesticides, formal institutions are more effective in constraining farmers' production behavior, which helps to reduce the probability of moral hazard, implying that the government should implement relevant policies, such as improving the frequency of random inspections, intensifying penalties, and strengthening market supervision for agricultural inputs, to evoke culturally conditioned cognitive behavior on the use of pesticides [8].

In a step toward the ambitious green growth pathway under the new climate 2020 regime, Korea just inaugurated a nationwide emissions trading scheme (ETS) in 2015. To establish the feasibility of this ETS policy, Choi and Lee analyzed its sustainable governance factors in terms of carbon technical efficiency, the shadow price of carbon emissions, and Morishima elasticity for green investment, using the non-radial directional distance function [9]. Unfortunately, they found that the market price of carbon emissions is far too low compared with its shadow price, suggesting that the Korean government's price-oriented market intervention has resulted in poor performance, at least in its initial stage [9].

Based on all these papers in this special issue, the Northeast Asian countries are seen to emphasize their harmonized interrelationship in order to enhance sustainable governance in the region. Even if the new climate 2020 regime focuses on efforts toward the mitigation of GHG emissions, most of these papers argue that eco-friendly efficiency could be a new source of green growth. This approach may create fewer budget demands than other technical measures require for their development and utilization; thus, enhancing efforts for efficiency toward more eco-friendly green growth could be a viable alternative for the new 2020 climate regime, especially in developing countries such as China and Korea [10]. This special issue highlights harmonizing these efforts with legacy systems instead of expensive, risky investments on green technology.

4. Conclusions

The research contents and methodologies examined in this special issue give us greater insights and open new frontiers to handle the contemporary challenges of sustainable governance. Most of these articles handle the multiple inputs and outputs with time and space in consideration. This emphasizes that sustainable governance requires complex procedural approaches in order to grasp workable mechanisms to harmonize all the interest groups in the cooperative network. Clarifying the causal relations in this network is not easy, but it is essential for the network manager or agency to ensure that all parties share values and face the challenges together. This is the catchphrase of the Sustainable Asia Conference (SAC): Once a friend, forever a friend.

Networking participants striving for harmonized and sustainable cooperative performance will need to adopt a more field- and performance-oriented approach to create these invisible but precious values—this is true sustainable governance [11]. In order to discover these sustainable governance factors, relevant issues and their methodologies should be highlighted in this rapidly-evolving Asian model. In particular, compared with the efficiency-oriented Western countries, the Northeast Asian countries have placed more emphasis on their harmonized interrelationship [11]. This social relationship is absolutely crucial in creating and sharing values in these countries. The world's priorities are presently changing from visible profits and efficiency toward these invisible values, which derive from sustainable cooperative networks in business, in the economy, and in society as a whole. As shown in the diverse perspectives on urbanization and other related issues in this special edition, we should work together to find the appropriate Asian models for this sustainable cooperation network mechanism in the future, especially for SAC 2017 in Nanjing in China on 24 June 2017.

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The Impact of Traditional Culture on Farmers' Moral Hazard Behavior in Crop Production: Evidence from China

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Abstract: To obtain higher yields, farmers may excessively use pesticides when they grow crops (like rice, vegetables, or fruit), causing moral hazard behavior. This paper examines how Chinese farmers' moral hazard behavior in crop production is influenced by their traditional culture. A semi-parametric logistic model is used to investigate the impact of Chinese traditional culture on farmers' moral hazard behavior. The results reveal that Chinese traditional culture has a positive effect on ameliorating the farmers' excessive use of pesticides in crop production, which leads to a moral hazard in agro-product safety. Specifically, when we control for extraneous variables, the probability of moral hazard decreases by 15% if farmers consider their traditional culture in their production decisions. Moreover, the probability of moral hazard decreases by 17% if farmers consider the traditional culture as a powerful restraint regarding the use of pesticides. Our analysis provides some supportive evidence on the effect of Chinese traditional culture on mitigating farmers' excessive use of pesticides.

Keywords: moral hazard; Chinese traditional culture; agro-products quality and safety; semi-parametric model; crops production

1. Introduction

As important input chemicals in agricultural production, pesticides play an irreplaceable role in promoting agricultural development, increasing production, and farmers' incomes [1,2]. However, pesticides are a toxic chemical substance, and the pollution caused by their excessive use has done serious damage to human health, ecological safety, and the sustainable development of agriculture [3]. According to the Ministry of Agriculture of China in 2014 [4], for the last five years, China's pesticide consumption is approximately 0.31 million tons per year, and the unit area pesticide consumption is 2.5–5 times higher than the world's average. Pesticide pollution has become a serious problem, especially to the agro-product quality and safety. In March 2015, the "pesticide reduction and efficiency promotion" campaign was undertaken by the Chinese government to reduce the use of pesticides and improve efficiency.

With people's changing consumption preferences, the demand for safe agro-products is increasing significantly. However, because of improper behavior concerning farmers' crop production, such as disobeying the relevant production standards or excessive use of pesticides and additives, agro-products safety incidents occur frequently, mainly characterized by excessive pesticide residue. Given the quality of asymmetric information in the agro-products market, farmers are inclined to use pesticides excessively for more profits, resulting in a large number of products with inferior quality in the markets [5,6]. Moral hazard is an economic concept, which states that those who engage in economic activities, in order to maximize their own utility, will have inherent incentives to take actions unfavorable for others. As in the agro-products market, there is a principal-agent relationship between buyers and farmers, the buyers (such as agricultural enterprises, wholesalers, supermarkets, and the final consumers) are the principal, while the farmers are the agent. They sign a production contract (sometimes farmers may use certificates instead of contracts, like organic certificates), the buyers commission the farmers to produce agro-products with safe quality, and there are strict regulations on the application of pesticides, including variety, time, and dose. However, as farmers' behaviors cannot be monitored during the production period, in order to get greater yields, they may pursue activities unfavorable to buyers, such as increasing pesticide concentration, adopting banned pesticides, and using pesticides during the harvest period; with farmers' behaviors seriously violating the agreement of the contract, this is thought to be moral hazard behavior (MHB) [7]. Moral hazard hinges crucially on information asymmetry; therefore, the risk-taking party knows more about his (or her) intentions than the party paying for the consequences of the risk [8]. Given the quality information asymmetry in the agro-products market, farmers may excessively use pesticides in the pursuit of higher profits.

Recently, there has been growing interest in studying farmer's MHB. Many analyses have been undertaken to uncover the factors affecting farmers' MHB devoted to crop production. In the literature, factors affecting farmers' MHB cover demographic characteristics, such as age, gender, level of education, risk preference, farmers' cognition, external environment of agricultural production, and characteristics of government regulation, among others [7,9–11]. In China, the government plays a significant role in regulating and supervising farm-level food safety, yet several unsafe food incidents have been uncovered, leading to examination of the causes of these problems. For example, the Chinese government has launched several programs aiming to create a favorable environment for safe farming, including operating quality safety training, providing agricultural technical guidance, and establishing cooperative organizations. Furthermore, the government enacted a series of strict regulatory measures, including an "agro-products quality and safety law", product or place certification, agro-products quality and safety checks, and an agro-products safety traceability system.

In addition to the factors discussed above, it is still debatable whether the Chinese traditional culture is also devoted to farmers' MHB. However, few studies attempt to uncover the relationship between Chinese traditional culture and farmer's MHB. To fill this gap, this study aims to analyze how Chinese traditional culture influences farmers' MHB. Based on the definition proposed by North [12], this paper classifies Chinese traditional culture as an informal institution, which is also known as informal constraints or informal rules, referring to the social rules which gradually formed while people were in the process of long-term social interaction, and it has been recognized and abided by the community vulgarly, including value beliefs, social customs, traditional culture, religious ceremony, moral standards, and so on. Through an investigation in China's rural areas, our study finds that Chinese traditional culture might affect farmers' tendency to conduct MHB in crop production; therefore, this study chooses a semi-parametric logistic model to study the impact of Chinese traditional culture on farmers' MHB. The evidence reveals that Chinese traditional culture has a positive effect on avoiding the MHB devoted to usage of pesticides. The estimated results imply that, when we control for extraneous variables, the probability of moral hazard decreases by 15% if farmers consider their Chinese traditional culture when making crop production decisions. In addition, the probability of moral hazard decreases by 17% if farmers consider the Chinese traditional culture as a powerful restraint when using pesticides. Finally, we conduct a sensitivity analysis to compare our model with the conventional logistic one. The results of logistic estimation demonstrate that the impact of regulating government's inspection is less effective than that of advertisement of traditional culture in the sense of reducing moral hazard. This information contradicts the common economic consensus.

This study aims to fill this gap by providing information about how Chinese cultural prosperity contributes to the mitigation of farmer's MHB in crop production. The results also provide useful information for related agricultural and cultural policy decisions. The rest of this paper is arranged as follows. The next section summarizes the relevant literature. Section 3 defines the variables. Section 4 presents the empirical methodology. Section 5 presents the empirical results and related discussion. The last section concludes the paper and provides important policy implications.

2. Literature Review

The main cause of MHB lies in the difference of benefit between principal and agent; as agents' behaviors cannot be monitored, the agents may engage in opportunistic activities. MHB seriously affects the quality and safety of agro-products, and even the physical health of consumers. To find the influencing factors and mechanism of moral hazard, a large number of studies have been conducted in different subject fields, such as behavioral, institutional, and information economics. Researchers have examined farmers' MHB in the field of agro-products quality and safety, with the following results:

2.1. Discussing What are Moral Hazards Related with Farming

Moral hazards related with farming are defined as the violation of "production orders", or "hidden action" in the process of agricultural activities, such as the non-observance of agricultural production laws, confrontation with the rules of safe farming, and overuse of agricultural chemicals [7–9,13–15].

2.2. Analyzing the Main Causes of Farmers' MHB

By using cost-benefit analysis and the Becker–Stiegler model, as well as principal-agent theory, researchers find that the main causes contributing to farmers' MHB are listed as follows: the asymmetric information between farmers and buyers, the low production cost of unsafe agro-products, light punishment, over-profit orientation, opportunism, market failure involved with agro-products, limitations of government regulation, and so on [16–18].

2.3. Studying on Impact Factors of Moral Hazard

Through empirical analysis of farmers' MHB regarding production, scholars propose that the main impact factors are additional incomes of moral hazard, discount rates of future incomes, fines, the probability of being caught, household structure, planting area, pressure from buyers, the distribution channels of agro-products, and so on [9,13,15,17].

2.4. Studying the Negative Effect of Moral Hazard

Researchers find that MHB may lead to failure in the agro-products market, leaving a large number of products of inferior quality in the markets while safe agro-products are being expelled from the market and seriously affect consumers' health and safety. As the "lemon market" theory predicts, agro-products with high quality cannot get a high price; therefore, farmers have fewer incentives to engage in safe farming [6,19–21].

2.5. Researching Countermeasures to Moral Hazard

The key countermeasures to prevent farmers' MHB include developing agricultural cooperative organizations, establishing agro-product quality control systems, strengthening the supervision of agro-products, and raising the standard of punishment. Moreover, positive-side incentives should also be adopted [13,14,22,23].

As the source of agricultural production, farmers' production behavior is the most important factor affecting agro-products quality and safety [5]. Farmers' production behavior is characterized by decision-making under multiple constraints, such as the farmers' self-discipline, organizational constraints, buyer's constraints, government's constraints, and so on; these factors have been proven by researchers. In fact, farmer behavior is complicated, in addition to the above factors, it may also be related to the long-term social environment, such as village regulations, ethics, social customs, moral standards, and so forth. A lot of research with regard to Chinese traditional culture primarily focuses on its influence on residents' correct outlook on life, worldview, and values [24], whereas less attention is given to its effect on farmers' MHB. To explore the factors that affect farmers' MHB, we try to examine how and why Chinese traditional culture affects farmers' MHB.

3. Data and Variables

3.1. Data

A sampling survey is conducted, as the data used in this study were not available from public databases. The survey was undertaken by combining stratified sampling and random sampling. We stratified the sample according to the planting types and crop yields, as the four provinces being chosen all mainly produce rice or wheat. The data used for this paper were collected from four provinces of rural China, as these provinces are China's major crop producing areas, and they play important roles in crop safety. In each selected province, two counties were randomly selected, and then two towns per county, then about 25 households were randomly picked from each town. The counties we chose in each province all have the same number of towns, so the conditions of a stratified sample are confirmed, and we can use the stratified sample to obtain household survey data. The sample collection was conducted in July and August 2013. The distribution of samples is shown in Table 1.

Table 1. Sampling Survey.

Province	County	Issued Questionnaires	Valid Questionnaires
Jiangxi	Yongfeng	52	47
	Ji'an	55	53
Anhui	Bunan	56	50
	Linquan	53	49
Jiangsu	Binhai	50	44
	Jianhu	53	49
Henan	Xinmi	56	50
	Xinzheng	53	47
Total	——	428	389

The survey instrument was a closed-ended questionnaire that was modified from the baseline survey instrument. The household survey used a structured questionnaire to collect data from the selected households including farmers' individual features, household characteristics, farmers' cognition on quality and environment, government regulation characteristics, farmers' cognition on traditional culture, as well as farmers' crop production behavior. In order to improve the effects of the investigation, we carried out a pre-investigation in Nanchang county, Jiangxi province, to check the rationality and feasibility of the questionnaire. According to the problems found in the pre-investigation, we then revised the questionnaire. In order to avoid deviation based on the different culture levels of farmers, the authors participated in recording answers in the questionnaire. The survey resulted in 428 distributed samples, but 39 samples did not provide sufficiently complete information on dependent and explanatory variables to be included in the analysis, so we discarded them, and we finally obtained 389 valid samples. The discarded information do not differ from those adopted for the analysis, and there is no sample selection bias.

3.2. Variable Selection

To analyze moral hazard in the use of pesticides by farmers, there are various economic and social factors associated with the benefits and costs regarding violating the rules of using pesticides. The choice of variables should be guided by previous research, economic theory, and the purpose of this research. Under those principles, the variables employed in this study include fifteen explanatory variables (in fact, the survey data contains 38 explanatory variables, and we select 15 of them according to the purpose of this study) and one dependent variable; the detailed definitions of each variable are shown in Table 2.

In crop production, in order to improve the effect of pesticides or to get higher yields, farmers may increase pesticide concentration ratios, adopt banned pesticides, or use pesticides during the harvest period. If one or more of the above behaviors occur, they are considered MHB. Therefore, moral hazard (Y) is a binary dependent variable indicating the existence of MHB. There are fifteen independent variables in this paper, including five continuous variables and ten discrete variables. The detailed definitions of each variable are shown in Table 2. Some variables need to be specified. Risk preference (X_4) is a dummy variable to show whether farmers are risk-lovers [25–27]. In our questionnaire, we set one question to measure farmers' risk preference, that is "there are two business program, you can earn two thousand yuan without any risk if you choose the first one, and you may have 50% probability to earn three thousand yuan or only one thousand yuan if you choose the second one, which one will you choose?". If farmers choose the first one, we classify him (or her) as risk averse, otherwise we classify them as a risk lover (in general, including "risk neutral" is more reasonable, but due to our negligence, we offered only two choices in our questionnaire). Employment (X_7) is a binary variable standing for whether people engaged themselves in non-agricultural employment. Environmental concern (X_{10}) is a dummy variable to show whether farmers are concerned with environmental protection in the decision of pesticide use. Quality concern (X_{11}) is a dummy variable to show whether farmers are concerned with the quality and safety of agricultural products. Inspection (X_{12}) is a dummy variable to show whether government inspection systems are strict. Penalty (X_{13}) is a dummy variable to show whether the penalty measures are strict. Culture_1 (X_{14}) is a dummy variable to show whether farmers consider the traditional culture when they make crop production decisions. Culture_2 (X_{15}) is a dummy variable to show whether farmers consider the traditional culture as a restraint [28,29].

Table 2. Variables' names and definitions.

Variables	**Definitions**
Farmers' crops production behavior	
Moral hazard behavior (Y)	A zero-one, discrete variable set equal to 1 if the farmers carry a hazardous behavior, such as using banned pesticides.
Farmers' individual features	
Age of household head (X_1)	The true age of household head (Years)
Gender (X_2)	0 = Male, 1 = Female
Education (X_3)	1 = Illiterate, 2 = Primary, 3 = Junior, 4 = High school, 5 = College
Risk preference (X_4)	0 = Risk Aversion, 1 = Risk lover
Household characteristics	
Number of family members (X_5)	Actual family members (Person)
Total income (X_6)	Actual family incomes (Yuan)
Employment (X_7)	0 = No, 1 = Yes
Non-agricultural income (X_8)	Actual non-agricultural income (Yuan)
Non-agricultural income share (X_9)	The ratio of Non-agricultural income to total income (%)
Farmers' cognition on quality and environment	
Environmental concern (X_{10})	0 = Not concern, 1 = concern
Quality concern (X_{11})	0 = Not concern, 1 = concern
Government regulation characteristics	
Inspection (X_{12})	0 = Not Strict, 1 = Strict
Penalty (X_{13})	0 = Not Strict, 1 = Strict
Farmers' cognition on traditional culture	
Culture_1 (X_{14})	0 = No, 1 = Yes
Culture_2 (X_{15})	0 = No, 1 = Yes

Note: "Culture_1" stands for whether farmers consider the traditional culture when they are making crop production decisions; "Culture_2" stands for whether farmers consider the traditional culture as a restraint in the use of pesticides.

3.3. Descriptive Analysis

3.3.1. Descriptive Analysis of Dependent Variables

In accordance with previous studies, farmers' MHB is measured in terms of pesticides used in crop production, where farmers increasing the concentration ratio of pesticides (A_1), adopting banned pesticides (A_2), or using pesticides during the harvest period (A_3) in the process of crop production are considered MHB. As long as one or more of the above behaviors occurred, it is considered MHB. Survey data show that the number of MHB is 168, accounting for 43.2% of the 389 simples, this means that the problem of MHB is considerably serious in the process of crop production. Table 3 reports the farmers' MHB, the above three behaviors, the number of farmers who increased the concentration ratio of pesticides is the highest at 144, while the other two kinds of behaviors are almost the same. The reason may be that the agricultural production is entirely in the control of farmers, which indicates that it is difficult for the government to regulate food safety. Specifically, the number of farmers with only one of the above behaviors is 76, all of the above three behaviors is 8, A_1 and A_2 are 42, A_1 and A_3 are 30, A_2 and A_3 are 12.

Table 3. Moral hazard behavior of farmers.

Happened or Not	A_1	A_2	A_3	Moral Hazard
NO (Y = 0)	245	331	335	221
YES (Y = 1)	144	58	54	168

3.3.2. Descriptive Analysis of Independent Variables

We divide the samples into two groups which, respectively, expressed whether farmers' MHB happened, and furthermore we use a t-test to identify whether variables have significant differences. Table 4 presents the differences in the characteristics of the happened and the not-happened group with their t-values. The t-values indicate that there are significant differences in some of the variables used in the empirical analysis. Specifically, most characteristics of the happened group are lower than the not-happened group. However, the risk preference and gender are all significantly higher factors for the happened group than for the not-happened group. The differences in the mean characteristics between the happened group and the not-happened group indicate that these factors may have impacts on farmers' MHB.

Table 4. Variable differences between the happened and not the happened group.

Variables	Units	Happened (n = 168)		Not Happened (n = 221)		*t*-Test
		Mean	SE	Mean	SE	
X_1 (Age of household head)	Years	52.36	9.9	52.84	11.3	0.217
X_2 (Gender)	-	1.40	0.491	1.28	0.450	0.016 **
X_3 (Education)	-	2.14	0.984	2.41	0.903	0.112
X_4 (Risk preference)	-	0.29	0.455	0.18	0.384	0.010 ***
X_5 (Number of family members)	Person	4.64	2.01	4.82	1.99	0.063
X_6 (Total income)	Yuan	41,539.1	40,807.3	51,163.3	53,802.2	0.081
X_7 (Employment)	-	0.73	0.384	0.82	0.443	0.039 **
X_8 (Non-agricultural income)	Yuan	28,427.8	37,843.8	38,915.2	50,206.2	0.351
X_9 (Non-agricultural income share)	%	54.5	36.3	66.1	35.2	0.211
X_{10} (Environmental concern)	-	0.41	0.494	0.88	0.150	0.002 ***
X_{11} (Quality concern)	-	0.46	0.500	0.91	0.068	0.005 ***
X_{12} (Inspection)	-	0.44	0.498	0.81	0.382	0.001 ***
X_{13} (Penalty)	-	0.48	0.501	0.97	0.096	0.000 ***
X_{14} (Culture_1)	-	0.58	0.402	0.87	0.177	0.002 ***
X_{15} (Culture_2)	-	0.40	0.478	0.84	0.364	0.001 ***

Note: *** and ** denotes significance at 1% and 5%respectively.

3.4. Correlation Analysis

Table 5 provides the summary statistics of these variables, including the mean, standard deviation, and Pearson's and Spearman's correlations of the samples, to identify possible affecting factors of farmer's MHB. We can see that the moral hazard, total income, non-agricultural income, and risk preference all have lower averages than their standard deviations, suggesting relatively high volatilities. The Pearson's pairwise correlations between the moral hazard dummy and each factor are reported in the last second column of Table 5. The Pearson's correlations vary from −0.630 to 0.131. The risk preference dummy has the largest correlation (i.e., 0.131), suggesting the stronger positive dependence of moral hazard and risk preference than that of the moral hazard and other factors. The largest negative correlation is detected between the moral hazard dummy and environmental concern, indicating that concern with environmental protection plays an important role in the decision of pesticide use.

Table 5. Summary of statistics.

	Units	Mean	Standard Deviation	Pearson's Correlation	Spearman's Correlation
Y (Moral hazard)	-	0.437	0.497	-	-
X_1 (Age of household head)	Years	52.820	10.720	−0.023	−0.031
X_2 (Gender)	-	1.331	0.471	0.123	0.123
X_3 (Education)	-	2.295	0.947	−0.142 **	−0.155 **
X_4 (Risk preference)	-	0.227	0.420	0.131 **	0.131 **
X_5 (Number of family members)	Person	4.750	2.084	−0.046	−0.052
X_6 (Total income)	Yuan	46,960.470	48,733.186	−0.098 *	−0.158 *
X_7 (Employment)	-	0.780	0.413	−0.105 *	−0.105 *
X_8 (Non-agricultural income)	Yuan	34,335.401	45,469.784	−0.115 *	−0.115 *
X_9 (Non-agricultural income share)	%	66.547	105.172	−0.159 **	−0.210 **
X_{10} (Environmental concern)	-	0.731	0.444	−0.630 **	−0.630 **
X_{11} (Quality concern)	-	0.762	0.426	−0.622 **	−0.622 **
X_{12} (Inspection)	-	0.649	0.478	−0.389 ***	−0.389 ***
X_{13} (Penalty)	-	0.767	0.423	−0.601 ***	−0.601 ***
X_{14} (Culture_1)	-	0.798	0.402	−0.480 ***	−0.480 ***
X_{15} (Culture_2)	-	0.649	0.478	−0.465 ***	−0.465 ***

Note: "Culture_1" stands for whether farmers consider the traditional culture into when they are making crop production decisions. "Culture_2" stands for whether farmers consider the traditional culture as a restraint in the use of pesticides. ***, **, and * denotes significance at 1%, 5%, and 10%, respectively.

4. Methodology

Our study aims to reveal whether Chinese traditional culture mitigates the moral hazard with regard to the farmer in the excessive use of pesticides. As this study indexes the attribute of moral hazard by means of a binary variable, the use of a conventional regression for a continuous dependent variable may result in a misleading inference. To address this concern, we use the logistic model, which remains the most widely used parametric method for the estimation of binary dependent variables. This model depends on two assumptions: a known index, which is assumed to influence choice, and a known parametric form for a distribution function, which is assumed to yield choice probabilities. The traditional parametric logistic model approach to model binary choice is as follows:

$$\mathrm{E}\left(Y|X=\mathrm{x}\right)=\Pr\left(Y=1|X\right)=\mathrm{F}\left(X\beta\right)=\frac{\exp\left(X\beta\right)}{1+\exp\left(X\beta\right)} \tag{1}$$

where the variable Y denotes the binary dependent variable with $Y = 1$, indicating the existence of moral hazard, and X stands for the independent variables including $\{X_p; p = 1, \ldots, 15\}$, which are listed in Section 3.2. The estimation problem is to estimate the unknown parameters β. F is the cumulative logistic distribution function. The estimation is typically facilitated by the maximum likelihood method.

The fitted models can be interpreted and estimated efficiently if the underlying assumptions are correct. However, if the model specifications are not satisfied, parametric estimates may be inconsistent and give a misleading regression result. It is possible to relax the restrictive assumption of the functional form by using either semi-parametric or nonparametric models. In these types of models, the functional form is unknown. The problems of estimating semi-parametric and nonparametric binary response models have generated considerable interest since the 1990s. There exists a rich literature of the semi-parametric estimation of binary response models, including Coslett [30], Manski [31], Rudd [32], Coslett [33], and so on. Pagan and Ullah [34] gave a recent survey of semi-parametric approaches to the estimation of binary response models. The semi-parametric logistic model generalizes a parametric logistic model by expanding the linear argument $(X\beta)$ to a partial linear argument $(X\beta + \mathrm{m}(\mathrm{Z}))$. The model expression is given as follows:

$$\mathrm{E}(Y|X=\mathrm{x}) = \mathrm{Pr}(Y=1|X) = \mathrm{F}(X\beta + \mathrm{m}(\mathrm{Z})) = \frac{\exp(X\beta + \mathrm{m}(\mathrm{Z}))}{1+\exp(X\beta + \mathrm{m}(\mathrm{Z}))} \quad (2)$$

where F(.) is a known function and m(.) is an unknown function. X contains $\{X_4, X_{10} \ldots, X_{15}\}$ and Z includes $\{X_1 \ldots X_3, X_5 \ldots X_9\}$ (this study categorizes the explanatory variables into two groups: parametric and nonparametric groups. The parametric group contains variables associated with important household characteristics, government regulation characteristics, and traditional culture, whereas the nonparametric one contains the rest of explanatory variables). This model allows for the modeling of the influence of a part the explanatory variables, **Z,** in a nonparametric way. The estimation process uses the method proposed by Severini and Staniswalis [35]. The method starts from fixing a value of β and to estimate a least favorable nonparametric function $m_\beta(\cdot)$. The estimated $m_\beta(\cdot)$ is then used to construct the profile likelihood forβ. As addressed in Severini and Staniswalis [35], the nonparametric function m (.) can be consistently estimated by $\hat{m}(\cdot) = \hat{m}_{\hat{\beta}}(\cdot)$. The profile likelihood function is given by:

$$\ell(Y, \nu_\beta, \theta) = \sum_{i=1}^{N} \ell\left(Y_i, \mathrm{F}\left(\mathrm{X_i}\beta + \mathrm{m}_\beta(\mathrm{Z_i})\right), \theta\right), \quad (3)$$

where $Y = \begin{pmatrix} Y_1 \\ \cdot \\ \cdot \\ \cdot \\ Y_N \end{pmatrix}$ and $\nu_\beta = \begin{pmatrix} \mathrm{F}\left(X_1\beta + \mathrm{m}_\beta(\mathrm{Z}_1)\right) \\ \cdot \\ \cdot \\ \cdot \\ \mathrm{F}\left(\mathrm{X_N}\beta + \mathrm{m}_\beta(\mathrm{Z_N})\right) \end{pmatrix}$. We maximize Equation (3) to estimate β.

On the other hand, the smoothed likelihood is used to estimate the nonparametric function $m_\beta(\mathrm{Z})$:

$$\ell_s\left(Y, \nu_{\mathrm{m}_\beta(Z)}, \theta\right) = \sum_{i=1}^{N} \ell\left(\mathrm{Y_i}, \mathrm{F}\left(\mathrm{X_i}\beta + \mathrm{m}_\beta(\mathrm{z})\right), \theta\right) \cdot \mathrm{K}\left(\frac{\mathrm{z}-\mathrm{Z_i}}{\mathrm{s}}\right), \quad (4)$$

where $\mathrm{K}(\cdot)$ is a Gaussian kernel function and s is the bandwidth (the details of nonparametric estimation can be found in Li and Rachine [36]). The optimal $m_\beta(z)$ can then be obtained by solving the equation:

$$0 = \sum_{i=1}^{N} \ell'\left(\mathrm{Y_i}, \mathrm{F}\left(\mathrm{X_i}\beta + \mathrm{m}_\beta(\mathrm{z})\right), \theta\right) \cdot \mathrm{K}\left(\frac{\mathrm{z}-\mathrm{Z_i}}{\mathrm{s}}\right) \quad (5)$$

5. Results and Discussion

This section begins with data analysis and follows with semi-parametric estimation of the logistic model. A conventional logistic estimator is additionally used for comparison. In China, the government prefers to use formal institutions to constrain farmers' behavior; therefore, our study will also compare the effect of formal institutions with informal institutions on MHB (in this paper, government regulations belong to formal institutions, while traditional culture belongs to informal institutions).

5.1. Estimation of Semi-Parametric Logistic Regression

In this section, we report the semi-parametric estimates of the logistic regression by Equation (2). The factors that affect farmers' MHB are divided into important and non-important variables, which are inserted into the parametric and non-parametric parts of the semi-parametric logistic model, respectively. Our purpose is to find the variables that have a significant impact on farmers' MHB, and the corresponding regression coefficients. As the estimated parameters can be easily transformed to the partial effect, this study provides the estimates of partial effects of important variables, which are categorized into the parametric part (due to the lack of a straightforward effects estimate, this study does not discuss the marginal effects of variables in the nonparametric section).

We write the model into the R programming language, and draw the regression results of the model with the aid of the R 3.2.2 software (Invented by Oakland University's Ihaka Ross and Gentleman Robert). The final regression results are shown in Table 6. It shows that risk preference (X_4), environmental concern (X_{10}), quality concern (X_{11}), inspection (X_{12}), penalty (X_{13}), culture_1 (X_{14}), and culture_2 (X_{15}) are significantly related to farmers' MHB, (while the variables that are not significant at the 10% level as shown in Table 4, are not shown in Table 6). As researchers have verified some of the factors, we hope to examine how the Chinese farmers' MHB in crop production is influenced by their traditional culture. Section 5.1.1 discusses the regression results of traditional culture cognition variables, Section 5.1.2 is a comparison between formal and informal institutions, and other factors are discussed in Section 5.1.3.

Table 6. Semi-parametric logistic regression.

Variables	Partial Effect
X_4 (Risk preference)	0.155 ***
X_{10} (Environmental concern)	−0.299 ***
X_{11} (Quality concern)	−0.299 ***
X_{12} (Inspection)	−0.132 **
X_{13} (Penalty)	−0.346 ***
X_{14} (Culture_1)	−0.149 **
X_{15} (Culture_2)	−0.167 ***

Note: *** and ** denotes significance at 1% and 5% respectively.

5.1.1. Regression Results of Traditional Culture Cognition Variables

As demonstrated in Table 6, the Culture_1 dummy is statistically significant with farmers' MHB, and the estimated marginal effect of the Culture_1 dummy is −0.149. This implies that when we control for extraneous variables, the probability of moral hazard decreases by 15% if farmers consider the traditional culture when they are making crop production decisions. The Culture_2 dummy is also statistically significant with farmers' MHB, and the estimated marginal effect of the Culture_2 dummy is −0.17. This implies that when we control for extraneous variables, the probability of moral hazard decreases by 17% if farmers consider the traditional culture as a powerful restraint when using pesticides. The evidence reveals that Chinese traditional culture has a positive effect on avoiding the moral hazard with regard to the farmer in the excessive use of pesticides.

Why can Chinese traditional culture restrict farmers' behavior? Chinese traditional culture was fostered in an agricultural society, including many traditional ideologies such as the golden mean, harmony, patriotism, self-improvement, moral standards, honesty, loyalty, cooperation, and solidarity. Conveying the harmonious relationship between human beings and nature, Chinese traditional culture has played a major role in improving farmer quality, regulating farmer behaviors, and developing rural society and economy. Farmers with high moral standards will internalize the excellent traditional culture, and this becomes a constraint factor on behavior. Therefore, under the influence of Chinese traditional culture and pushed by inner moral constraints, farmers will hesitate to perform harmful agricultural activities, such as increasing the concentration ratio of pesticides or using banned pesticides.

5.1.2. Comparison of the Effect of Formal Institutions and Informal Institutions on MHB.

In China, farmer's behaviors are constrained by formal and informal institutions. Specifically, government regulations (such as inspection, penalty, and law) belong to formal institutions, while traditional culture is considered an informal institution. China mainly depends on formal institutions to constrain farmers' behaviors. Therefore, it is necessary to verify whether the formal institutions (inspections, penalties) constrain farmers' behaviors.

As discussed in Starbird [37], legalistic terms are the most powerful instruments to mitigate the moral hazard, as they are compulsory. We examine whether the government's inspection mechanism is strict and whether the penalty system really works. In principle, the primary findings in our study confirm the theory. As can be seen from Table 6, inspection (X_{12}) is statistically significant with farmers' MHB, and the estimated marginal effect is −0.132. This implies that the probability of moral hazard decreases by 13% when the governmental inspection mechanism becomes strict while the other variables remain constant. Farmers will be inclined to control the use of pesticides, as they are conscious that the possibility of agro-products being detected is increasing. Penalty (X_{13}) is also statistically significant with farmers' MHB, and the estimated marginal effect −0.346. Implying that the probability of moral hazard decreases by 34.6% if farmers who are caught by the supervision department are eventually punished, while the other variables remain constant. Moreover, our findings address the importance of the execution of the punishment system. The estimated marginal effect of the penalty variable, −0.346, is twice as much as that of the inspection variable. In China, the penalty measures of the government are very effective in regulating the behavior of farmers. If one farmer who disobeys the rules of crop production pays a large fine, most farmers will adjust their application of pesticides accordingly. As a result, the MHB is going to decrease, in comparison with a light penalty. After comparing with the informal institutions (Chinese traditional culture), we find that formal institutions (inspection and penalty) are more effective in constraining of farmers' MHB.

5.1.3. Regression Results of Different Independent Variables

As numbers of samples for A2 (58 samples) and A3 (54 samples) are not enough to provide a consistent estimation of the semi-parametric model, this study only considers the A1 type. The results are reported in Table 7. In our paper, A1 represents the behaviors of farmers increasing pesticide concentration ratios while producing crops. From Table 7 we know that Chinese traditional culture is also statistically significant with farmers' above behavior, but the partial effect is lower than that of moral hazard behavior (as can be seen from Table 6), the reason may be that the pesticide concentration ratio is hard to control, and some farmers' behaviors have certain randomness. However, under the influence of Chinese traditional culture, there are still some farmers properly using pesticides; they do not increase the pesticide concentration ratio while producing crops.

Table 7. Semi-parametric logistic regression of independent variables (type A1).

Variables	Partial Effect
X_4 (Risk preference)	0.115
X_{10} (Environmental concern)	−0.290 ***
X_{11} (Quality concern)	−0.135 *
X_{12} (Inspection)	−0.112
X_{13} (Penalty)	−0.146
X_{14} (Culture_1)	−0.126 **
X_{15} (Culture_2)	−0.071 ***

Note: ***, **, and * denotes significance at 1%, 5%, and 10%, respectively.

5.1.4. Regression Results of Other Factors

In the literature, there have been several findings of how risk preference and farmers' attitudes towards the environment influence farmers' MHB in the use of pesticides (including Gleen [15], Philippe [18], and Teresa [38], Arthur [39], Salvatore [40]). Consistent with previous studies, our results find that the odds of MHB will decrease if farmers are concerned with environmental protection.

As demonstrated in Table 6, risk preference (X_4) is statistically significant with farmers' MHB, and the estimated marginal effect of risk preference dummy is 0.155, implying that the probability of moral hazard increases by 15.5% if farmers are risk-lovers. The reason could be that those farmers are not concerned about the negative effects of the excessive use of pesticides on environmental pollution. Therefore, in order to save the time of agricultural production, farmers dare to take risks. That is, risk-lover farmers have a higher inclination of moral hazard. Environmental concern (X_{10}) is also statistically significant with farmers' MHB and the estimated marginal effect of environmental concern dummy is -0.299. This suggests that the probability of moral hazard decreases by 29.9% if farmers are concerned about environmental pollution in rural areas. This indicates that the farmers concerned about environmental pollution in rural areas have less of a chance of MHB than those who are not. It may be that farmers who are concerned about environmental pollution in rural areas know the harm of excessive use of pesticides on the rural ecological environment, so those farmers will regulate the use of pesticides. Quality concern (X_{11}) is also statistically significant with farmers' MHB and the estimated marginal effect of quality concern dummy is -0.299. This implies that the probability of moral hazard decreases by 29.9% if farmers are concerned about the quality of agro-products. It is possible that the farmers concerned about the quality of agro-products have lower probability of moral hazard than those who are not. It could be possible that farmers who are concerned about the quality of agro-products are aware of the side effects of excessive use of pesticides on agro-products quality and safety, for example, excessive pesticide residues, so farmers will regulate the use of pesticides.

5.2. Sensitivity Analysis

In 5.1, the estimation of a semi-parametric logistic regression is conducted as we argue that there may exist model misspecification. For comparison, we also report the estimations of a parametric logistic regression of Equation (1) which assumes each variable should have a linear relationship with the dependent variable.

The estimates of parameters are demonstrated in Table 8. It can be observed that the odds ratios vary largely from 0.011 to 4.156. The risk preference has the highest odds ratios, 4.156, implying that the farmers with risk- taking propensity are 4.156 times more likely to use pesticides excessively.

The risk of moral hazard is 0.133 times greater for farmers who take the traditional culture into account when they using pesticides than those who do not. On the other hand, the risk of moral hazard is 0.279 times greater when the government's inspection mechanism is strict than when it is not strict. Comparing these two cases, the effect of regulating government's inspection is less effective than that of the advertisement of traditional culture regarding reducing moral hazard. However, this result seems to contradict the conventional economic senses. Thus, the model misspecification may yield incorrect inferences about the MHB.

Table 8. Parametric logistic regression.

Variables	Odds Ratios
X_4 (Risk preference)	4.156 ***
X_{10} (Environmental concern)	0.036 ***
X_{11} (Quality concern)	0.011 ***
X_{12} (Inspection)	0.279 ***
X_{13} (Penalty)	0.028 ***
X_{14} (Culture_1)	0.133 ***
X_{15} (Culture_2)	0.313 **

Note: *** and ** denote significance at 1% and 5% respectively.

5.3. Discussion

As the quality and safety incidents in agro-products are highly related to the farmers' MHB, many researchers try to uncover the factors that impact farmers' MHB. This study aims to analyze how Chinese traditional culture impacts farmers' MHB. From the above analysis, we know that Chinese traditional culture has a positive effect on avoiding the MHB with regard to the excessive use of pesticides. The results of this paper contribute to the literature on factors influencing farmers' MHB from a new perspective. Meanwhile, it is of great importance to guarantee agro-products quality and safety at the source. Compared with previous research, this paper analyzes the farmers' MHB restricting factors and puts forward policy implications, and we find a new factor restricting farmers' behavior. This is part of the research of farmers' behavior, which enriched the research of farmers' MHB, and deepened the understanding of the Chinese farmer's economic and social behavior.

6. Conclusions and Implications

Agricultural chemicals, such as pesticides, play a critical role in crop production and food safety in China. However, with the purpose of getting higher yields or better pesticide effect, farmers may excessively use pesticides, causing the occurrence of MHB. Farmers' MHB has resulted in serious agro-product quality and safety problems. Regulating pesticide usage to provide safe and nutritional agro-products remains one of the meaningful projects in 21st-century China. Therefore, finding out the factors affecting farmers' MHB is of great importance. As other factors have been verified by researchers, this study examined how the Chinese traditional culture influences farmers' MHB in the use of pesticides based on a household survey in four provinces of rural China. The previous research adopted binary logistic models to study farmers' MHB, but if the model specifications are not satisfied, parametric estimates may be inconsistent and give a misleading regression result. Instead we conduct semi-parametric estimation of a logistic model to reveal how the Chinese traditional culture influences farmers' MHB. This helps in estimating the true effect of factors related to farmers' MHB.

Three main conclusions can be drawn from the results of this study. First, we find that the Chinese traditional culture has a significant impact on avoiding the moral hazard with regard to the excessive use of pesticides. The estimated marginal effect of the Culture_1 dummy is −0.1468. This implies that when we control for extraneous variables, the probability of moral hazard decreases by 15% if farmers consider the traditional culture when making crop production decisions. The estimated marginal effect of the Culture_2 dummy is −0.17. This implies that when we control for extraneous variables, the probability of moral hazard decreases by 17% if farmers consider the traditional culture as a powerful restraint when using pesticides. Second, this study suggests that formal institutions are more effective in constraining farmers' production behavior, which helps to reduce the probability of moral hazard. Third, after comparing the estimated results with a conventional logistic model, we find that the model misspecification may yield incorrect inferences about the moral hazard. The reason could be that some variables are not necessarily linear with dependent variables, but we assume that there is a linear relationship between them.

Agriculture is largely affected by weather fluctuations and climate changes, and it is full of risks. There are abundant public risk management programs both in developed and developing countries, it offers useful risk management strategies, such as crop insurance subsidies and crop disaster payments. However, the risk programs, like crop insurance subsides, may cause farmers to increase chemical use, which may also promote environmental degradation. A vast literature focuses on the potential environmental impacts of government-sponsored risk management programs [7,9,10,41,42]. Our study examines the relationship between Chinese traditional culture and farmers' MHB in crop production. The results show that the Chinese traditional cultures has a positive effect on avoiding the MHB with regard to the excessive use of pesticides, and it provides a new idea of risk management. It is necessary to compare our results with the existing literatures [43–46]. The existing literature mainly evaluated the effects of public risk management policies, the results showing that the risk management programs may incentivize activities harmful for the environment, while our study mainly examines how Chinese farmers' moral hazard behavior in crop production is influenced by traditional culture, and our results confirm the conventional view that Chinese traditional culture helps to guide farmers to adopt positive behaviors, such as environmental friendly behavior.

This study has important policy implications. First, as government regulation measures are more effective, in order to have a long-term and more significant impact on farmers' MHB, government should formulate and perfect relevant policies, such as improving the frequency of random inspections, intensifying the penalty, and strengthening market supervision for agricultural inputs. Meanwhile, as most farmers have little knowledge about production safety or environmental protection, training and guidance is also needed. Second, Chinese traditional culture has a significant impact on avoiding the MHB devoted to usage of pesticides, so we should pay more attention to the important role of Chinese traditional culture. Therefore, it is necessary to make full use of Chinese traditional culture in regulating farmers' behavior. For example, we can spread the Chinese traditional culture to farmers by mobile phone, TV, newspaper, and other forms. By strengthening the traditional culture education, we can enhance farmers' moral sentiments, moral standards, conscience, and social responsibility, enabling farmers to achieve harmony between human beings and nature. Considering that farmers' attitudes towards agro-products and environmental protection have a significant effect on farmers' MHB, it is crucially important to improve farmers' quality, safety, and environmental consciousness. Village committees can also regularly publicize some agro-product quality and safety incidents to farmers. The public can also inform farmers of the importance of environmental protection on their health, on the quality and safety of agro-products, and the sustainable development of agriculture. In all, our purpose is to guide farmers to regulate the use of pesticides.

While this study has made significant advancements in knowledge about the impact of Chinese traditional culture on farmers' MHB it, nevertheless, have its limitations. That is, the number of samples is not large enough, we did not compare the farmers' MHB of different regions, and we do not consider other factors such as agricultural organizations, buyers, or the farmers' self-discipline, but these factors may significantly affect farmers' MHB. There are still unresolved questions with this paper. For example, we can refine the influence of Chinese traditional culture on farmers' behavior into constraints and incentives. In addition, we can expand the investigation province and increase the sample to achieve better statistical testing and, hence, we can study whether the influence of Chinese traditional culture varies with different rural economic development levels.

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sustainability

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Article

Forested Land Use Efficiency in China: Spatiotemporal Patterns and Influencing Factors from 1999 to 2010

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Abstract: More attention needs to be paid to efficiency in the use of forested land. This article is devoted to the study of forested land use efficiency (FLUE) and its spatiotemporal differences in China during the period from 1999 to 2010. The global generalized directional distance function (GGDDF) and global Malmquist–Luenberger (GML) index models are used to measure and analyze forested land use efficiency. The empirical results showed that forested land use efficiency continued to increase during the study period. The FLUE of Shanghai was always highest, whereas Tibet, Inner Mongolia, and Qinghai suffered the most inefficiency in forested land use. There were obvious spatial differences in forested land use efficiency among the 31 provinces. Urbanization, economic development context, and population density were the main factors influencing spatial differences in forested land use efficiency. The growth in the non-radial Malmquist forested land performance index (NMPFI) in the east was driven mainly by technological change, whereas the growth in the central region was mostly derived from progress in efficiency change. For the western region, the change in the productivity of forested land was the result of the interactive effect between technological change and effect change, and only in the western region did an absolute β-convergence exist.

Keywords: forested land use efficiency; global generalized directional distance function (GGDDF); global Malmquist–Luenberger (GML index); China

1. Introduction

As one of the dominant land resources in China, forested land covers approximately 305.90 million hectares, accounting for 31.75% of the land area in China according to the Seventh National Forest Resource Inventory [1]. In addition to economic output, forested land delivers a diversity of ecological services ranging from climate regulation, soil erosion control, and biodiversity maintenance to water quality amelioration and recreational opportunity supply [2,3] that are related to the ecological security of the state. In the early 1980s, the opening of commercial timber markets brought an increased annual rate of commercial harvesting; this growth rate was often greater than the speed of natural forest regrowth by the mid-1980s [4]. In recent decades, urbanization—the most powerful driver of world development—has aggravated the forestland conversion and increased the demand for forestry [2,5], which is attributed to forest fragmentation and loss. A series of floods occurred in the 1990s, which spurred the implementation of the Natural Forest Protection Program (NEPP, in 1998) and the Sloping Land Conversion Program (SLCP, in 1999) to protect natural forests and the fragile ecological zone [4]. Even so, forest fragmentation and loss due to historical reasons are still the current context for forested land [6]. However, forest fragmentation and loss not only destroy ecological functions but also threaten forestry development. On the one hand, forest loss directly reduces the quantity and quality of forest resources and forestry products, whereas on the other hand, forest landscape pattern changes (e.g., fragmentation, isolation) increase the difficulty and cost of forestry management; that is to say, these changes will influence forested land use efficiency. Simply, forested land use efficiency can be defined as follows: under the premise of rational use of forested land resources, the quantity and quality of forested outputs can be maximized. Hence, it is necessary to understand the current situation and impact mechanism of forested land use efficiency in China.

2. Literature Review

Forestry efficiency research has been conducted by a large number of scholars. LeBel and Stuart [7] used the data envelopment analysis (DEA) model to measure and analyze the input–output efficiency of 23 woodcutters from 1988 to 1994, marking the earliest research in forestry efficiency. Differing from the research objective of LeBel and Stuart, Viitala and Hänninen [8] used the same model to analyze the efficiencies of 19 public forestry organizations in Finland and concluded that the efficiency of the 19 public forestry organizations showed obvious discrepancies and that investment could save at least 20% through more efficient management. Since then, due to the popularity of the DEA model, many studies of forestry efficiency have been conducted. For example, Lee [9] measured the relative efficiency of global forest and paper companies, and Salehirad and Sowlati [10] analyzed the efficiency of the wood industry in Canada. In China, research in forestry efficiency started relatively late. In the beginning, most researchers used qualitative research methods to express their points of view. Recently, with the development of computer technology, many scholars have used empirical analysis methods to study the input–output efficiency of forestry. For instance, Lai and Zhang [11] used the DEA model to measure, sort, and discuss the input–output efficiency of forestry for 21 cities in Guangdong, China. They used the super-efficiency DEA model to evaluate multiple decision-making units at the same time [12]. Shi and Zhang [13] used the DEA model to analyze collective forestland management efficiency from the perspective of farmers, which is different than the management efficiency of state-owned forestland. Li et al. [14] and Tian and Xu [15] used the same model to analyze the forestry efficiency of China; the former measured efficiency in the year 2006, whereas the latter measured efficiency for the period from 1993 to 2010 and analyzed the changing trends.

Although studies in the area of forestry efficiency are plentiful, there is little research that considers an input factor as a research object to analyze its efficiency. Measuring the efficiency of a certain input factor can help us further deepen our understanding of comprehensive utilization efficiency. Research into forested land use efficiency seems more meaningful than research on capital use efficiency and labor use efficiency in forestry. In 1993, the International Geosphere-Biosphere Programme (IGBP) and the International Human Dimensions Programme on Global Environmental Change (IHDP) developed a scientific research plan for Land Use/Land Cover Changes (LUCC) and established this plan as the core content of global change research [16–18]. On this basis, the Global Land Project (GLP) was started in 2005, with the measurement, simulation, and understanding of land use and change from the perspective of the human social–ecological coupling system as its core objectives [19,20]. What is more, the challenges of forested land use in China need to be visualized and attempts should be made to solve them. Hence, the study of forested land use efficiency has special significance to regions and even to the whole world, which not only helps to determine the status quo of the input and output of forested land, but also provides a basis for decisions regarding more effective use of forested land.

By examining the literature, we concluded that the reasons few people study the utilization efficiency of forested land are twofold: (1) forested land use efficiency has not attracted much attention and (2) the commonly used method in the study of forestry efficiency is the DEA model or the super-efficiency DEA model. This type of model cannot provide an effective way to measure the utilization efficiency of a certain input factor; it measures only comprehensive utilization efficiency.

However, it is still necessary to introduce the DEA model, as it is the basis for follow-up efficiency models. The data envelopment analysis (DEA) model is an effective evaluation method for the same type of unit because it uses the observed values of multiple inputs and multiple outputs. A meaningful conclusion of the DEA model is that there will always be a certain gap between actual resource allocation and optimal resource allocation, and this gap can be called the slack variable, expressed as an input excess or output shortage of the observation [21]. One problem of the traditional DEA model is that the slack variables are not considered in the objective function, which can lead to inaccurate results in efficiency evaluations [22]. Tone [23] has proposed a non-radial and nonparametric slacks-based measure (SBM) model to solve this defect. The SBM model can comprehensively consider inputs and outputs for each decision-making unit, and slack variables can be placed directly into the objective function. The SBM model has been widely adopted. For example, Yang et al. [24], Pan and Ying [25], Yang et al. [26], and Xie and Wang [21] introduced the SBM-undesirable model to analyze and evaluate highway transportation efficiency, agricultural eco-efficiency, urban land use efficiency, and urban industrial land use efficiency, respectively. Recently, the efficiency measurement model has evolved into a sequential generalized directional distance function (SGDDF) for the purpose of analyzing dynamic changes in the performance of different resources [27]. The global generalized directional distance function (GGDDF) model—an improvement to the SGDDF model—performs efficiency evaluation under the global benchmark technology. Xie et al. [28] used the model to analyze the dynamic changes of industrial land green use efficiency in China. In addition, the Malmquist–Luenberger (ML) index is used to measure total factor productivity (TFP) for some resources or industries pertaining to the dynamic analysis [22,29–31]. Wang et al. [32] have extended the model with the global ML (GML) index, which analyzes the productivity of China from the point of view of energy, the environment, and economics.

This paper aims to apply GGDDF and GML models to analyze the dynamic changes in forested land use efficiency (FLUE) in China. The total factor index can be referred to as the non-radial Malmquist forested land performance index (NMFLPI). We then explore the main contributors to the growth in the NMFLPI by decomposing the FLUE into two indices, i.e., efficiency change (EC) and technological change (TC). Lastly, the factors influencing spatiotemporal differences in forested land use efficiency and convergence patterns among regions are explored to further deepen our understanding of forested land use efficiency in China.

Therefore, this paper makes two main contributions to the relevant studies. First, we computed the FLUE for each province in China under a global environmental technology framework and analyzed their spatiotemporal differences. Then, we determined the main factors that influence the spatiotemporal differences in forested land use efficiency. Second, we computed the NMFLPI to measure the dynamic changes in the FLUE and determine which NMFLPI decomposition index, i.e., EC or TC, is the main contributor to the growth of the NMFLPI.

The remainder of this paper is organized as follows: Section 3 introduces the methods and data; Section 4 shows the results of the empirical analysis, and Section 5 concludes the paper and presents the discussion.

3. Methods and Data

3.1. Non-Radial Directional Distance Function (NDDF)

We assume that there are N provinces in our study and that each city has M inputs (x) to produce J desirable outputs (y) and K undesirable outputs (b), with the matrices of inputs, desirable outputs, and undesirable outputs in city n as follows [22,33–35]:

$$X = [x_{11}, \cdots, x_{Mn}] \in R^{M \times n},$$

$$Y = [y_{11}, \cdots, y_{Mn}] \in R^{J \times n},$$

$$B = [b_{11}, \cdots, b_{Mn}] \in R^{K \times n}$$

where $X > 0$, $Y > 0$ and $B > 0$. The production possibility set $T(x)$ can be expressed as follows:

$$T(\mathrm{x}) = \{(x, y, b) |\ x \text{ can produce } (y, b),\ x \geqslant X\lambda,\ y \leqslant Y\lambda,\ b = B\lambda,\ \lambda \geqslant 0\} \tag{1}$$

where the production possibility set $T(x)$ is assumed to satisfy the production function theory [23], and a benchmark for global technology can be expressed as the accumulation of each period: that is, $T_G = T_1 \cup T_2 \cup \cdots \cup T_N$. In addition, the traditional radial DDF approach always assumes that the linear programming solution allows both inputs and outputs to expand or contract, proportional to the original inputs and outputs, which is almost impossible in real production. To overcome this shortcoming, a non-radial DDF approach was developed and has become widely used in studies of resource efficiency evaluation. Moreover, $w^T = (x, y, b)^T$ in Equation (3) is the standard weight matrix of inputs and outputs, and $g = (-g_x, g_y - g_b)$ are the direction vectors. $\Phi = (x, y, b)$ represents the adjustment ratios of all the inputs and outputs that are nonnegative numbers. The parameter *diag* is the diagonal matrix. Thus, the adjustment ratios of all the inputs and outputs can be different, which is more likely to reflect the actual production reality. Equation (4) represents the efficiency evaluation model under the contemporaneous benchmark technology set, and Equation (5) is under the global benchmark technology set.

$$\vec{D}(x, y, b; g) = sup\{\varphi : ((x, y, b) + g \times \varphi) \in T\} \tag{2}$$

$$\vec{D}(x, y, b; g) = sup\left\{w^T \varphi : ((x, y, b) + g \times \mathrm{diag}(\varphi)) \in T\right\} \tag{3}$$

$$\vec{D} = \max(\alpha_1 + \cdots + \alpha_i + \beta_1 + \cdots + \beta_j + \gamma_1 + \cdots + \gamma_k)$$
$$\text{s.t.} \begin{cases} \sum\limits_{n=1}^{N} \lambda_n x_{mn} \leqslant (1 - \alpha_m g_m) X_{m0} \\ \sum\limits_{n=1}^{N} \lambda_n y_{jn} \geqslant (1 + \beta_j g_j) Y_{J0} \\ \sum\limits_{n=1}^{N} \lambda_n b_{kn} = (1 - \gamma_k g_k) B_{K0} \end{cases} \tag{4}$$

and $\lambda \geqslant 0, \alpha_m \geqslant 0,\ \beta_j \geqslant 0,\ \gamma_k \geqslant 0,\ m = 1, 2, \cdots, M; j = 1, 2, \cdots, J; k = 1, 2, \cdots, K$, where the superscripts m, j, and k, respectively, represent the mth input, the jth desirable output, and the kth undesirable output of the province under evaluation. The parameters $\alpha_{i,}$, γ_k, and β_j are the adjustment ratios of the inputs, desirable outputs, and undesirable outputs, respectively, and λ is a nonnegative vector. The superscripts t and n refer to the year t in the study period and the number of provinces in the sample. The province is located on the frontier of production if $\alpha_{i,}$, γ_k, and β_j have zero values. In addition, we can use the global generalized directional distance function (GGDDF) model to perform the study under the global benchmark technology set, which is expressed in Equation (5), and the solutions of different years can be compared with each other.

$$\vec{D} = max(\alpha_1 + \cdots + \alpha_i + \beta_1 + \cdots + \beta_j + \gamma_1 + \cdots + \gamma_k)$$
$$s.t. \begin{cases} \sum\limits_{t=1}^{T} \sum\limits_{n=1}^{N} \lambda_n^t x_{mn}^t \leqslant (1 - \alpha_m g_i) X_{m0}^t \\ \sum\limits_{t=1}^{T} \sum\limits_{n=1}^{N} \lambda_n^t y_{jn}^t \geqslant (1 - \beta_j g_j) Y_{j0}^t \\ \sum\limits_{t=1}^{T} \sum\limits_{n=1}^{N} \lambda_n^t b_{kn}^t = (1 - \gamma_k g_k) B_{k0}^t \end{cases} \tag{5}$$

and $\lambda^t \geqslant 0$, $\alpha_m \geqslant 0$, $\beta_j \geqslant 0$, $\gamma_k \geqslant 0$, $m = 1, 2, \cdots, M$; $j = 1, 2, \cdots, J$; $k = 1, 2, \cdots, K$, where the meanings of the superscripts are the same as in Equation (4).

In this paper, we assume that the inputs are forested land, labor, and fixed asset investments in forested land. In forestry, there is no undesirable output, so the output is forestry GDP, which is a desirable output. According to previous studies [22,33,34], we set the weight vectors of inputs and output as (1/6, 1/6, 1/6, 1/2), and the direction vector as (1, 1). Thus, forested land use efficiency (FLUE) can be expressed as follows:

$$FLUE = \frac{(1 - \alpha_{land})}{\left(1 + \beta_{gdp}\right)} \tag{6}$$

where α_{land} and β_{gdp} are the adjustment ratios of the corresponding indicators. The FLUE is obviously between 0 and 1, where forested land is efficiently used when FLUE is equal to 1 and is inefficiently used when FLUE is less than 1.

3.2. Global Malmquist Index for Measuring Forested Land Productivity Growth

The traditional Malmquist–Luenberger (ML) index faces potential limitations of linear programming that cannot provide effective solutions when dealing with extreme data, and it does not have cyclicity or transitivity [22]. In response, Oh [35] combined the concept of productivity and the directional distance function, constructing a global Malmquist–Luenberger (GML) index to replace the traditional ML index. Here, we adopted this approach to measuring the dynamic changes of FLUE by using the GML index, which can be called the non-radial Malmquist forested land performance index (NMFLPI), as follows:

$$\text{NMFPI} = \left(LD^{t,t+1}, LB^{t,t+1}, K^{t,t+1}, GDP^{t,t+1}\right) = \frac{FLUE\left(LD^{t+1}, LB^{t+1}, K^{t+1}, GDP^{t+1}\right)}{FLUE\left(LD^{t}, LB^{t}, K^{t}, GDP^{t}\right)} \tag{7}$$

where the $FLUE^G\left(.^t\right)$ is given by solving the model in Equation (6), and if the NMFLPI index is greater than, equal to, or less than 1, these situations represent the FLUE of the province under estimation enjoying positive progress, not changing, or suffering a deterioration, respectively, during the time t and $t + 1$. The NMFLPI index can be decomposed as follows:

$$\begin{aligned} \text{NMFPI} = \left(LD^{t,t+1}, LB^{t,t+1}, K^{t,t+1}, GDP^{t,t+1}\right) &= \frac{FLUE^G\left(.^{t+1}\right)}{FLUE^G\left(.^t\right)} = \frac{FLUE^G\left(.^{t+1}\right)/\text{CRS}}{FLUE^G\left(.^t\right)/\text{CRS}} \\ &= \frac{\frac{FLUE^G\left(.^{t+1}\right)/\text{CRS}}{FLUE^D\left(.^{t+1}\right)/\text{CRS}}}{\frac{FLUE^G\left(.^{t}\right)/\text{CRS}}{FLUE^D\left(.^{t}\right)/\text{CRS}}} \times \frac{FLUE^D\left(.^{t+1}\right)/\text{CRS}}{FLUE^D\left(.^t\right)/\text{CRS}} = TC^{t,t+1} \times EC^{t,t+1} \end{aligned} \tag{8}$$

where CRS implies constant returns to scale and variable returns to scale. It is CRS when the constraint of $\sum_{i=1}^{N} \lambda^t = 1$ is imposed in Equations (7) and (8). The superscripts G and D relate to the solutions under the global benchmark technology set T^G and the contemporaneous benchmark technology set T^D, respectively. Additionally, technological change (TC) refers to the shift of the production frontier, and a value of TC greater than, equal to, or less than 1 indicates that production technology is enjoying progress, is not changing, or is suffering deterioration, respectively. The efficiency change (EC), which occurs on the same production frontier, has values greater than, equal to, or less than 1, indicating that the technical efficiency has gained, has not changed, or has been lost, respectively.

3.3. Data

We constructed an indicator system for the evaluation of FLUE, as has been performed in many previous studies [29,33,34], using the following input and output indicators. (1) Input indicators: The factors include mainly land, capital, and labor in accordance with production function theory, and they refer to the area of forested land and annual fixed asset investments in forestry and forestry workers, respectively; (2) Output: The forestry GDP was selected as the output in the process of forestry production according previous literature [29,33,34]. The forestry GDP and fixed asset investments in forestry have, respectively, conversed by the GDP minus index and price index of fixed assets, taking the year of 1999 as the base. The above data come from the *China Statistical Yearbook* and the *China Forestry Statistical Yearbook* from 2000 to 2011 [36].

4. Empirical Results

4.1. FLUE

In this section, we used Equation (5) to compute FLUEs for China and the 31 provinces during the study period. Figure 1 shows the changing trend of FLUE for China from 1999 to 2010. During the period from 1999 to 2008, FLUE in China experienced slow fluctuating growth. The lowest efficiency appeared in 2000 with a value of 0.09, and the highest efficiency appeared in 2007 with a value of 0.19. The average annual growth rate was 0.138. While the FLUE in China rose in a straight line during the period after 2008, the highest FLUE appeared in 2010 with a value of 0.40. The annual growth rate was 0.325 during the period from 2008 to 2010. The main reason for this changing trend in FLUE may be that forestry in the state maintained economic growth mainly through increases in fixed asset investment before 2008 [37], which is shown in Figure 2. However, in 2008, the Central Committee of the Communist Party of China (CPC) and the State Council promulgated the “opinions on comprehensively promoting the reform of collective forest right system” [38], which has allowed the contractual management rights of collective forest land and forest ownership to actually reach the farmers, established the independent position of peasant management, and achieved a great liberation of the rural productive forces. This policy greatly improved farmers’ enthusiasm for afforestation, forest protection, and silviculture. Obvious evidence can be found in Figure 2, which illustrates a case in which forestry practitioners and the area of forested land have not changed very much, and the investment of fixed assets in forested land has declined. Although the growth trend of FLUE in China is obvious during the 1999–2010 period, the efficiency values were all less than 1; that is to say, forested land use in China was lacking in efficiency during the time of the study.

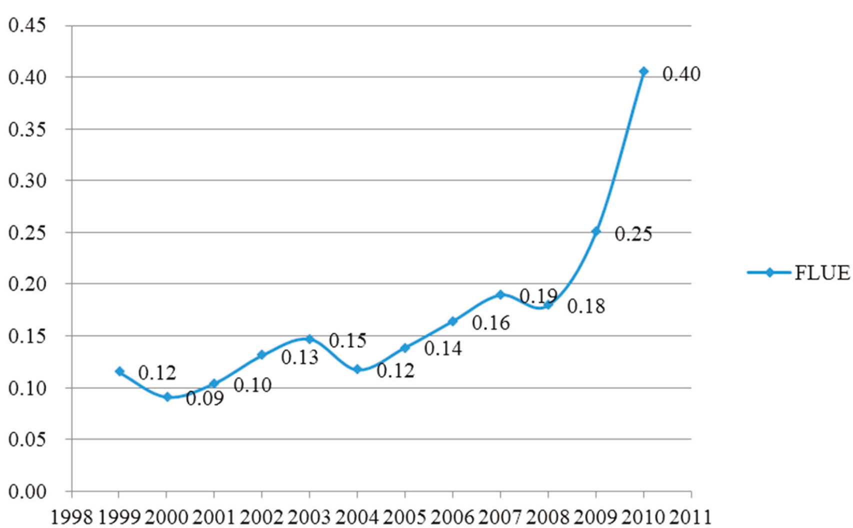

Figure 1. Forested land use efficiency in China from 1999 to 2010.

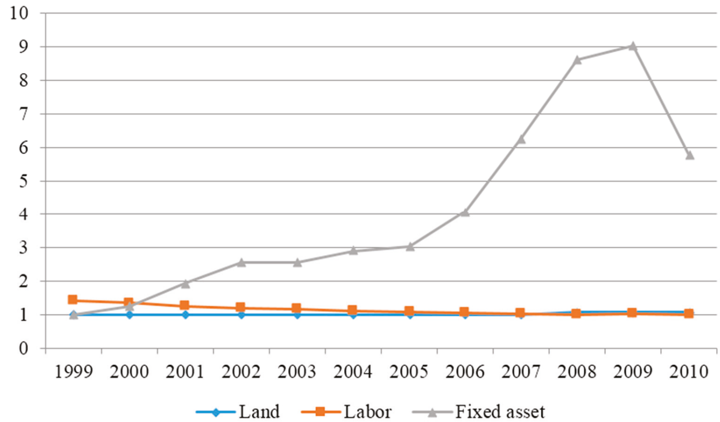

Figure 2. Variation of input factors from 1999 to 2010.

Figure 3 shows the FLUEs of the 31 provinces in representative years during the study period. In 1999, the FLUE values for Shanghai and Tianjin reached 1, which indicates that their forested land use was at the forefront of production technology. The remaining provinces were in an inefficient state, especially Tibet, Inner Mongolia and Qinghai, which had FLUE values near zero. In 2003, the overall efficiency in China improved slightly. Shanghai was still at the forefront of production technology, whereas the FLUEs of Tibet, Inner Mongolia, and Qinghai remained in an inefficient state. In 2007, the growth trend of FLUE in China continued, especially in Liaoning, Jilin, Heilongjiang, Jiangsu, Zhejiang, Anhui, Fujian, Jiangxi, Shandong, Henan, Hubei, Hunan, Guangdong, Guangxi, and Hainan. Shanghai still had the highest efficiency in forested land use, whereas the FLUEs of Tibet, Inner Mongolia, and Qinghai were still in an inefficient state. In 2010, there were obvious improvements in FLUE: the number of provinces with FLUE values equal to 1 increased to 6; the remaining provinces continued to increase their values, with the exception of Tibet, Inner Mongolia, and Qinghai. In summary, the FLUE of Shanghai was always highest, whereas Tibet, Inner Mongolia, and Qinghai suffered the most inefficiency in forested land use with efficiency values near zero, indicating that forested land use cannot produce enough economic output.

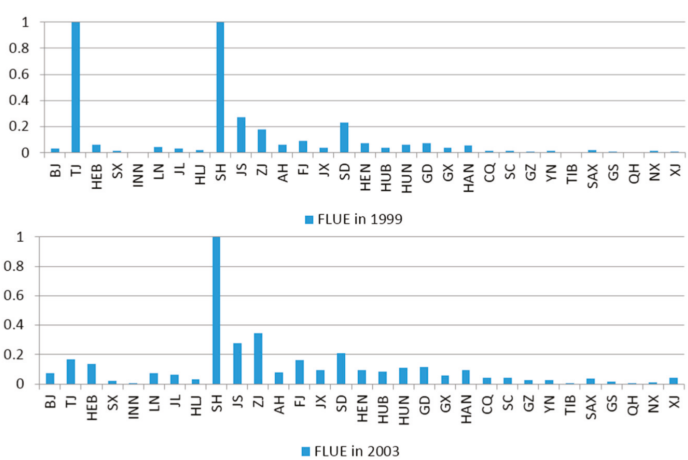

Figure 3. *Cont*.

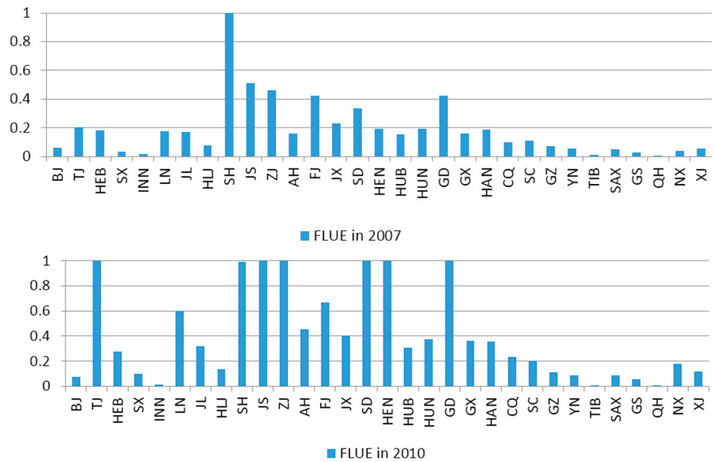

Figure 3. The forested land use efficiency (FLUE) of 31 provinces in China from 1999 to 2010. Abbreviation: Beijing (BJ), Tianjin (TJ), Hebei (HEB), Shanxi (SX), Inner Mongolia (INN), Liaoning (LN), Jilin (JL), Heilongjiang (HLJ), Shanghai (SH), Jiangsu (JS), Zhejiang (ZJ), Anhui (AH), Fujian (FJ), Jiangxi (JX), Shandong (SD), Henan (HN), Hubei (HUB), Hunan (HUN), Guangdong (GD), Guangxi (GX), Hainan (HAN), Chongqing (CQ), Sichuan (SC), Guizhou (GZ), Yunnan (YN), Tibet (TIB), Shannxi (SAX), Gansu (GS), Qinghai (QH), Ningxia (NX), Xinjiang (XJ).

To discover the spatiotemporal difference in the FLUEs of the 31 provinces, we used the Natural Breaks tool in Arcgis10.2 software (ESRI, Redlands, CA, USA) to classify their FLUEs. The results are shown in Figure 4.

The spatiotemporal pattern change of forested land use efficiency (FLUE) in China is displayed in Figure 4. In 1999, there were two eastern coastal municipalities (Tianjin and Shanghai) with FLUE values greater than 0.3, three eastern coastal provinces (Shandong, Zhejiang, and Jiangsu) with FLUE value between 0.1 and 0.3 and the remaining provinces had FLUE values of less than 0.1. In 2003, the spatiotemporal pattern changed slightly, the FLUEs of Shanghai and Jiangsu were the highest and the number of provinces with FLUE values between 0.1 and 0.3 increased to 6. In 2007, the number of provinces with FLUE value greater than 0.1 increased to 18, the provinces with FLUE values greater than 0.3 were mainly distributed in southeastern coast China, the provinces with FLUE values between 0.1 and 0.3 contained the 6 provinces of Mid-China, two northeastern provinces, a province on the North China Plain, and a province in southwestern China. In 2010, the trend of growth in FLUE continued to extend to the west, which is highlighted by the expanded number of provinces with FLUE values greater than 0.3. On the whole, forested land use efficiency in China shows obvious regional differences, presenting a declining trend from east to west with the exception of several provinces.

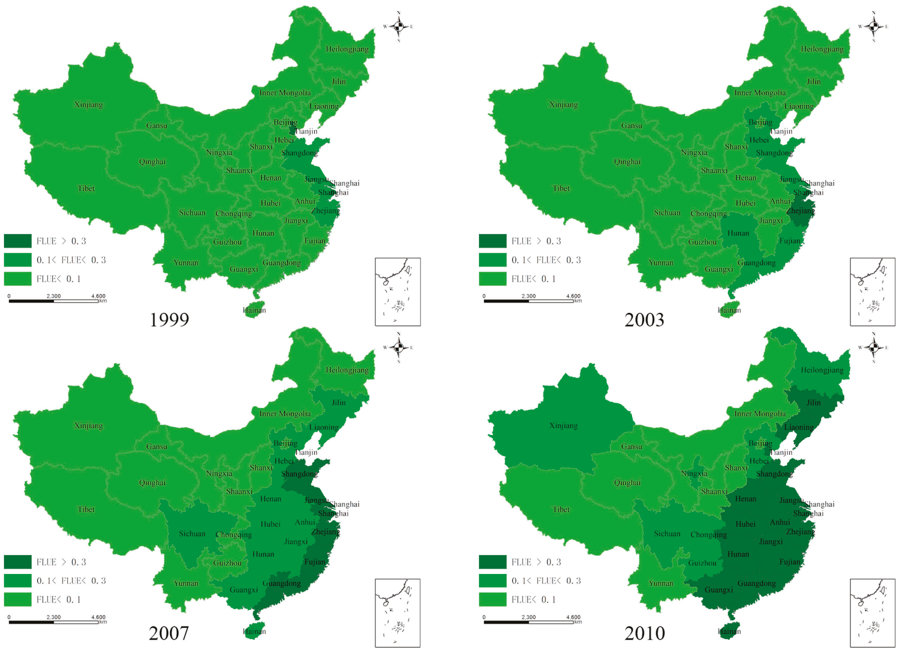

Figure 4. Spatiotemporal pattern change of forested land use efficiency (FLUE) in China.

4.2. Influential Factors in Regional FLUE Differences

It is easy to associate regional socioeconomic differentiation and regional climate differences with the obvious regional differences of FLUE. Hence, we selected potential explanatory variables based on a literature review of each category (demography, economy, societies and arctic climate) [39–41]. Three variables were selected to indicate demography: total population, population density, and nonagricultural population proportion. Gross domestic product, total forestry output, the proportion of secondary industry, the proportion of tertiary industry, and tourism revenue in forestry were selected for economy. Four variables were selected to indicate social activities: foreign investment in forestry, road mileage, railway mileage, and number of employees in forestry [41]. Two variables were selected to indicate arctic climate. A correlation analysis and principal component analysis were also applied to select the most important indicator. The final set included nine indicators: population density (PD), proportion of nonagricultural population (PNAP), gross domestic product per capita (PGDP), total forestry output (TFO), investment in fixed assets (IFA), road mileage (RM), land urbanization rate (LUR), annual rainfall (AR), and annual average temperature (AAT). Moreover, the Moran's I index [42] was calculated to examine the autocorrelation of the variables. The results showed that the global Moran's I values were not statistically significant, indicating that no spatial autocorrelation exists. There will be a very natural difference among different cross-sectional data and different individual values, so we built a fixed effects regression model based on panel data. The model is as follows:

$$\begin{aligned} ln\ y_{it} = \alpha_{it} + \beta_1 ln\ IFA_{it} + \beta_2 ln\ TFO_{it} + \beta_3 PGDP_{it} + \beta_4 ln\ PD_{it} + \beta_5 AR_{it} + \beta_6 AAT_{IT} \\ + \beta_7 RM_{it} + \beta_8 PNAP + \beta_9 LUR_{it} + \mu_{it} \end{aligned} \quad (9)$$

where i and t (t = 1999, . . . , 2010) represent province i and year t, respectively. The term α_{it} is a constant, and μ_{it} is the random error term. The term y_{it} is the FLUE value for province i. The regression result is shown in Table 1.

Table 1. Result of regression. *** $p < 0.001$, ** $p < 0.05$, * $p < 0.01$.

	Coefficient	***p* Value**
Ln IFA	−0.0419841	0.399
Ln TFO	0.0338353	0.477
PGDP	0.0021411	0.092 *
Ln PD	0.3525266	0.041 **
AR	0.368872	0.141
AAT	0.0235676	0.251
RM	−0.61059	0.426
PNAP	0.024445	0.014 **
LUR	0.0303061	0.000 ***
adjusted R-squared = 0.6768		

The adjusted R-squared is 0.6768, which indicates that the results explain the model reasonably well. From the results of the *p* value, we know that the coefficients of the land urbanization rate (LUR) and the proportion of nonagricultural population (PNAP) are statistically significant. The positive coefficients imply that the land urbanization rate and proportion of nonagricultural population had a significant positive impact on FLUE in China. The land urbanization rate and the proportion of nonagricultural population measure urbanization from two different perspectives; the common results of the improvement of the two indicators are increasing demand in all types of products, and forestry products are no exception. Population density (PD) was also an important factor influencing forested land use efficiency; similar to LUR and PNAP, population density had an impact on the demand for forestry products. The coefficient of gross domestic product per capita (PGDP) is statistically significant at the 10% level, the positive coefficient indicates that economic development will promote the efficiency. We did not find specific evidence that climate factors have a significant impact on the spatial differentiation of forested land use efficiency in China from the results of this regression.

4.3. NMPFI and Its Decompositions

We know that there was an obvious spatial differentiation of forested land use efficiency in China. According to geographical closeness and forestry development, we divided the 31 provinces across China into three regions: eastern (E), central (C) and western (W). The eastern region includes three municipalities (Beijing, Tianjing, and Shanghai) and eight coastal provinces (Hebei, Liaoning, Jiangsu, Zhejiang, Fujian, Shandong, Guangdong, and Hainan). This region enjoys advanced production technology and well-developed transportation. The central region consists of eight inland provinces (Shanxi, Jilin, Heilongjiang, Anhui, Jiangxi, Henan, and Hunan); this region is famous for its high resource consumption. The western region consists of one municipality (Chongqing) and eleven inland provinces and autonomous regions (Inner Mongolia, Xinjiang, Gansu, Qinghai, Shaanxi, Ningxia, Sichuan, Yunnan, Guizhou, Guangxi, and Tibet). This region has poor economic development.

According to Equations (7) and (8), we computed the NMPFI and its decompositions of forested land productivity. Figure 5 shows the trends of the NMPFI and its decompositions in China during the study period. We find that the NMPFIs in China were always above 1, indicating that the productivity of forested land in China was always increasing. There were three peak values, corresponding to the period from 2001 to 2002, the period from 2005 to 2006, and the period from 2009 to 2010, and a valley value corresponding to the period from 2007 to 2008. The NMPFI grew rapidly after the year 2008, which was consistent with the time of introduction the policy of "opinions on comprehensively promoting the reform of collective forest right system" [38]. During the period of 1999–2007, the trend for EC was relatively stable, and the values were always above 1, indicating that the efficiency change was progressing. During the 2007–2008 period, the EC was less than 1, indicating that the efficiency change suffered deterioration. After 2008, the EC rocketed, and the value of EC reached 1.60 during the period from 2009 to 2010. The trend for TC was always above 1, indicating that technological change was progressing during the study period. We find that the change in forested land productivity in the whole country was the interactive effect of these two decompositions.

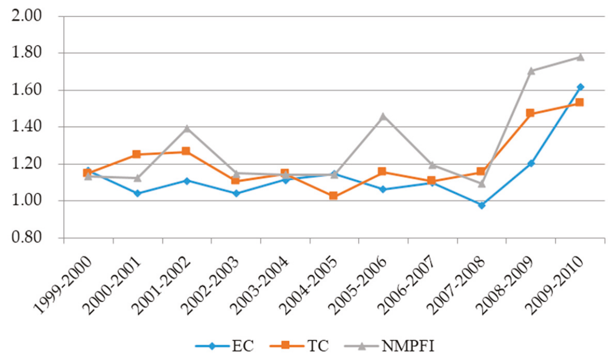

Figure 5. Trends of the non-radial Malmquist forested land performance index (NMFLPI) and its decompositions in China.

With regard to the NMPFI and its decompositions in the three regions, Figures 6–8 show the changing trends of the NMPFI, EC, and TC, respectively.

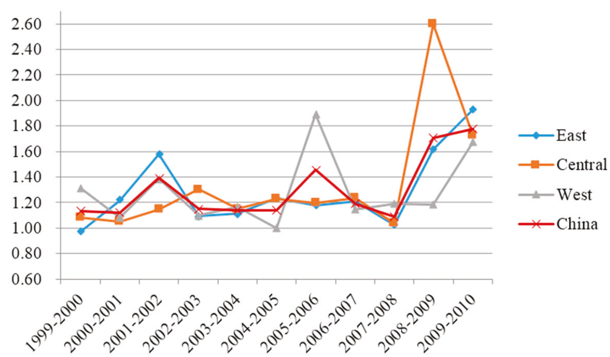

Figure 6. Trends in the NMFLPI for different regions.

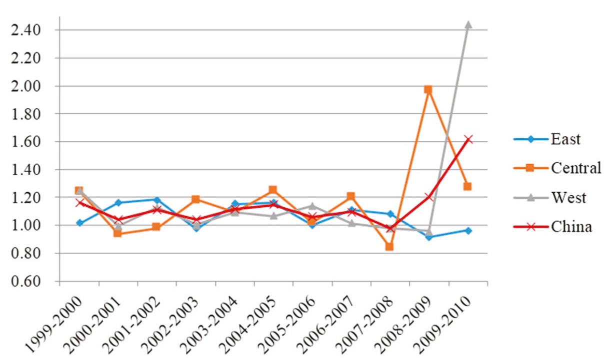

Figure 7. Trends in efficiency change (EC) for different regions.

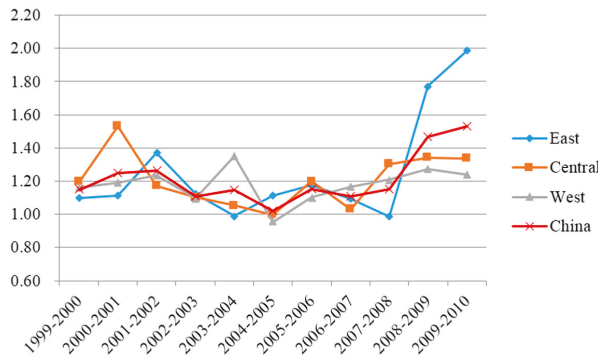

Figure 8. Trends in technological change (TC) for different regions.

From Figure 6, we know that the trend in the NMPFI in the eastern region was similar to the trend in China, except for the period from 1999 to 2000. During the 1999–2000 period, the NMPFI of the eastern region was less than 1, indicating that its forested land productivity had suffered deterioration. Combining the results of Figures 7 and 8 indicates that the changes in the productivity of the forested land in the eastern region derived mostly from the progress of technology change. The NMPFIs in the central region were always above 1. During the period from 2008 to 2009, the NMPFI reached 2.6, and the progress of forested land productivity in the central region derived mostly from the progress of the efficiency change shown in Figures 7 and 8, which was different from the eastern region. The trend of the NMPFI in the western region shows larger fluctuations. Its valley value appeared in the period from 2004 to 2005, and the NMPFI was less than 1, indicating that the forested land productivity suffered deterioration. The peak value appeared in the 2005–2006 period. Combining the results of Figures 6 and 7 indicates that the change in the productivity of the forested land in the western region was the interactive effect of these two decompositions.

4.4. Convergences

From the previous analysis, we know that there were large differences in the evolving trends among the three regions. Will the difference between the regions be reduced over time? Do the regions show the same convergence pattern? The concept of convergence originates from neoclassical economics, which applies this tool to analyze differences in per capita income among regions [43]. Here, we used the method to analyze the disparity of the NMPFIs among the three regions. The convergence usually contains σ-convergence and β-convergence, and β-convergence also includes two types of convergence called absolute convergence and conditional convergence. The σ-convergence exists if there is a clear decline in the standard deviation over time, which indicates that the NMPFI gap among regions has gradually been narrowing. Absolute β-convergence exists if the coefficient of β is significantly negative, which implies that the efficiencies for all provinces in a certain region converge to the same steady state. In addition, conditional β-convergence exists if the coefficient of β is significantly negative, which implies that the efficiencies of provinces in different regions converge to their own steady state [44]. Their formulas are as follows:

σ-convergence:

$$\sigma_t = \sqrt{\left[\sum_{i=1}^{n}\left(\ln Y_{i,t} - \frac{1}{n}\sum_{i=1}^{n}\ln Y_{i,t}\right)^2\right] \Big/ n} \tag{10}$$

absolute β-convergence:

$$\frac{1}{T}\ln\left(\frac{Y_{i,t+T}}{Y_{i,t}}\right) = \alpha_0 + \beta_0 \ln Y_{i,t} + \varepsilon_{i,t} \tag{11}$$

conditional β-convergence:

$$\frac{1}{T}\ln\left(\frac{Y_{i,t+1}}{Y_{i,t}}\right) = \alpha_1 + \beta_1 \ln Y_{i,t} + \sum_{j=1}^{J} \gamma_j x_{i,t}^{j} + \varepsilon_{i,t} \quad (12)$$

where α_0 and α_1 are constants and $i = 1, \ldots, n$ represents the provinces. Y represents the NMPFI, and $x_{i,t}^{j}$ is the jth influencing factors of the ith province in period t. T is the study period, and $\varepsilon_{i,t}$ is the stochastic error.

4.4.1. σ-Convergence

The result of σ-convergence is shown in Figure 9. We find that σ-convergence did not exist in the three regions because the NMPFI gaps in all the regions have fluctuated continuously in the figure, indicating that the gaps did not narrow in the study period. The standard deviation of the NMPFI in the western region ranked first with 0.70, and the central region ranked last with 0.55. These results indicate that the NMPFI gap among provinces in the western region was greater than the gap in other regions.

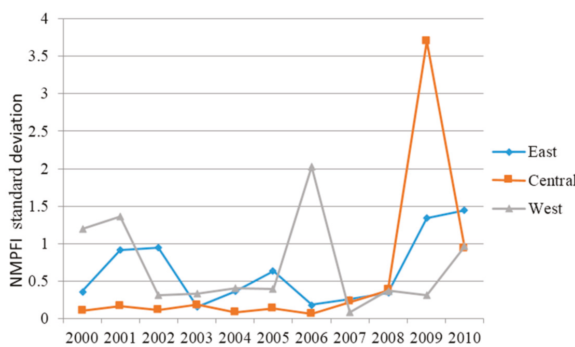

Figure 9. Trends in the NMFLPI standard deviation in regions.

4.4.2. Absolute β-Convergence

According to Equation (11), we obtained the result of absolute β-convergence as shown in Table 2. The β-convergence model fits well in the western region, where its coefficient β is significantly negative, indicating that absolute β-convergence existed in the western region: the NMPFI values of all the provinces in the western region converged to the same steady state. The coefficient β of the eastern region is also significantly negative, but the adjusted R-squared is not high, therefore, the model cannot fit well. Because the coefficient β of the central region is not statistically significant and the adjusted R-squared is very low, absolute β-convergence did not exist in the region; that is to say, the NMPFI of all of the provinces in the central region did not converge to the same steady state.

Table 2. Absolute β-convergence results for the NMPFI. ** $p < 0.05$, * $p < 0.01$.

	Eastern Region	Central Region	Western Region
constant	0.046 * (2.862)	0.043 * (2.492)	0.039 * (3.434)
$\ln Y_{i,0}$	−0.078 * (−2.72)	−0.096 (−0.679)	−0.113 ** (−4.869)
Adjusted R-squared	0.451	0.071	0.703

4.4.3. Conditional β-Convergence

According to Equation (12), we obtained the result of conditional β-convergence, shown in Table 3. We find that the values of coefficient β in the three regions are all significantly negative, whereas the adjusted R-squared values are not high; thus so that they cannot explain the actual situation well.

Table 3. Conditional β-convergence results for the NMPFI. *** $p < 0.001$, * $p < 0.01$.

	Eastern Region	Central Region	Western Region
constant	0.016 * (3.791)	0.021 *** (4.610)	0.017 * (2.391)
$\ln Y_{i,0}$	−0.109 *** (−12.603)	−0.108 *** (−10.060)	−0.091 *** (−10.870)
Adjusted R-squared	0.595	0.564	0.500

5. Discussion and Conclusions

5.1. Conclusions

This paper used the GGDDF model to measure the forested land use efficiency in China and 31 provinces during the period from 1999 to 2010. In this country, forested land use efficiency continued to increase during the study period. The FLUE of Shanghai was always highest, whereas Tibet, Inner Mongolia, and Qinghai suffered the most inefficiency in forested land use. From the spatial perspective, a declining trend was observed from east to west, with the exception of several provinces. There were obvious spatial differences in forested land use efficiency among the 31 provinces. According to the fixed effects regression model based on panel data—which considers population density (PD), proportion of non-agricultural population (PNAP), gross domestic product per capita (PGDP), total forestry output (TFO), investment in fixed assets (IFA), road mileage (RM), land urbanization rate (LUR), annual rainfall (AR), and annual average temperature (AAT) as independent variables—urbanization, the economic development situation, and population density were the main influencing factors in spatial differences in forested land use efficiency.

Because of the obvious spatial differences in the forested land use efficiency among the provinces, we divided them into three regions (eastern region, central region, and western region). Then, by using the GML model, we analyzed forested land performance and its decompositions for China and the three regions. For the eastern region, the NMPFIs were always above 1 after 2000, indicating that the productivity of forested land was always increasing, and the change in the productivity of forested land in the eastern region derived mostly from the progress of technological change. For the central region, the NMPFIs were always above 1, and the progress in forested land productivity derived mostly from the progress of efficiency change. For the western region, the trend in the NMPFI had larger fluctuations, and the change in the productivity of forested land in the western region was the interactive effect of these two decompositions. Finally, the results of convergence tell us that only in the western region did an absolute β-convergence exist; that is to say, the NMPFI of all the provinces in the western region converged to the same steady state.

5.2. Discussion

In this study, we attempted to calculate the efficiency of a specific input (forested land) and to explore the mechanisms that influence spatiotemporal changes to this input. However, there are still some limitations. First, we adopted only an 11-year sample period because of the unavailability of data. We will try to obtain more data to extend the study period to produce more convincing and meaningful results. Second, some factors that play important roles in determining the forested land use efficiency were not considered in this paper for the same reason. Third, economic externalities are not considered in the econometric model, although forested land not only provides economic outputs but also ecosystem services. However, economic efficiency was the main research object in this paper; therefore, we ignored the ecological efficiency. Last, although this paper attempted to explore forested land use efficiency and its spatiotemporal patterns, uncertainty may still exist; thus, methods for verifying our evaluation will be considered in future work. We will make improvements to these limitations in future studies.

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Author Contributions: Yafen He and Hualin Xie had the original idea for the study. Yafen He was responsible for data collecting. Yafen He, Yuanhua Fan, Wei Wang, Xue Xie and Hualin Xie carried out the analyses. All the authors drafted the manuscript, and approved the final one.

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

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Urbanization and Its Effects on Industrial Pollutant Emissions: An Empirical Study of a Chinese Case with the Spatial Panel Model

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Abstract: Urbanization is considered a main indicator of regional economic development due to its positive effect on promoting industrial development; however, many regions, especially developing countries, have troubled in its negative effect—the aggravating environmental pollution. Many researchers have addressed that the rapid urbanization stimulated the expansion of the industrial production and increased the industrial pollutant emissions. However, this statement is exposed to a grave drawback in that urbanization not only expands industrial production but also improves labor productivity and changes industrial structure. To make up this drawback, we first decompose the influence of urbanization impacts on the industrial pollutant emissions into the scale effect, the intensive effect, and the structure effect by using the Kaya Identity and the LMDI Method; second, we perform an empirical study of the three effects by applying the spatial panel model on the basis of the data from 282 prefecture-level cities of China from 2003 to 2014. Our results indicate that (1) there are significant reverse U-shapes between China's urbanization rate and the volume of industrial wastewater discharge, sulfur dioxide emissions and soot (dust) emissions; (2) the relationship between China's urbanization and the industrial pollutant emissions depends on the scale effect, the intensive effect and the structure effect jointly. Specifically, the scale effect and the structure effect tend to aggravate the industrial wastewater discharge, the sulfur dioxide emissions and the soot (dust) emissions in China's cities, while the intensive effect results in decreasing the three types of industrial pollutant emissions; (3) there are significant spatial autocorrelations of the industrial pollutant emissions among China's cities, but the spatial spillover effect is non-existent or non-significant. We attempt to explain this contradiction due to the fact that the vast rural areas around China's cities serve as sponge belts and absorb the spatial spillover of the industrial pollutant emissions from cities. According to the results, we argue the decomposition of the three effects is necessary and meaningful, it establishes a cornerstone in understanding the definite relationship between urbanization and industrial pollutant emissions, and effectively contributes to the relative policy making.

Keywords: industrial pollutant emissions; urbanization; the spatial panel model; Chinese case

1. Introduction

The theme of Shanghai World Expo in 2010—Better City, Better Life—exhibits China's great ambition for urbanization. In fact, the state of urbanization in China is experiencing much disappointment with the aggravating environmental pollution, which is one of the most serious problems in current China's cities. The World Bank [1,2] indicated in its reports that since 1978, China's economy had produced economic growth that rated it one of the fastest growing economies in the world; even though tremendous efforts had been made in abating environmental pollution, China had suffered from an increase of environmental pollution and stern criticism simultaneously.

The deteriorated environment in China has lowered the people's quality of life, and showing that cities do not bring a better life. Just as Easterlin et al. [3] documented, self-reported life satisfaction indicators were not increased in China as much as the expected 8 percent annual economic growth in a parallel period.

What makes China suffer from such a large number of serious environmental pollution incidents? Vennemo et al. [4] noted that China appeared to be following a path similar to the one trodden by some earlier industrialized countries, and the increase of the industrial pollutant emissions have deteriorated the environmental situation. Furthermore, many researchers stated that the rapid urbanization in China stimulated the expansion of the industrial production, which then generated a great deal of air and water pollutants and consequently resulted to the deterioration of air and water quality. Thus, urbanization aggravates environmental pollution.

However, we hold the opinion that this statement is exposed to a grave drawback. On the one hand, it is true that China's urbanization expands the industrial production, but on the other hand, the process of urbanization also promotes the industrial labor productivity and upgrades the industrial structure. Even though the expansion of the industrial production will aggravate the industrial pollutant emissions, the improvement of the industrial labor productivity and the upgrading of the industrial structure will relief the increasing trend of industrial pollutant emissions. As a result, the relationship between urbanization and industrial pollutant emissions is ambiguous, which should be considered cautiously.

In this paper, we highlight our research in the following aspects: first, we explore the mechanism analysis between urbanization and industrial pollutant emissions and then apply the Kaya Identity and the LMDI Method to decompose out three effects (i.e., the scale effect, the intensive effect and the structure effect) of the urbanization impacts on the industrial pollutant emissions; second, we elaborate a description of the relationship between urbanization rate and industrial pollutants emissions of China, and re-examine the reverse U-shapes between them, then we perform an empirical study of the three effects on the basis of the data from 282 cities of China from 2003 to 2014; third, as economic developments are strongly related with each other in different regions, and the assumption of no spatial autocorrelations has been questioned by many scholars, we amend the traditional panel model by introducing the spatial panel model to incorporate the spatial spillover effect.

The rest of the paper is arranged as follows: Section 2 briefly reviews the previous studies; Section 3 analyses the mechanisms between urbanization and industrial pollutant emissions; Section 4 establishes the spatial panel model and introduces the parameters; Section 5 presents the empirical analysis; and Section 6 presents the study's conclusions and offers a discussion.

2. Literature Review

From an early time, understanding the trade-off between the positive and negative externalities of urban growth has been the core issue in urban and environmental economics (Tolley [5], Glaeser [6]). Urbanization is considered as a main indicator of regional economic development due to its positive effect on promoting industrial development, but many regions, especially developing countries, have trouble of its negative effect—the aggravation of environmental pollution (Wan and Wang [7]). The relationship between economic development and environmental pollution has been analyzed by early representative works such as Grossman and Krueger [8,9] and Panayotou [10], which similarly proposed the Environmental Kuznets Curve (i.e., the EKC theory). Based on these influential studies, an entire subfield of environment economics has emerged in focusing on the association between economic and environmental indicators.

One subfield of environment economics studies focuses on the re-examination of the validity of the EKC theory. For example, Lindmark [11], Nasir and Rehman [12], Eeteve and Tamarit [13], Jalil and Mahmud [14], and Li et al. [15] applied Swedish, Pakistani, Spanish and Chinese data to perform empirical tests on the reverse U-shapes between national income per capita and environmental pollution status, and their results strongly supported the EKC theory in various scenarios. However, many other empirical studies, especially those based on time series models, argued that the declining portions of the Environmental Kuznets Curve were illusory, either because they were cross-sectional snapshots that masked a long-run "race to the bottom" in environmental standards or because industrial societies continually produced new pollutants because the old ones were controlled (Stern [16], York et al. [17], Kwon [18]).

Another subfield is the study of the causes of the reverse U-shape in the Environmental Kuznets Curve. Dasgupta et al. [19] suggested that the driving forces of making the Environmental Kuznets Curve flatten and shift to the right appeared to be the economic liberalization, clean technology diffusion, and new approaches to pollution regulation. Panayotou [20] proposed another visualized explanation based on the decomposition of the influence of economic development on environmental pollution into three effects: the scale effect, the technology effect and the composition effect. He noted that the reverse U-shape of EKC was the comprehensive impact of the three effects.

In terms of the relationship between urbanization and industrial pollutant emissions, Kanada et al. [21], Qin et al. [22], and Dong et al. [23] studied the way in which urban population growth impacted local pollution levels and indicated that as the urban population became richer, the demand of private transportation and electricity sharply increased; thus, the activities and demands of individuals exacerbated urban pollution externalities. However, Tao et al. [24] obtained an opposite result arguing that the overall quantity of pollutant discharge decreased as cities became more economically developed during the period from 2000 to 2010, and they attributed such positive effect to higher urban production efficiencies. Zhou et al. [25] used the STIRPAT model (Stochastic Impacts by Regression on Population, Affluence and Technology) to evaluate whether the urbanization would lead to greater environmental pollution. Their study indicated that the estimated contemporaneous coefficients on the urbanization variables were presented as significant reverse U-shapes. In China's case, Zheng and Kahn [26] documented that one-quarter of the rural people who relocated to cities all over the world have been settled down in China over the last thirty years, and China got prepared in supplying a massive amount of industrial products to meet the demands of growing cities with higher-income urban people. In recent years, China's urbanization has been roundly criticized for its stimulation of the expansion of industrial scale and the aggravation of industrial pollutant emissions.

In summary, until now, most studies have focused on the empirical testing of the shape between economic and environmental indicators, and many of their results have strongly supported the EKC theory in various scenarios. Other studies have discussed the underlying driving forces that made the Environmental Kuznets Curve present as a reverse U-shape and have hinted that such reverse U-shape was the comprehensive impacts of different types of effects, but they failed to model the decomposition of these effects and to calculate the impact of each effect with empirical data.

Therefore, this paper attempts to address the above shortcomings by decomposing the influence of urbanization on industrial pollutant emissions into the scale effect, the intensive effect and the structure effect by using the Kaya Identity and the LMDI Method and by performing an empirical study of the impact of the three effects by applying the spatial panel model on the basis of the data from 282 prefecture-level cities of China from 2003 to 2014.

3. Mechanisms Analysis and Hypotheses

The mechanisms between urbanization and industrial pollutant emissions can be briefly and vividly described as the following process (see Figure 1): on the one hand, urbanization leads to redistribution of population and labor force between urban and rural areas. Many young, able-bodied rural people migrate to cities to work in the link of industrial production, which aggravates the total industrial pollutant emissions by expanding industrial production. On the other hand, Nakamura [27] and Fogarty and Garofalo [28] pointed out that agglomeration economic effects would be generated and enhanced during the process of urbanization, and then brought the rise of efficiency of the industrial production. Many empirical studies also stated that urban size had a clear positive relationship with the industrial production efficiency (Moomaw [29], Ciccone [30]). Consequently, we propose the core viewpoint that each unit of the industrial production's pollutant emissions will be decreased due to urban higher productivity. Additionally, the industrial structure will also be upgraded for the reason of urban economic development and labor division, which will affect industrial pollutant emissions accordingly because different industrial sectors have different pollutant emissions intensities. For example, compared with a heavy industry-oriented economy, a service-oriented economy is always regarded as a kind of environment-friendly development mode.

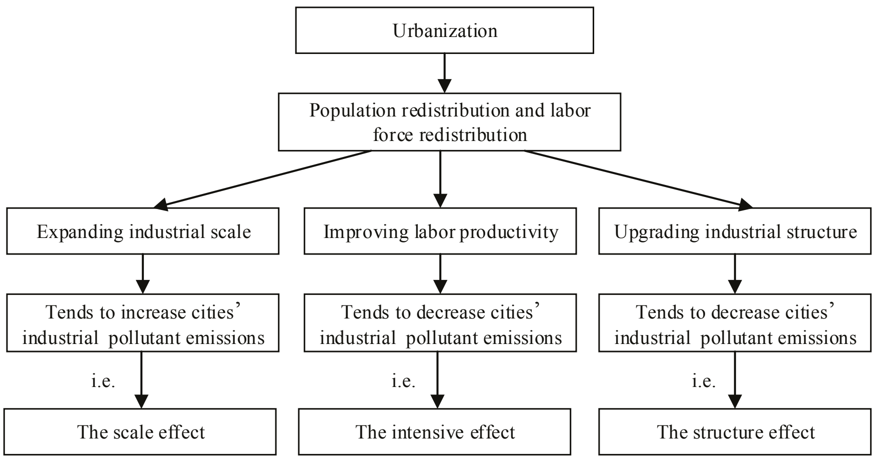

Figure 1. The mechanisms between urbanization and industrial pollutant emissions.

In summary, the influence of urbanization on industrial pollutant emissions can be decomposed into three types of effects according to their diverse mechanisms. The scale effect indicates the expansion of industrial production and denotes a greater consumption of fossil energy and water. The intensive effect indicates the improvement of industrial technologies and denotes higher production efficiencies. The structure effect indicates the upgrading of industrial structure shifting from high-intensity pollutants emission sectors to low-intensity pollutants emission sectors. In this paper, we propose three hypotheses and we will test their validities in empirical analyses sections.

Hypothesis 1: The scale effect of urbanization tends to increase industrial pollutant emissions.

Hypothesis 2: The intensive effect of urbanization tends to decrease industrial pollutant emissions.

Hypothesis 3: The structure effect of urbanization tends to decrease industrial pollutant emissions.

We employ the Kaya Identity and the LMDI Method to establish a model to present the mechanisms between urbanization and industrial pollutant emissions in Equation (1):

$$\begin{aligned} pollutant &= \frac{pollutant}{output} \times \frac{output}{labor} \times \frac{labor}{population} \times population \\ &= e \times p \times q \times population \end{aligned} \tag{1}$$

where *pollutant* denotes the total industrial pollutant emissions, *output* denotes the total industrial production, *labor* denotes total industrial labor force, and *population* denotes the total population. Thus, $e = \frac{pollutant}{output}$ denotes the industrial pollutant emission intensity, $p = \frac{output}{employee}$ denotes the industrial labor productivity, and $q = \frac{labor}{population}$ denotes the employment rate.

Taking urbanization process into account, Equation (1) can be specified as:

$$\begin{aligned} pollutant &= \frac{pollutant_u + pollutant_r}{output} \cdot \frac{output_u + output_r}{labor} \cdot \frac{labor_u + labor_u}{population} \cdot population \\ &= [\alpha_u e_u + (1-\alpha_u)\, e_r]\, [\beta_u p_u + (1-\beta_u)\, p_r]\, [\phi_u q_u + (1-\phi_u)\, q_r]\, population \end{aligned} \quad (2)$$

where subscripts u and r denote urban and rural areas respectively; $\alpha_u = \frac{output_u}{output}$ denotes the proportion of urban industrial output in total industrial production; $\beta_u = \frac{labor_u}{labor}$ denotes the proportion of urban industrial employees in total industrial labor force; and $\phi_u = \frac{population_u}{population}$ denotes urbanization rate.

Then taking industrial structure into account, Equation (2) can be specified as:

$$\begin{aligned} pollutant &= \tfrac{pollutant_u + pollutant_r}{output} \cdot \tfrac{output_u + output_r}{labor} \cdot \tfrac{labor_u + labor_u}{population} \cdot population \\ &\quad \cdot \frac{\sum\limits_{j=1...n} labor_{u,j} + \sum\limits_{j=1...n} labor_{r,j}}{\sum\limits_{j=1...n} labor_j} \\ &= [\alpha_u e_u + (1-\alpha_u)\, e_r]\, [\beta_u p_u + (1-\beta_u)\, p_r]\, [\phi_u q_u + (1-\phi_u)\, q_r]\, population \\ &\quad [\beta_u \sum_{j=1...n} s_{u,j} + (1-\beta_u) \sum_{j=1...n} s_{r,j}] \end{aligned} \quad (3)$$

where subscript j denotes different industrial sectors and $s_{u,j} = \frac{labor_{u,j}}{labor_u}$ denotes the proportion of employees who work in the industrial sector j.

Taking the logarithm for Equation (3), and then we have:

$$\begin{aligned} \ln pollutant &= \underbrace{\ln \{[\phi_u q_u + (1-\phi_u) q_r] \times population\}}_{the\ scale\ effect} + \underbrace{\ln [\beta_u p_u + (1-\beta_u) p_r]}_{the\ intensive\ effect} \\ &\quad \underbrace{+ \ln \{[\alpha_u e_u + (1-\alpha_u) e_r] \times [\beta_u \sum_{j=1,...,n} s_{u,j} + (1-\beta_u) \sum_{j=1,...,n} s_{r,j}]\}}_{the\ structure\ effect} \end{aligned} \quad (4)$$

In Equation (4), β_u, ϕ_u and α_u are variables that reflect population redistribution and labor force redistribution during the process of urbanization. According to the mechanisms analysis, we split the scale effect as $\ln \{[\phi_u q_u + (1-\phi_u)\, q_r] \times population\}$ due to the fact that this monomial reflects the scale expansion of industrial production; we split the intensive effect as $\ln [\beta_u p_u + (1-\beta_u)\, p_r]$ due to the fact that this monomial reflects the promotion of industrial productivity; we split the structure effect as $\ln \left\{ [\alpha_u e_u + (1-\alpha_u) e_r] \times [\beta_u \sum\limits_{j=1...n} s_{u,j} + (1-\beta_u) \sum\limits_{j=1...n} s_{r,j}] \right\}$ due to the fact that this monomial reflects structure upgrading.

We argue that the decomposition is necessary and meaningful, it establishes a cornerstone in understanding the relationship between the urbanization and the industrial pollutant emissions, and effectively contributes to the relative policy making.

4. Modeling and Parameters

4.1. Modeling

According to the mechanisms analysis in Section 3, by applying the Kaya Identity and the LMDI Method, we have decomposed out the scale effect as $\ln \{[\phi_u q_u + (1-\phi_u)\, q_r] \times population\}$, the intensive effect as $\ln [\beta_u p_u + (1-\beta_u)\, p_r]$, and the structure effect as $\ln\left\{[\alpha_u e_u + (1-\alpha_u)e_r] \times [\beta_u \sum_{j=1\ldots n} s_{u,j} + (1-\beta_u) \sum_{j=1\ldots n} s_{r,j}]\right\}$. In order to analyze the three effects independently, we establish the traditional panel model as follows:

$$\begin{aligned} \ln pollutant &= \rho_1 \ln scale\_effect_{i,t} + \rho_2 \ln intensive\_effect_{i,t} + \rho_3 \ln structure\_effect_{i,t} + \pi + \varepsilon_{i,t} \\ &= \rho_1 \ln\{[\phi_{u,i,t} q_{u,i,t} + (1-\phi_{u,i,t})\, q_{r,i,t}] \times population_{i,t}\} + \rho_2 \ln[\beta_{u,i,t} p_{u,i,t} + (1-\beta_{u,i,t})\, p_{r,i,t}] \\ &+ \rho_3 \ln\left\{[\alpha_{u,i,t} e_{u,i,t} + (1-\alpha_{u,i,t}) e_{r,i,t}] \times [\beta_{u,i,t} \sum_{j=1\ldots n} s_{u,j,i,t} + (1-\beta_{u,i,t}) \sum_{j=1\ldots n} s_{r,j,i,t}]\right\} + c + \varepsilon_{i,t} \end{aligned} \quad (5)$$

where subscript i denotes the cross-sections; t denotes the time series; c denotes the constant; $\varepsilon_{i,t}$ denotes the random errors; and ρ_1, ρ_2 and ρ_3 are the regression coefficients of the scale effect, the intensive effect and the structure effect severally. Specifically, according to the three hypotheses in section 3, ρ_1 is expected to be positive and indicates that the scale effect will aggravate industrial pollutant emissions; ρ_2 and ρ_3 are expected to be negative and indicate that the intensive effect and the structure effect will relief the increasing trend of industrial pollutant emissions.

One of the assumptions for establishing a traditional panel model, such as Equation (5), is that different cities are completely independent from each other; that is to say, the spatial autocorrelations are non-existent or non-significant. However, this assumption has been questioned by many scholars (Arbia and Thomas-Agnan [31], LeSage [32]), who addressed that different regions' economic developments were strongly related with each other benefiting from the development of transportation networks and communication technologies.

Therefore, the empirical results of the traditional panel model may generate biased errors due to the omission of spatial autocorrelations. To remedy the drawback, we try to apply the spatial panel model as follows:

$$\begin{aligned} \ln pollutant_{i,t} &= \psi \sum W \ln pollutant_{i,t} + \rho_1 \ln scale\_effect_{i,t} + \rho_2 \ln intensive\_effect_{i,t} \\ &+ \rho_3 \ln structure\_effect_{i,t} + \pi + \varepsilon_{i,t} \\ \varepsilon_{i,t} &= \tau \sum W \varepsilon_{i,t} + v_{i,t} \end{aligned} \quad (6)$$

where W denotes the spatial weight matrix, ψ is the spatial lag coefficient, and τ is the space error coefficient. Compared to the traditional panel model in Equation (5), the spatial panel model in Equation (6) is supposed to be more reasonable in two ways: firstly, it focuses on the spatial autocorrelation of the dependent variable by introducing $\sum W \ln pollutant_{i,t}$; and secondly, it focuses on the spatial autocorrelations of the omitted variables by extending $\varepsilon_{i,t}$ into $\sum W \varepsilon_{i,t}$.

Moreover, under different situations, the spatial panel model can also be subdivided into the Spatial Lag Model (SLM) and the Spatial Error Model (SEM), and which model should be chosen can be assessed by the Lagrange Multipliers (LM) and the robustness tests (Lee and Yu [33], Elhorst [34]). Specifically, if the Lagrange Multiplier of SLM (LM_lag) is more significant than that of SEM (LM_error), and the robustness of SLM (robustness_lag) passes significance testing while the robustness of SEM (robustness_error) does not, then the Spatial Lag Model will be more suitable. Otherwise, the Spatial Error Model will be more suitable.

4.2. Parameters

In this paper, the spatial panel model is established on the basis of the data from 282 prefecture-level cities in China from 2003 to 2014. The main data are extracted from the China City Statistical Yearbook. In addition, the following is a brief introduction to the parameters.

In terms of the dependent variables, industrial pollutant emissions (*pollutant*) are measured by the volume of industrial wastewater discharge (*pollutant_water*), the volume of industrial sulfur dioxide emissions (*pollutant_sulphur*) and the volume of industrial soot (dust) emissions (*pollutant_soot*), respectively.

In terms of the independent variables, employment rates (q_u, q_r) are measured by the ratio of industrial employees to the total population; industrial labor productivities ($p_{u,j}$, $p_{r,j}$) are measured by industrial output per unit of labor; pollutant emissions intensities ($e_{u,j}, e_{r,j}$) are measured by the ratios of each sector's pollutant emissions to their industrial output; industrial structures ($s_{u,j}, s_{r,j}$) are measured by the proportions of employees in each industrial sector; and the distributions of population (ϕ_u), industrial employee (β_u) and industrial output (α_u) between urban and rural areas are measured by their proportions in cities.

The spatial weight matrix (W) is measured by the reciprocal of the geographic distances between different cities.

5. Empirical Analysis

5.1. Description of the Relationship between Urbanization and Industrial Pollutants Emissions

Figure 2 reports the trends of China's urbanization rate and the industrial output from 2003 to 2014. It exhibits that China's urbanization rate rose steadily from 40.53% in 2003 to 54.77% in 2014. During the same period of time, China's industrial output also showed a gradual upward trend. Figure 2 supports the view that China's urbanization expands the industrial production, which is referred as the demographic dividend by many economic scholars (Peng [35], Golley and Tyers [36]).

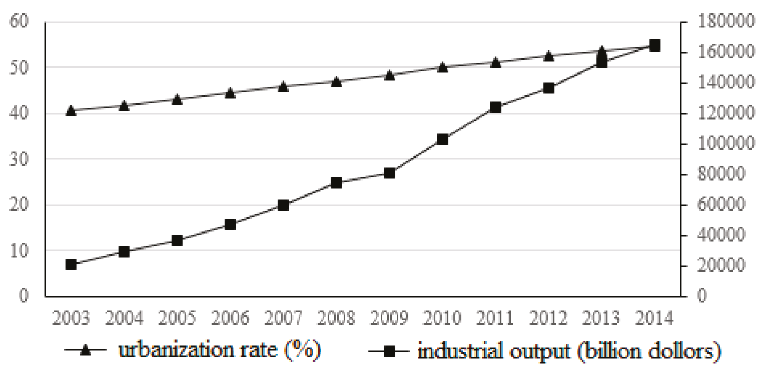

Figure 2. The trends of China's urbanization and the industrial output.

Figure 3a–c report the relationships between China's urbanization rate and the three types of industrial pollutant emissions from 2003 to 2014. It has been found that with the steady rise of China's urbanization rate, the volume of the industrial wastewater discharge increased continually and reached its peak in 2007. After that, the volume of industrial wastewater discharge showed a downward trend. The curves of the volume of industrial sulfur dioxide emissions and industrial soot (dust) emissions of China also fitted reverse U-shapes, especially from the year 2003 to the year 2010.

In conclusion, the relationships between China's urbanization rate and the three types of industrial pollutant emissions indicate that at the beginning stage of China's urbanization, the three types of industrial pollutant emissions are positive related with the increase of the urbanization rate. However, with further development in China's urbanization, the three types of industrial pollutant emissions are negative related with the increase of the urbanization rate. Therefore, we argue that the relationship between China's urbanization and the industrial pollutant emissions is not constant.

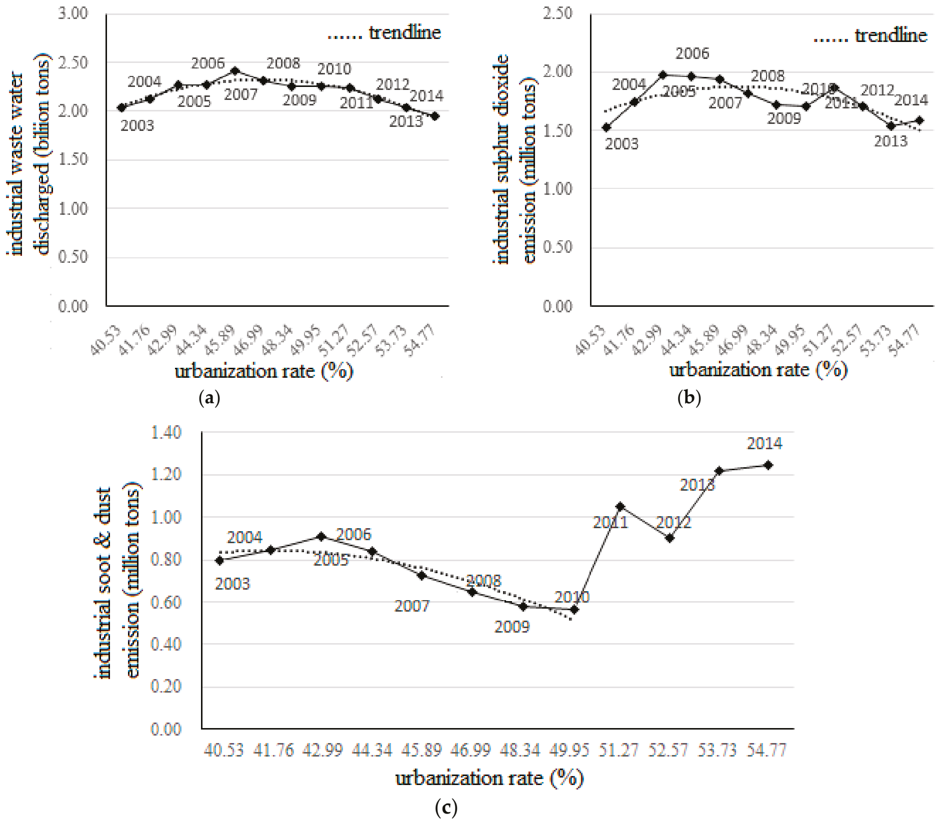

Figure 3. (**a**) The relationship between China's urbanization rate and the industrial wastewater discharge; (**b**) The relationship between China's urbanization rate and the industrial sulfur dioxide emission; (**c**) The relationship between China's urbanization rate and the industrial soot (dust) emission.

5.2. Test of the Spatial Autocorrelations of Industrial Pollutant Emissions

In this paper, we apply the Moran's Index to test the spatial autocorrelations of the industrial pollutant emissions among China's cities. The Moran's Index can be calculated in Equation (7).

$$Moran's\ I = \frac{\sum\limits_{c2}\sum\limits_{c1} W(pollutant_{c1} - \overline{pollutant})(pollutant_{c2} - \overline{pollutant})}{S^2 \sum\limits_{c2}\sum\limits_{c1} W} \quad (7)$$

where $c1$ and $c2$ denote different cities, $\overline{pollutant}$ denotes the average industrial pollutant emissions of all the cities, W denotes the spatial weight matrix, $S^2 = \frac{1}{n}\sum\limits_{c1}(pollutant_{c1} - \overline{pollutant})$ and n denotes the number of cities.

Table 1 reports the Moran's Indexes of the three types of industrial pollutant emissions among China's cities from 2003 to 2014. We can conclude from Table 1 that all the Moran's Indexes are significant and positive, which indicates that there are significant spatial autocorrelations of the industrial pollutant emissions among different cities.

Table 1. The Moran's Indexes of the industrial pollutant emissions among China's cities.

	2003	2004	2005	2006	2007	2008
pollutant_water	0.050 *** (8.054)	0.057 *** (9.136)	0.064 *** (10.183)	0.076 *** (12.019)	0.078 *** (12.349)	0.075 *** (11.866)
pollutant_sulfur	0.048 *** (7.851)	0.045 *** (7.328)	0.052 *** (8.416)	0.053 *** (8.473)	0.036 *** (6.049)	0.040 *** (6.639)
pollutant_soot	0.085 *** (13.390)	0.080 *** (12.593)	0.083 *** (13.068)	0.086 *** (13.563)	0.071 *** (11.303)	0.066 *** (10.500)
	2009	**2010**	**2011**	**2012**	**2013**	**2014**
pollutant_water	0.080 *** (12.663)	0.082 *** (12.967)	0.087 *** (13.646)	0.085 *** (13.293)	0.084 *** (13.152)	0.084 *** (13.272)
pollutant_sulfur	0.035 *** (5.877)	0.031 *** (5.390)	0.052 *** (8.507)	0.058 *** (9.469)	0.083 *** (13.229)	0.057 *** (9.620)
pollutant_soot	0.063 *** (10.121)	0.053 *** (8.637)	0.094 *** (14.795)	0.087 *** (13.737)	0.086 *** (13.488)	0.085 *** (13.297)

Notes: The figures in () are *Z* statistics; ***, ** and * denote the level of significance at 1%, 5% and 10%, respectively.

Figures 4–6 show the cluster maps of three types of industrial pollutant emissions of China's cities in 2014, respectively. It can be found that the High-High clusters of the industrial wastewater discharge are concentrated in most of eastern cities and some of central cities in China. The High-High clusters of the industrial sulfur dioxide emissions and the soot (dust) emissions are concentrated in China's Beijing-Tianjin-Hebei region and the Yangtze River Delta. Most cities in western China present the state of Low-Low clusters or do not pass the statistical significance testing.

The most important conclusion we can draw from the above testing is that there are significant spatial autocorrelations of industrial pollutant emissions among different cities, and therefore it is more reasonable to apply the spatial panel model in this paper.

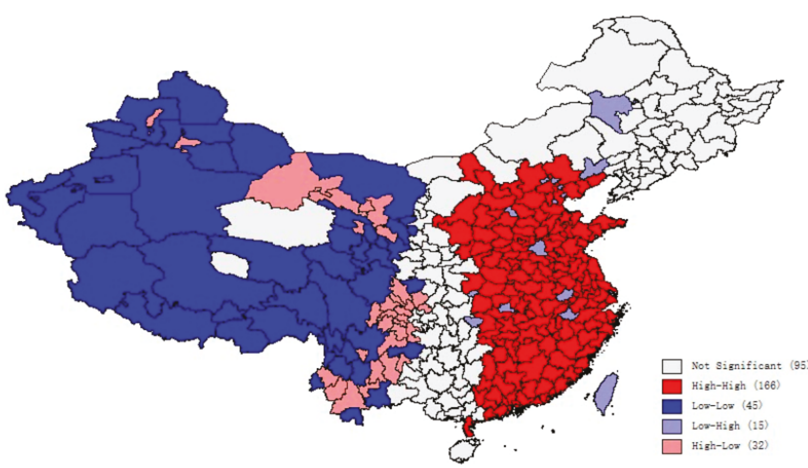

Figure 4. The cluster map of the industrial wastewater discharge in 2014.

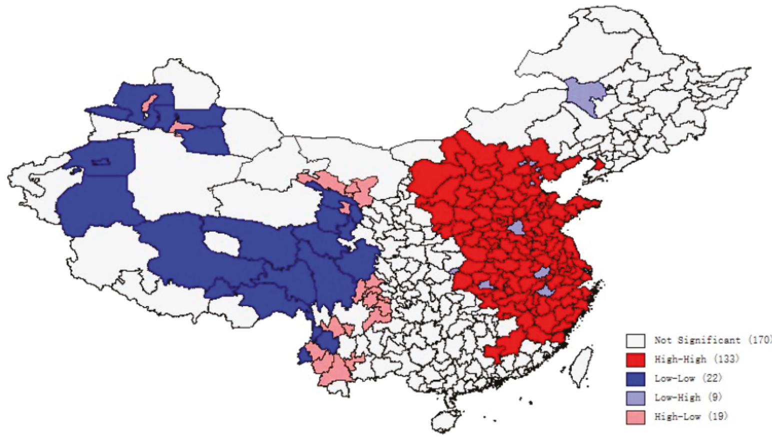

Figure 5. The cluster map of the industrial sulfur dioxide emissions in 2014.

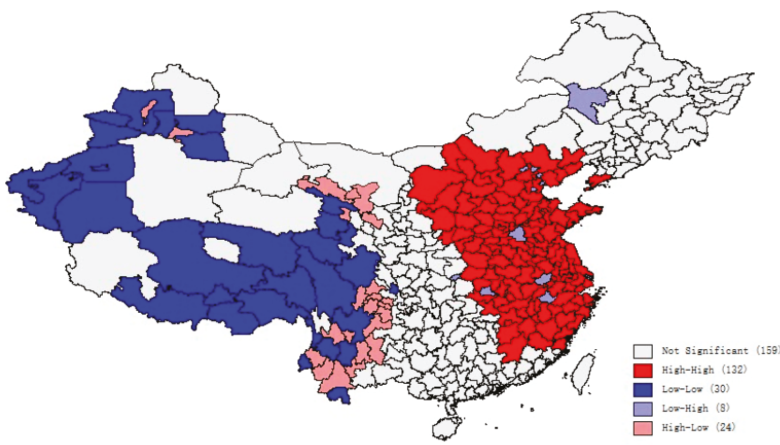

Figure 6. The cluster map of the industrial soot (dust) emissions in 2014.

5.3. Regression Result Analyses

5.3.1. Analyses of the Scale Effect, the Intensive Effect and the Structure Effect

Table 2 reports the regression results of the scale effect, the intensive effect and the structure effect of China's urbanization impacts on the industrial wastewater discharge, the sulfur dioxide emissions, and the soot (dust) emissions.

Table 2. The regression results of the scale effect, the intensive effect and the structure effect.

Model	OLS		SLM		SEM	
	Non-FE	**FE**	**Non-FE**	**FE**	**Non-FE**	**FE**
dependent variables	pollutant_water					
scale effect ($\rho1$)	0.532 ***	0.547 ***	0.511 ***	0.499 ***	0.495 ***	0.492 ***
	(25.433)	(25.513)	(24.861)	(24.347)	(24.888)	(24.666)
intensive effect ($\rho2$)	−0.114 ***	−0.140 ***	−0.087 ***	−0.059 ***	−0.074 ***	−0.068 ***
	(−5.692)	(−5.917)	(−4.435)	(−3.390)	(−5.050)	(−4.958)
structure effect ($\rho3$)	0.585 ***	0.605 ***	0.544 ***	0.515 ***	0.543 ***	0.534 ***
	(12.814)	(12.914)	(12.098)	(11.596)	(12.482)	(12.292)
LM spatial lag	373.112 ***	445.778 ***				
Robust LM spatial lag	97.479 ***	34.532 ***				
LM spatial error	278.750 ***	434.746 ***				
Robust LM spatial error	3.117 *	23.500 ***				
Adj-R^2	0.301	0.304	0.332	0.323	0.330	0.322
Log-likelihood	-4.428×10^3	-4.416×10^3	-1.451×10^3	-4.380×10^3	-4.361×10^3	-4.382×10^3
dependent variables	pollutant_sulfur					
scale effect ($\rho1$)	0.361 ***	0.366 ***	0.359 ***	0.360 ***	0.360 ***	0.356 ***
	(15.289)	(15.223)	(15.183)	(15.283)	(15.279)	(15.128)
intensive effect ($\rho2$)	−0.054 **	−0.049 *	−0.053 **	−0.062 ***	−0.054 **	−0.058 ***
	(−2.399)	(−1.847)	(−2.334)	(−3.079)	(−2.413)	(−2.938)
structure effect ($\rho3$)	0.779 ***	0.771 ***	0.777 ***	0.776 ***	0.779 ***	0.771 ***
	(15.118)	(14.679)	(15.030)	(15.240)	(15.147)	(15.172)
LM spatial lag	9.492 **	195.330 ***				
Robust LM spatial lag	48.477 ***	4.176 **				
LM spatial error	0.378	205.698 ***				
Robust LM spatial error	39.363 ***	14.544 ***				
Adj-R^2	0.212	0.218	0.213	0.201	0.212	0.199
Log-likelihood	-4.836×10^3	-4.803×10^3	-4.835×10^3	-4.867×10^3	-4.836×10^3	-4.864×10^3
dependent variables	pollutant_soot					
scale effect ($\rho1$)	0.343 ***	0.367 ***	0.341 ***	0.362 ***	0.341 ***	0.356 ***
	(14.153)	(15.045)	(14.122)	(15.042)	(14.110)	(14.791)
intensive effect ($\rho2$)	−0.084 ***	−0.170 ***	−0.083 ***	−0.076 ***	−0.080 ***	−0.053 ***
	(−3.643)	(−6.326)	(−3.578)	(−3.709)	(−3.507)	(−2.648)
structure effect ($\rho3$)	0.485 ***	0.556 ***	0.483 ***	0.452 ***	0.481 ***	0.424 ***
	(9.177)	(10.443)	(9.138)	(8.683)	(9.119)	(8.148)
LM spatial lag	1.811	719.109***				
Robust LM spatial lag	5.722 **	74.425 ***				
LM spatial error	0.518	644.690 ***				
Robust LM spatial error	4.430 **	0.006				
Adj-R^2	0.130	0.132	0.130	0.122	0.130	0.118
Log-likelihood	-4.921×10^3	-4.851×10^3	-4.921×10^3	-4.949×10^3	-4.921×10^3	-4.944×10^3

Notes: The figures in () are *Z* statistics; ***, ** and * denote the level of significance at 1%, 5% and 10%, respectively.

We list the regression results of three models: the OLS is the regression results by applying the traditional panel model and the SLM and the SEM are the regression results by applying the Spatial Lag Model and the Spatial Error Model in the proper order. The Non-FE denotes regression results without fixed effects, while FE denotes regression results with fixed effects. Following the rules in Section 4.1, we finally choose the Spatial Lag Model with fixed effect as the optimal model, and regard other models as control groups.

We can infer from Table 2 that the regression coefficients $\rho1$, $\rho2$ and $\rho3$ have passed the significance testing, and $\rho1$, $\rho3$ are positive in each model, while $\rho2$ are always negative. As $\rho1$, $\rho2$ and $\rho3$ reflect the impacts of the scale effect, the intensive effect and the structure effect of China's urbanization on the industrial pollutant emissions, we can draw the conclusion that the scale effect and the structure effect tend to aggravate the industrial wastewater discharge, the sulfur dioxide emissions and the soot (dust) emissions in China's cities; however, the intensive effect results in decreasing the industrial pollutant emissions in China's cities.

The signs of the scale effect and the intensive effect are in line with our expectations, but the sign of the structure effect is beyond our expectation. That is to say, our results accept Hypothesis 1 and Hypothesis 2 but clearly reject Hypothesis 3. Specifically, the population redistribution and labor force redistribution during China's urbanization enhance the expansion of the industrial production and generate increasing industrial pollutant emissions. The improvement of the industrial labor productivity in China's cities decreases each unit of the industrial production's pollutant emissions and generates an ameliorative impact on the industrial pollutant emissions. However, the changes of the industrial structure in China's cities aggravate the industrial pollutant emissions rather than decelerate them. Accordingly, we conclude that China appears to be following a path similar to that trodden by some earlier industrialized countries, and the development of its high-tech and service industries shows slow growth tendencies.

5.3.2. Analyses of the Spatial Spillover Effect

Table 3 reports the spatial lag coefficient (ψ) and the spatial error coefficient (τ). By analyzing these coefficients, we can shed light on the spatial spillover effect of China's urbanization on the industrial pollutant emissions.

Table 3. The regression results of the spatial spillover effect.

Model	SLM		SEM	
	Non-FE	**FE**	**Non-FE**	**FE**
dependent variables	pollutant_water			
spatial lag coefficient (ψ)	−0.766 *** (−3.968)	0.673 *** (−3.579)		
spatial error coefficient (τ)			−0.990 *** (−3.719)	−0.990 *** (−3.719)
dependent variables	pollutant_sulfur			
spatial lag coefficient (ψ)	−0.073 (−0.423)	0.107 (0.712)		
spatial error coefficient (τ)			−0.030 (−0.161)	−0.026 (−0.140)
dependent variables	pollutant_soot			
spatial lag coefficient (ψ)	−0.021 (−0.119)	0.150 (0.999)		
spatial error coefficient (τ)			−0.028 (−0.150)	−0.069 (−0.359)

Notes: The figures in () are *Z* statistics; ***, ** and * denote the level of significance at 1%, 5% and 10%, respectively.

In terms of the industrial wastewater discharge in China's cities, both the spatial lag coefficient (ψ) and the spatial error coefficient (τ) are significant and negative; however, in terms of the industrial sulfur dioxide emissions and the industrial soot (dust) emissions in China's cities, neither of the spatial coefficients passes the statistical significance testing. That is to say, the spatial spillover of the industrial pollutant emissions from other cities does not aggravate the local city's industrial pollutant emissions. This result is beyond our expectation, moreover, it contradicts the conclusion, which we draw from Section 5.3.1: there are significant spatial autocorrelations of the industrial pollutant emissions among different cities, but the spatial spillover effect is non-existent or non-significant.

We come up with an explanation to the contradiction that there are vast rural areas around China's cities, such vast rural areas serve as sponge belts and absorb the spatial spillover of the industrial pollutant emissions from cities, so the spatial spillover effect is non-existent or non-significant. However, from another point of view, cross-regional economic relationships are shown in many forms, such as population flows, industrial associations, and resource exchanges, these cross-regional activities induce significant spatial autocorrelations among different cities, but the industrial pollutant emissions themselves in different cities fail to affect each other.

6. Discussion and Conclusions

In this paper, we first decompose the influence of urbanization impacts on the industrial pollutant emissions into the scale effect, the intensive effect and the structure effect by using the Kaya Identity and the LMDI Method; second, we perform an empirical study of the three effects by applying the spatial panel model on the basis of the data from 282 prefecture-level cities in China from 2003 to 2014. Our results indicate that (1) there are significant reverse U-shapes between China's urbanization rate and the volume of industrial wastewater discharge, sulfur dioxide emissions and soot (dust) emissions; (2) the relationship between China's urbanization and the industrial pollutant emissions depends on the scale effect, the intensive effect and the structure effect jointly. Specifically, the scale effect and the structure effect tend to aggravate the industrial wastewater discharge, the sulfur dioxide emissions and the soot (dust) emissions in China's cities, while the intensive effect results in decreasing the three types of the industrial pollutant emissions. The signs of the scale effect and the intensive effect are in line with our expectations, but the sign of the structure effect is beyond our expectation, we conclude that China appears to be following a path similar to that trodden by some earlier industrialized countries, and the development of its high-tech and service industries shows slow growth tendencies; (3) there are significant spatial autocorrelations of the industrial pollutant emissions among China's cities, but the spatial spillover effect is non-existent or non-significant, we attempt to explain this contradiction due to the fact that the vast rural areas around China's cities serve as sponge belts and absorb the spatial spillover of the industrial pollutant emissions from cities.

Based on the above conclusions, we argue that even though urbanization has correlations with industrial pollutant emissions, their definite relationship should be considered cautiously, because it depends on the combined influence of the scale effect, the intensive effect and the structure effect. China is in a phase of rapid urbanization, and tremendous efforts have been made in relieving the industrial pollutant emissions, but our research suggests that the lock-in of the heavily polluting industries has challenged our attempt to reduce the environmental pollution. Fortunately, the vast rural areas around China's cities have absorbed and eased the spatial spillover of the industrial pollutant emissions from cities. However, with the spreading of industrialization to China's countryside, the rural areas are facing a growing threat of industrial pollution.

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Ecological Security and Ecosystem Services in Response to Land Use Change in the Coastal Area of Jiangsu, China

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Abstract: Urbanization, and the resulting land use/cover change, is a primary cause of the degradation of coastal wetland ecosystems. Reclamation projects are seen as a way to strike a balance between socioeconomic development and maintenance of coastal ecosystems. Our aim was to understand the ecological changes to Jiangsu's coastal wetland resulting from land use change since 1977 by using remote sensing and spatial analyses. The results indicate that: (1) The area of artificial land use expanded while natural land use was reduced, which emphasized an increase in production-orientated land uses at the expense of ecologically important wetlands; (2) It took 34 years for landscape ecological security and 39 years for ecosystem services to regain equilibrium. The coastal reclamation area would recover ecological equilibrium only after a minimum of 30 years; (3) The total ecosystem service value decreased significantly from $2.98 billion per year to $2.31 billion per year from 1977 to 2014. Food production was the only one ecosystem service function that consistently increased, mainly because of government policy; (4) The relationship between landscape ecological security and ecosystem services is complicated, mainly because of the scale effect of landscape ecology. Spatial analysis of changing gravity centers showed that landscape ecological security and ecosystem service quality became better in the north than the south over the study period.

Keywords: reclamation area; land use/cover change; coastal ecological environment

1. Introduction

Urbanization is a major cause of the loss of coastal wetlands [1], and can directly transform landscapes and affect biodiversity, ecosystem productivity, and biogeochemical cycles [2–6]. Furthermore, it can also indirectly influence ecosystems across various scales by altering abiotic environmental conditions, including climate, and soil properties, and biotic components, such as introduced exotic species [7–10]. Land use/cover change (LUCC), partly driving by rapid urban growth [11], has occurred at an unprecedented rate in recent human history and is having a marked effect on the natural environment, including the quality of water [12], soil [13] and air resources, ecosystem services [14–16] and climate [17], at regional and global scale. As urbanization requires more infrastructure for housing, businesses, and transport networks, the demand for such development in coastal region is often met through exploiting natural lands (e.g., tidal flats, salt marshes, water bodies, and open spaces), which ultimately considerably reduces the ecological land of that region.

Apart from urbanization, coastal wetland is, per se, a vulnerable ecosystem with a dynamic interaction between the ocean and land. The vulnerability brings it reduced habitat complexity, decreasing biodiversity, and declining productivity, as well as high risks of storm surges, severe waves, and tsunamis. Furthermore, the Intergovernmental Panel on Climate Change (IPCC) has reported that global climate change has a serious effect on the natural environment and human society in coastal zones [18–20]. Additionally, the global change currently observed is deemed to accelerate coastal erosion and increase the frequency and intensity of extreme weather events [21]. For example, 15% of the 84-km Tuticorin coastal stretch is deemed high risk, and coastal erosion, slope and relative sea level rise are the major factors affecting its coastal vulnerability in Tuticorin [22]; 20.1% (57.9 km) of the total coastline in the Ganges delta is very highly vulnerable [23]; and 31% (365 km) of the Red Sea coast in Egypt is classified as the most severely sensitive [24]. Coastal place vulnerability is highly differentiated and influenced by a range of social, economic, and physical indicators [25]. Thus, coastal wetlands with multi-hazard threats attract greater attention worldwide.

The ecological restoration of coastal wetland has been under way. The International Geosphere-Biosphere Programme (IGBP, 1986–2015) and the International Human Dimensions Programme on Global Environmental Change (IHDP, 1996–2014) launched an international research project in 1993—Future Earth Coasts (formerly the Land-Oceans in the Coastal Zone, LOICZ), the vision of which is to support sustainability and adaptation to global change in the coastal zones. Natural coastal wetlands play a vital role in sustainable development of China [26]. However, with the spread of urbanization, reclamation projects have become an important measure to solve the contradiction between the rapid expansion of economic development and the shortage of resources. Reclamation projects appear worldwide, such as the Zuiderzee project in the Netherlands [27], the Isahaya Bay project in Japan [28], and the Saemangeum reclamation project in Korea [29]. In recent decades, sea enclosing and land reclamation have also become important ways for China to accommodate the increasing need for living space and development, seen for example, in Jiangsu, Shanghai, Zhejiang and Fujian Provinces [30]. This is directly reflected by LUCC and has resulted in the building of many seawalls. The seawalls, called the new "Great Wall", cover 60% of the total length of coastline of mainland China, which have caused a significant decrease in biodiversity and ecosystem services, and will threaten regional ecological security and sustainablility [31]. Therefore, researchers worldwide are focusing on methods to guarantee the health and sustainable development of coastal wetland ecosystem.

In China, the coastal zone is a densely populated area within a fragile ecological system. The *Outline of Jiangsu Coastal Reclamation Development Plan* (2010–2020) was passed by the State Council of China in 2009, and predicted that the reclamation area in the Jiangsu coastal wetland would increase to 0.18 million ha by 2020 [32]. This suggests that the wetland is and will suffer from increasingly serious degradation. Chinese scholars have extensively studied the land use and environmental change of the coastal wetlands in Jiangsu Province over the last couple of decades, specifically including deposition, soil quality, spatial pattern, invasive species, biodiversity, and ecological security [33–37]. Because the pace of China's coastal reclamation has been steadily increasing, the deteriorating trend of its detrimental influences on the coastal wetland ecosystems and their services has not been turned around [30]. It is necessary to quantify the chronological influence on coastal wetland ecosystem to provide a reference for policymakers.

Landscape ecology is often considered "a holistic and transdisciplinary science of landscape study, appraisal, history, planning and management, conservation, and restoration" [38,39]. A variety of landscape metrics have been built and used to quantify spatial patterns of land cover patches, classes, or entire landscape mosaics of a geographic area [40,41]. A large amount of recent studies have quantitatively evaluated the structures and patterns of landscapes [42–46] and ecological security [47–49] using land use/cover data with a range of landscape metrics or indices. Therefore, comprehensive knowledge about the chronology and process of land use change and its effect on the ecosystem integrity and health plays an important role in curbing human impacts on the environment [50], in ecological restoration, and in formulating appropriate land use planning [51]. Landscape ecology and landscape metrics are also helpful to enrich current knowledge.

In this paper, we selected the main body of the Jiangsu coastal wetland—the Jiangsu central coastal zone—as our study area. We explored ecological environmental quality (e.g., landscape ecological security and ecosystem service) from 1977 to 2014 with the aim of guaranteeing the future sustainability of these coastal wetlands under reclamation activities (reflected by land use and land cover). Figure 1 demonstrates the framework of this study. Here, the varying features of landscape ecological security and ecosystem services values were analyzed to get a comprehensive picture of the environmental quality of the coastal reclamation area. The objectives of this study were to: (1) briefly describe land use change and its dynamic degree; (2) analyze landscape ecological security and the relationship with the reclamation year; (3) estimate variations in ecosystem services values in response to land use change and their relationship with the reclamation year; and (4) explore the spatially changing characteristics of landscape ecological security and ecosystem service values and the correlation between them.

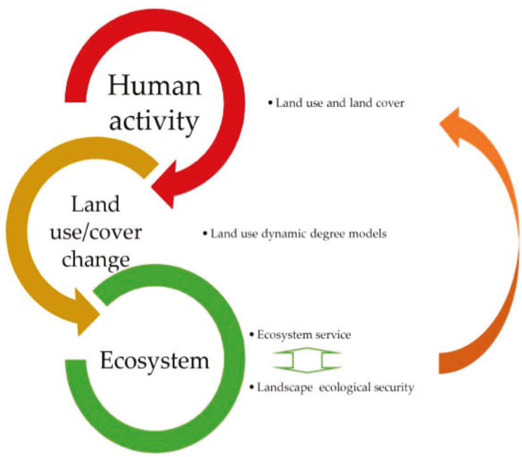

Figure 1. A brief framework of this study. Human activity results in broad change to land use and land cover. We assessed land use change with two land use dynamic degree models. Linking human activity and the ecosystem via land use change, we analyzed the variation of ecosystem services and ecological security to explore how the ecosystem responded to human activity.

2. Data and Methodology

2.1. Study Area

The coastal wetland of Jiangsu Province, China, ranging from the mouth of the Xiuzhen River in the north to the northern branch of the Yangtze River in the south, covers one fourth (10,623 km^2) of the total coastal area in China [52] and is considered Asia's largest prograding mudflat [53]. The mainland coastline is about 954 km long, 93% of which is silty mud [35]. Ninety percent of the entire coastline along the Jiangsu coast is tidal flat [54]. Research shows that the coastal tidal flat is currently expanding seaward at a rate of ±20 cm per year [55–57]. The study area, which is about 0.38 million ha, including part of the Yellow Sea and South Yellow Sea Radial Sand Ridges, is located in the central part of the coastal zone of Jiangsu Province (Figure 2). Dafeng Père David's Deer National Nature Reserve and Yancheng Rare Birds National Nature Reserve are located here because of the region's abundant tidal flat resources. The study area contains four administrative units: Sheyang, Dafeng, Dongtai and Rudong. The climate is classified as subtropical monsoon with an average annual temperatures of 14 °C, annual precipitation of 1000 mm and annual sunshine of 2238.9 h [55].

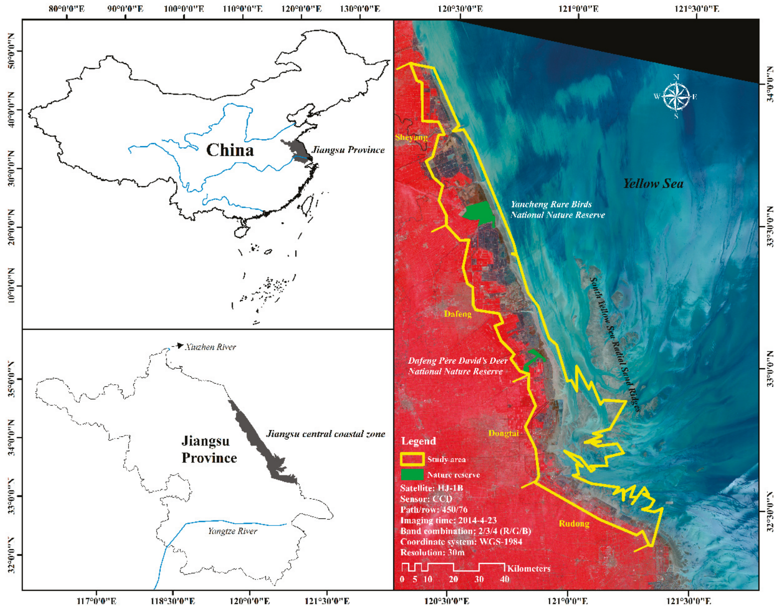

Figure 2. The administrative region of Jiangsu central coastal zone, its location and the distribution of natural reserves in the study area. The detailed information on remote sensing images can be found in Table 1.

2.2. Data Collection

The land use and land cover information of the study area was mainly calculated from remote sensing images (Table 1) and the accuracy of classification was checked through field work. The dates of the images were in the growth period of plants to help acquire land cover information. Geometric rectification and spatial registration technology with ENVI 5.0 (Exelis, Boulder, CO, USA) was carried out to keep spatial consistency across different images and ground objects. Then, we clipped the images to the same boundary as administrative demarcation using ArcGIS 10.2 (Environmental Systems Research Institutes, Inc., Redlands, CA, USA). Supervised classification and visual interpretation was combined to interpret the five remotely sensed images, with a classification precision of over 85%. The output was five shapefiles of land use and land cover in the Jiangsu coastal zone.

Table 1. The parameters of remotely sensed images of the study area.

Satellite	Sensor	Path/Row	Acquisition Date	Resolution/m
HJ-1B	CCD	450/76	23 April 2014	30
Landsat 5	TM	119/37	17 June 2007	30
Landsat 7	ETM	119/37	20 May 2000	30
Landsat 5	TM	119/37	4 August 1984	30
Landsat 2	TM	128/37	20 April 1977	79

Note: the HJ-1B remote sensing image was from China Centre for Resources Satellite Data and Application [58]; the Landsat 2–7 remote sensing images were from Geospatial Data Cloud [59].

2.3. Land-Use and Land-Cover Classification

The coastal area is a unique wetland ecosystem that is different from the rest of the landscape. To accurately describe the landscape of the Jiangsu coastal area, we adapted the land cover classification from common standards, as shown in Table 2.

Table 2. Descriptions of land use and land cover classes used in this study.

No.	LUCC Class	Description	w_i
1	Cropland	Land in either a vegetated or nonvegetated state used for the production of food and oil, including cultivated and uncultivated croplands	0.6
2	Seawater	Part of Yellow Sea	0.7
3	Tidal flat	Tidal flats are common along shallow-water coastlines and estuaries worldwide, accumulating fine-grained sediments on gently sloping beds, forming the basic structure upon which coastal wetlands built	1
4	Aquaculture pond	The farming of fish and other aquatic life in regular ponds	0.5
5	Halophytic vegetation	Grow in salt-affected habitats with many species	0.8
6	Built-up area	Rural residential land	0.2
7	River	A large amount of fresh water flowing continuously in a long line across the land	0.8

Note: w_i is a parameter used in the calculation of the land vulnerability index (LVI) [60], and the LVI is used to calculate the landscape ecological security index.

2.4. Methodology

2.4.1. Land Use Dynamic Degree Models

Land use dynamic degree (LUDD) describes the quantity of annual change of one land use type in the study area over a certain period [61]. The formula is

$$K_{\mathrm{i}} = \frac{U_b - U_a}{U_a} \times \frac{1}{T} \times 100\% \quad (1)$$

in which K_i stands for land use dynamic degree of land use category "i" (in this study i = 1–7); U_a and U_b refer to the quantity of each land use type at the beginning and the end of the study period, respectively; T is the scope of study period.

Land use integrated dynamic degree is the total land use change in the study area, which can quantitatively describe the rate of land use change. The equation is

$$K_t = \frac{I(D)}{\mathrm{S}} \times \frac{1}{T} \times 100\% \quad (2)$$

where K_t represents land use integrated dynamic degree; I and D refer to the total increased and decreased area over the time of T, respectively; S is the total area of the whole study region; T is the scope of study period.

2.4.2. Landscape Ecological Security (LES)

We analyzed ecological security by using the landscape ecological security index (LESI) based on the research of Zhang et al. [47]. According to the previous research, LESI included landscape disturbance (landscape disturbance index, LDI) and vulnerability (landscape vulnerability index, LVI) in order to fully depict the landscape ecological security pattern in the reclamation area. LDI is the extent to which landscape pattern is interfered under human activities. The higher the LDI value, the greater the risk of being disturbed. LVI is the degree to which landscape pattern resist the interference from reclamation activities. The lower the LVI value, the weaker the ability of resisting disturbance.

The formula of LDI is

$$\mathrm{LDI} = a \cdot \mathrm{PD} \times b \cdot \mathrm{SPLIT} \times c \cdot \mathrm{FRAC} \times d \cdot \mathrm{SHDI} \times e \cdot \mathrm{SHEI} \quad (3)$$

where we chose five landscape metrics to expound LDI. They were patch density (PD), splitting index (SPLIT), fractal dimension (FRAC), Shannon's diversity index (SHDI), and Shannon's evenness index (SHEI). The a, b, c, d, and e represented index weight, and the values of them were 0.4, 0.2, 0.2, 0.1, and 0.1, respectively [47,62].

The formula for LVI is

$$LVI = \sum_{i=1}^{n} w_i r_i \tag{4}$$

where w_i is the vulnerability value of land use category i and r_i is the area ratio of land use category i. As tidal flat is the most likely to be developed compared with other land use categories, so tidal flat exhibits the highest landscape vulnerability value [63,64]. The vulnerability values can be assigned to different land use categories as w_i displaying in Table 2.

Thus, LESI can be built from the LDI and LVI comprehensively on the basis of normalized landscape metrics. The higher the LESI, the greater the landscape ecological security in the reclamation area.

$$\mathrm{LESI} = |1 - \mathrm{LDI} \times \mathrm{LVI}| \tag{5}$$

In ArcGIS 10.2, 5 × 5-km raster grid cells were generated based on the land use/cover data from 1977 to 2014 using the Create Fishnet tool. After converting grid data to a geotiff format using the conversion tool—"Feature to Raster" (under the batch grid mode), we calculated the landscape indices (PD, SPLIT, FRAC, SHDI, SHEI) of every cell by using Fragstats 4.2 [65].

2.4.3. Ecosystem Service Value (ESV)

The equivalent weighting factors listed in Table 3 can be applied to different regions across China by localizing the average natural food production [66]. The factor for the economic value of average natural food production of farmland per hectare per year was set at 1.0. All other coefficients were adjusted on the basis of this factor. In general, the proposed natural food production is 1/7 of the actual food production. In the study area, the dominant crops planted for food production are paddy rice, wheat, maize, and soybean. From 2000 to 2014, the average actual food production from farmland in Sheyang, Dafeng, Dongtai and Rudong was 5.49 t/ha [67]. The average price for grain was 293.77 USD/tonne [68], which was calculated based on the weighed planting area. Applying the ecosystem service coefficient of 1.0 yielded an ecosystem value of 230.58 USD/ha (1.0 × 293.77 × 5.49/7).

Table 3. Equivalent weighting of ecosystem services per hectare of terrestrial ecosystems in China.

Ecosystem Service		Farmland	Forest	Grassland	Wetland	Water Body	Barren Land
Provisioning	Food production	1	0.1	0.3	0.3	0.1	0.01
	Raw material	0.1	2.6	0.05	0.07	0.01	0
Regulating	Gas regulation	0.5	3.5	0.8	1.8	0	0
	Climate regulation	0.89	2.7	0.9	17.1	0.46	0
	Water regulation	0.6	3.2	0.8	15.5	20.38	0.03
	Waste treatment	1.64	1.31	1.31	18.18	18.18	0.01
Supporting	Soil formation	1.46	3.9	1.95	1.71	0.01	0.02
	Biodiversity protection	0.71	3.26	1.09	2.5	2.49	0.34
Cultural	Recreational	0.01	1.28	0.04	5.55	4.34	0.01
Total		6.91	21.85	7.24	62.71	45.97	0.42

The ESV of each land use type unit area in the Jiangsu coastal zone was assigned based on the nearest equivalent ecosystems reported by Xie et al. [66] (Table 4). For example, cropland equates to farmland, and tidal flat and halophytic vegetation equate to wetland, aquaculture pond and river/ditch use the value of water body, and built-up area is equivalent to barren land. Although the biomes we used as proxies are not perfect matches with land use types in every case [69], they are related.

Table 4. Ecosystem service value per hectare of the Jiangsu central coastal zone, China.

Ecosystem Service		Cropland	Tidal Flat	Aquaculture Pond	Halophytic Vegetation	Built-up Area	River/Ditch
Provisioning	Food production	230.58	69.17	23.06	69.17	2.31	23.06
	Raw material	23.06	16.14	2.31	11.53	0.00	2.31
Regulating	Gas regulation	115.29	415.05	0.00	184.47	0.00	0.00
	Climate regulation	205.22	3942.96	106.07	207.52	0.00	106.07
	Water regulation	138.35	3574.03	4699.27	184.47	6.92	4699.27
	Waste treatment	378.15	4191.99	4191.99	302.06	2.31	4191.99
Supporting	Soil formation	336.65	394.30	2.31	449.64	4.61	2.31
	Biodiversity protection	163.71	576.46	574.15	251.33	78.40	574.15
Cultural	Recreational	2.31	1279.73	1000.73	9.22	2.31	1000.73
Total		1593.32	14,459.83	10,599.89	1669.41	96.86	10,599.89

The total value of the ecosystem services represented by each land-cover type was obtained by multiplying the estimated size of each land type by the value coefficient of the biome used as the proxy for that category.

$$ESV = \sum (A_k \times VC_k) \tag{6}$$

where ESV ($/year) is the estimated ecosystem service value; A_k the area (ha) and VC_k the value coefficient ($/ha/year) for land use type k. The change in ecosystem service values was estimated by calculating the difference between the estimated values for each category in 1977, 1984, 2000, 2007 and 2014.

2.4.4. Changing of the Gravity Center of LES and ESV

Gravity modeling, which has been widely used in the domains of urban planning, economic geography, and land use science, is an approach that identifies movement direction and distance to the center of gravity for targeted objects. Movement direction and distance to the center of gravity can reflect changes in quantity and trend of the target object over time [70]. Here, we applied gravity modeling to obtain an estimated change of LES and ESV in the Jiangsu central coastal area for 1977–2014.

Based on the calculation formulas of gravity center applied in land use science and ecological quality assessment [71,72], equations for the gravity center for LES and ESV were applied as follows:

$$x_t = \sum_{j=1}^{n} (LESI_{tj} \times X_{tj}) / \sum_{j=1}^{n} (LESI_{tj}) \tag{7}$$

$$y_t = \sum_{j=1}^{n} (LESI_{tj} \times Y_{tj}) / \sum_{j=1}^{n} (LESI_{tj}) \tag{8}$$

$$X_t = \sum_{j=1}^{n} (ESV_{tj} \times X_{tj}) / \sum_{j=1}^{n} (ESV_{tj}) \tag{9}$$

$$Y_t = \sum_{j=1}^{n} (ESV_{tj} \times Y_{tj}) / \sum_{j=1}^{n} (ESV_{tj}) \tag{10}$$

where t is the time of study (t = 1977, 1984, 2000, 2007 and 2014); j is the number of grid cell, and each cell has a unique number; n is the total number of cells, and there are the same amount of n for LESI and ESV because of the same study area; $LESI_{tj}$ and ESV_{tj} are the value of LESI and ESV of grid cell j at the time of t; X_{tj} and Y_{tj} are the x and y coordinates of gravity center of the grid cell j in the year of t; X_t, Y_t and x_t, y_t are the x and y coordinates of gravity center for LESI and ESV in the year of t at the whole study area, respectively. X_{tj} and Y_{tj} could be automatically calculated by ArcGIS 10.2.

2.5. Data Analysis

We calculated the LESI and ESV for each cell, and acquired the spatial feature of LESI and ESV at the cell scale by relating the LESI and ESV of each cell to the shapefile. Then we obtained the spatial data of LESI and ESV with the ordinary kriging interpolation method using exponential semivariogram and a variable search radius [73,74]. Kriging is a geostatistical method that uses a powerful statistical technique to predict values derived from the measure of relationship in samples and employs sophisticated weighted average techniques. Kriging is most appropriate when a spatially correlated distance or directional bias in the data is known and is often used for applications in soil science and geology [75]. Previous research showed that kriging performed reliably in most circumstances [76–80]. Moreover, ordinary kriging is the most commonly used method, and is generally more accurate in a landscape with a smaller ratio (E/A) of elevation change over total study area [81]. The E/A ratio in the reclamation area of the Jiangsu coastal zone was approximately 0 [54]. From this point of view, ordinary kriging is suitable here.

We generated the data with both the reclamation year (Figure 3) and LESI/ESV using the Intersect tool in ArcGIS 10.2. Afterwards, locally weighted linear regression [82–85] was used to determine the relationship between LESI (and ESV) and reclamation year, using the LOWESS/LOESS function of the ggplot2 package in R, version 3.2.4 (R Development Core Team, Vienna, Austria, 2015). The dashed area in Figures 7 and 10 represents the 95% confidence interval.

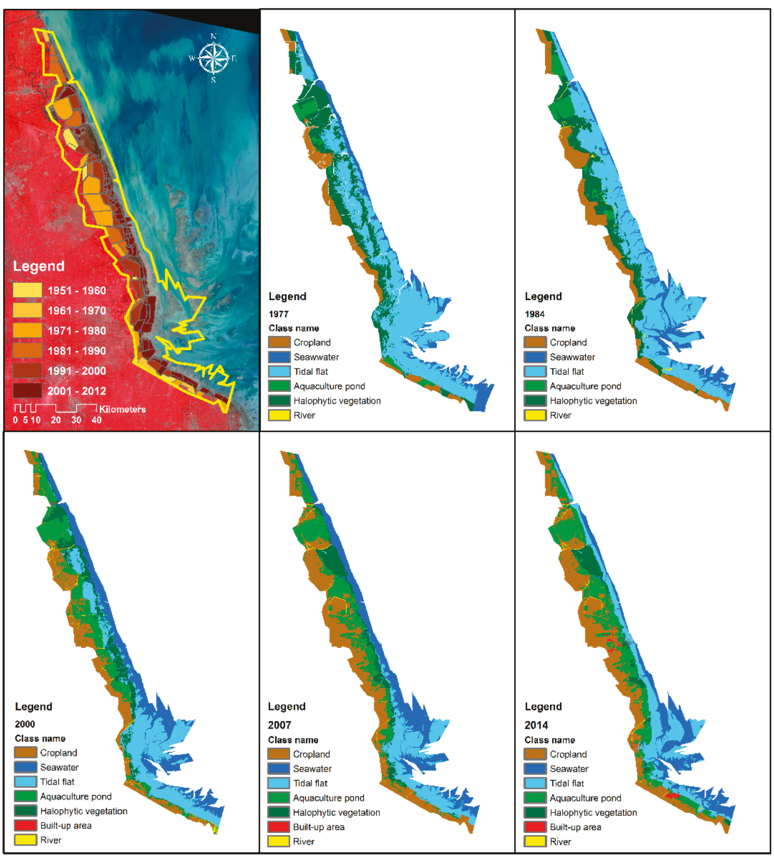

Figure 3. Classified land use/cover maps of the Jiangsu central coastal zone in 1977, 1984, 2000, 2007 and 2014.

3. Results

3.1. Changes in Land Use and Land Cover

The variations of each of the seven land use types are displayed in Figure 3. The most impacted land-use type was tidal flat, which declined from 177,052 ha in 1977 to 69,826 ha in 2007, and slightly rebound to 79,724 ha in 2014. Halophytic vegetation declined from 95,548 ha in 1977 to 21,602 ha in 2014. Cropland increased from 41,282 ha to 115,204 ha. Aquaculture ponds rapidly increased to 86,043 ha in 2014 from 12,848 ha in 1977. Built-up areas first appeared in 2000, but their area jumped to 2944 ha (more than 15-fold over 7 years) in 2014 from 190 ha in 2007. The least affected land use category was river, which dropped from 5735 ha in 1977 to 2048 ha in 2014. The area of seawater tended to grow during the study period, perhaps because of coastal erosion.

The transitions are further emphasized in Figure 4, which shows the relative percentage of each land use type from 1977 to 2014. In 1977, over 46% of study area was covered with tidal flat, more than 25% by halophytic vegetation, almost 11% with cropland, and about 3% by aquaculture ponds. In 1984, the proportion of these land use types had changed to 46%, 18%, 16%, and 5%, respectively. In 2000, they changed to 28%, 10%, 19%, and 18%, respectively. By 2007, the percentages of tidal flat and halophytic vegetation had decreased to 18% and 8% as a result of reclamation activity, while the proportion of cropland and aquaculture ponds had increased to 30% and 19% of study area. By 2014, these four land use types (tidal flat, halophytic vegetation, cropland and aquaculture ponds) accounted for 21%, 6%, 30%, and 23%, respectively. The percentage of seawater and river also had a tendency to increase.

Figure 4. The area of each land use/cover type in study area over the period of 1977–2014.

Land use dynamic degree models were applied here to describe the dynamic change of each land use type (Figure 5). The land use integrated dynamic degree gave an overall outline of the transition intensity of land use types in the whole study area from 1977 to 2014, which depicted a single-peak tendency with 1.15% in 1977–1984, 1.06% in 2007–2014 and 1.76% in 2000–2007. It suggests that the transition intensity of the study periods 1984–2000 and 2000–2007 was higher than the average (1977–2014), and 1984–2000 was the highest figure. With regard to the LUDD of each land use type, cropland reached a peak (8.39%) in 2000–2007 and then declined to a low of 0.03% in 2007–2014. Aquaculture ponds had a highest dynamic degree (36.16%) in 1984–2000 and then reached a low of 0.76% in 2000–2007. Built-up areas had been the highest value of dynamic degree among the seven land categories, growing rapidly by 9.45% in 2000–2007 and 207.33% in 2007–2014. The dynamic degrees of these three land use types were always above zero during the study period, but the following four types (tidal flats, halophytic vegetation, rivers and seawater) were usually negative. Tidal flats and halophytic vegetation shrank significantly and the rate reached the peak in 1984–2000, after which tidal flats increased slightly in 2007–2014. Over the total period of 1977–2014, the dynamic degree of tidal flats, halophytic vegetation and rivers was below zero. The dynamic degrees of most land use types were much lower than built-up areas between 2000 and 2014.

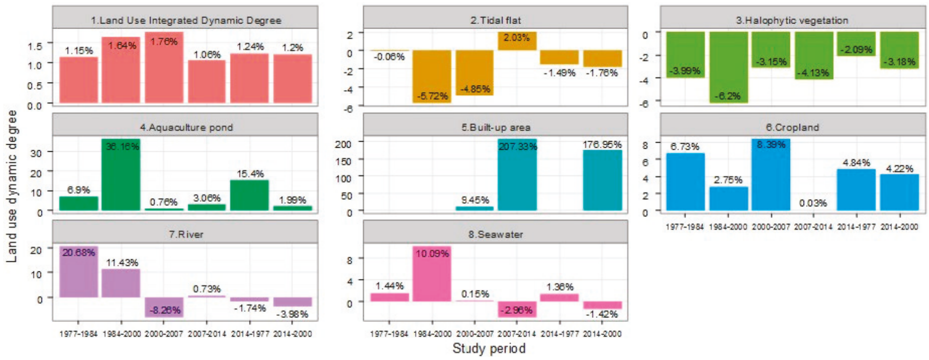

Figure 5. The land use dynamic degree of each land use/cover type and the land use integrated dynamic degree of the whole study area from 1977 to 2014.

3.2. Analysis of Ecoenvironment Response to Land Use Change

3.2.1. The Features of Landscape Ecological Security

The spatiotemporal pattern and changing features of LES at the cell scale in the Jiangsu central coastal zone over 37 years is shown in Figure 6. In 1977, the LESI of each cell varied from 0.162 to 0.489 with a mean value 0.317. The high values were in Sheyang and Dongtai and low values were in Dafeng and Rudong. In 1984, LESI fluctuated between 0.216 and 0.587 at the cell scale, with the highest value in the northwest of the study area (Sheyang and Dafeng) and the lowest values in Dongtai and Rudong. In 2000, the value of LESI ranged from 0.243 to 0.755 with a distribution pattern from the north to south of the Jiangsu central coastal zone. By 2007 and 2014, the maximum LESI plateaued around 0.619, mostly distributed in the northwest around the natural reserves.

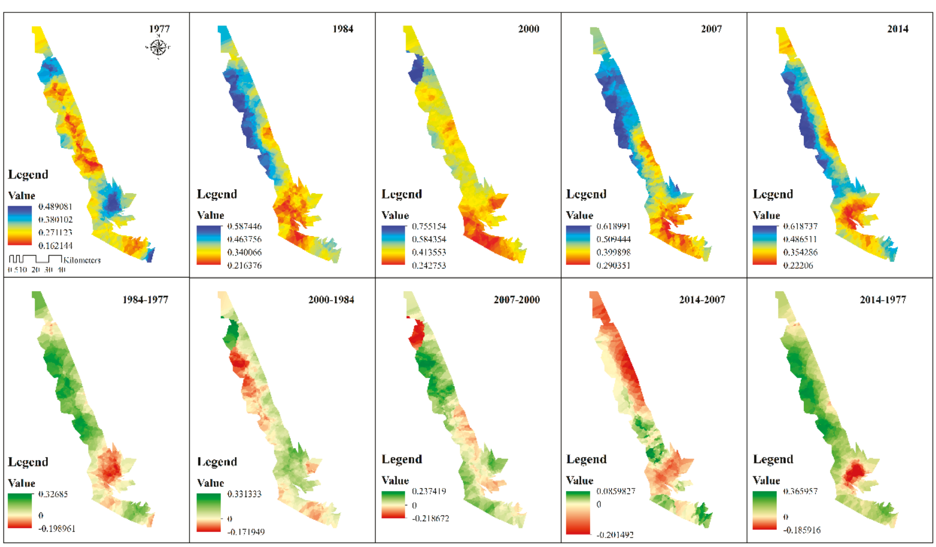

Figure 6. The spatiotemporal features and dynamic variation of LESI at the cell scale over 37 years.

The varying features of LESI between periods are also illustrated in Figure 6. The LESI in 1977–2014 decreased mostly in the Radial Sand Ridge, with the maximum and minimum values of −0.186 and 0.366. The majority of the study area had a higher LESI in 2014 than in 1977. The characteristic of LESI between 1977 and 1984 was remarkably similar to that of 1977–2014, with the most extreme values of this period being −0.199 and 0.327. In the period of 1984–2000, LESI in the west of Dafeng and southwest of Sheyang decreased the most, and the north of Sheyang increased the most. Between 2000 and 2007, the changes were the opposite of those in 1984–2000. By the period 2007–2014, the LESI value reduced most in the north of study area and the Radial Sand Ridge of Dongtai.

3.2.2. Relationship between LESI and Reclamation Year

This analysis is based on the land use/cover in 2014 of reclamation zones with different reclamation years as a unit. The detailed information of the reclamation year was shown in Figure 3. Figure 7 shows the relationship between LESI and reclamation year. In 1977, the LESI stayed stable in 1951–1975 and had some fluctuations from 1975 to 2012, with a mean value of 0.259. In 1984, the general situation showed a downward trend with some variations and the mean value of different reclamation years was 0.357. By 2000, the LESI was steady, with a mean value of 0.374. By 2007 and 2014, the trends were similar, where both remained constant during the first 30 years and then decreased. The mean values were 0.424 and 0.422, respectively. Except for the stable tendency in 1977 and 2000, there was a downward trend in the remaining years of 1984, 2007 and 2014. Therefore, it can be concluded that the longer the time since reclamation, the lower was the LESI. However, the LESI around 1980 became steadier with increasing time since reclamation in the study periods of 1977, 2007 and 2014.

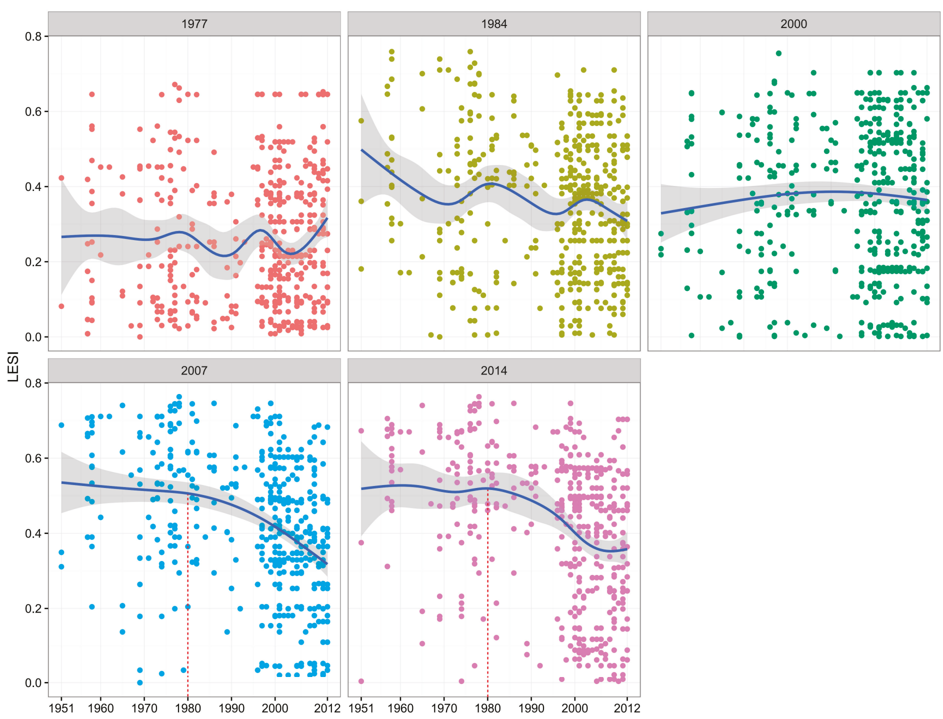

Figure 7. Relationship between LESI and reclamation year. The detailed information of the reclamation year in the study area was shown in Figure 3.

3.3. Changes in Ecosystem Services Values

3.3.1. Spatiotemporal Features of Ecosystem Services Values

Figure 8 shows the spatiotemporal feature of ecosystem services at the cell scale in the Jiangsu central coastal zone from 1977 to 2014. It is obvious that Dongtai's Radial Sand Ridge always had the highest ESV during the study time, however, the maximum of each fishnet cell declined over the period from 1977 to 2014. The divergences between the periods are also described in Figure 8. The ESV at the most northern areas (Sheyang and Dafeng) increased in 1977–1984, while it decreased at Dongtai and Rudong. From 1984–2000, the ESV showed the opposite pattern, decreasing in the northern area and increasing in part of Dongtai and the whole Rudong area. From 2000–2007, the ESV of almost the whole study area declined, except for small patches. From 2007–2014, the majority of the area had a growing ESV but part of Dongtai and Rudong had a downward tendency in ESV. Throughout the period of 1977–2014, the ESV fell in much of the study area and went up in the extreme north. Overall, the ESV decreased with the time, no matter what the study area scale or cell scale.

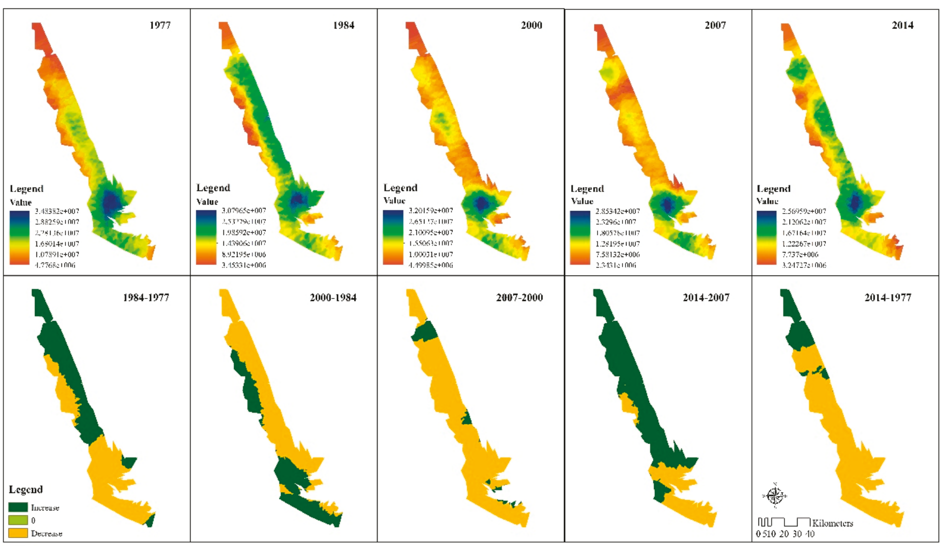

Figure 8. The spatiotemporal features and dynamic change of ecosystem service at the cell scale in Jiangsu central coastal zone from 1977 to 2014.

3.3.2. Ecosystem Service Functions

The above analysis was about the total ESV. Here we report on the traits of each single ecosystem service function which composed the total ESV. According to the classification in Xie et al. [66] and the actual land use condition of coastal wetland in the context of reclamation activities, ecosystem services were divided into nine ecosystem service functions. As can be seen from Figure 8, the first ecosystem service is food production, which had an increasing trend from $28.8 million per year in 1977 to $35.6 million per year in 2014 with a downward change ($28.4 million per year) in 2000. Raw materials decreased overall (from $4.9 million to $4.4 million per year) with a peak in 1984 ($5.1 million per year). Gas regulation and climate regulation had very similar decreasing features; and their values fell from $95.9 million per year to $50.4 million per year and from $728.4 million per year to $351.8 million per year, respectively. In regard to water regulation, the ESV went down gradually from $743.5 million per year in 1977 to $613.2 million per year in 2007 and then rebounded to $718.8 million per year in 2014. Waste treatment had a similar trend to water regulation. Values fell from $864.6 million per year in

1977 to \$650.5 million per year in 2007 and then went up to \$753.6 million per year in 2014. The ESV of soil formation decreased consistently from \$126.7 million per year in 1977 to \$80.1 million per year in 2014. There was strong similarity between the two more ecosystem service functions—biodiversity protection and recreational, which dropped to their lowest point in 2007 and rose again in 2014. The exact value of biodiversity protection varied from \$143.5 million per year in 1977 to \$108.5 million per year in 2007 then went up to \$121.1 million per year in 2014. Recreational values fell from \$246.2 million per year in 1977 to \$162.8 million per year in 2007 then increased to \$190.7 million per year in 2014. From 1977 to 2014, food production was the only service that had an increasing trend.

The ESV of nine ecosystem service functions are further illustrated in Figure 9, which shows the relative proportion of each ecosystem service function over the period of 1977–2014. The first group included waste treatment, water regulation and climate regulation, which were all above 15%. The ratio of waste treatment increased sharply from 28.99% in 1977 to 32.67% in 2014. Water regulation also went up rapidly from 24.93% in 1977 to 31.17% in 2014. The percentage of climate regulation declined moderately from 24.42% in 1977 to 15.25% in 2014. The proportion of recreational service was the fourth highest value at about 8%. Another group contained biodiversity protection, soil formation and gas regulation, which were between 2% and 6%. The last group consisted of food production and raw material, the ratios of which were above 0% but below 2%. Their ratios peaked at 1.74% and 0.21%, respectively, in 2007.

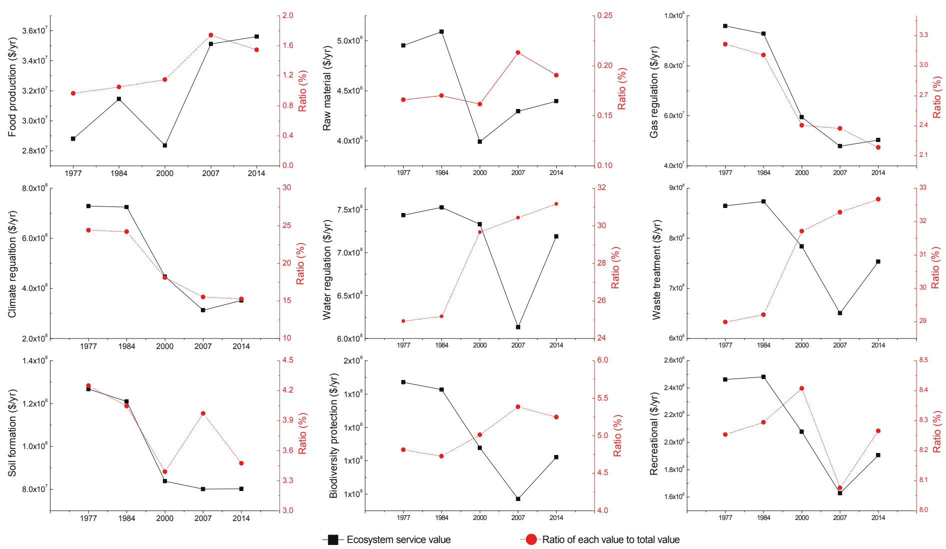

Figure 9. The value and ratio of each ecosystem service function in study area from 1977 to 2014.

3.3.3. Relationship between ESV and Reclamation Year

Figure 10 depicts the relationship between total ESV and reclamation year. Considering the different areas in different reclamation years, here we used the ESV of every hectare to compare trends over time. In 1977, the ESV was declining gradually with increasing time since reclamation and it had a steady trend until about 1975. The tendencies of ESV in other study times (1984, 2000, 2007 and 2014) were the same as in 1977, with all decreasing to some extent over the reclamation time. The exact values of each study time are as follows: from 2051.45 \$/ha/year (1951) to 12,172.05 \$/ha/year (2012) in 1977, values grew from 1593.32 \$/ha/year (1951) to 13,574.21 \$/ha/year (2012) in the study time of 1984, rose from 4299.75 \$/ha/year (1951) to 13,110.92 \$/ha/year (2011) in the study time of 2000, 1593.31 \$/ha/year (1951) to 6573.11 \$/ha/year (2012) in 2007, and increased from 1593.31 \$/ha/year (1951) to 11,370.82 \$/ha/year (2012) in the study time of 2014.

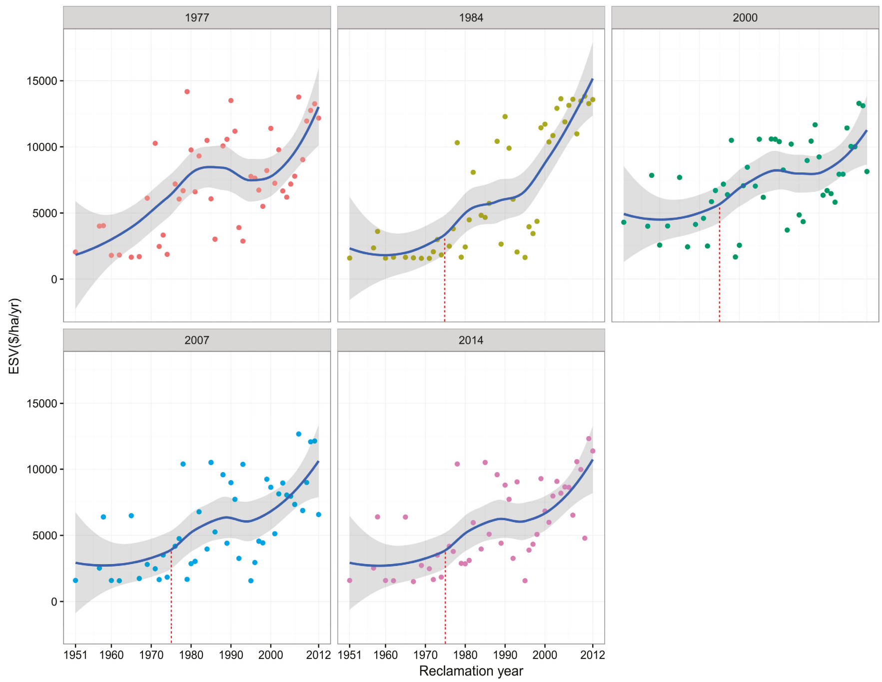

Figure 10. Relationship between ESV and reclamation year. The detailed information of the reclamation year in the study area was shown in Figure 3.

3.4. LESI and ESV

3.4.1. Relationship between LESI and ESV

In this section, we analyzed the connection and difference between LESI and total ESV at two scales. The study area scale uses the whole study area as a research object, while the fishnet cell scale means each of the cells, which were created by the Create Fishnet tool of ArcGIS 10.2 were used as the research unit.

The features of LESI were different at the two scales (Figure 11). At the study area scale, it reached a peak of 1.574 in 1984 then dropped to 0.670 in 2007 and rebounded to 0.840 in 2014. At the cell scale, LESI had an upward trend first reaching a maximum of 0.475 in 2007 and then falling to 0.438 in 2014.

Total ecosystem service values at different scales had a strong similarity in both value and trend (Figure 11). Using the estimated change in the size of each land use type together with the ecosystem service value coefficients suggestted by Xie et al. [66], we found that LUCC in the 381,837.3 ha of our study area led to an average net decline of $675.96 million per year at the study area scale ($673.78 million per year at the cell scale) in total ecosystem services during the 37 years of our study. The ESV (mean value) of each fishnet cell had the same trend as the total ESV, which was $14.05 million in 1977 then reduced to about $9.45 million in 2007 and rose to $10.81 million in 2014.

The relationship between LESI and ESV varied with the scale of research (Figure 11). The correlation coefficient between the variables was 0.328 at a study area scale. In contrast, the correlation coefficient between LESI and ESV (mean value) was −0.865 at the fishnet cell scale. We analyzed the correlation between LESI and ESV for each fishnet cell (Table 5). There was an obviously negative relationship between the two in each study period. In 1977, the correlation coefficient (R) was 0.134, and this was not significant. In 1984, R was 0.179 ($p < 0.1$). By 2000, 2007 and 2014, it was 0.364 ($p < 0.001$), 0.353 ($p < 0.001$) and 0.375 ($p < 0.001$), respectively.

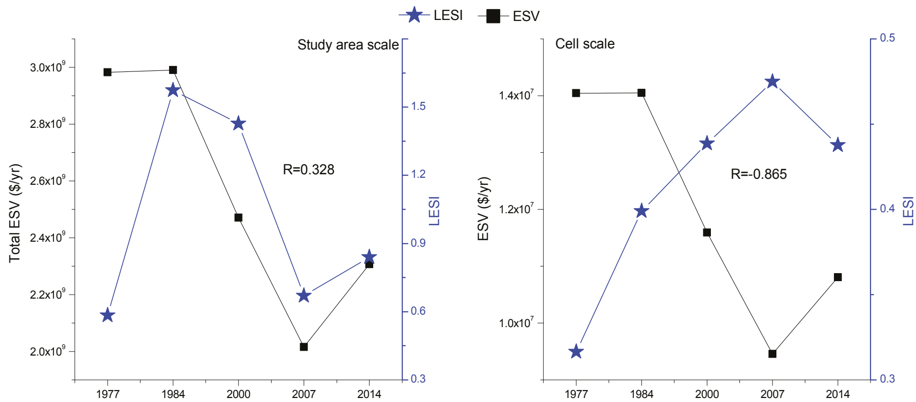

Figure 11. Relationship between total ESV and LESI at two scales.

Table 5. Correlation coefficient between LESI and ESV based on the cell scale.

Correlation Coefficient *R*		ESV
LESI	1977	−0.134
	1984	−0.179 *
	2000	−0.364 ***
	2007	−0.353 ***
	2014	−0.375 ***

Note: Levels of significance test: * $p < 0.1$; *** $p < 0.001$.

3.4.2. Changing Track of the Gravity Center of LESI and ESV

The land use and land cover characteristics of the Jiangsu central coastal zone changed over time. This led to an imbalanced distribution of ecological environmental quality, which generates a gravity center on the surface of its spatial distribution. The gravity center moves with the variation of ecological environment quality. Therefore, with the movement of the gravity center, we can understand the spatial trends of ecological environmental quality. To explore the general spatial features of ecological environment quality in the Jiangsu central coastal zone with time, a gravity model was applied (Figure 12). Here, ecological environment quality was represented by LESI and ESV.

The gravity centers of LESI and ESV from 1977 to 2014 were all distributed between the two natural reserves that were located in Dafeng. For ESV, the changing track moved northward eventually in 2014, though it had a backward movement from 1984 to 2007. The actual distance between the gravity center in 1977 and 2014 was 9.89 km. The shifting track of the LESI gravity center also moved from south to north over the period of 1977–2014, with a movement distance of 3 km.

To sum up, the gravity centers of LESI and ESV in the Jiangsu coastal zone moved from south to north, which indicated that the ecological environment quality became better on a north-south axis.

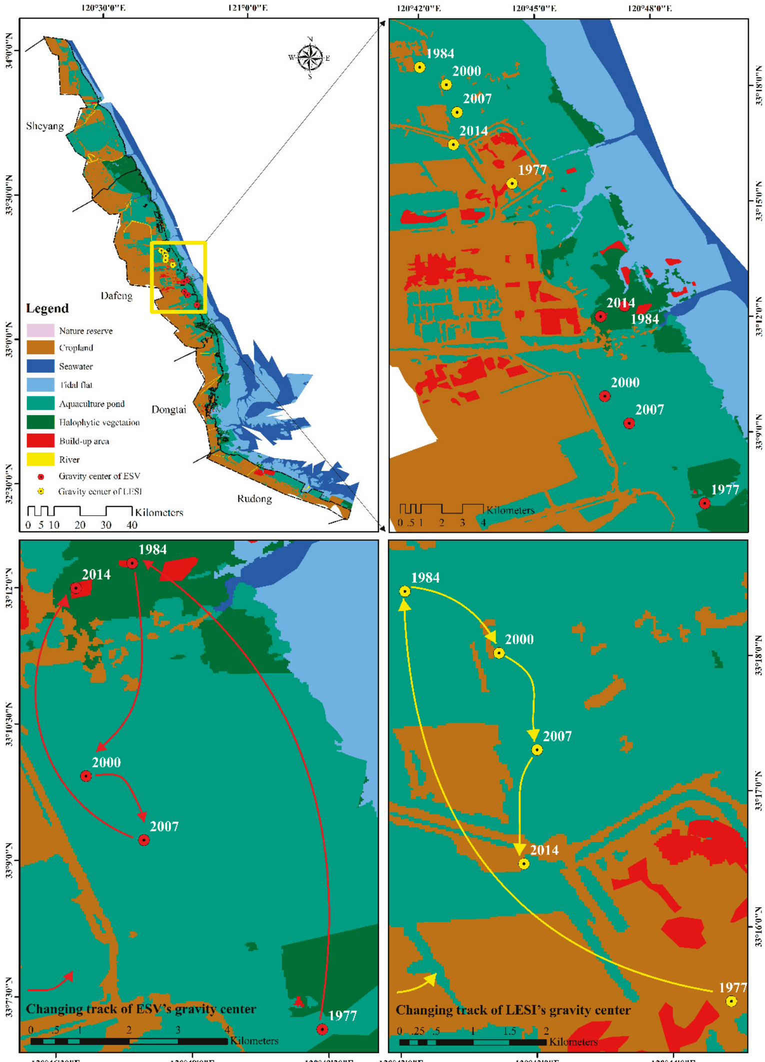

Figure 12. The changing track of LESI and ESV gravity centers.

3.5. Comprehensive Analysis with Policy

Land use change is extremely relevant to the urbanization process and the policies practiced by local government. The land use dynamic degree can illustrate the variation of land transformation. Here, we took the study area as an example and explained it using LUDD (Figure 13). The development of the Jiangsu coastal zone had a period of stagnation from 1953 to 1984 [86], and slow socioeconomic development allowed the coastal area to remain in a stable situation. In 1995, the government of Jiangsu Province proposed the "*Eastern Jiangsu on the sea*" strategy and exploited the coastal zone to use local ocean resources [86]. The LUDD was 1.145% in each year from 1977 to 1984 and increased to 1.765% annually over the period of 1984–2000. Since 2007, the development of the Jiangsu coastal zone reached new levels with the guidance of local government policies and national planning [32], which orchestrated the development activities. Thus, the LUDD declined to 1.055% in 2007–2014 from 1.644% in 2000–2007.

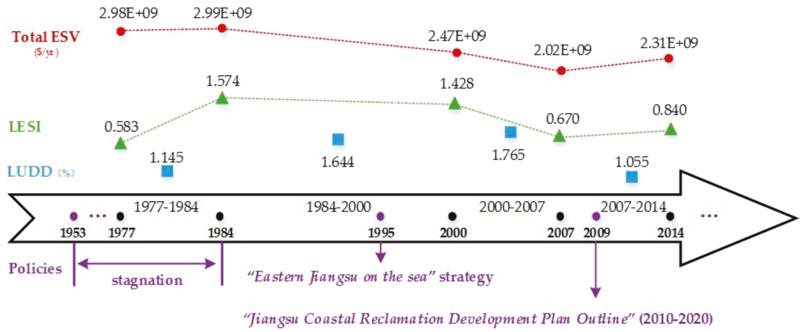

Figure 13. The comprehensive comparison among ecosystem service value (ESV), landscape ecological security index (LESI), land use dynamic degree and policies with time.

4. Discussion

Urbanization is a process that inevitably results from economic development and rapid population growth. It is one of the most prevalent anthropogenic causes of habitat destruction [87], loss of arable land [88], and decline of coastal wetland [1], and seriously threatens environmental sustainability in China [31]. The greatest threat to coastal wetlands is the development-related conversion of coastal ecosystems, leading to large-scale losses of habitats and services through, for example, coastal reclamation projects. Our study showed that the area of artificial land use in coastal wetlands expanded (from 54,130.42 ha to 204,191 ha) while natural land use decreased (from 327,706.89 ha to 177,646.10 ha). In the evolution of coastal wetlands worldwide, especially in developing regions, human activity is the key driving force, and the natural wetlands are being gradually transformed into artificial areas. Between 1952 and 2002, approximately 33.7% of the total wetlands in Jiaozhou Bay were transformed into artificial wetlands [89]. In the tidal flat reclamation zone of Rudong County, Jiangsu Province, 16.43% of natural wetland (which was named as unused land in the study) was transformed into artificial land between 1990 and 2008 [47]. The same is true of urban areas. For example, in the Dhaka metropolitan area in Bangladesh between 1960 and 2005, the areas of natural use (water bodies, wetland/lowland, and vegetation) reduced from 54.3% to 31.4%, and artificial use (cultivated land, built-up and bare soil/landfill) increased from 45.6% to 68.7% [90].

The response of the coastal wetland ecosystem to the LUCC had been analyzed from two angles: ecological security and ecosystem services. Ecological security refers to the security of natural and seminatural ecosystems: ecosystem integrity and health. This also includes the security the ecosystems provides to human living conditions, health, fundamental rights, livelihood guarantees, essential resources, social orders and the ability to adapt to environmental changes [47,91–98]. Ecological security was analyzed using the theory and methodology of landscape ecology. Here the analysis was conducted at two scales: the study area scale and the cell scale. The results showed that the two scales had different features, mainly due to the scale effect [99–102]. At the cell scale, the spatiotemporal pattern of LESI showed high values located landward and low values distributed seaward. At the study area scale, the value of LESI rose in most study areas from 1977 to 2014, except in the Radial Sand Ridge of Dongtai.

Ecosystem services are the conditions and processes through which natural ecosystems, and the species that create them, sustain and fulfill human life [103]. The services of ecological systems and the natural capital stocks that produce them are critical to the functioning of the Earth's life-support system [104]. With the theories of ESV and LUCC, as proposed by Costanza et al. [104] and Xie et al. [66], we found that the ESV decreased from 1977 to 2014, albeit with fluctuations, while the maximum always appeared in the Radial Sand Ridge of Dongtai. There was an average net decline of $675.96 million per year over the period 1977–2014. Furthermore, only food production had an increasing trend in 37 years. The primary reason is probably the policy in the *Outline of Jiangsu Coastal Reclamation Development Plan*, where the planned land use structure of reclamation zones chiefly consists of agricultural land, industrial land and ecological land, and the ratio of these is 6:2:2 [32]. This policy plays a powerful role in the growth of food production. The correlation between ESV and reclamation year showed that the ESV rapidly decreased with the reclamation year. The main reason for this result was that the artificial land use type occupied natural land, which had a high ESV. Natural land use types without human disturbance contribute more to the sustainability of wetland ecosystem than any artificial areas. Therefore, the earlier the reclamation year, the lower the ESV. This tendency appeared not only in coastal areas but also in other regions subject to human activities. For example, land use/cover changed from a natural forest to a rubber plantation in the township of Menglun, Xishuangbanna, Southwest China, resulting in a great loss of ecosystem services [105].

Rapid urbanization has simultaneously induced many adverse impacts on the environment of coastal wetland [1], not just in urban area [106]. The time required for coastal ecosystem to regain the balance was briefly discussed here from two aspects—LESI and ESV. We found that it took ~34 years for LESI and ~39 years for ESV to become balanced. Xu et al. reported that the varying features of land use in coastal reclamation areas fitted an S-type curve, and leveled off after 30 years [107]. Zhang et al. [47] suggested that 37 years was required to form an artificial system in a coastal reclamation area, which is very similar to our study. Furthermore, it has been shown that soil properties approached a relatively stable level nearly 30 years after reclamation, especially in Eastern Asia [108]. Thus, considering to our results, the coastal reclamation area would take a minimum of 30 years to recover its equilibrium.

Finally, the relationship between ecological security and ecosystem services was also explored, since this area of research is typically less studied. We found the two aspects had different correlations with the different scales of the study. This was mainly because of the varying features of LESI for the two scales. The ESV was calculated based on the value method and land use change, while LESI was based on landscape ecology. We examined the spatial transformation of the gravity center. In general, both ESV and LESI both had northward changing tracks, which means that the values of LESI and ESV were increasing from south to north for the 1977–2014 period. Therefore, between 1977 and 2014, the environmental quality of the study area in the north improved to a higher level than that in the south.

5. Conclusions

China had approximately 5.8 million ha coastal wetlands in 2014, accounting for 10.82% of the total area of natural wetlands [109]. Over the past 60 years, China's coastal wetlands have decreased enormously due to the increasing threats and pressures on wetlands arising from the growing population and rapidly developing economy [109,110]. "*Jiangsu Coastal Reclamation Development Plan Outline*" may be a signal that there are large and broad scale development projects to be launched in the Jiangsu coastal area in the future. Therefore, the Jiangsu coastal wetland is a key area that may experience severe land-use and eco-environment quality changes. In this research, the results can be summarized as follows:

(1) The features of land use change in Jiangsu coastal area were in accordance with the most of development zones: artificial area with an increasing trend and native area with a decreasing trend. The former class contained cropland, aquaculture ponds, built-up areas, and seawater. The later class included tidal flats, halophytic vegetation, and rivers. These variations emphasize a drastic increase in production-orientated land uses and a concomitant decrease in the ecologically important wetlands. Being an ecologically fragile zone, Jiangsu coastal area should receive adequate attention.

(2) Intensive human activities break the ecological balance of coastal wetland ecosystem. According to the relationship between LESI/ESV and reclamation year as well as land use and soil quality, it could be concluded that the coastal reclamation area would recover its equilibrium after 30 years at least.

(3) In the development of coastal area, the policy is the key driving force. The total ecosystem service value declined significantly from \$2.98 billion per year to \$2.31 billion per year over the period

1977–2014. Food production was the only one ecosystem service function that had an increasing trend mainly because of government policy.

(4) The relationship between landscape ecological security and ecosystem service is complicated and requires further research. The main cause of the complexity is attributable to the scale effect of landscape ecology. Through the spatial analysis of the gravity center, both landscape ecological security and ecosystem services showed that the environmental quality northward became better than the south in the study period. Thus, at large scales, ecological security and ecosystem service had the same trend.

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

Abbreviations

The following abbreviations are used in this manuscript:

LES	landscape ecological security
LESI	landscape ecological security index
ESV	ecosystem service value
LUCC	land use and cover change
LUDD	land use dynamic degree
PD	patch density
SPLIT	splitting index
FRAC	fractal dimension
SHDI	Shannon's diversity index
SHEI	Shannon's evenness index
LVI	landscape vulnerability index
LDI	landscape disturbance index
LOWESS/LOESS	locally weighted scatterplot smoothing

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sustainability

Article

Are Emissions Trading Policies Sustainable? A Study of the Petrochemical Industry in Korea

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Abstract: In 2015, Korea inaugurated an emissions trading scheme (ETS). In this regard, many studies have considered the sustainable performance and efficiency of industries that emit carbon; however, few have examined ETS at company level. This paper focuses on companies' data related to Korean ETS in the petrochemical industry. Based on the non-radial, nonparametric directional distance function (DDF), the paper evaluates the governance factors related to ETS policies and sustainable performance in terms of carbon technical efficiency (CTE), the shadow price of carbon emissions, and Morishima elasticity between the input and undesirable output of carbon emissions. Using a dual model, the paper shows that Korean ETS has huge potential for participating companies to improve CTE. If all companies consider the production possibility frontier, they could potentially improve efficiency by 52.8%. Further, Morishima elasticity shows strong substitutability between capital and energy, implying that green technology investment should bring a higher degree of energy-saving performance. Unfortunately, however, the market price of carbon emissions is far too low compared with its shadow price, suggesting that the Korean government's price-oriented market intervention has resulted in the ETS producing poor sustainable performance. As the title suggests, ETS of Korea is not sustainable at the current stage, but with more efforts on the transition period, all the developing countries should support the governance factors of the ETS in terms of the more effective green investment with easier access to the green technology.

Keywords: ETS; emissions trading scheme; carbon technical efficiency; CTE; shadow price; Morishima elasticity of substitution; governance

1. Introduction

Since the historic meeting of the United Nations Framework Convention on Climate Change (UNFCCC) in 1994, numerous efforts have been made to find the optimal path toward worldwide sustainable development. At Paris in 2015, the 21st session of the Conference of the Parties (COP) agreed to keep the increase in the global average temperature to below two degrees centigrade above the pre-industrial level. The session also agreed to pursue efforts to limit the temperature increase to 1.5 degrees centigrade above the pre-industrial level. These agreements recognized that temperature-control efforts would significantly reduce the risks and impacts of climate change. In order to achieve the UNFCCC's goals, all 195 member countries are required to make clear and measurable efforts for worldwide sustainable development. As one of the leading countries, Korea has promoted its version of green growth policies since the government hosted the G20 Seoul Summit in 2010. Since then, using one of the most powerful market-oriented frames, the Korean government has prepared and promoted its nationwide emissions trading scheme (ETS). This scheme became regulated in 2015; however, it has caused diverse conflict among politicians, industrial leaders, and even academic experts. Thus, the government has provided a cautious pilot scheme that involves a weak and constrained ETS. Emissions trading rights are traded only among regulated companies. Moreover, emissions targets have been initially set at 95% of the regime. Because of this loose, yet uncomfortable, arrangement among ETS interest groups, it is easy for regulated companies not to invest in the sustainable performance of green productivity and to avoid the extra burden of carbon targets in the short run. Consequently, even though many trials have evaluated the effectiveness of ETS-related policies, it is difficult to measure the performance or efficiency of such policies from a field-oriented company perspective. This paper aims to analyze, from a company perspective, whether the milestone policy of ETS in Korea is successful in terms of decreasing carbon emissions efficiently. Since carbon emissions form most greenhouse gas (GHG) emissions, we evaluate the GHG emissions of companies based on their efforts to decrease ETS targets.

In 2012, total GHG emissions in Korea were 688.3 million tons. This figure represents a 133% increase compared with the base year of 1990. Carbon dioxide (CO_2) emissions overall were 593 million equivalent tons, a figure that places Korea as the seventh highest producer of such emissions in the world. Carbon emissions per person were 11.7 tons, which places Korea as the 18th highest producer of carbon emissions per person in the world and places it sixth among Organization for Economic Cooperation and Development (OECD) countries. These rankings imply that many other developing countries are more proactive than Korea; thus, Korea should be more aggressive in its attempts to decrease GHG emissions and carbon dioxide. The Korean government set its own target in November 2009, saying that it would reduce GHG emissions by 30% from BAU (business as usual) levels by 2020. In the Paris agreement of 2015, the Korean government decided to reduce GHG emissions by 37% from BAU levels by 2030. In order to achieve this target, the government published an emissions trading master plan (2015–2025) in 2014. It also implemented its ETS nationwide in 2015. Unfortunately, however, in spite of these proactive government efforts, the carbon trading market is regarded as a failure because very few transactions took place in the first year. Many experts blame the unreliable carbon price for this failure. They say that the carbon price is so low that companies with emissions permits are reluctant to sell them. Moreover, regulated companies are uninterested in green technology investment because of the low opportunity costs for such innovation. During most of 2015, the carbon price barely exceeded US $10, resulting in the lack of trading. Thus, it is important to analyze whether this price is appropriate or not for achieving the future sustainable performance of the Korean ETS. This issue is the basic motivation of the current research.

In order to monitor and measure efficient carbon reduction, many researchers have conducted carbon efficiency studies based on the distance function because of its reliable clarity about relative efficiency. Although there are numerous sustainable performance modeling methods, the distance function approach has become popular because it can simultaneously model joint-production technology with eco-friendly desirable and undesirable output. Another benefit of the distance function approach is that compared with other cost functions, it does not require any price-specific functional form that is relatively difficult to obtain. Given the quantity of data for input and output, which are comparatively easy to obtain, various critical environmental production characteristics can be formally analyzed. These include environmental technical efficiency, environmental productivity growth, the shadow prices of pollutants, and intra-factor substitution possibilities [1].

Even if Shepherd distance function provides a basic logical frame for the treatment of multi-input/output analysis [2], it is limited in the sense that it treats desirable and undesirable output proportionately; thus, it overlooks the possibility that it decreases undesirable output without any loss in desirable output. Consequently, most directional function research uses the directional distance function (DDF) introduced by Chambers, Chung, and Färe [3]. According to the literature review of Zhang and Choi [1], more than 100 papers have analyzed energy efficiency and the shadow prices of industrial emissions by using distance function models. Studies that use the DDF method employ either the parametric method [4] or the nonparametric method based on data envelopment analysis (DEA) [3,5]. The former can easily calculate the shadow price but has to compute the theoretic distance function coefficients; the latter does not need to preset functional forms and thus can analyze the shadow prices of pollutants in all directions with significant flexible implications. Since it is not easy to accept a specific production possibility curve a priori without significant in-depth analysis on the characteristics of the decision units, this research is based on the DDF_DEA.

Most early research on the DDF is based on a radial model that estimates efficiency proportionately for all output [3]. However, several later studies have reported limitations regarding this radial approach. First, radial measures may overestimate efficiency when slack exists [6]. Second, the radial model has relatively weak discriminating power when ranking entities that require evaluation [7]. Third, a radial efficiency measure cannot provide a single-factor efficiency measure, such as energy efficiency, because the DDF can only give the same rate of inefficiency [8]. Because of these limitations, a number of studies have extended the conventional DDF to a non-radial DDF by considering slacks [6,9–11]. Thus, we employ the non-radial DEA-based DDF to examine the sustainable performance of the eco-friendly policies of Korea's ETS.

Most studies in this field have been conducted in the power plant sector [12–16], the steel and iron sector [17–19], the electricity sector [20–22], and other sectors such as the chemical, cement, and ceramic industries. Nearly all of these sectors emit a great deal of CO_2 [23–26]. Although these studies have employed the DDF to measure the performance of environmental policies, to the best of our knowledge no research has yet been conducted using company data related to real ETS trading. Moreover, Korea is the only country in the world to promote a nationwide, and not a regional or localized, ETS frame.

Since Korea is in a transitional stage between a developing and developed economy, this research has insightful implications about a stepwise approach to performance-oriented sustainable development. Moreover, this research has potential practical importance because it is based on a comparison between the shadow price and the price in the real world. Further, it evaluates the sustainability of the unduly cautious ETS policies in Korea. In this paper, the sustainability of ETS policies is analyzed from three perspectives. First, the Korean government's ETS policies are excessively price-oriented; thus, we need to check that the semi-regulated market price of carbon emissions permits is acceptable compared with their shadow prices. If the market price is too low, it may result in low investment in green IT technologies, which is contrary to the government's ultimate goal. Of course, the shadow price of carbon could be unrelated to the market carbon price for one important reason: the carbon allowances are given for free and all firms are allocated 100% of the allowances they need for at least in the first stage of three years. Under these conditions, it is reasonable for carbon allowances to have a low market value in the first few years of the ETS. Hence, it is hard to argue that the shadow prices reflect what the market price should be. However, the government should narrow this gap between the shadow price and market price as early and effectively as possible, and thus if the government stimulates companies to invest more on green technology, the price gap will be more effectively decreased. According to Oestreich and Tsiakas [27], during the first few years of the scheme, firms that received free carbon emission allowances on average significantly outperformed firms that did not in the European Union Emissions Trading Scheme (EU ETS). Even if this kind of transition trial and errors on the inappropriate carbon market price, however, they found that this kind of carbon premium is present for a specific period that commences about one year before the beginning of Phase I and disappears about one year into Phase II [27]. If this is true, then the Korean government should make this trial and error on the carbon market price as short as possible. In this paper, we will check the feasibility of this carbon premium in terms of the price gap between the shadow price and market price.

Second, in order to boost investment in energy-saving green technologies by ETS member companies, there must be significant elastic substitutability between energy and other input. Third, it is necessary to check whether the potential sustainability of ETS policies is increasing the eco-friendly efficiency of participating companies. If not, such companies have no incentive to exert too much effort in proactively participating in ETS trading.

Thus, the purpose of this paper is to examine these three points regarding the sustainability of governmental policies. In this context, we use the ETS data of participating member companies.

However, the Korean ETS covers 525 companies from diverse industries. Consequently, since the clarity and credibility of the implications are important in order to check the sustainability of the ETS policies, this research focuses on the petrochemical industry. This industry is the largest in the ETS with 85 companies, which represent 16% of all ETS members. Thus, based on the arguments regarding an examination of the ETS policies' sustainability, this paper estimates the eco-friendly efficiency of the participating member companies in the major field of the petrochemical industry. It compares the shadow price with the market trading carbon price and considers the potential of green investment in terms of Morishima elasticity between capital and energy.

The rest of this paper is organized as follows: Section 2 presents a methodological framework of the non-radial DDF models with Morishima elasticity and describes the data collection. Section 3 presents the results of the empirical study of the petrochemical industry. Section 4 concludes with some policy implications for sustainable governance.

2. Methodology

In this section, the non-radial DDF model is presented. This model shows how to estimate carbon technical efficiency. Moreover, a dual model is introduced to calculate the shadow price of undesirable output. Then, the Morishima elasticity of input is articulated from the ratio of the shadow price.

2.1. Carbon Technical Efficiency

In order to introduce the non-radial DDF, the term "environmental production technology" should be defined. Assume that there are $j = 1, \ldots, N$ decision-making units (DMUs). These DMUs are petrochemical manufacturing companies in our research. Suppose that each DMU uses input vector $x \in \Re_{+}^{M}$ to produce jointly a good output vector $y \in \Re_{+}^{S}$ and a bad output vector $b \in \Re_{+}^{J}$ Environmental production technology is expressed as

$$T = \{(x, y, b) : x \text{ can produce } (y, b)\}, \tag{1}$$

where T is often assumed to satisfy the standard axioms of production theory. Inactivity is always possible, and finite amounts of input can produce only finite amounts of output. In addition, input and desirable output are often assumed to be freely disposable. With regard to regulated environmental technologies, weak disposability must be imposed on T [28]. The weak disposability assumption implies that reducing bad output, such as CO_2 emissions, is costly in terms of relative decreases in production. Further, the null-jointness assumption implies that CO_2 emissions are unavoidable in production and that the only way to remove CO_2 is to stop production. Mathematically, these two assumptions can be expressed as follows:

(1) $if\ (x, y, b) \in T\ and\ 0 \leq \theta \leq 1,\ then\ (x, \theta y, \theta b) \in T;$
(2) $\text{if } (x, y, b) \in T \text{ and } b = 0, \text{then } y = 0.$

The DEA piecewise linear production frontier is used to construct environmental production technology. Then, regulated environmental technology T_1 for N DMUs exhibiting constant returns to scale can be expressed as

$$\begin{aligned} T_1 = \{(x, y, b) \ : \ & \sum_{n=1}^{N} z_n x_{mn} \leq x_m, m = 1, \ldots, M, \\ & \sum_{n=1}^{N} z_n y_{sn} \geq y_s, s = 1, \ldots, S, \\ & \sum_{n=1}^{N} z_n b_{jn} = b_j, j = 1, \ldots, J, \\ & z_n \geq 0, n = 1, \ldots, N\}. \end{aligned} \tag{2}$$

A formal definition of the non-radial DDF is proposed by Zhou et al. [9] with undesirable output as

$$\vec{D}(x, y, b; g) = \sup\{\mathbf{w}^T \beta : ((x, y, b) + g \cdot diag(\beta)) \in T\}, \tag{3}$$

where $\mathbf{w} = (w_m^x, w_s^y, w_j^b)^T$ denotes a normalized weight vector relevant to the amount of input and output, $g = (-g_x, g_y, -g_b)$ is an explicit directional vector, and $\beta = (\beta_m^x, \beta_s^y, \beta_j^b)^T \geq 0$ denotes the vector of scaling factors. The value of $\vec{D}(x, y, b; g)$ under environmentally regulated technology can be calculated by solving the following DEA-type model:

$$\begin{aligned} \vec{D}^r(x, y, b; g) \quad &= \max w_m^x \beta_m^x + w_s^y \beta_s^y + w_j^b \beta_j^b \\ \text{s.t.} \quad & \sum_{n=1}^{N} z_n x_{mn} \leq x_m - \beta_m^x g_{xm}, m = 1, \ldots, M, \\ & \sum_{n=1}^{N} z_n y_{sn} \geq y_s + \beta_s^y g_{ys}, s = 1, \ldots S, \\ & \sum_{n=1}^{N} z_n b_{jn} = b_j - \beta_j^b g_{bj}, j = 1, \ldots J, \\ & z_n \geq 0, n = 1, 2, \cdots, N \\ & \beta_m^x, \beta_s^y, \beta_j^b \geq 0. \end{aligned} \tag{4}$$

The directional vector g can be set up in different ways, based on given policy goals. If $\vec{D}(x, y, b; g) = 0$, then the specific unit to be evaluated is located on the frontier of best practices in the direction of g. Carbon technical efficiency (CTE) is defined based on the non-radial DDF. Here, there are three inputs, one desirable output, and one undesirable output. We set the weight vector of S, M, and J as one-third each for input, desirable output, and undesirable output respectively. We also set the directional vectors as $g = (-x, y, -b)$, based on Zhou et al. [9].

According to Zhang and Xie [23], the overall eco-friendly efficiency or CTE for industries is defined as the average efficiency of each factor. Suppose that β_x^*, β_y^*, and β_b^* represent the optimal solutions to Equation (5), then the CTE can be formulated as:

$$CTE = 1 - \frac{1}{M + S + J} \left(\sum_{m=1}^{M} \beta_{xm}^* + \sum_{s=1}^{S} \beta_{ys}^* + \sum_{j=1}^{J} \beta_{bj}^* \right) \tag{5}$$

2.2. The Shadow Price of Undesirable Output and the Morishima Elasticity of Substitution

In this subsection, a dual DDF model is used to estimate the shadow prices of CO_2 and the elasticity of substitution for input. The shadow cost function of a non-radial DDF may be defined as

$$\begin{aligned} & \min v x_0 - u y_0 + r b_0 \\ & s.t. \\ & vx - uy + rb \geq 0 \forall n \\ & v \geq \left[\frac{1}{g_1^x}, \ldots, \frac{1}{g_m^x}, \ldots, \frac{1}{g_M^x} \right] \\ & u \geq \left[\frac{1}{g_1^y}, \ldots, \frac{1}{g_s^y}, \ldots, \frac{1}{g_S^y} \right] \\ & r \geq \left[\frac{1}{g_1^b}, \ldots, \frac{1}{g_j^b}, \ldots, \frac{1}{g_J^b} \right]. \end{aligned} \tag{6}$$

In Equation (6), $v \in R^m$, $u \in R^s$, and $r \in R^j$ are the dual-variable vectors of the input ($x \in R^m$), the desirable output ($y \in R^s$), and the undesirable output ($b \in R^j$) respectively. The dual variables of the input, desirable output, and undesirable output can be estimated by the linear programming of Equation (6). The dual Equation (6) aims to minimize the virtual cost of the specific company concerned. In this regard, the dual DDF model is a type of product maximization model in which the virtual cost is at best zero (non-positive) when $\vec{D}^{u}(x, y, b; g) = 0$ for the DDF-efficient unit.

The dual variables $v \in R^m$ and $r \in R^j$ can be interpreted as the shadow prices of the input and undesirable output, respectively. $u \in R^s$ denotes the marginal virtual income of the desirable output. Assuming that the absolute shadow price of the undesirable output is equal to its market price (p^b), the relative shadow price of the undesirable output with regard to the desirable output (p^y) can be measured by

$$r = u \times \frac{p^b}{p^y} \tag{7}$$

In other words, the shadow price of the undesirable output can be interpreted as a marginal abatement cost that represents the marginal rate of transformation between undesirable and desirable output. Under the environmental regulations, the abatement of pollutants is not free but costly for companies because they incur an opportunity cost associated with reducing desirable output.

The curvature of the isoquant curve reflects the degree of substitutability of the input factors in the production function. Following Lee and Zhang [29], the elasticity of substitution between input x_i and x_j can be estimated by employing the idea of indirect Morishima elasticity of substitution, as shown in Equation (8). Morishima elasticity is defined as the shadow price ratio between the two factors [30]. As shown in Table 1, most research on Morishima elasticity is based on the distance function approach with input-orientation. This is because the substitution between traditional input, such as capital and labor, and energy input is crucial in order to find the potential of energy-saving efficiency enhancement through additional investment in energy-saving technologies. Based on the table, this paper analyzes the input elasticity of substitution among three types of input: capital, labor, and energy. It also examines the shadow price of the undesirable output of carbon emissions in accordance with the literature. In the simplest format, Morishima elasticity for input captures the degree to which the relative shadow prices of types of input should be altered to allow substitutability among such input along the isoquant curve. A high value for Morishima elasticity indicates low-level substitutability. It should be noted that $M_{ij} \neq M_{ji}$ because the ratios related to the two input shadow prices differ depending upon which input is used as the basis. The degree of substitution of x_j for x_i does not coincide with the substitution of x_i for x_j in general. Further, even if Morishima elasticity can be calculated for all three types of input and output perspective, we focus only on the elasticity between input and undesirable output. This is because we want to examine the potential of green technology investment for the sustainability of the ETS policies. It should also be noted that this application of Morishima elasticity is especially important in our research field of the capital-intensive petrochemical industry. Thus, it may provide useful insights with regard to the green investment promotion effect of the ETS policies. Hence,

$$M_{ij} = \frac{v_i}{v_j} \tag{8}$$

Table 1. Literature that considers Morishima elasticity.

Researchers	Sector	Finding	Model
Färe et al. [31]	Electric utilities	Output elasticity of substitution between electricity and sulfur dioxide (SO_2), shadow price of SO_2	Distance function
Lee and Zhang [29]	Manufacturing industry	Input elasticity of substitution among energy and non-energy shadow price of CO_2	Distance function
Lee and Jin [30]	Electric power generation industry	Input elasticity of substitution between thermal capital and nuclear capital and their shadow prices	Distance function
Zhang et al. [32]	Poyang Lake	Input and output elasticity of substitution, shadow price of carbon	Slacks-based measure (SBM) DEA
Zhang and Xie [23]	Health information management (HIM) industry	Input and output elasticity of substitution, shadow price of carbon	Distance function

3. Characteristics of Data and Empirical Results

3.1. Data

At the initial stage of the ETS, the Korean government selected 525 ETS member companies from all industrial fields, as shown in Table 2. These companies are substantial carbon emitters with more than 1.25 billion tons emitted per business, or 25,000 tons per factory site, as calculated from three-year averages of 2012 to 2014. During the initial ETS stage, from 2015 to 2017, all these companies are allowed 100% free permits. As long as the companies maintain carbon production at the same levels as the prior three years, they have no obligation to buy carbon allowance permits. However, because production volume increases every year, the companies must emit less carbon from the increased production processes. Since the free allowance permit is excessively generous at this initial stage, there has been no significant carbon trading. In the first year (2015), the volume of carbon trading was less than 1%, and the average price was about US $5 per carbon ton. The reason is that many ETS member companies are export-oriented; thus, they are concerned that because of the unilateral ETS burden, they may lose their price competitiveness. Such companies believe that the government should consider this issue; thus, the government has established an initial stage goal at a modest average of the BAU level. In order to avoid unexpected third-party manipulation, only ETS member companies can buy and sell the carbon allowance permits. However, in the second stage from 2018 to 2020, member companies will be allowed 97% of emissions targets free of charge; then, certified third parties can participate in carbon trading.

Table 2. The industries and the numbers of companies in the Korean ETS.

Industry	Numbers	Industry	Numbers
Construction	40	Textiles	15
Mining	2	Water	3
Machinery	19	Cement	25
Wood processing	7	Glass	24
Electronic, displays, and semiconductors	45	Food and drink	23
Power and energy	38	Car manufacturing	24
Nonmetallic	24	Oil refining	4
Petrochemical	85	Paper	44
Shipbuilding	8	Steel	40
Telecommunications	6	Waste	44
Aviation	5	Total	525

In order to examine this ETS policy, we collected data from 63 companies in the petrochemical industry in 2014. We chose the petrochemical industry because it is the main group in the ETS that has homogeneity. We used the data to evaluate CTE, the shadow prices of carbon emissions, and the substitutability of types of input by using Morishima elasticity.

With regard to the output variables, we selected sales turnover (*T*) as a sole desirable output and carbon (*C*) as an undesirable output. We also selected two basic types of input, labor (*L*), and capital (*K*), and added energy (*E*) as the third input for environmental performance. The data for labor, capital, and turnover were derived from DART (the Data Analysis, Retrieval, and Transfer System) and Alio (Public Information Online). Energy and carbon data were taken from the Greenhouse Gas Inventory & Research Center of Korea. The CO_2 data was unavailable for the research period; thus, we interpolated the numeric values from the GHG emissions data, which includes other gases such as methane (CH_4), nitrogen (N_2O), hydrofluorocarbons (HFCs), perfluorinated compounds (PFCs), and sulfur hexafluoride (SF_6). In general, studies on the energy and environment (E&E) field have extracted pure CO_2 values under the International Panel on Climate Change (IPCC) guidelines by using a macro type of data such as fuel [13,23,33], consumption rate, and so on. However, we focus on the company level; and in Korea, only GHG data is available. Thus, we interpolate GHG data into a company's carbon value because carbon consists of 80% of GHG emissions worldwide, a percentage that according to the UNFCCC is the same in Korea. Because of the scarcity of some data, only 63 of 85 companies were included in the analysis. The basic data statistics for these companies are shown in Table 3.

Table 3. Descriptive statistics.

Variable	Type	Unit	Mean	Std. Dev.	Max.	Min.
Sales turnover	Desirable output	US $ Billion	2,102,894	3,800,331	18,076,229	59,824
Carbon	Undesirable output	CO_2 equivalent tons	756,249.6	1,436,648	7,063,768	23,461
Capital	Input	US $ Billion	110,867	195,610	1,125,781	3666
Labor	Input	Per person	1236.742	2198.649	2669	57
Energy	Input	Terajoules (TJ)	13,438.59	2,626,7.12	134,604	356

Sources: Greenhouse Gas Inventory & Research Center of Korea (http://www.gir.go.kr/) [34]. DART: Data Analysis, Retrieval, and Transfer System (http://dart.fss.or.kr/) [35]. Alio: Public Information Online (http://www.alio.go.kr/) [36].

Table 4 presents the input and output correlation matrix. The results show that the correlation between the types of input and output is positive. Capital and labor are significantly related with desirable output, and energy influences carbon significantly. Thus, an overall increase in input causes an increase in output, which strongly suggests that our approach is feasible for an empirical study.

Table 4. Input and output correlation matrix.

Variable	Capital	Labor	Energy	Turnover	Carbon
Capital	1				
Labor	0.900	1			
Energy	0.565	0.424	1		
Turnover	0.913	0.837	0.491	1	
Carbon	0.554	0.410	0.984	0.478	1

3.2. CTE and the Shadow Price of Carbon

Based on Equations (4) and (5), CTE is calculated in Table 5. The CTE scores range from 0.094 to 1 and the average CTE score is approximately 47.2%. The latter result implies that it is possible to accomplish a 52.8% efficiency enhancement in the petrochemical industry when it operates on the frontier of environmental production technology. Of the ETS group, 12.7% (eight companies) exhibit best practice in CTE, while a further eight companies have CTE levels that are lower than 20%.

This result implies that there is a strong tendency for bipolarization among the leading companies in Korea; thus, the government should take measures to support (or regulate more strictly) those companies with low CTE scores in order to improve their efficiency. Since there is a potential of more than 50% to improve eco-friendly efficiency, more proactive regulation is urgently needed for companies with lower CTE levels to encourage them to make greater efforts to enhance such levels.

Table 5. Carbon technical efficiency and the shadow prices of carbon emissions.

DMU	Efficiency	Shadow Prices	DMU	Efficiency	Shadow Prices
DMU1	0.240	40.56	DMU33	0.203	15.20
DMU2	0.704	57.66	DMU34	1.000	8.94
DMU3	0.108	0.71	DMU35	0.371	5.67
DMU4	0.903	14.80	DMU36	0.226	2.71
DMU5	0.548	0.24	DMU37	0.351	11.20
DMU6	0.157	19.45	DMU38	0.223	38.77
DMU7	0.233	73.15	DMU39	0.581	8.92
DMU8	0.147	28.22	DMU40	1.000	24.11
DMU9	0.217	43.93	DMU41	0.276	7.20
DMU10	0.199	37.18	DMU42	0.608	0.24
DMU11	1.000	53.37	DMU43	0.353	73.46
DMU12	0.273	27.42	DMU44	0.251	69.85
DMU13	0.505	45.66	DMU45	0.232	17.37
DMU14	0.395	18.30	DMU46	0.537	24.27
DMU15	0.195	2.09	DMU47	0.618	6.09
DMU16	0.255	3.05	DMU48	0.260	53.55
DMU17	0.435	13.12	DMU49	0.231	29.40
DMU18	1.000	0.57	DMU50	0.094	4.37
DMU19	0.243	4.48	DMU51	0.547	2.86
DMU20	0.701	23.89	DMU52	1.000	15.12
DMU21	0.723	7.23	DMU53	0.107	0.48
DMU22	0.460	2.78	DMU54	0.361	1.64
DMU23	0.283	18.72	DMU55	0.480	22.09
DMU24	0.337	13.80	DMU56	1.000	6.32
DMU25	0.409	3.66	DMU57	0.294	8.93
DMU26	1.000	18.19	DMU58	0.650	3.62
DMU27	0.438	0.10	DMU59	0.175	1.10
DMU28	1.000	2.60	DMU60	0.223	23.80
DMU29	0.196	1.19	DMU61	0.855	2.14
DMU30	0.450	4.52	DMU62	1.000	0.51
DMU31	0.348	12.81	DMU63	1.000	2.89
DMU32	0.555	1.59	Average	0.472	17.27

Table 5 also shows another shadow price result. The concept of the shadow price is widely used to measure the abatement cost caused by environmental regulations [29,32]. The shadow price not only presents an estimated value of the opportunity cost for undesirable output but also provides such output with meaningful guidelines to formulate regulatory policies for public decision-makers. In this study, the shadow price is equal to the carbon price for each unit of carbon emissions abatement.

The calculated average shadow price of all 63 companies is US $17.27. This result is far from the real value of US $10 at the end of 2014. In other words, the market price reflected just 58% of the shadow price. This situation indicates that the carbon price in the ETS market is too low to encourage companies to participate actively in the market. The small trading volume supports the hypothesis that the low carbon price prevents the ETS from being proactively pursued. As shown in Figure 1, the market price of carbon emissions remained at approximately US $10 dollars for almost a year and then began to rise, increasing to US $18 when each company had to register its carbon emissions performance at the end of March, 2016. This trend implies that companies do not regard carbon emissions regulation seriously; thus, they do not have a strong motivation to invest in energy-saving technologies or less energy-intensive production processes. Indeed, the market price only increased, almost doubling from its initial price, when each company had to register its carbon emissions performance. An ETS member company could and should buy a carbon emissions permit at the doubled price, otherwise it should pay triple the price as a penalty for its unfulfilled carbon emissions target. Moreover, most companies did not participate in carbon trading because of the 100% free allowance; thus, the market price could not accurately reflect the willingness of companies to engage in the additional abatement of carbon emissions.

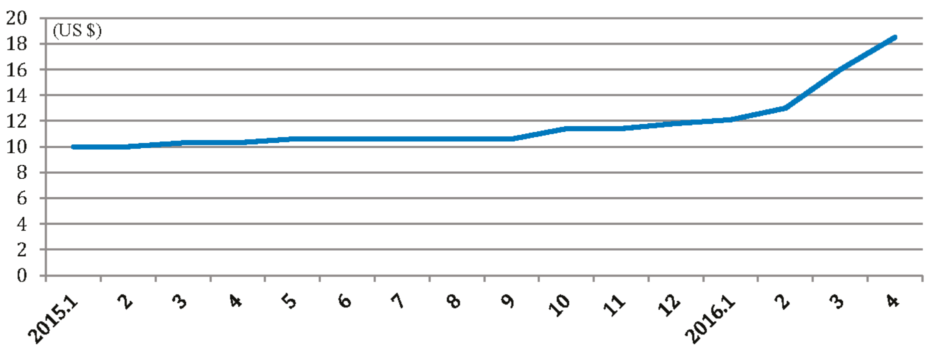

Figure 1. Market price trend of the carbon emissions allowance under the ETS.

3.3. Morishima Elasticity of Substitution

As shown by the CTE results, the Korean government should regulate the ETS more proactively because most companies show a very lower level of eco-friendly efficiency. Moreover, the market price for the carbon emissions allowance is much lower than its shadow price. This difference implies that even if a significant gap exists between the market price and the shadow price of carbon emissions, companies are not very willing to enhance their CTE and proactively participate in carbon trading. So that these companies take strategic decisions about investment in energy-saving green technology more seriously, capital-intensive enhancement of CTE performance should be more feasible. In order to evaluate the feasibility of green investment, we examine input/output-oriented Morishima elasticity. Table 6 presents the results of the Morishima elasticity of substitution that we employ to evaluate the sustainability of ETS policies for green investment promotion. The figures are calculated from Equation (8) and evaluated based on the shadow price ratio of inputs. As shown in Table 6, M_{kl} is 2252.9, which is much higher than an M_{lk} of zero. It should be noted that a higher Morishima value implies lower substitutability. The findings indicate that there is no difficulty in capital substituting for labor, although labor cannot substitute for capital. Such a result is to be expected in the capital-intensive petrochemical industry.

Table 6. Morishima-type elasticities of substitution (input).

Elasticity of Substitution	Estimate
M_{kl}	2252.9
M_{lk}	0
M_{ke}	33.70317
M_{ek}	0
M_{le}	0.34207
M_{el}	52.17643

In addition, M_{ke} is 33.7, implying that capital can easily be substituted by energy. Thus, it is strongly recommended that energy-intensive companies should expand their investment in facilities and energy-saving technology. Finally, M_{el} is higher than M_{le}, which means that energy can be substituted by labor but not vice versa. Hence, the results show that in a capital-intensive industry, labor is easily substituted with energy; thus, green technology also leads to labor-saving operations.

4. Conclusions

One year has passed since the Korean government inaugurated its ETS in 2015; consequently, it may be too early to evaluate the sustainability of the government's ETS policies. Although there have been problems such as a low volume of carbon trading and unduly low semi-fixed prices, such policies must continue successfully. The reason is that ETS policies are necessary for optimal control of future challenges and for a low carbon society, both of which are goals that the Korean government should pursue because the achievement of low carbon emissions is an engine for future development. From the beginning, there have been excessive claims and opposition from diverse interest groups such as politicians, industrial leaders, business managers, and experts. Because of the complaints from these people, the government has set its carbon-reduction targets at much lower levels than originally planned, resulting in a lack of governance for sustainable performance. In this research, we examined three governance factors of sustainability with regard to Korean ETS policies.

First, the eco-friendly efficiency of CTE shows that companies have significant potential to enhance their efficiency. The average CTE for the 63 ETS member companies in our sample was 0.472. This figure suggests that there is potential for a 52.8% enhancement of such companies' CTE. In other words, the proactive participation of companies in the ETS should lead to an efficiency improvement that more than doubles the current average. If such companies can obtain information about the best practices of companies on the frontier, they can certainly improve their CTE. Moreover, in order to avoid bipolarization of carbon-reduction performance, the government should make cross-learning from best practices easier and more profitable for the ETS member companies.

Based on this empirical result, we examined the second governance factor of market price appropriateness. Using the shadow price of carbon emissions, the empirical result showed that the market price was approximately half that of the shadow price for almost a year. This result implies that an excessively regulated market price prevents companies from proactively participating in carbon trading. Further, it is clear that there is a missing link in the carbon trading policy of the ETS. In order to find this missing link, we used a third stage of empirical testing in terms of Morishima elasticity between the input and undesirable output of carbon emissions. The findings showed that there is significantly high substitutability between capital and energy input, implying that greater investment in green technology results in higher levels of energy-saving efficiency. This improvement is the ultimate goal of the Korean government's ETS policies. However, unfortunately, the current severely distorted restriction of unduly generous carbon emissions targets has resulted in poor performance from efficiency and shadow price perspectives. Thus, the empirical results strongly suggest that the Korean government should encourage the ETS member companies to make greater efforts to decrease their carbon emissions. Such encouragement should not rely on a voluntary approach but should be in the form of a stricter regulated system with much lower free allowances for carbon emissions. In particular, CTE is bipolarized, implying that there is significant potential for companies with low CTE to improve easily and effectively. Such improvements can originate from intra-industry technological transfers or the learning effects of best practice taken from those companies on the frontier of the DDF production possibility curve.

This research used duality theory with a non-radial, non-parametric DDF approach to examine diverse production characteristics from the sustainable development perspective. Using input-oriented DDF, CTE was measured in the first stage. Further, by using the dual model of non-radial DDFs, we obtained the shadow prices of carbon emissions and input substitutability. Because the methodology could not reflect the dynamic effect of the ETS, it may have limited implications. Moreover, the empirical test was undertaken in the petrochemical industry only. Thus, even if the research provides clearer insights because of the homogeneity of the DMUs, it still needs to expand its empirical base to encompass diverse industries by using the meta-frontier approach. All the data in the paper is based on the one year of 2015, and it may be too short to infer the significant implications and suggestions. However, since the Korean government initiated the target management system (TMS) five years before ETS, all the covered companies are ready to participate in the ETS and their efforts are relevant to be analyzed even in the short term. Of course, our research need to be complemented with the dynamic changes of the policy effects over time for the future research issue.

Are emissions trading policies sustainable in Korea? This paper showed clearly the lack of governance for a sustainable ETS policy in Korea; thus, the Korean government should engage in greater proactive efforts to upgrade the future sustainable performance of the ETS [37]. Especially, for the sustainable performance of ETS, the covered companies should make efforts to invest in green technology to improve its environmental efficiency, and the paper showed that there is huge potential for benefits from green investment to enhance environmental efficiency. However, the government should support for the companies to invest on the green technology as early as possible to fill the missing link between the target and the current huge lack of the environmental efficiency.

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International Comparison of Total Factor Ecology Efficiency: Focused on G20 from 1999–2013

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Abstract: Little attention has been paid to international ecological efficiency, especially taking ecological footprint (EF), labor, and capital into account as multi-inputs to produce GDP in the total-factor framework. This study evaluates the total-factor ecological efficiency (TFEcE) of G20 during the period of 1999–2013 by employing slack-based measure (SBM) with EF as the index of comprehensive ecological inputs. Findings show that the average level of TFEcE of G20 from 1999 to 2013 is at a low level of about 0.54, which means there is a large space for the improvement of TFEcE. Furthermore, TFEcE of G20 is very imbalanced and there is a big gap between developed countries and developing countries in the G20. For the developing countries and developed countries in the G20, the analysis of factors that affect national TFEcE shows different statistical significance in the truncated regression model.

Keywords: slack-based measure (SBM); ecological footprint (EF); total-factor ecological efficiency (TFEcE)

1. Introduction

Efficient ecology consumption is a top priority in the ecological field in terms of both resource conservation and control of climate change. Over the last few decades, the world has witnessed large ecological degradation problems, including increasing greenhouse gas emission, high energy consumption, deforestation, land erosion, and groundwater exhaustion. Thus, it is necessary to take both economic and ecological factors into account in policy-making. In general, accepting declining economic growth as a consequence of decreased ecological consumption is not practicable. Improving ecological efficiency, not only maximizing economic objectives but also minimizing ecological concerns, is important for every economy.

Ecological efficiency is concerned with creating more value with less impact [1]. In empirical studies, ecological efficiency has always been measured in the presence of the ratio of macroeconomic variables (especially GDP (gross domestic product)) to ecological inputs. Despite the wide-ranging literature that has investigated the relationship between GDP and ecological inputs, most of the studies have focused on utilizing CO_2 emissions or energy consumption as an indicator of ecological inputs which just represents a portion of them. Thus, to have a better understanding of ecological efficiency, this study will utilize the ecological footprint (EF) as a comprehensive indicator of ecological inputs.

Ecology input alone cannot produce any output. Ecology must be put together with other inputs, such as labor and capital, to produce GDP. Consistent with the view that single-factor energy efficiency index has some disadvantages in empirical studies [2], likewise, single-factor ecological efficiency index (ecological inputs to GDP ratio) in the previous literature would also lead to misleading conclusions. Therefore, a multi-input model considering other inputs in a total-factor framework should be applied to correctly assess the ecological efficiency.

Different from the papers such as Hu and Wang [3] who only took energy into account as ecological inputs in a total-factor framework, and different from the existing papers using EF to evaluate single-factor ecology efficiency, this paper considers EF, labor, and capital as multi-inputs to assess the ecological efficiency in a total-factor framework, and we have named this index total-factor ecological efficiency (TFEcE).

The purpose of this study is to evaluate the TFEcE of the G20 during the period of 1999–2013 by employing slacks-based measure (SBM). To our knowledge, little attention has been paid to international ecological efficiency, especially taking ecological footprint (EF), labor, and capital into account as multi-inputs to produce GDP in the total-factor framework. This paper is organized as follows. Section 2 reviews the previous studies. Section 3 gives the methodology and describes the data we use for our analysis. Section 4 presents the empirical results and discussions. Finally, Section 5 concludes this paper.

2. Literature Overview

Different from the previous research which studies the EF and total-factor framework separately, this paper combines the concept of EF with the framework of total-factor. Our study is particularly related to two strands of literature.

The first strand focuses on ecological efficiency. Ecological-efficiency is concerned with creating more value with less impact [1]. The concept of ecological efficiency was originated from environmental efficiency [4], then in 1989 Schaltegger and Sturm (1989) [5] first described it as a "business like to sustainable development". Later, ecological efficiency was popularized by the establishment of the World Business Council for Sustainable Development (WBCSD) [6].

Although ecological efficiency assessment is a complicated and multidisciplinary task [7], it is widely measured as the ratio between the added value of a product or service and the ecological impacts of the product or service. In empirical study, GDP is often used as the numerator, and consumption of energy [3], emissions of CO_2 [8], domestic extraction [9] or material flow [10] is usually placed in the denominator as indicators of ecological pressure.

The most comprehensive measure of humanity's overall impact may be EF, which was first proposed by Rees [11] and elaborated by Wackernagel and Rees [12]. Since then, EF is widely applied to assess sustainability. Moffatt [13] suggested that by combining EF with more methods, further detailed work of relevance to policy makers would become available. Kratena [14] described the concept of ecosystem pricing in an input-output system based on the concept of the EF. Chen et al. [15] stated that the ratio of GDP to EF can be considered as a measure of the resource efficiency. Fu et al. [16] calculated the resource productivity (RP) by using the EF as an indicator of the natural resource input and GDP as the output in the equation of RP = GDP/EF. By using the data of EF, Miao et al. [17] measured ecological carrying capacity, ecological deficit, and surplus in Anhui province in China.

The second strand of research related to this paper is concerned with total-factor framework, especially with total-factor energy efficiency. Hu and Wang [3] argued that energy alone cannot produce any output and energy needs to be put together with labor and capital in order to produce outputs. Therefore, a multiple model should be applied to correctly evaluate the energy efficiency. Under the total-factor framework, Hu and Wang [3] first proposed the total-factor energy efficiency (TFEE) index and employed it to analyze energy efficiencies of 29 administrative regions in China. By incorporating water as an input as well as using conventional inputs such as capital stock and labor employment, Hu et al. [18] calculated the total-factor water efficiency and found that there was a U-shape relation between the total-factor water efficiency and per capita real income among areas in China. Furthermore, Hu and Kao [19] studied energy-saving target ratios for 17 APEC economies and discovered an increasing trend except for Canada and New Zealand. Honma and Hu [20] employed the data envelopment analysis (DEA) to calculate the regional TFEE in Japan, and 14 inputs (3 production factors, 11 energy sources) are included in this model. Zhang et al. [21] used a total-factor framework to investigate energy efficiency in 23 developing countries during the period of 1980–2005, and found that China experienced the most rapid rise in TFEE. Chang and Hu [22] introduced the total-factor energy productivity index (TFEPI) based on the concept of TFEE and the Luenberger productivity index to evaluate the energy productivity change of regions in China. Li and Hu [23] computed the ecological total-factor energy efficiency (ETFEE) of 30 provinces in China for the period 2005–2009 through the SBM with undesirable outputs. Zhang et al. [24] proposed a metafrontier slack-based efficiency measure approach to assess ETFEE and empirically analyzed regional ETFEE of China during 2001–2010.

The first strand of literature related to ecological efficiency only regarded ecological input as a single input to produce GDP, while neglecting other key inputs such as capital and labor; the second strand of literature related to the total-factor energy efficiency only considered energy as ecological input, while ignoring other ecological inputs such as water, forest, and land. Therefore, this paper attempts to use EF as the index of comprehensive ecological inputs, as well as taking labor and capital into account, to assess the ecological efficiency of G20 in a total-factor framework.

3. Methodology and Data Source

In this section, we first calculate EF which is the aggregate area of land and water in six ecological categories, then consider EF as the comprehensive measurement of ecological inputs and introduce it into the SBM model which takes capital and labor into account, to assess the TFEcE of G20 in a total-factor framework.

3.1. Ecological Footprint

EF is a simple assessment method for sustainable development from the perspective of the aggregate area of productive lands and water required to produce all the resources consumed and to assimilate all the wastes produced [25]. EF transfers the consumption of different ecological resources into various productive lands, and the lands can be divided into six types: arable land, pasture land, forest land, fisheries land, fossil energy land, and built-up land.

The calculation method of EF from 1999–2013 for G20 is mainly based on the compound approach proposed by Wackernagel et al. [26]. The computational formula for EF is as follows:

$$\text{EF} = \sum \frac{P_i}{Y_{Pi}} \times YF_i \times EQF_i \tag{1}$$

In the above Equation (1), EF represents the total ecological footprint; i is the type of resource consumed by a certain amount of population; P_i is the quantity of the ith resource consumed; Y_{Pi} is the average productivity for producing ith type of resource; YF_i is the yield factor of ith land type, which describes the extent to which a biologically productive area in a given country is more (or less) productive than the global average of the same bioproductive area; EQF_i is the equivalence factor of ith land type, which represents the world average productivity of given productive land relative to the global average productivity of all productive lands.

The consumption of biological resources (including arable land, pasture land, forest land, and fisheries land) cannot be calculated directly, so the trade adjustment is conducted. The steps are as follows. First, calculate the biological resources manufacturing footprint based on national statistics of biological production. Second, calculate the biological resources net export trade footprint based on national trade data of biological resources. Third, deduct net export trade footprint from manufacturing footprint.

3.2. Slacks-Based Measure (SBM) Model

Data Envelopment Analysis (DEA) is a non-parametric statistical method based on linear programming technique to assess the efficiencies of decision-making units (DMU) that refer to a set of firms or a set of countries in empirical studies. Built upon the basic DEA models of Charnes et al. [27] and Banker et al. [28], Tone [29] proposed the SBM to measure efficiency based on input excesses and output shortfalls. Being a non-radial approach, SBM overcomes the conventional radial DEA method's overestimating-limitation which is caused by neglecting slack variables [30]. Furthermore, SBM directly accounts for input and output slacks in efficiency measurements, with the advantage of capturing the whole aspect of inefficiency [24].

Assume that there are $i = 1, \ldots, N$ countries, and each country is a DMU using input vector $\boldsymbol{x} \in R_+^m$ to produce output vector $\boldsymbol{y} \in R_+^n$. In this paper, the output vector is national GDP. The input vector contains EF, capital stock, and labor employment. The fractional programming problem of SBM model is expressed as follows:

Minimize

$$\rho = \frac{1 - (1/m)\sum_{i=1}^{m} s_i^- / x_{io}}{1 + (1/n)\sum_{r=1}^{n} s_r^+ / y_{ro}} \tag{2}$$

Subject to

$$\begin{aligned} x_o &= X\lambda + S^-, \\ y_o &= Y\lambda - S^+,\ \lambda \geq 0, \\ s^- &\geq 0, \qquad s^+ \geq 0\,. \end{aligned} \tag{3}$$

where each country has m inputs and n outputs; s_i^-, s_r^+, x_o, and y_o represent the input slack, the output slack, the inputs, and the outputs for the oth country respectively; S^-, S^+, X, and Y are the corresponding matrices of the input slack, the output slack, the inputs, and the outputs; λ is a nonnegative multiplier vector. ρ is the overall efficiency score for the oth country. If $\rho = 1$ (which indicates that all the slack variables are 0), the oth country is SBM-efficient.

3.3. Total-Factor Ecology Efficiency (TFEcE)

TFEE in Hu and Wang [3], Li and Hu [23] is defined as:

$$\text{TFEE}\,(o,t) = \frac{\textit{Target energy input}\,(o,t)}{\textit{Actual energy input}\,(o,t)} \tag{4}$$

where TFEE(o,t) is the total-factor energy efficiency for region o at time t. In Hu and Wang [3], Li and Hu [23], the target energy input for each region is defined as:

$$\text{Target energy input}\,(o,t) = \text{Actual energy input}\,(o,t) - \text{Total energy input slack}\,(o,t) \tag{5}$$

Total energy input slacks, which can be obtained from SBM in Hu and Wang [3] and Li and Hu [23], represent the gap between the target level and actual level. Total energy input slack can be regarded as the inefficient portion of actual energy consumption.

Following the TFEE proposed by Hu and Wang [3] and Li and Hu [23], this paper uses EF instead of energy as the ecological inputs to build the index of TFEcE for country o at time t.

According to Formula (3), the input slacks are the total amount that can be reduced without decreasing the output levels. With respect to ecological inputs, the above slacks are called the "ecology input slacks" and the amount of slacks in ecological input is regarded as the inefficiency portion of actual ecological consumption. Based on the slacks of ecology input obtained from Formula (3), considering labor, capital, and EF simultaneously, we can work out the ecology-saving target ratio (ESTR). The formula is as below:

$$\text{ESTR}\,(o,t) = \frac{\text{Ecology input slack}\,(o,t)}{\textit{Actual ecology input}\,(o,t)} \tag{6}$$

where ESTR represents each country's inefficient level of ecology consumption. ESTR (o,t) refers to the ESTR in the oth country and the tth year. TFEcE in this paper has the following relation with ESTR:

$$\text{TFEcE}\,(o,t) = 1 - \text{ESTR}\,(o,t) \tag{7}$$

where TFEcE (o, t) refers to the TFEcE in the oth country and the tth year. A zero ESTR value implies a country on the frontier with the best TFEcE up to one among the observed countries, while a country with the value of ESTR larger than zero indicates that ecology should and could be saved at the same output level. Therefore, TFEcE lies always between zero and unity and a higher TFEcE implies higher ecological efficiency in a total-factor framework.

3.4. Data and Material

The G20 member countries are chosen as the research object because they have worldwide representatives including both developed and less-developed countries. Furthermore, the GDP of G20 accounts for about 90% of the world GDP and their population accounts for about two-thirds of the world population. G20 consists of the following economies: Argentina, Australia, Brazil, Canada, France, Germany, India, Indonesia, Italy, Japan, Republic of Korea, Mexico, Russian Federation, Saudi Arabia, South Africa, Turkey, UK, USA, and China. The EU is excluded due to the incompleteness of data. The data used in this paper comes from that of 19 countries in the G20 from 1999–2013.

EF refers to various types of resources meeting the daily consumption of a certain human population. In this paper, arable products include cereals, pulses, oil crops, eggs, and vegetables. Forest products include fruit and wood. Pasture products include cattle, mutton, pig, and milk. Fisheries products include fish. Fossil energy land is related to oil, natural gas, and coal. In addition, the consumption of hydro-electricity is converted into that of built-up land.

The above data of the agricultural products (including arable products and pasture products), forest products, and fisheries products are mainly from the FAO STAT, provided by Food and Agriculture Organization of the United Nations. The consumption quantities of oil, natural gas, coal, and hydro-electric can be obtained from BP's statistical review of world energy. We adopt the value of the equivalence factors proposed by Wackernagel and Rees [12].

In SBM model, EF, capital stock and labor are employed as inputs, and GDP as output. EF is calculated by the above method. Capital stock from 1993 to 2013 with 2005 prices is calculated using the Perpetual Inventory Method as the following equation shows:

$$K_t = I_t + K_{t-1}\,(1-\delta) \tag{8}$$

where I_t is the capital formation in the year t, which can be obtained from Penn World Table 7.1. δ is depreciation rate and is set to be 6% according to the relevant literature [31]. K_t is the capital stock in the year t. Initial capital stock is estimated by the equation proposed by Nehru and Dhareshwar [32]:

$$NK_i = I_i/\,(\delta + g) \tag{9}$$

where NK_i is the initial capital stock of the research period, I_i is the initial capital formation. g is the average capital growth rate during the research period. δ is depreciation rate.

Data on labor and GDP are collected from the World Development Indicators of the World Bank, and GDP is transformed into constant 2005 U.S. dollars by GDP deflators.

4. Empirical Analysis

4.1. Evaluation of EF in G20 from 1999 to 2013

As shown in Figure 1, the total EF of G20 maintains a stable growth trend from 1999 to 2013, increasing from 9.62 billion ha in 1999 to 12.03 billion ha in 2013, and achieving a growth of about 25%.

The six different land types of EF are also shown in Figure 1. Fossil energy land contributed most to the total EF among the six components, accounting for 33.77%, and followed by forest and pasture land, whose contributions were 25.38% and 23.42% respectively. Arable land ranked fourth with the percentage of 16.9%. The contributions of fisheries and built-up land to total EF were relatively small, and the average proportions were 0.03% and 0.52%, respectively.

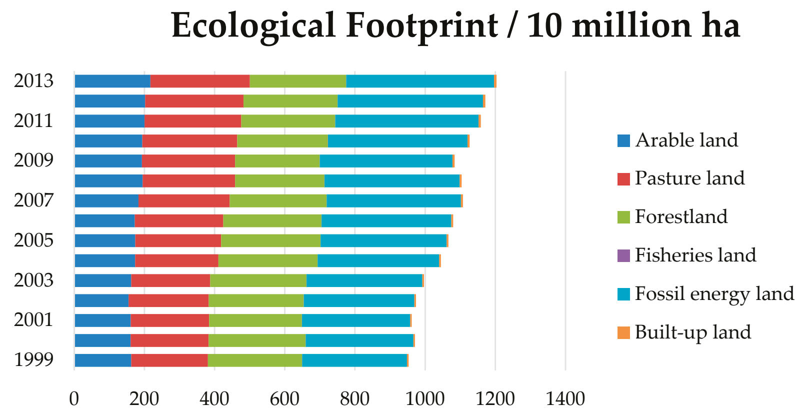

Figure 1. Time series of total EF components in G20 countries 1999–2013.

Over the study period, the proportions of six land types have changed considerably. The EF of fisheries land was the fastest growing component during 1999–2013, and it increased by 67.75% from 2.6 million ha in 1993 to 4.4 million ha in 2013. The EF of forest land obtained the lowest growth rate of only 2%. The growth rates of pasture, arable, fossil energy, and built-up land were 29.62%, 33.69%, 40.97%, and 53.57% respectively.

The national level of EF is shown in Table 1. Due to the limited space, only data in some specific years are listed. According to the results in Table 1, the EF of G20 countries displays two evolving trends during the research period. Firstly, the EF of seven countries (Australia, Canada, France, Italy, Japan, UK, and USA) declined over time, with the biggest fall taking place in Italy. Secondly, the remaining 12 countries presented an upward trend in EF, with China increasing the most.

Table 1. EF by countries from 1999 to 2013 (10 million ha).

Country	1999	2001	2003	2005	2007	2009	2011	2013
Argentina	14.300	12.697	13.011	14.628	15.451	15.806	15.668	17.982
Australia	18.171	19.589	20.588	20.148	19.967	19.079	19.038	18.047
Brazil	56.337	56.131	63.123	62.603	65.376	64.610	70.363	72.958
Canada	52.264	50.286	50.966	55.581	47.944	38.424	44.034	45.613
France	32.510	32.970	31.140	31.796	31.779	30.973	30.466	29.471
Germany	39.436	39.998	41.125	42.017	44.893	40.650	42.199	43.103
India	105.680	109.126	113.883	121.451	131.497	137.890	148.858	153.258
Indonesia	28.795	26.894	29.429	28.806	29.879	31.059	34.722	35.370
Italy	22.529	21.891	22.016	22.485	21.955	20.385	20.495	18.806
Japan	36.860	35.777	36.273	36.309	35.873	32.181	33.826	35.254
Republic of Korea	12.980	13.604	14.287	14.384	15.003	15.064	16.264	16.908
Mexico	22.168	23.402	23.925	24.882	26.087	25.356	26.274	26.512
Russian	66.106	75.103	74.506	74.765	80.060	75.070	81.699	80.829
Saudi Arabia	7.237	7.731	8.707	9.747	10.553	11.609	13.195	14.351
South Africa	11.473	11.599	12.446	13.077	13.141	13.682	13.398	13.321
Turkey	14.643	14.168	15.593	16.530	18.293	18.366	21.336	23.095
UK	22.343	22.470	22.628	22.537	22.338	21.039	20.612	20.949
USA	244.785	240.907	245.511	255.476	252.503	226.666	234.256	239.207
China	153.842	156.807	167.147	209.142	234.635	254.332	281.315	298.441

China and USA were the two countries with the highest EF. China's EF, with the total growth of 94% from 1999 to 2013, exceeded that of the USA in 2008 and the gap of EF between China and USA extended to 59.25 10 million ha in 2013. India's EF ranked the third and increased by nearly half from 105.68 10 million ha in 1999 to 153.26 10 million ha in 2013. Compared with these three countries, the EF of the remaining countries were at lower levels. Among all the countries, the EF of Saudi Arabia was the smallest, but its growth rate was the highest, which was 98.31%, from 7.24 10 million ha in 1993 to 14.35 10 million ha in 2013.

4.2. Analysis of the G20's TFEcE

According to the Formulas (6) and (7) in Section 3, we calculate the TFEcE of G20, and the results are shown in Table 2. In general, the average TFEcE of G20 from 1999 to 2013 is at a low level of about 0.54, which urgently needs to be improved. The actual ecological inputs could be reduced by almost 46%, with output unchanged, through ecological efficiency improvement. This indicates that the improvement of ecological efficiency is an effective way to maintain economic growth, and meanwhile, to relieve ecological pressure.

Table 2. Total-factor ecology efficiency (TFEcE) by countries (1999–2013).

Country	1999	2001	2003	2005	2007	2009	2011	2013
Argentina	0.267	0.290	0.270	0.182	0.167	0.150	0.191	0.154
Australia	0.384	0.373	0.356	0.379	0.389	0.378	0.376	0.408
Brazil	0.333	0.334	0.288	0.323	0.312	0.208	0.283	0.260
Canada	0.220	0.269	0.354	0.208	0.225	0.408	0.307	0.251
France	0.930	0.933	0.672	0.657	0.642	0.630	0.647	0.648
Germany	0.758	0.743	0.688	0.652	0.615	0.641	0.620	0.598
India	0.245	0.250	0.299	0.392	0.264	0.265	0.177	0.203
Indonesia	0.356	0.414	0.417	0.507	0.363	0.365	0.357	0.359
Italy	1.000	1.000	0.811	0.770	0.766	0.770	0.741	0.830
Japan	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
Republic of Korea	0.702	0.675	0.711	0.693	0.669	0.668	0.594	0.593
Mexico	0.557	0.569	0.574	0.425	0.508	0.580	0.568	0.614
Russian	0.467	0.629	0.436	0.394	0.230	0.121	0.238	0.239
Saudi Arabia	0.648	0.673	0.568	0.568	0.593	0.640	0.545	0.514
South Africa	0.462	0.582	0.574	0.533	0.404	0.203	0.204	0.208
Turkey	0.649	0.585	0.612	0.552	0.275	0.248	0.254	0.242
UK	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
USA	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
China	0.238	0.253	0.238	0.271	0.281	0.330	0.268	0.285
Developed countries	0.764	0.767	0.716	0.692	0.690	0.714	0.683	0.684
Developing countries	0.397	0.434	0.412	0.398	0.312	0.274	0.282	0.285

According to the human development index of United Nations Development Program (UNDP) and the classification of countries proposed by the World Bank, the developed countries mentioned in this study include Australia, Canada, France, Germany, Italy, Japan, Republic of Korea, Saudi Arabia, USA, and UK, and the rest belong to the developing countries.

As Table 2 presents, TFEcE of the G20 is very imbalanced. There is a big gap between developed countries and developing countries. For the average value, TFEcE of developed countries reached 0.714, double what it is in developing countries, 0.352. For the median value, TFEcE of developed countries reached 0.705, which is 1.97 times that of developing countries, 0.358. For the degree of divergence, the standard deviation of TFEcE in developed countries is 0.031, just a half of that in developing countries, 0.062. According to the gap between developed countries and developing countries in the G20 in terms of their TFEcE, it showed an upward trend with fluctuation, rising from 0.367 in 1999 to 0.399 in 2013. In 2009, the gap reached a maximum, which is 0.439.

In order to further confirm the gap between developed countries and developing countries, Mann-Whitney U rank test is applied to carry out a significance test. We can see from Table 3, there exists a significant difference between the TFEcE of developed countries and that of developing countries.

Table 3. Significance test of TFEcE between developed and developing countries.

Countries	Mann-Whitney U	Wilcoxon W	*Z*-Value	*p*-Value
Developed vs. Developing	0.000	120.000	−4.666	<0.001

Notes: Mann-Whitney U test is a nonparametric test of the null hypothesis that the distribution of the two populations which the two independent samples come from has no significant difference.

In terms of specific countries, three countries—USA, UK, and Japan—found the optimal efficiency during the research period, and they are all developed countries. These three countries are followed by Italy, France, Republic of Korea, and Germany at 0.84, 0.71, 0.67, and 0.66, respectively. The TFEcE of Saudi Arabia, Mexico, and Turkey are around the average level of all the countries. South Africa, Indonesia, and Australia gain almost the same TFEcE, fluctuating around 0.39. The country with the lowest TFEcE score is Argentina, and the average score is 0.21 during 1999–2013.

It is worth noting that among those developed countries, TFEcEs of Canada and Australia, respectively 0.386 and 0.275, are relatively lower than other developed countries. TFEcE assessment involves input variables (EF, labor, and capital), as well as an output variable (GDP). The main reason of the lower TFEcEs of the two countries is that their EF inputs are relatively high. Statistics data can be used to illustrate. Compared with France, labor, capital, and GDP values of Australia were 37.5%, 41.7%, and 32.5%, respectively, while the EF value that Australian occupied is just 60.1% of that of France. Compared with France, labor, capital, and GDP values of Canada were respectively 62.2%, 52.3%, and 52.9%, but the EF value that Canada occupied is 153.7% of that of France. EF consists of six different ecological land types. Different resource endowments of Australia and Canada lead to different occupation of ecological land types. The pasture land footprint in Australia (which accounts for 40.5% of the country's total EF) and the forestland footprint in Canada (which accounts for 57.7% of the country's total EF) are relatively higher, and which lead to the higher total EF and also the lower TFEcEs of them.

Russia, Brazil, and China, the three most populous developing countries, have relatively low TFEcE scores. Though China's TFEcE is small, its growth rate is the highest at 19.7% from 0.238 in 1999 to 0.285 in 2013. The TFEcE of China in 1993 was only 0.238, which was lower than that of Argentina, while in 2013 the TFEcE of China was 1.85 times as high as that of Argentina. China's TFEcE ranked 18th in 1999 and 12th in 2013, which may benefit from the relevant effective measures taken by Chinese government, including the "National Program on Climate Change" first proposed by developing countries in 2006 and the "Energy Conservation Binding Targets" established in 2009.

4.3. Comparison of G20 Countries' TFEcE and TFEE

The essential difference between TFEE proposed by Hu and Wang [3] and TFEcE in this paper is whether to incorporate the comprehensive ecological impacts. TFEcE takes not only the energy inputs, but also the water, forest, and arable inputs into account, which evaluates ecology efficiency more comprehensively. Tables 2 and 4 respectively show the TFEcE and TFEE of G20, and Table 4 also presents the difference between TFEcE and TFEE of G20.

Without considering other ecological impacts, TFEE may overestimate the country's performance. As Table 4 shows, during 1999–2013, the average of TFEE of G20 is 0.617, while the average of TFEcE is 0.543. The Mann-Whitney U rank test proves that the difference between TFEE and TFEcE presents a statistical significance with a p-value less than 0.001 as Table 5 shows. The comparative result means that consideration of EF as comprehensive ecological inputs has a significant influence on the country's ecology efficiency.

At the national level, Table 4 shows the gap between TFEE and TFEcE of G20. The countries can be divided into three groups. The first group includes UK and USA. There is no difference between TFEE and TFEcE for these two countries, because they always stand on the efficient frontier and rank first for both TFEE and TFEcE for each year. The second group includes Japan, Republic of Korea, Saudi Arabia, and South Africa. The TFEE of these countries are lower than their TFEcE. In this group, Saudi Arabia presents the biggest difference between TFEE and TFEcE, which are 0.35 and 0.6 respectively. The main reason may be that Saudi Arabia is an "oil kingdom", one of the countries that has the largest oil reserves and production. The process of production, exploration, and exploitation of petroleum need to consume much energy, and the relative low price of oil also induces more energy consumption. These factors lead to low TFEE score in Saudi Arabia. However, Saudi Arabia's TFEcE is higher than its TFEE, which indicates that Saudi Arabia has made efforts to improve efficiency of other ecological inputs. The efforts on other ecological impacts made by these countries in the second group would be ignored if we only considered the energy input as the whole ecological inputs. The rest of the countries belong to the third group, whose TFEE is higher than their TFEcE. These countries have paid more attention to energy consumption, with less attention to biological EF (including arable lands, pasture lands, forest lands, and fisheries lands). Taking China as an example, the average of TFEE is 0.31, while the TFEcE score is 0.28. This indicates that China has achieved much more progress in energy saving, with less progress in other ecological inputs reduction. For the countries in the last group, they should vigorously promote energy savings and other biological EF reduction at the same time.

Table 4. TFEE, difference between TFEcE and TFEE by countries (1999–2013).

Country	Total-Factor Energy Efficiency					Difference between TFEcE and TFEE				
	1999	2001	2005	2009	2013	1999	2001	2005	2009	2013
Argentina	0.558	0.563	0.409	0.312	0.295	0.291	0.273	0.228	0.162	0.141
Australia	0.604	0.604	0.588	0.521	0.524	0.219	0.231	0.210	0.143	0.116
Brazil	0.527	0.571	0.477	0.560	0.445	0.194	0.237	0.154	0.352	0.186
Canada	0.483	0.565	0.459	0.443	0.430	0.263	0.296	0.251	0.034	0.179
France	1.000	1.000	1.000	1.000	1.000	0.070	0.067	0.343	0.370	0.352
Germany	0.720	0.709	0.896	0.880	0.799	−0.038	−0.034	0.244	0.238	0.200
India	0.383	0.320	0.476	0.458	0.454	0.138	0.070	0.084	0.193	0.250
Indonesia	0.481	0.419	0.432	0.512	0.450	0.125	0.005	−0.075	0.148	0.091
Italy	1.000	1.000	0.914	0.905	0.938	0.000	0.000	0.144	0.135	0.108
Japan	0.784	0.754	0.908	0.872	0.741	−0.216	−0.246	−0.092	−0.128	−0.259
Republic of Korea	0.633	0.691	0.660	0.637	0.461	−0.069	0.016	−0.033	−0.030	−0.133
Mexico	0.674	0.664	0.739	0.660	0.555	0.117	0.095	0.314	0.080	−0.059
Russian	0.509	0.510	0.418	0.386	0.327	0.042	−0.119	0.025	0.265	0.088
Saudi Arabia	0.360	0.367	0.266	0.272	0.229	−0.288	−0.306	−0.301	−0.367	−0.285
South Africa	0.450	0.501	0.481	0.186	0.186	−0.013	−0.080	−0.052	−0.017	−0.023
Turkey	0.533	0.644	0.770	0.577	0.437	−0.116	0.059	0.218	0.330	0.195
UK	1.000	1.000	1.000	1.000	1.000	0.000	0.000	0.000	0.000	0.000
USA	1.000	1.000	1.000	1.000	1.000	0.000	0.000	0.000	0.000	0.000
China	0.328	0.391	0.269	0.284	0.318	0.090	0.139	−0.002	−0.046	0.033

Table 5. Significance test between TFEcE and TFEE in G20.

Indicators	Mann-Whitney U	Wilcoxon W	*Z*-Value	*p*-Value
TFEcE vs. TFEE	66,386.000	146,186.000	−4.071	<0.001

4.4. Factors of National TFEcE

TFEcE of all the G20 countries every year lies always between zero and unity, thus it is a limited dependent variable. In order to distinguish the influential factors of national TFEcE, we follow the method of Li and Hu [23] and employ the truncated regression model based on the truncated characteristics of TFEcE data. Truncated regression models arise in many applications of statistics, cases where observation values in the outcome variable are below or above certain thresholds are systematically excluded from the sample.

Three factors are investigated in this paper. *R&D* represents the ratio of research and development expenditure to GDP. *Tra* is on behalf of the foreign dependence degree, which is the ratio of total exports and imports to GDP. *Ind* refers to the ratio of the secondary industry to GDP. All the data are obtained from the World Bank (World Development Indicators). Due to data limitations, the reduced sample data set from 2003–2013 is employed in this section. Saudi Arabia is excluded due to data missing in this section.

The truncated regression model is set as:

$$\text{TFEcE}_{o,t} = \beta_0 + \beta_1 R\&D_{o,t} + \beta_2 Tra_{o,t} + \beta_3 Ind_{o,t} + \varepsilon_{o,t} \quad (10)$$

where $\text{TFEcE}_{o,t}$ refers to the TFEcE in the oth country and the tth year; β_0 is the constant term; β_1, β_2, and β_3, are the parameters of the independent variables, respectively; and $\varepsilon_{o,t}$ is the error term.

From the above descriptive statistics analysis and significance test in Section 4.2, we can find that there is significance difference in TFEcE between developed countries and developing countries, while an analysis on all the G20 countries of Formula (10) may cover it up. Therefore, Table 6 respectively analyzes the factors that influence TFEcE of the whole G20 countries, G20 developed countries and G20 developing countries. Overall, the result of all the G20 countries is basically consistent with that of G20 developed countries, while different from the one of G20 developing countries. Such results show the necessity of dividing G20 into developing countries and developed countries when analyzing the factors that influence TFEcE.

Table 6. Factors of national TFEcE scores in G20.

Variables	All the Countries		Developed Countries		Developing Countries	
	Coefficient	Significant Test *p*-Value	Coefficient	Significant Test *p*-Value	Coefficient	Significant Test *p*-Value
Independent Variable						
R&D	0.2507	0.000	0.5328	0.019	−0.0950	0.001
Tra	−0.0010	0.594	−0.0085	0.138	0.0045	0.000
Ind	−0.0214	0.000	−0.0738	0.024	−0.0003	0.894
Constant term	0.8487	0.000	2.3007	0.002	0.1934	0.013

First, to all the G20 countries, the coefficient of *R&D* is significantly positive which indicates that *R&D* has a significantly positive impact on TFEcE. It can be seen from Table 6 that *R&D* shows different statistical significance in the truncated regression model. The higher *R&D* contributes to the higher TFEcE in developed countries, while it is opposite in developing countries. For the developed countries, the increase of *R&D* can boost technical progress, which may enhance the ecological resources usage efficiency and introduce much more ecologically-friendly technology to replace the traditional technology. For the developing countries, the improvement of labor efficiency and capital efficiency would be superior to that of ecological efficiency, because ecological resources are at a relatively low price or even free in developing countries. So, the *R&D* is more likely to be distributed to boost the technical progress related to labor or capital efficiency, rather than the improvement of the ecological efficiency. Therefore, we could not find that *R&D* promotes the increase of TFEcE in developing countries.

Second, to all the G20 countries, the coefficient of *Ind* is significantly negative which indicates that the ratio of the secondary industry to GDP has a significantly negative impact on TFEcE. It can be seen from Table 6 that the relationship between *Ind* and national TFEcE is different in developing countries and developed countries. Although *Ind* has led to a decrease in TFEcF in developed countries on average, it has not significantly done so to the developing countries. For developing countries, the ratio of the secondary industry to GDP not only stands for the industry structure but also represents the level of industrial development. Although the countries with a high ratio of secondary industry to GDP may develop a certain energy-intensive industry, the economic level of which are still above-average among the developing countries, which means compared with other developing countries with lower *Ind*, they tend to pay more attention to ecological problems. Due to the above-mentioned reasons, the relationship between *Ind* and national TFEcE is not significant in the developing countries.

Third, to all the G20 countries, the coefficient of *Tra* is not significant which indicates that there is not a significant relation between foreign dependence degree and TFEcE. It can be seen from Table 6 that *Tra* is beneficial to the higher national TFEcE in the developing countries, which is consistent with the internationalization effect. Based on imports and exports, the enterprises in developing countries could be affected by the strict ecological regulations of developed countries, and so their ecological protection awareness and technology level have improved. For the developed countries, we do not find internationalization effect is significantly beneficial to TFEcE. Developed countries are always the exporting countries of green technology and eco-friendly concepts in international trade. Thus, from the perspective of TFEcE, international trade may be not significantly beneficial to developed countries.

5. Conclusions

This paper studies the ecological efficiency of G20 using the index of TFEcE which is constructed on the viewpoint of total-factor framework by taking the ratio of target ecology input from an SBM model to the actual ecology input. The TFEcE index not only considers EF as the comprehensive ecological inputs, but also takes capital and labor into account as multi-inputs to produce GDP. The main conclusions are as follows:

For the G20 countries, the total EF of G20 maintains a stable growth trend from 1999 to 2013, increases from 962.459 10 million ha in 1999 to 1203.475 10 million ha in 2013, and achieves a growth of about 25%. Fossil energy land contributes most to the total EF among the six components, accounting for 33.77%. The contribution of forest and pasture land are 25.38% and 23.42%, respectively.

In general, the average level of TFEcE of G20 from 1999 to 2013 is at a low level of about 0.54, which means there is a large space for improvement in the TFEcE of G20 countries. This indicates that the improvement of ecological efficiency is an effective way to maintain economic growth, and meanwhile, to relieve ecology pressures. Furthermore, TFEcE of G20 is very imbalanced. There is a big gap between developed countries and developing countries. The average level of developed countries is 0.727, of which the USA, UK, and Japan always have optimal efficiency from 1999 to 2013, while the average value of developing countries is only 0.376, among which Argentina is at the lowest level of 0.21.

Without considering other ecological impacts, TFEE in Hu and Wang [3] may overestimate the countries' performance. We find that there are significant differences between TFEE and TFEcE. Some countries—such as Japan, Republic of Korea, and Saudi Arabia—obtain higher score in TFEcE than that in TFEE due to a good performance in biological footprint. Some countries such as China, gain lower score in TFEcE than that in TFEE due to too much biological footprint consumption.

For the developing countries and developed countries, the analysis of factors that affect national TFEcE shows different statistical significance in the truncated regression model. The higher ratio of *R&D* expenditure to GDP contributes to a higher TFEcE in the developed countries, while a lower TFEcE in developing countries. Although the ratio of the secondary industry to GDP have negative effects on the developed countries' TFEcE, it has not significantly done so to the developing countries. The higher foreign dependence degree is beneficial to the higher national TFEcE in the developing countries.

Our study presents several policy implications.

First, as global warming, deforestation, land erosion, and loss of biodiversity have become global issues nowadays, governments should not only focus on the consumption and utilization of energy efficiency, but analyze the use efficiency of ecological resources from the view of ecological footprint. TFEcE indicator that integrates labor, capital, and ecological inputs could provide more comprehensive evaluation criteria for the policy-making of sustainable development.

Second, although there exists significant difference between developed countries and developing countries, not all the developed countries have a high TFEcE. Australia and Canada, as developed countries, have higher total EF values because of a larger pasture and forest land footprint. For these two countries, we recommend they pay more attention to improving the use efficiency of pasture and forest land footprint to cut down the occupation of the total EF and thus increasing their TFEcE.

Third, developed countries and developing countries should take different measures to promote TFEcE. Since developing countries have to realize ecological protection when pursuing economic growth, they face more severe challenges. We suggest that developing countries, on the one hand, guide R&D expenditure and its distribution to improve ecological efficiency, thus promoting domestic green technology innovation, on the other hand, developing countries should actively obtain internationalization effects, promoting TFEcE by acquiring green spillovers through international trade.

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The Economic Efficiency of Urban Land Use with a Sequential Slack-Based Model in Korea

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Abstract: Since the inauguration of the government-led five year economic plans in the 1960s, Korea has achieved remarkable economic development. Korea's economic strategy, known as 'The Miracle on the Han River', focused on heavy and chemical industries such as ship building and petrochemicals and was based on resource intensive urbanization. This rapid urban development caused a series of problems, such as over-development in urban areas, bottlenecks in utilities, and environmental degradation. Nevertheless, the Korean government has recently moved toward deregulation of the greenbelts of major city areas. Since very few studies have analyzed the urban land use economic efficiency (ULUEE) in Korea, this paper assesses the feasibility of recent deregulation policy concerning the greenbelts utilizing the sequential slack-based measure (SSBM) model under environmental constraints across 16 South Korean cities from 2006 to 2013. Our research makes three significant contributions to urbanization research. First, this paper uses an SSBM model to analyze the dynamic changes of urban land use economic efficiency in Korea at the regional level; Second, this paper analyzes factors influencing ULUEE in Korea, and the feasibility of the deregulation policies on the greenbelts; Third, this paper suggests more performance-oriented policy alternatives to improve the ULUEE and implement sustainable greenbelt management.

Keywords: urban land use economic efficiency (ULUEE); sequential slack-based measure (SSBM) model; green land policies; Korea

1. Introduction

1.1. Background of the Research

A common phenomenon in developing countries is unplanned, and thus unexpected, urbanization mishaps. In most urbanized countries, opening of natural or agricultural land into built-up land is one of the major features of land use changes, predominantly in developing countries [1,2]. As urbanization proceeds rapidly in most developing countries, the selective concentration policies in strategic areas create excess demand for land due to the complex yet unexpected expansion of the urbanization process. Unfortunately, this unbalanced urbanization may create great inefficiency in land use [3,4]. Due to this fact, the Korean government uses the greenbelts of the city boundaries to accommodate the excess demand for land use. However, when the green, natural land is transformed during the urbanization process, achieving future sustainability is a daunting challenge, and there is often irreversible loss for future generations. Therefore, urban expansion should be carefully and efficiently implemented, with complete sustainability prioritized in deregulation policies to increase the land for apartments in urban areas as well as to boost the regional economy in rural areas. The Korean government has taken measures to transform the greenbelt regions into built-up land.

In general, inefficient land use shapes are connected with rapid population growth inside and outside of suburbs [5]. Unexpected rapid urbanization has resulted in the rapid loss of arable land for many areas [6–8]. The rapidly expanding built-up land and associated land use have resulted in countless undesirable environmental and social effects [9–11], such as traffic jams, resource shortages, housing shortages, loss or reduction of biodiversity, and pollution [12–15]. The threatening factors of greenfield transformation by urban extension are best understood in relation to their various and substantial ecological effects resulting from complicated yet increased disturbance of the natural environment [16–20].

It is not easy to expand the city borders to alleviate urbanization issues, because once land is developed, it is irreversible [20], creating more severe urbanization problems due to the larger scale of urbanization, and it requires large amounts of time and money to recover the natural environment. Prior to implementation of deregulation policies, the promotion of increasingly efficient practices for existing urban land will be extremely important for the sustainable development of the city, because the transformation of land use may result in enormous costs, and most of these costs are irreversible when the environmental demand is higher than its urbanization use [21].

From an economic standpoint, land supply is inelastic. Raising land use efficiency allows for the same economic output while slowing the land transformation for economic activities. This implies that improving the urban land use economic efficiency (ULUEE) is an effective method for alleviating diverse urbanization problems and realizing sustainable urban management [1].

Due to the increased population coupled with the average household down-sizing in recent years, South Korea has converted increasing amounts of greenbelt for metropolitan development. Many metropolitan cities such as Seoul and Incheon have met with urbanization problems in the urban expansion mode [22]. Bhatta et al. [23] emphasized "general consensus that urban sprawl is characterized by unplanned and uneven pattern of growth, driven by multitude of processes and leading to inefficient resource utilization." Because of the negative effects such as loss of natural space and damage to the natural habitat, extensive urban growth is generally considered undesirable.

Against this backdrop, many regulatory policies have been planned and applied. Therefore, to preserve farmland, urban containment policies have emerged as a popular method [24], including the management of greenbelts for conserved lands around cities. The Korean greenbelt system was promulgated in 1971. It became the legal platform for anyone to utilize land on this restricted development zone [24].

Greenbelts in South Korea can be considered one of the successful environmental-friendly regulations in Asian countries [25], due to effective preservation of nature surrounding the cities, as well as restraining extensive development. However, Korean greenbelt policies have been deregulated in recent years in response to urban expansion demand for sustainable new town development. The planning agendas such as smart growth and the compact city are all explicit or implicit responses to excessive urban extension [26]. Due to this urgent demand, the greenbelt of Korea has been experiencing adjustment and partial removal since its inauguration in 1971. Since the year 2001, 3862 square kilometers of the Korean greenbelts, meaning 3.9% of the total land area has been transformed into built-up land [27].

On 26 April 2016, however, the Korean government introduced the Urban Master Plan to set the direction of long-term economic development and the future image of cities, featuring deregulation adjustment for sustainable development [24]. The Urban Master Plan sketches out the large-scale transformation of the greenbelts into land for development, adding to the conflict between companies seeking new investment opportunities and the public demanding sustainable policy. Government has made a series of regulatory policies and laws for environmental protection, including the greenhouse gas reduction (GHG) law and low-carbon green growth law, as well as commitments to save environmental resources and to promote green production and consumption [1]. Additionally, the Korean government regulated industrial emissions limits to improve environment-friendly efficiency in industries. In order to enhance the citizens' life quality, environment-friendly policies should extend to land transformation as well.

Unfortunately, the current economic downturn forced the Korean government to deregulate the greenbelts in order to boost regional economies. Due to the strict regulation, most city borders have been protected, resulting in their lower stable land price. However, due to the urgent demand on the regional development, the deregulation on the land means easier transformation of open, natural land to built-in land, resulting in huge unexpected booms on these land. There are no management strategies affecting the four elements of urban environmental conditions, meaning noise, indoor air quality, artificial lighting, and pollution, within the Urban Master Plan [24,26].

Challenges in analyzing land use efficiency, such as ULUEE, were first studied to describe the peripheral form of urban land usage [1]. Most of these studies are based on the historical urban land use experiences [28]. Subsequently, economics and econometric models are introduced to the research of urban land. The economic models argued that the regulation of the land market can achieve the optimal allocation of land resources and realize the effective utilization of land resources [1]. In addition, social behavior researchers put forward the humanistic idea in urban land use study, emphasizing the human and other related factors in the process of urban land resource allocation [29]. Researchers from political economics emphasized political power over the influence of city land utilization, focusing on the main political factors affecting the efficiency of urban land use [30,31].

In 1993, 42% of semi-agricultural and forested areas were transformed into built land areas by the Korean government. As the pace of economic development increased, huge urban extension has claimed suburban forest and natural land resources [32]. In South Korea, 5% of the people own 65.2% of private land, and thus there is great opportunity for these private land owners to realize massive profits through land speculation regarding deregulation policies. Therefore, the purpose of this study is to analyze land use efficiency to answer whether the urban land use in Korea is efficient, and whether the Korea Urban Master Plan can deliver efficiency and sustainability as an environmentally friendly initiative.

1.2. Current Situation of the Korean Greenbelt Policies

The focus of this research includes all land area of the Republic of Korea (hereafter, Korea), covering 100,560.87 km^2 (Figure 1) [33]. Including the landfill expansion of the reclaimed land from 1985 to 2005, in the last 30 years Korea's land area has risen by 1%, and the income level by 27% and population has increased by 27% times over the same period of 1985 through 2005 [34]. As population density has increased, particularly in the suburban areas of major cities, many problems have developed. To overcome these urban challenges, the Korean government has transformed the greenbelts into built-land, resulting in 16% decrease of agricultural forest with 55% increased residential area and 96% increased roads (see Table 1) [34].

Selective concentration of economic development policies in major city areas have drawn numerous migration from the country into the cities. The urbanization rate of Korea increased from 39.1% to 90.5% for a period of 1960–2008, with the rapid nationwide population increase from 25 million to 48.9 million during the same period [34]. The current population of Korea is estimated at 51,529,338 in 2015 (see Table 1), and 49.7% (25,140,000) of the population lives in Seoul, Incheon, and Gyeonggi-do. In recent years, metropolitan type of expansion has accomplished especially in Seoul and its vicinity. Approximately half of the nation's population now lives in Seoul and its surrounding suburban areas [34]. Due to this deepening urbanization, the bipolarization of real estate prices has become more severe in Korea.

There is high demand for new houses in the southern part of Seoul, particularly in Gangnam, resulting in prices skyrocketing for apartments, while the rural areas lack government support for real estate development. This bipolarization of real estate development may result in challenges for the Korean government for their uniform measures. Contrasting with many vacant apartments in rural areas, there are also huge housing shortages in urban areas, with more than 100 people bidding for one new apartment in the Gangnam area. Due to this bipolarization within the real estate market, the Korean government has to change its policy paradigm quickly and frequently between the strengthening and weakening regulations for the real estate market. Therefore, the government has to apply deregulation policies more thoughtfully with greenbelts in order to solve apartment shortages in urban areas, and to boost investment in manufacturing facilities. The Korean government has taken measures to transform the greenbelt regions toward built-land.

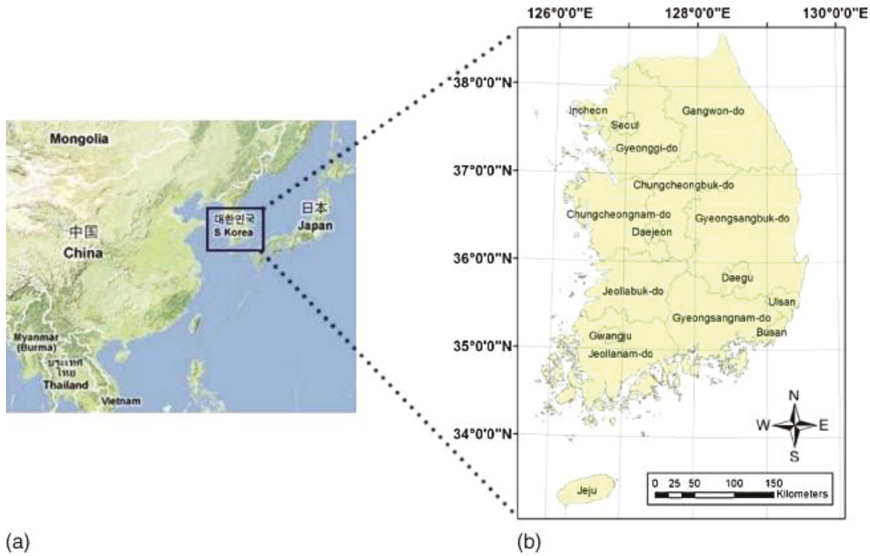

Figure 1. The research area in this study: (**a**) location of South Korea and (**b**) map of South Korea [34].

Table 1. Demographic characteristics of South Korea.

	Area (km^2)	Population (1000 Person)	Population Growth Rate (%)	Growth Domestic Product (100,000 USD)	Farmland Growth Rate (%)	Building Site Growth Rate (%)	Road Growth Rate (%)
1980	99,011	38,124	1.57	387,749	100	100	100
1990	98,730	42,869	0.99	1,866,909	94	113	129
2000	99,461	47,008	0.84	6,514,153	87	137	159
2008	99,828	48,607	0.31	10,239,377	84	155	196

Source: Growth rate of population, GDP, and roads from 1985 to 2008, Statistics Korea [34,35].

2. Methodologies and Data

2.1. Sequential Slack-Based Measure (SSBM) Model

Data envelope analysis (DEA) was used to analyze the complex process of land transformation policies, because DEA can deal with multiple inputs and outputs simultaneously and does not require any prior information on the theoretical frame of the production function [1,36]. In general, DEA models assume an efficiency gap between optimal and actual resource allocation, which is called the slack variable, implying the output shortage or input surplus in the decision making unit (DMU) [1,36]. Since the traditional radial DEA models do not consider these slack variables in the objective function, it can produce inaccurate results in efficiency evaluations. In order to overcome this difficulty, a new approach called the non-radial and non-parametric slack-based measure (SBM) model has been developed [1,36], incorporating the slack variables directly into the objective function. Considering the dynamic change of production technology during the research period, the sequential slack-based measure (SSBM) model will be introduced to incorporate the concept of sequential production technology over time. This SSBM is crucial to analyze the land use efficiency over time. Based on Zhang's and Xie's approaches on SSBM [1,36], we try not only to consider industrial wastewater and industrial sulfur dioxide as undesirable outputs, but also to add noise status to analyzes factors influencing ULUEE in Korea, and the feasibility of the deregulation policies on the green belts. Suppose for N Decision Making Units (DMUs), every DMU demands M inputs (x) for J desirable outputs (y) with K undesirable outputs (b) as well. In our research, these will be evaluated using the vectors $x \in R^M, y \in R^J, b \in R^K$, and our matrix X, Y, B are defined as $X = [x_{11}, \cdots x_{MN}] \in R^{M \times N}, Y = [y_{11}, \cdots y_{MN}] \in R^{J \times N}, B = [b_{11}, \cdots b_{MN}] \in R^{K \times N}$, $X > 0, Y > 0, B > 0$.

Based on these definitions, the production technology can be defined as follows:

$$P = \{s: y, b) \mid x \text{ can produce } (y, b), x \geq X\lambda, y \leq Y\lambda, b \geq B\lambda, \lambda \geq 0\} \quad (1)$$

where P is assumed to satisfy the theory of production function [1,37]. Production technology will change over time, and thus, the constraints of the variable returns to scale (VRS) are imposed on the objective function. Then, the optimization problem of sequential SBM (SSBM) planning will take the following form:

$$\rho^* = \min \frac{1 - \frac{1}{M}\sum_{m=1}^{M}\left(\frac{s_{m0}^x}{x_{m0}}\right)}{1 + \frac{1}{J+K}\left(\sum_{j=1}^{J}\frac{s_{j0}^y}{y_{j0}} + \sum_{k=1}^{K}\frac{s_{k0}^b}{b_{k0}}\right)}$$
$$S.T.\begin{cases} x_0 = \sum_{t=1}^{T} X^t \lambda_n^t + s_0^x \\ y_0 = \sum_{t=1}^{T} Y^t \lambda_n^t - s_0^y \\ b_0 = \sum_{t=1}^{T} B^t \lambda_n^t + s_0^b \\ \sum_{n=1}^{N} \lambda = 1, s_0^x \geq 0, s_0^y \geq 0, s_0^b \geq 0 \end{cases} \quad (2)$$

where m, k, and j denote the indexes of inputs, desirable outputs and undesirable outputs discretely; t (t = 2003, . . . , 2013) denotes the year, and the subscript denotes the decision making unit's estimation in the model; sx^* denotes the slack variables of inputs, sy^* and sb^* denote desirable outputs and undesirable outputs respectively; and ρ and λ denote the efficiency of DMU estimation and the non-negative multiplicative vector respectively in the model.

When $\rho^* = 1$, the DMU is on the perfect, efficient position on the production possibility curve. When $\rho^* < 1$, the DMU is inefficient, and thus it is necessary to modify the input-output structure. In order to increase DMU efficiency, we had better adjust the form $x^* = X\lambda + sx^*$, $y^* = Y\lambda - sy^*$, and $b^* = B\lambda + sb^*$ so we can carry out the efficiency evaluations confronting with undesirable outputs by SBM model.

On the other hand, we can analyze the slack variable ratios of inputs, desirable outputs and undesirable outputs to find out how to enhance the input–output efficiency.

The ratio of input surplus is proportion of input reduction as follows:

$$\overline{X} = \frac{1}{M}\sum_{m=1}^{M}\left(\frac{s_{m0}^x}{x_{m0}}\right) \quad (3)$$

Insufficient expectation output ratio is the proportion of increased desirable output:

$$\overline{Y} = \frac{1}{J}\sum_{j=1}^{J}\left(\frac{s_j^y}{y_j}\right) \quad (4)$$

The ratio of redundant undesirable output is the proportion of undesirable output reduced:

$$\overline{B} = \frac{1}{K}\sum_{k=1}^{K}\left(\frac{s_k^b}{b_k}\right) \quad (5)$$

2.2. Selection of Input and Output Indicators

Efficiency of land use is influenced by economic, social and environmental factors [4,31,36], so we must consider both environmental and economic performance. Our research constructs an integrated indicator evaluating efficiency of land use, using input and output data described in Table 2. First, the main input factors consist of land, capital, and labor for the differentiated land use efficiency. Due to the objects of this study focused on Korean greenbelt areas, built-up area is selected as the land input, and the total investment in fixed assets is selected as capital inputs. The number of employees in the manufacturing and service industries is selected as the labor inputs.

Based on these input factors, the value added in manufacturing and service industries is selected as desirable outputs, and industrial chemical emissions, industrial wastewater and city noise as undesirable outputs. The undesirable outputs from the model are based on the three factors of chemical emissions, wastewater and industrial noise, all resulting from the transformation of natural land into built-land. The ULEE will be measured at the first stage of our research based on these input and output indicators. Based on all the outputs of DMUs, we want to find the best performance and based on that best performance, we shall measure the relative efficiency of all the inputs of DMUs.

Table 2. Descriptive statistics.

Variables	Variable Notation	Measure Description	Units
Input	AREA	Built-up area	m^2
	FIX	Total investment in fixed assets	10^3 ₩
	EM23	Number of manufacturing and service industry employees	10^3 Persons
Desirable output	P23	Value added in manufacturing industry and service industry	10^7 ₩
Undesirable output	CE	Industry chemical emissions	Kg/year
	WA	Industrial wastewater	Ton/Year
	CN	Cities degree of Noise Status	Leq dB (A)

2.3. Econometric Model and Data

This research is based on the stepwise approach to find out the sustainable factors of the greenbelt deregulation policies. The measured level of ULEE in the first stage will be used as a dependent variable to determine the sustainable factors on this ULEE by the panel data regression model in the second stage. In order to determine the external variables on the input variation, we shall draw the candidate variables from the comparative analysis on the preceding papers, and all these argued issues on the pressure for the transformation of the land use shall be used as independent variables in our model.

In general, the increased per capita GDP will enhance the input efficiency or vice versa. This is because a region with relatively high per capita GDP may have a better quality of economic development, resulting in enhanced input efficiency, such as urban land use economic efficiency [38]. Thus, we assume that there is a progressive relationship between per capita GDP and ULUEE. In addition, increase in land use efficiency will produce more economic value. Thus, we assume that there is a bidirectional relationship between ULUEE and land use intensity. As is well known, the higher urbanization rate, economic development and the production technological improvement, and land use efficiency are all interrelated each other [39]. Therefore, we assume that there is a positive relationship between ULUEE and urbanization rate. The carbon green growth law conserves water, electricity gas, and promotes green production, leading to a high efficiency of land resource use. Thus we assume that there is a positive relationship between the low carbon green growth law and ULUEE.

Based on these arguments, we introduce the multivariate linear regression model to analyze the ULUEE determinants in Korean cities as follows:

$$y_{it} = \alpha_{it} + \beta_1 PGDP_{it} + \beta_2 LUI_{it} + \beta_3 URB_{it} + \beta_4 LCP_{it} + \mu_{it} \quad (6)$$

where i (i = 1, ..., 16) and t (t = 2006, ..., 2013) denote city and year respectively. The term α_{it} denotes a constant, and μ_{it} is the random error term. The term y_{it} denotes the ULUEE for the city i and $PGDP$ denotes the GDP per capita. LUI denotes the land use intensity, with every square kilometers of land for the economic value. URB denotes the urbanization rate, referring to the urban population proportion of the total population in the city. LCP refer to the low carbon green growth law.

This paper uses data from 2006 to 2013 accessed from the Korea statistical websites [34,35]. All the data from 16 cities, accounting for all Korean cities, will be used for our empirical tests.

3. Empirical Results

3.1. Empirical Results of Land Use Efficiency

The ULUEEs for 16 cities in Korea during 2006–2013 was computed using the SSBM model as shown in Table 3. For comparison, the ULUEE was calculated with as well as without undesirable outputs. As expected, the ULUEE values with the undesirable outputs are less than for ULUEE without considering the undesirable outputs all over the research period, with scores between 0.692 and 0.789. This implies that undesirable outputs certainly influence ULUEE. Ignoring undesirable outputs could result in overestimation of land use efficiency, and thus we will adopt land use efficiency with undesirable outputs using the SSBM model.

ULUEE in Korea was consistently low during the research period, and economic risks during 2008 resulted in its lowest point as shown in Table 3. In 2012–2013, the ULUEE values with and without considering undesirable outputs yielded similar results. This may be due to increased environmental protection laws, such as the low carbon green growth law. This implies that government regulation has significantly increased the ULUEE with undesirable outputs. Thus, Korea has made great achievements in environmental protection performance.

Seoul, Ulsan, Chungnam, and Jeju consistently feature relatively high ULUEE scores compared with Korean cities from 2006 to 2013, as shown in Figure 2. Jeju island is an underdeveloped province, with the industrial layout mostly focused on tertiary industry such as tourism, but exhibits relatively high economic output and low environmental pollution relative to other Korean cities studied. This result in Jeju may come from the intensive environmental promotion policies by the central and local governments. Incheon, Busan and Gyeonggi provinces have emphasized policies for environment-friendly sustainable development, resulting in the continuing enhancement in the land use efficiency. However, it is challenging to achieve higher urban land use efficiency in other regions due to the conflict between economic development (desirable output) and environmental pollution (undesirable output).

In summary, the regions such as Seoul and Ulsan with more advanced economies show enhanced performance in ULUEE due to the advantages of easily accessible capital and technology, which can alleviate bottleneck problems in resource allocation and utilization. This enables for equilibrium between economic development and environmental protection problems. One interesting phenomena is evident in Gyeonggi province, which featured one of the lowest ULUEE before 2008. Gyeonggi province is just located as the surrounding areas of metro Seoul area, and thus the local government has emphasized on the better quality of sustainable development, resulting in the utmost front of the land use efficiency. Recently, Gyeonggi province has experienced a large influx of immigration, with lower production costs and living expenses representing driving factors. With these driving factors, Gyeonggi province has focused on its ULUEE enhancement compared with other provinces, implying that urbanization possibly accompanies higher ULUEE.

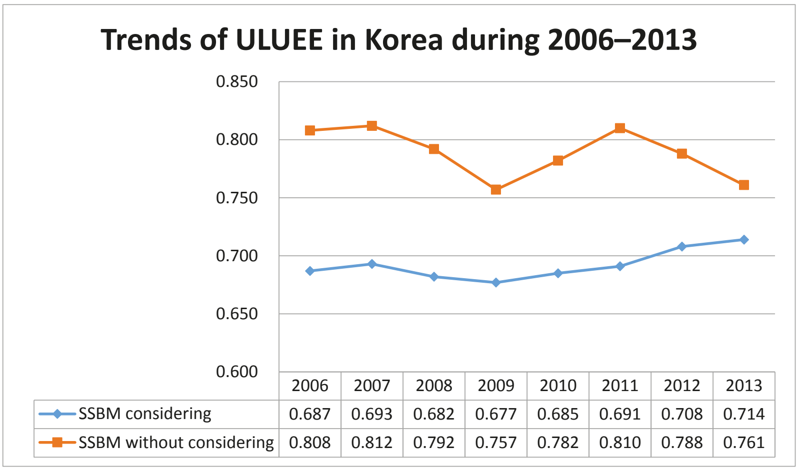

Figure 2. Trends of ULUEE in Korea during 2006–2013.

Table 3. Score of ULUEE in Korean cities during 2006–2013.

Citys	2006	2007	2008	2009	2010	2011	2012	2013
Seoul	1.000	0.897	1.000	1.000	1.000	1.000	1.000	1.000
Busan	0.425	0.433	0.430	0.425	0.433	0.430	0.427	0.418
Daegu	0.472	0.505	0.499	0.485	0.496	0.497	0.502	0.495
Incheon	0.721	1.000	0.638	0.560	0.615	0.741	0.804	0.745
Gwangju	0.596	0.599	0.663	0.643	0.631	0.631	0.643	0.605
Daejeon	0.677	0.890	1.000	1.000	1.000	0.982	0.995	1.000
Ulsan	1.000	1.000	1.000	1.000	0.880	0.837	0.846	1.000
Gyeonggi	0.366	0.434	0.495	0.589	0.699	0.802	1.000	1.000
Gangwon	0.620	0.609	0.568	0.577	0.593	0.573	0.560	0.587
Chungbuk	0.660	0.654	0.644	0.572	0.548	0.548	0.582	0.651
Chungnam	1.000	1.000	0.911	1.000	1.000	1.000	0.985	1.000
Jeonbuk	0.552	0.557	0.526	0.512	0.523	0.499	0.480	0.470
Jeonnam	1.000	0.572	0.590	0.510	0.558	0.544	0.554	0.543
Gyeongbuk	0.541	0.561	0.585	0.592	0.596	0.594	0.561	0.533
Gyeongnam	0.363	0.370	0.361	0.369	0.388	0.384	0.386	0.383
Jeju	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000

3.2. Influencing Factors of the ULUEE

From Equation (6), we used the fixed effect model to explore the explanatory factors influencing ULUEE. In the Table 4, the results of the panel data regression are shown for 7 Korean cities and 9 provinces. Per capita GDP (PGDP), urbanization rate (URB), and land use intensity (LUI) show significantly positive impacts on ULUEE, which is consistent with our hypotheses. This implies that regional economic development, accompanied by the urbanization process, will enhance its land use efficiency and more intensive use of land will result in improved land use efficiency. Therefore, in order to enhance land use efficiency, more land-intensive economic development is required and government policies should emphasize land-saving development, by e.g., subsidizing the remodeling of existing apartments instead of rebuilding or reconstructing. This is because remodeling provides more land-intensive utilization without stimulating speculation, while rebuilding or reconstructing will result in costs skyrocketing and increased speculative competition on new apartments.

However, the low carbon green growth law (LCP) shows a significantly negative impact on ULUEE, which is inconsistent with our hypotheses. This implies that stronger regulation on green growth policies restricts the innovative use of land, and thus there is a lack of effective improvement of land efficiency resulting from strict environmental regulation. Greenbelt policies have restricted the conversion of land use, resulting in the worsening of land use efficiency. It is noteworthy that the strong greenbelt policies are not only effective at limiting urban sprawl but also deteriorate land use efficiency. It is crucial for government to persuade land owners to promote land use efficiency and, thus, regional governments face claims against the greenbelts from land owners. However, once the government allows greenbelts to be used for built-use purposes, then the price of the land will increase, resulting in speculative pressures on the government policies. It is challenging for local governments to promote low-carbon green growth policies on land use as well as avoiding worsening land use efficiency. This implies that there are new challenges in the harmonization of green growth with land use efficiency, and government should work with the private sector to improve land use efficiency.

Table 4. Results of the panel data regression for Korean cities.

Variable	Coefficient	Std. Error	*t*-Statistic	Prob.
PGDP	0.05724	0.01150	4.977437	0
URB	0.004404	0.000412	10.69089	0
LCP	−0.067887	0.016836	−4.03218	0.0001
LUI	0.066111	0.009533	6.93513	0
Weighted Statistics				
R-squared	0.939236	Mean dependent var		1.026964
Adjusted *R*-squared	0.937766	S.D. dependent var		0.701334
S.E. of regression	0.17496	Sum squared resid		3.795766
Prob(*F*-statistic)	0			
Unweighted Statistics				
R-squared	0.385459	Mean dependent var		0.692132
Sum squared resid	3.919573			

4. Conclusions

In this study, we empirically tested the dynamic trend of urban land use economic efficiency (ULUEE) and its determinant factors with various constraints under Korean government policies, in 16 cities and provinces across the South Korean peninsula from 2006 to 2013. Since SSBM measures land use efficiency changes over time, our empirical results conclude that there has been limited improvement in land use efficiency. Nevertheless, greenbelts have been transformed into built-in land at an excessively ambitious rate for the appropriate realization of subsequent benefits, and this has resulted in problems associated with speculation. There are many companies seeking high rates of return on land investment, and thus there is a strong tendency for these companies to want additional investment in suburban areas, especially in greenbelt areas.

This paper found that economic development in Korea promoted land use efficiency from diverse perspectives. Unfortunately, this land-saving economic development should be reevaluated due to greater building susceptibility to damage from weather-related phenomena such as earthquakes, severe rainfall, and city floods. The uniformity of apartments does not improve the quality of the life for residents. With the population decreasing nationwide, these uniform apartment buildings are unlikely to promote sustainable development of land use within the traditional land-saving paradigm. Within this context, the Korean government issued a new urban development plan featuring higher flexibility for transforming the greenbelts into built-in land for regional economic recovery from the current recession and decreasing corporate investment. Many leading companies in Korea, such as Samsung, LG, and Hyundai car group, have been reducing investment due to the gloomy economic environment. Local governments want to encourage these companies to boost the local economy. This is particularly true for the construction industry, which is well known for its leading role of providing economic spillover effects. Unfortunately, building new apartment complexes may promote the speculative opportunities as well. However, economic development harmonized with land use efficiency enhancement is more effective due to the new paradigm of promoting low-carbon green growth policies. Thus, government and the private sector should cooperate to promote land-saving economic development from the city center and the remote areas, instead of easy but risky deregulation of the greenbelts.

The main conclusions from this paper include three implications and suggestions. First, for government policies to be sustainable, it is necessary to consider undesirable outputs, such as industrial chemical emission and water problems, in evaluating ULUEE. This is because undesirable outputs have negative effects on the ULUEE. Our results show that even if the overall land use efficiency has not improved, the environmental land use efficiency has significantly improved, implying that more precise regulatory measures on ULUEE are required for the sustainable performance of the greenbelt areas.

Second, regions with more developed economies such as Seoul showed better performance in urban land use resulting from the advantages of easily accessible capital, technology and other resources such as appropriate land. This highlights economic development with higher mobility of resources can effectively solve the bottleneck problems in the process of resource allocation and utilization between economic development and environmental protection. Therefore, in order to enhance the ULUEE, the government should utilize the positive influence of economic development on social and environmental performance, implying that the surrounding areas of city center development should precede opening of the greenbelt areas.

Third, even less developed provinces such as Jeju-do can achieve harmonized land use efficiency enhancement through the appropriate public private partnership (PPP). Economic development is not the only way to improve land use efficiency. Land use efficiency is enhanced when the private sector participates voluntarily in the movement toward more resilient cities, such as slow cities and/or smart cities oriented toward improving quality of life, safety, and restoration capacity. To avoid the creation of ghost towns, government needs to cooperate with the private sector to enhance environment-friendly land use efficiency, and PPP could play a significant role in addressing future sustainability challenges.

In this paper, we used a sequential slack-based measure (SSBM) model to examine the dynamic ULUEE in South Korea. For future research, we should mention our study's limitations, such as three undesirable outputs in the form of industry chemical emissions, industrial wastewater and city noise, meaning carbon dioxide emissions and light emissions are not considered in our research due to unavailability of data, but the inclusion of more appropriate variables in our model would certainly broaden its implications for urbanization policies.

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Determinants of Residential Solid Waste Management Services Provision: A Village-Level Analysis in Rural China

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Abstract: Providing residential solid waste collection (RSWC) services is the first and most indispensable part of residential solid waste management and is crucial for rural environment protection. This paper seeks to analyze the determinants of RSWC services' provision at the village level, based on a latest survey data set of 150 villages in the Poyang Lake Eco-Economic Zone (PLEEZ) in Jiangxi Province. Using a Probit regression model and a Bivariate Probit regression model, our results indicated that: (1) The provision of RSWC services is not evenly distributed and richer villages have more RSWC services; (2) A showcasing phenomenon exists in the provision of RSWC services. Villages that are more populous, nearer to the township government, and located in the new countryside and old liberated areas saw an increase in the provision of RSWC facilities, services that will more easily showcase village leaders' political achievement, while the provision of RSWC workers and both RSWC facilities and workers, services that will less easily showcase village leaders' political achievement, do not increase in these villages; (3) Informal governance characteristics, such as the ratio of largest family clans, whether village leaders come from the village's largest family clans, and the number of people working in the upper-level government have strong predictive power over the provision of RSWC services, while formal governance characteristics, such as elections, do not matter in RSWC services' provision.

Keywords: residential solid waste management; public goods; informal governance; Bivariate Probit

1. Introduction

Rural areas, which account for 90% of mainland China, are now faced with serious environmental problems caused by the increase in residential solid waste (RSW) [1]. Traditionally, most RSW in rural China was recycled onto agricultural land as organic fertilizer, and the environmental pollution from RSW was not serious [2]. However, with the steady development of rural living standards and a rapid rise in rural population, the quantity of RSW has increased dramatically [3]. It is estimated that the annual growth rate of RSW is about 8%–10% in rural China. In 2015, the officially estimated data showed that the total quantity of RSW in rural China is 150 million tons, which is 2.25 times the removal quantity of municipal solid waste; about half of RSW was discharged directly into environment [4].

Providing sufficient RSW management services to decrease the pollution from RSW is an important task for Chinese Government. In rural China, since the "Rural Tax Reform" in 2006, when village levies and direct fees were formally abolished, it is often the responsibility of villagers' committees to determine and finance RSW management services. The provision of RSW management services is uneven across villages in rural China. The results of Wang et al. [5] show that in Jiangsu province, a relatively rich province in China, almost 90% of villages have RSW management services, while in Hebei province, a relatively poor province in China, only 20% of villages have RSW management services. What caused this great difference among villages in the provision of RSW management services?

Few studies have examined the determinants of RSW management services provision from the village-level perspective in rural China. Two exceptions are Ye et al. [6] and Wang et al. [5]. However, deficiencies remain in the extant studies. First, as the data used in Ye et al. [6] is from 2005 and the data used in Wang et al. [5] is from 2011. They are out of date and, thus, cannot reveal the latest progress of RSW management services in rural China. Second, the conventional factors supposed to determine the provision of RSW management services include village characteristics, such as village income, geographic location, village size, and village density; village leaders' characteristics, such as age, gender and education; and formal governance characteristics, such as elections. These factors have also been found to be important determinants of the provision of other public goods, such as roads, schooling, and electricity [7–9]. In addition, informal governance characteristics, such as clans and social capital, have been empirically confirmed to have great effect on public goods provision in general [10,11]. However, despite the evidence, to the best of our knowledge, no studies have yet investigated the effect of informal governance characteristics on the determinants of RSW management services provision in rural China.

The contributions of this work to current literatures are at least two ways. First, in addition to the conventional determinants of RSW management services provision, informal governance characteristics will also be considered. The need to consider informal governance characteristics in the provision of RSW management services is especially important for rural China, because the informal connections have thrived there over many years [12]. The second contribution is that our analysis is based on a latest data from 2015 in rural China. It is our belief that, with the great improvement of economic and social transformation, RSW management services in rural China have changed a lot. By using the latest data, we can reflect the real situation of RSW management services in rural China.

The main goal of this work is to analyze the determinants of RSW management services provision by using the latest data from 2015 in rural China. In general, according to the lifecycle of RSW, the process of proper RSW management services consists of three steps: RSW collection (RSWC), RSW transportation, and RSW disposal [13]. In this paper, we focus on the RSWC step. Our logic is that RSW must be properly collected before it can be transported and treated. In addition, as suggested by He [14] and Tai et al. [15], due to low densities of rural areas, the cost of RSWC accounts for up to 40% of the total cost of RSW management, which is almost twice of the RSWC cost of urban solid waste. Therefore, providing enough RSWC services will become increasingly important for the Chinese Government.

The rest of the paper is organized as follows: Section 2 introduces the background of RSW management in rural China. Section 3 specifies the empirical model. Section 4 describes the case study area and presents data descriptive statistics. Section 5 presents the baseline results of Probit regression and the Bivariate Probit regression results considering endogeneity. The final section concludes the paper.

2. RSW Management in Rural China

The Chinese Government has issued a succession of regulations to tackle the environmental problem caused by RSW. In 2010, ten departments in China, including the Ministry of Housing and Construction, the Ministry of Finance, and the Ministry of Environment Protection, enacted the "Guidance for Comprehensively Promoting Rural Garbage Management", which is the first guidance for RSW management. Government investment has also been increasingly allocated to RSW management. In 2008, the Chinese Government set up a "Rural Environmental Protection Special

Fund". It is estimated that, with the help of this fund, a total of 37.5 billion RMB (which is equal to 5.36 billion USD at a 7:1 exchange rate) was allocated to protect the rural environment, benefiting more than 80,000 villages in rural China [4]. However, although remarkable progress has been made in rural environmental protection, the provision of RSW management services is still poor and is far less than the people's need. As a result, illegal RSW discharge is pervasive in rural China. The phenomenon of "Garbage Besieging Villages" is often reported. Inadequate provision of RSW management services not only pollutes the ecological environment of rural areas, such as water, soil, and air [16], but also does great harm to the health of rural people [17]. It is estimated that inappropriate disposal of RSW has caused severe pollution of 24% of drinking water and 18% of lake water in China [2].

There are typically two different types of institutional arrangements in RSW management. Under the most popular arrangement, it is the responsibility of local government to provide RSW facilities and hire RSW workers. The upper-level government is the regulator of the quality of RSW services. The other is private provision arrangement which is less pronounced but still relevant. Under this arrangement, the local government usually assigns the RSW management work to private firms. Accordingly, the local government is the regulator of quality of RSW services. The privatization of RSW management has both advantages and disadvantages (see Simoes et al. [18] for a detailed discussion). The performance of public provision arrangement and private provision arrangement vary across different regions in rural China, depending on the political ideology, village characteristics, farmers' cooperation, among others [18,19].

The fundamental mode of RSW management in rural China is "household classification, village collection, township transfer and county treatment". In the RSWC stage, RSWC facilities, such as refuse chutes and outdoors trash cans, have been implemented widely. RSWC workers, who are responsible for transporting all the RSW in the village, have also been introduced in some developed rural areas. In the RSW transfer or transportation stage, the RSW is transported to county or above the county level for downstream treatment and disposal. In the RSW treatment stage, sanitary landfill, incineration and composting are the main treatment technologies, while sanitary landfill is the dominant treatment technology [20].

3. Methods

3.1. Probit Model

The dependent variable in our analysis is whether villages have provided RSWC services in 2015, which is a binary outcome variable. Thus, we employed a "binary choice model", specifically, a Probit model, to analyze the determinants of RSWC services. The model can be specified as follows:

$$\mathrm{RSWC} = 1[\delta X + \mu > 0] \tag{1}$$

$$\mathrm{RSWC}^* = \delta X + \mu \tag{2}$$

$$\mathrm{RSWC} = \begin{cases} 1 & \text{if } \mathrm{RSWC}^* > 0 \\ 0 & \text{if } \mathrm{RSWC}^* < 0 \end{cases} \tag{3}$$

where RSWC is a binary variable, which is equal to 1 if the village provides RSWC services, and 0 otherwise; δ is the parameter vector; μ is the error term; and X is the vector of the determinants of RSWC services' provision.

Based on the theoretical analysis and literature review, the determinants of RSWC services' provision consist of two types of factors, including village characteristics and governance characteristics. The definition of these variables and the expected signs of the coefficients associated with these variables are presented in Table 1. *Income* is expected to have a positive impact because villages with higher income would have more financial resources that can be invested to provide RSWC services. *Population and Group* have positive expected signs because more populous villages will generate more RSW and have higher demand to treat RSW. *Density* is expected to have a negative impact because the costs of providing RSWC services are higher in villages with higher density. *Distance* has a negative expected sign because villages nearer to the township government are often more richer and have more resources to provide RSWC services. *Ncountryside* is expected to have a positive impact because new-countryside villages can get more financial support from the upper-level government to invest in RSWC services. The expected effects of *Liberated* and *Mountain* are "unknown". The reason is that, on one hand, villages located in old liberated and mountain areas are often poorer and have fewer resources to provide RSWC services, on the other hand, in recent years, the Chinese government has been increasingly investing in the public projects in old liberated and mountain areas. *Elected* is expected to have a positive impact because elected village leaders are more likely to provide RSWC services in order to satisfy voters' demands. Informal governance characteristics, including *Rclans, Lclans and Hleaders,* are expected to have positive impacts because informal governance has thrived over many years in rural China and have great effect on public goods provision [11].

Table 1. Definition of the explanatory variables and their expected sign on dependent variable.

Variables	Definition	Expected Sign
Village characteristics		
Income	Per capita income in 2015 (thousand RMB)	+
Population	Total population in 2015 (thousand people)	+
Group	Number of small groups in a village	+
Density	The farthest distance between two households in the same small group of villages (km)	−
Distance	The distance from village committee to the township government (km)	−
Ncountryside	Dummy of new countryside area(yes = 1; no = 0)	+
Liberated	Dummy of old liberated area(yes = 1; no = 0)	unknown
Mountain	Dummy of mountain area(yes = 1; no = 0)	unknown
Governance characteristics		
Formal governance		
Elected	Dummy of elected leader (yes = 1; no = 0)	+
Informal governance		
Rclans	Ratio of the village's largest family clans (%)	+
Lclans	Whether the village leader comes from the village's largest family clans (yes = 1; no = 0)	+
Hleaders	Number of people working in the upper-level government (person)	+

Note: "+" means the variable has positive effect on RSWC services' provision; "−"means the variable has negative effect on RSWC services' provision;"unknown" means the expected effect of the variable on RSWC services' provision is not sure.

3.2. Bivariate Probit Model

If all the explanatory factors included in the X vector are exogenous, then the Probit regression results will be consistent. However, we may have a potential endogeneity problem because some explanatory factors included in the X vector could be endogenous. One of the explanatory factors found in the previous literature is whether the village leader is elected or not—the *Elected* variable [7]. First, there may be a reverse effect between the *Elected* variable and RSWC services' provision.

For example, village leaders who provided more RSWC services during their terms of office will generate higher support from villagers and are more likely to be reelected in the next round of election. Meanwhile, villagers expect elected village leaders to provide more RSWC services and, therefore, villagers elect candidates for village leadership on the basis of the candidates' commitment to providing more RSWC services. Second, both *Elected* and RSWC services' provision may be affected by some omitted variables. There will be a bias in the coefficient of the *Elected* variable if it is endogenous.

Two-stage least squares (2SLS) method is often used to tackle the endogenous problem. However, in our analysis, both the outcome variable (RSWC services provision) and the exogenous variable (*Elected*) are binary, 2SLS is no less appropriate [21]. Sajaia [22] pointed out that a Bivariate Probit model is appropriate to control endogeneity when dependent variable and exogenous variable are binary. By computing full-information maximum likelihood estimates, the Bivariate Probit model can produce unbiased and more efficient estimates compared to 2SLS estimators [22]. The Bivariate Probit model has been widely used in recent years [23,24]. Therefore, we employed a Bivariate Probit model to control endogeneity. The Bivariate Probit model can be written as:

$$\text{RSWC} = 1[\delta \text{X} + \alpha \text{Elected} + \mu > 0] \tag{4}$$

$$\text{Elected} = 1[\beta \text{Z} + \varepsilon > 0] \tag{5}$$

where Z is the vector of the determinants of *Elected*, β is the parameter vector, and ε is the error term. Z includes all the factors in the X vector of Equation (4). In addition, we also include an additional instrumental variable in Equation (5) to predict *Elected*.

4. Case Study and Data

4.1. Study Area

This paper took the Poyang Lake Eco-Economic Zone (PLEEZ) in Jiangxi Province as the study area. PLEEZ contains 38 counties, and more than 20 million people reside in this area (Figure 1). PLEEZ was officially approved by State Council of China as a national strategy in 2009 to become a comprehensive development model for China's other lake areas and large rivers. In recent years, pollution from RSW has imposed serious environmental degradation on PLEEZ. This includes eutrophication, deterioration of surface water and groundwater quality, and biodiversity losses. Reducing the pollution from RSW has become an extremely important issue in PLEEZ. To the best of our knowledge, no studies have analyzed the RSW management problem in PLEEZ.

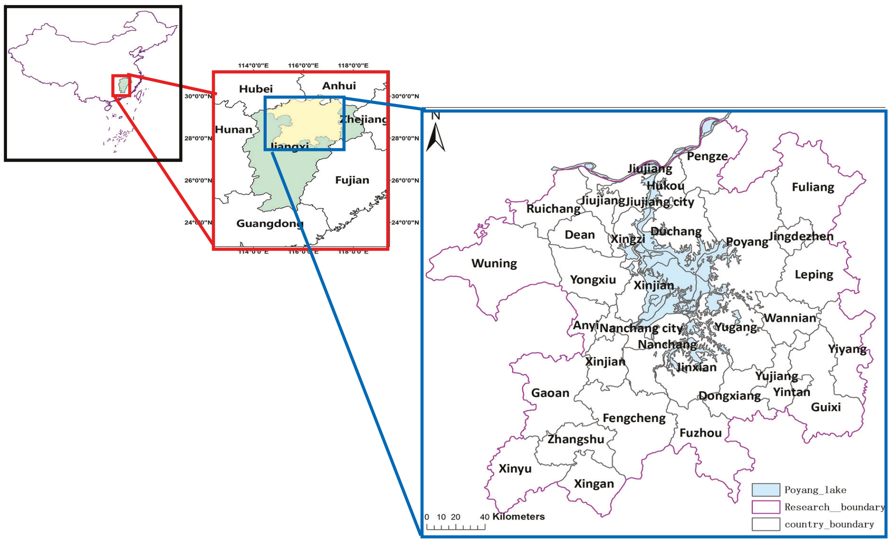

Figure 1. The Location of the Poyang Lake Eco-Economic Zone.

4.2. Data Source

Data were collected by the authors in March 2016, through face-to-face interviews with village leaders. As there are vast differences in economic development and RSWC services' provision among different areas of PLEEZ, we used a stratified random sampling method, based on the per capita gross value of industrial output (GVIO), to identify our sample villages. The GVIO is used as a basis because Rozelle [25] indicated that GVIO can predict peoples' living standards and economic development more accurately than can per capita income. The stratified random sampling procedures are as follows. First, we ordered and divided all the 38 counties in PLEEZ into 10 groups based on the condition of the GVIO, and one sample county was randomly selected from each group; Second, as per the county selection procedure mentioned above, five townships were randomly selected, according to the GVIO in each county from the counties identified in the first step. Third, we randomly chose three villages in each township, according to the GVIO. Thus, a total of 150 villages were included in our dataset.

A structured questionnaire was used to obtain the primary data. The questionnaire basically has two parts. The first part collected information about RSW management in each sampled village, including RSWC facilities and RSWC workers. The second part relates to the information regarding village characteristics and governance characteristics.

4.3. Descriptive Statistics

Variable descriptive statistics of the total sample villages are presented in Table 2. The per capita income of the surveyed villages in 2015 is 4.29 thousand RMB (which is equal to 614 USD at a 7:1 exchange rate). There are, on average, 5.48 small groups in a village. The farthest distance between two households in the same small group of village is 2.13 km, and the average distance from village committee to the township government is 4.86 km. Most surveyed villages are located in the old liberated areas and mountain areas. Almost all the village leaders are elected. The ratio of the village's largest family clans averages 54.76% and most of the village leaders come from the village's largest family clans. The number of people working in upper-level government is 6.64, on average.

Table 2. Variable descriptive statistics of the total sample villages.

Variables	Mean	Standard Deviation	Minimum	Maximum
Village characteristics				
Income	4.29	2.38	1.21	10.36
Population	2.69	1.76	0.78	6.35
Group	5.48	3.96	1.0	26.0
Density	2.13	1.59	0.15	4.76
Distance	4.87	3.21	0.32	7.85
Ncountryside	0.22	0.12	0.0	1.0
Liberated	0.56	0.28	0.0	1.0
Mountain	0.72	0.24	0.0	1.0
Governance characteristics				
Formal governance				
Elected	0.92	0.14	0.0	1.0
Informal governance				
Rclans	54.76	24.57	12.43	76.54
Lclans	0.58	0.39	0.0	1.0
Hleaders	6.64	13.56	0.0	21.0

Figure 2 shows the proportion of villages and the proportion of people in sampled villages with RSWC services. In our sample, 73.33% villages provided RSWC facilities. The proportion of villages with RSWC workers is lower than is the proportion of villages with RSWC facilities, which is 57.33%. Only 46% villages in our sample provided both RSWC facilities and RSWC workers. In terms of the proportion of people with RSWC services, 65.35% people in our sampled villages have RSWC facilities, which is lower than the proportion of villages with RSWC facilities. This is because, under the budget constraint, a RSWC facility is jointly used by several farmers in rural China (our survey data showed that the maximum number of farmers jointly used a RSWC facility is 12, while the minimum number of farmers jointly used a RSWC facility is 1). By the same token, the proportion of people with both RSWC facilities and RSWC workers is much lower than the proportion of villages with both RSWC facilities and RSWC workers, which is only 38.94%. The proportion of people with RSWC workers is the same as the proportion of villages with RSWC workers. This is because RSWC workers serviced all farmers in the village.

Figure 2. Proportion of villages with residential solid waste collection (RSWC) services.

Compared with the proportion of villages with RSWC services in previous literature, we can see that, even though our sample area is a low-income area of China, the proportion of villages with RSWC services in our sample is the highest (Table 3). This is mainly because the Chinese government has put RSW management as a policy priority since 2005; thus, increasing investment has been allocated to provide RSWC services. This indicates that the RSWC management services have seen a remarkable growth in recent years. The latest data in our paper allow us to reflect the real situation of RSW management services in rural China.

Table 3. Proportion of villages with RSWC services in previous literature.

Literature	Villages with RSWC Facilities	Villages with RSWC Workers	Survey Year	Sample Area
Ye et al. [6]	10%		2005	Jiangsu, Sichuan, Shaanxi, Hebei, and Jilin
Huang et al. [26]	52%		2009	Beijing, Jilin, Hebei, Anhui, Sichuan, and Yunnan
Wang et al. [5]	50%	45.5%	2011	Jiangsu, Sichuan, Shaanxi, Hebei, and Jilin

Table 4 compares the characteristics of villages with and without RSWC services. The results show that villages providing RSWC services have higher per capita income, greater total population, and a higher number of small groups. In addition, villages with a higher population density and that are nearer to the township government seem more likely to provide RSWC services. Villages located in the new countryside and old liberated areas provide more RSWC services. RSWC services are more likely to be provided in villages that have a higher ratio of the village's largest family clans and where more village leaders come from the village's largest family clans. We also find that villages with a higher number of people working in the upper-level government are more likely to provide RSWC services.

Table 4. Comparison of villages with and without RSWC services.

Variables	RSWC Facilities		RSWC Workers		Both RSWC Facilities and Workers	
	Yes	No	Yes	No	Yes	No
Village characteristics						
Income	4.53	3.65	4.82	3.61	5.48	3.29
Population	2.88	2.19	3.04	2.23	3.09	2.36
Group	6.29	3.26	7.24	3.13	8.44	2.98
Density	2.04	2.37	2.00	2.31	1.82	2.39
Distance	4.75	5.21	3.96	6.09	2.42	6.94
Ncountryside	0.24	0.16	0.28	0.14	0.34	0.12
Liberated	0.59	0.48	0.62	0.48	0.73	0.42
Mountain	0.72	0.71	0.73	0.71	0.76	0.69
Governance characteristics						
Formal governance						
Elected	0.92	0.91	0.94	0.89	0.94	0.90
Informal governance						
Rclans	56.04	51.26	60.10	47.63	66.50	44.85
Lclans	0.61	0.51	0.65	0.48	0.76	0.43
Hleaders	6.99	5.68	7.08	6.05	8.42	5.14

5. Results

The descriptive statistics mentioned above do not take other factors into account. To further examine the determinants of RSWC services provision, we use two empirical regressions in this section. The first is the baseline Probit regression results. In this model, we assume that all the explanatory factors included in the X vector in Equation (1) are exogenous. The second is the Bivariate Probit regression results. In this model, we relax the exogenous assumption and assume that some explanatory factors included in the X vector in Equation (1) could be endogenous.

5.1. Probit Regression Results

The Probit regression results of the factors that influence RSWC services provision are shown in Table 5. The regression equations appear to perform well. The Prob > chi^2 values suggest that the models are statistically significant. The pseudo-R^2 values indicate that 27.82%, 28.76%, and 25.34% variation are included in the models for RSWC facilities, RSWC workers, and both RSWC facilities and workers, respectively. Although there are several exceptions, our results of the Probit analysis of the determinants of RSWC services provision are consistent with our general findings from the descriptive statistics in Table 4.

The coefficient of *Income* is positive and significant in all three models, indicating that in villages with higher per capita income, there is relatively more RSWC facilities' provision, RSWC workers' provision, and both RSWC facilities' and workers' provision. As we stated in the introduction section, funding for RSWC services' provision in China mainly comes from the village itself. Villages with higher per capita income have more financial resources to provide RSWC services. The importance of economic development in the provision of public goods has been verified in other studies; for example, Zhang et al. [27] and Luo et al. [28] also found that villages with higher income have more public projects investment.

The coefficients of *Population*, *Group* are positive and significant and the coefficient of *Density* is negative and significant in the model of RSWC facilities, which means that more populous villages tend to have more RSWC facilities. A larger village population will generate more RSW, which, in turn, induces government to provide more RSWC facilities. On the other hand, RSWC costs are higher in sparsely populated villages than in more populous villages. Thus, under the budget constraint, more RSWC facilities will be provided by village leaders in more populous villages. However, the coefficients of *Population*, *Group*, and *Density* are not significant in the models of RSWC workers and both RSWC facilities and workers, indicating that the provision of RSWC workers and both RSWC facilities and workers is not influenced by the size and density of villages. One explanation is plausible. Under the consideration of welfare, villages often hire people who are of low-income and unfit to be RSWC workers. In addition, on average, there is only one RSWC worker in each small group. Therefore, the relationship between the provision of RSWC workers and village size is not strong.

Table 5. Probit regression results of the determinants of RSWC services provision.

Variables	RSWC Facilities		RSWC Workers		Both RSWC Facilities and Workers	
	Coefficient	S.E.	Coefficient	S.E.	Coefficient	S.E.
Village characteristics						
Income	0.089 ***	0.032	0.035 ***	0.012	0.066 ***	0.024
Population	0.143 ***	0.051	0.076	0.087	0.102	0.095
Group	0.384 **	0.158	0.292	0.187	0.207	0.169
Density	−0.198 ***	0.047	−0.083	0.072	−0.174	0.126
Distance	−0.329 ***	0.126	−0.214	0.198	−0.263	0.187
Ncountryside	0.876 ***	0.293	0.632	0.564	0.603	0.495
Liberated	0.762 **	0.301	0.485	0.326	0.389	0.253
Mountain	−0.104	0.208	−0.186 ***	0.093	−0.087	0.066
Governance characteristics						
Formal governance						
Elected	1.654	1.149	1.043	0.965	1.396	0.985
Informal governance						
Rclans	0.063 **	0.026	0.075 **	0.031	0.054 **	0.025
Lclans	0.087 ***	0.023	0.079 **	0.033	0.063 ***	0.021
Hleaders	0.321 ***	0.108	0.295 ***	0.102	0.204 ***	0.076
Constant	−7.486	4.984	−9.841	6.532	−6.293	3.652
Pseudo-R^2	0.2782		0.2876		0.2534	
Prob > chi^2	0.000		0.000		0.000	

Note: *** and ** denotes significance level at 1% and 5%.

The coefficient of *Distance* is negative and significant and the coefficients of *Ncountryside*, *Liberated* are positive and significant in the model of RSWC facilities, which means that villages nearer to the township government and located in the new countryside and old liberated areas are likely to provide more RSWC facilities. Two possible explanations are as follows. First, as villages that are near township government and located in the new countryside area are often richer, government has enough funding to provide RSWC facilities. Second, village leaders can showcase their political achievements more easily by investing in villages that are near township government and are located in the new countryside areas. As we found in our survey data, two economically similar villages, one located in the new countryside areas, the other does not located in the new countryside areas. There are nearly five times as many RSWC facilities in the village located in the new countryside areas as are found in the village that does not. By the same token, by investing in villages located in the old liberated areas, village leaders can also showcase their political achievements more easily. However, the coefficients of *Distance*, *Ncountryside*, and *Liberated* are not significant in the models of RSWC workers and both RSWC facilities and workers, indicating that the provision of RSWC workers and both RSWC facilities and workers are not influenced by *Distance*, *Ncountryside*, and *Liberated*. The reason for this is that, compared with RSWC workers and both RSWC facilities and workers, the benefits of providing RSWC facilities are more obvious. Thus, village leaders prefer RSWC facilities to showcase their political achievements.

Villages located in the mountain areas (*Mountain*) are shown to have a negative and significant correlation with the provision of RSWC workers. Mountainous areas are often in poor natural and geographical conditions, which will result in high transportation costs and greater difficulties for workers to collect RSW. This is in line with the findings of He et al. [29], who found that the relationship between natural terrain and public goods provision efficiency is negative.

The coefficient of the formal governance variable, *Elected*, is not significant in all three models, which means that village leaders who are directly elected do not provide more RSWC services than do those who are not directly elected. This is not consistent with previous studies on the role of formal governance in the provision of public goods. For example, the findings from Luo et al. [7] and

Martinez-Bravo et al. [30] suggest that elections have strong predictive power over the provision of public goods. Two explanations are plausible. First, as formal governance improves, such as electoral rules and procedures, most of the villages in rural China are being directly elected by villagers, rather than being appointed by the upper-level government, and the homogeneity of elections reduces the impact of election on RSWC services' provision. Second, unlike the other public goods investments, such as in school construction, road and bridge construction, drinking water services construction, electricity construction, and irrigation construction, the provision of RSWC services cannot generate political achievement in the short term. Thus, village leaders lack adequate incentives to provide RSWC investment.

The coefficients of informal governance variables, *Rclans*, *Lclans*, *and Hleaders*, are positive and significant in all three models, indicating that villages with a higher ratio of largest family clans, where more village leaders come from the village's largest family clans, and where more people are working in the upper-level government, are more likely to provide RSWC services. With the help of the informal governance of large clans, the village leaders can get more levies from the villagers for public goods expenditure and are more able to mobilize resources needed for providing public goods. This is in line with previous studies regarding the role of informal governance on public goods provision. For instance, Tsai et al. [10] show that villages with informal groups, such as temple associations and village-wide lineage groups, are more likely to invest in public goods. Yao et al. [11] indicates that a large increase in public goods expenditure is highly associated with the presence of a village leader that comes from the two largest family clans. Villages with more people working in upper-level government seem to have a strong predictive power over the provision of RSWC services. This finding is consistent with the findings from Zhang et al. [31], who found that villages with more people working in upper-level government will favor their home village when allocating resources and will facilitate their own home villages' application for public goods investment. This finding is not surprising in rural China where informal connections (*guanxi*) have thrived over many years [12].

A comparison of the role of formal governance and informal governance on RSWC services' provision indicates that formal governance does not matter in RSWC services' provision. In contrast, informal governance becomes the primary factor influencing RSWC services' provision. The reasons may be that village election in rural China has become highly normative and universal, and the situation of formal governance is homogeneous in villages, with the result that the impact of formal governance on public goods provision has decreased. Conversely, the traditional informal governance matters more than formal governance.

5.2. Accounting for the Endogeneity:Bivariate Probit Regression Results

In this section, we employ a Bivariate Probit model to take account of the potential endogeneity of the variable *Elected*, because concerns of reverse causality and unobserved confounders remain.

Based on the findings of Luo et al. [7], we used the number of conferences convened by the upper government for election (*Conferences*) as an additional instrumental variable in Equation (5). The logic is that the more conferences are convened by the upper government for election, the more likely it becomes that county election protocol will happen in the process of election. Our data show that, on average, four conferences were convened for election. The correlation coefficient between *Conferences and Elected* was significant.

According to the suggestion by Wooldridge et al. [32], the instrumental variable should be related to the endogenous variable (*Elected*) but should not be related to the outcome variable (RSWC services provision). In theory, *Conferences* is considered to be a proper instrumental variable, since it is positively correlated with *Elected* but not with RSWC services' provision. Meanwhile, we also test the validity of *Conferences* through statistical analysis. Specifically, we test whether *Conferences* is correlated with other control variables. We divide our sample villages into two groups: those villages that have more than four conferences and those villages that have less than four conferences. The results from Table 6 indicate that the value of control variables is almost the same between the two groups. Therefore, the instrumental variable used in our paper is sound, both by logic and by statistical analysis.

Table 6. The relationship between instrumental variable and other control variables.

Variables	More Than 4 Conferences Convened by the Upper Government for Election	Less Than 4 Conferences Convened by the Upper Government for Election
Village characteristics		
Income	4.32	4.24
Population	2.71	2.65
Group	5.43	5.57
Density	2.07	2.24
Distance	4.79	5.01
Ncountryside	0.19	0.27
Liberated	0.58	0.52
Mountain	0.75	0.67
Governance characteristics		
Formal governance		
Elected	0.94	0.88
Informal governance		
Rclans	53.98	56.15
Lclans	0.59	0.56
Hleaders	6.53	6.84

Table 7 reports the Bivariate Probit regression results of the determinants of RSWC services' provision. Accordingly, a comparison of the coefficients associated with the variables in the Bivariate Probit and Probit regression model is presented in Table 8. We can find that most of the estimated coefficients are the same as Probit estimates. This finding convinces us that our results remain robust when considering endogeneity problems.

Table 7. Bivariate Probit regression results of the determinants of RSWC services provision.

Variables	RSWC Facilities		RSWC Workers		Both RSWC Facilities and Workers	
	Coefficient	S.E.	Coefficient	S.E.	Coefficient	S.E.
Village characteristics						
Income	0.075 ***	0.026	0.041 **	0.018	0.059 **	0.026
Population	0.137 **	0.055	0.082	0.083	0.114	0.099
Group	0.217 *	0.113	0.185	0.135	0.223	0.184
Density	−0.163 **	0.076	−0.067	0.046	−0.097	0.102
Distance	−0.315 **	0.132	−0.232	0.187	−0.189	0.125
Ncountryside	0.823 ***	0.254	0.543	0.431	0.597	0.421
Liberated	0.721 **	0.285	0.424	0.265	0.279	0.188
Mountain	−0.123	0.187	−0.193 **	0.087	−0.082	0.058
Governance characteristics						
Formal governance						
Elected	1.236	0.985	1.321	0.927	1.218	0.976
Informal governance						
Rclans	0.072 **	0.036	0.079 **	0.035	0.061 **	0.028
Lclans	0.091 ***	0.027	0.082 **	0.037	0.058 **	0.029
Hleaders	0.304 **	0.127	0.226 **	0.098	0.235 **	0.114
Constant	−9.385	5.231	−7.317	4.265	−11.327	7.276
Pseudo-R^2	0.2904		0.2945		0.2789	
Prob > chi^2	0.000		0.000		0.000	

Note: ***, **, and * denotes significance level at 1%, 5%, and 10%.

Table 8. Comparison of Bivariate Probit regression results and Probit regression results.

Variables	RSWC Facilities		RSWC Workers		Both RSWC Facilities and Workers	
	Bivariate Probit	Probit	Bivariate Probit	Probit	Bivariate Probit	Probit
Village characteristics						
Income	0.075 ***	0.089 ***	0.041 **	0.035 ***	0.059 **	0.066 ***
Population	0.137 **	0.143 ***	0.082	0.076	0.114	0.102
Group	0.217 *	0.384 **	0.185	0.292	0.223	0.207
Density	−0.163 **	−0.198 ***	−0.067	−0.083	−0.097	−0.174
Distance	−0.315 **	−0.329 ***	−0.232	−0.214	−0.189	−0.263
Ncountryside	0.823 ***	0.876 ***	0.543	0.632	0.597	0.603
Liberated	0.721 **	0.762 **	0.424	0.485	0.279	0.389
Mountain	−0.123	−0.104	−0.193 **	−0.186 ***	−0.082	−0.087
Governance characteristics						
Formal governance						
Elected	1.236	1.654	1.321	1.043	1.218	1.396
Informal governance						
Rclans	0.072 **	0.063 **	0.079 **	0.075 **	0.061 **	0.054 **
Lclans	0.091 ***	0.087 ***	0.082 **	0.079 **	0.058 **	0.063 ***
Hleaders	0.304 **	0.321 ***	0.226 **	0.295 ***	0.235 **	0.204 ***
Pseudo-R^2	0.2904	0.2782	0.2945	0.2876	0.2789	0.2534
Prob > chi^2	0.000	0.000	0.000	0.000	0.000	0.000

Note: ***, **, and * denotes significance level at 1%, 5%, and 10%.

6. Conclusions and Discussion

China has been facing an increasing challenge to properly manage a massive amount of RSW. Providing RSWC services is the first and most indispensable part of RSW management and is crucial for rural environment protection. Although there has been much effort by the Chinese Government to provide RSWC services in recent years, there is still huge insufficiency and remarkable variation among regions in the level of RSWC services' provision, which poses a great threat to rural areas' long-term development. Based on the latest survey data set collected in PLEEZ in Jiangxi Province, this paper seeks to understand the determinants of RSWC services provision at the village-level. Our analysis, which uses a Probit regression model as the baseline estimation strategy and a Bivariate Probit regression model considering endogeneity as a robustness check, yields three important findings.

First, we find that villages that are richer are more likely to provide all the RSWC services, including RSWC facilities, RSWC workers, and both RSWC facilities and workers. This suggests that provision of RSWC services is not evenly distributed across different regions; Second, villages that are more populous, nearer to the township government, and located in the new countryside and old liberated areas have seen an increase in the provision of RSWC facilities, but not the provision of RSWC workers and both RSWC facilities and workers. This suggests that showcasing exists in the provision of RSWC services; Third, informal governance characteristics, such as the ratio of largest family clans, whether village leaders come from the village's largest family clans, and the number of people working in upper-level government, have strong predictive power over the provision of RSWC services, while formal governance characteristics, such as elections, do not affect RSWC services' provision. This suggests that, due to the steady improvements of the normative and universal of formal governance in China, traditional informal governance matters more than formal governance in the provision of public goods.

This study might provide some policy implications for the related policy-makers. First, the upper-level government should provide more fiscal support to the local villagers' committees to improve their financial capacities. Moreover, relatively underdeveloped rural areas, such as poorer and mountain areas, should get more support from the upper-level government in the future; Second, RSWC facilities should be constructed to optimize the route and decrease RSW management costs. To achieve this, related facilities need to be well designed and managed; Third, the showcasing phenomenon in the provision of RSWC services should be taken into account by officials in their works. This necessitates changes in the evaluation of local government performance in RSWC services provision. For example, not only the provision of RSWC facilities, but also the provision of RSWC workers should be evaluated. In addition, farmers' satisfaction of RSW management should also be considered. Fourth, the government should take into account the informal governance in different regions of rural China and let informal governance play a due role in promoting public goods' provision.

Finally, a note on the limitations of this study is in order. Nowadays, the funding of RSWC services' provision mainly comes from two channels: one is government finance, the other is monthly or yearly bills paid by rural people who enjoy RSWC services. Therefore, rural peoples' willingness to pay for RSWC services provision is a prerequisite for sustainable provision of RSWC services. However, this study only analyzes the determinants of RSWC services' provision at the village level. Thus, follow-up studies are needed to understand rural people's willingness to pay for RSWC services' provision.

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Can High-Tech Ventures Benefit from Government *Guanxi* and Business *Guanxi*? The Moderating Effects of Environmental Turbulence

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Abstract: The construct of *guanxi* has become an interesting topic for analyzing how to do business more effectively and successfully in China's economic transition period. Drawing on the *guanxi* strategy theory, this study examines when government *guanxi* (*guanxi* with the government and its officials) and business *guanxi* (*guanxi* with the business sectors) matter to new venture performance under two typical turbulent environments (institutional turbulence and market turbulence). According to empirical results using original data from 146 new ventures in clusters driven by China's local governments, both government *guanxi* and business *guanxi* were positively related to new venture performance, and market turbulence was an important contextual factor influencing performance benefits of *guanxi*. However, the results reveal no moderating effects of institutional turbulence on direct relationships. Furthermore, the study provides a better conceptual and empirical understanding of why market turbulence is a double-edged sword for performance implications of *guanxi* in the rapidly changing business environment.

Keywords: government *guanxi*; business *guanxi*; institutional turbulence; market turbulence; new venture performance

1. Introduction

As noted in the literature, doing business in Western countries focuses mainly on "what you know" and "what you are good at", indicating that firms need to invest substantial resources in developing various firm capabilities such as technological, marketing, learning, and management capabilities. However, doing business in China often needs to focus on "whom you know" and "who can help you", indicating that firms need to invest resources in developing and maintaining effective formal or informal connections with appropriate individuals or organizations [1–4]. Such connections or ties are referred as "*guanxi*", which consists of "*guan*" (gate) and "*xi*" (tie). *Guanxi* reflects the nature and characteristics of the social progress or human life of China's Confucian society over the last two millennia [5,6]. To date, *guanxi* is an important research topic in strategic management and entrepreneurship to examine how business can be done more effectively and successfully in contemporary China.

As a centralized country, China consistently focuses on shifting from a planned economy to a market-based economy since the start of its openness and economic reform in 1978. On the one hand, the market is expected to play a dominant role in resource allocation and economic growth and thus can facilitate job creation and income growth [7]. It indicates that firms should establish and expand their *guanxi* connections with business sector, such as primary suppliers, customers, cooperators, and even rivals. For instance, having good *guanxi* connections with suppliers may help a focal firm much easily obtain low-cost materials with acceptable quality. In this respect, it seems that industries tend to be much less affected by political systems and government policies in a market-based economy than in a planned one. On the other hand, however, the Chinese government still has strong "soft power" to regulate the development of an industry [8]. Moreover, the government can promote or hinder industrial development and business operations by enacting a series of business policies in economic transition period [9,10]. Consequently, this study argues that both government *guanxi* (*guanxi* with the government and its officials) and business *guanxi* (*guanxi* with the business sector) may be two antecedents of doing business in China.

In addition, previous literature has shown that performance implications of *guanxi* (or network) are contingent on environmental factors. As known, China is experiencing economic transition which leads the business environment to undergo volatile turbulence in terms of its institutions, markets, technologies, and culture [11,12]. In this regard, potential effects of different types of *guanxi* on business performance may vary across a rapidly changing business environment. The present study considers two typical *guanxi* types (government *guanxi* and business *guanxi*) under two typical business environments (institutional turbulence and market turbulence) to fill two important gaps in the literature. First, with empirical evidence from a survey of 146 new ventures located in government-driven high-tech clusters, the study examines general effect of government *guanxi* on new venture performance. Firms can undoubtedly benefit from developing and keeping good *guanxi* connections with the business sector, because a strong firm–business interaction enables firms to be embedded in a business network and establish legitimacy as quickly as possible [13]. However, the relationship between government *guanxi* and business performance remains unclear and thus has been a topic of an ongoing debate. Some studies have argued that developing government *guanxi* may help firms establish institutional confidence and obtain sufficient government resources, whereas others have failed to find any direct effects of government *guanxi* (or political ties) on business performance [8,10]. A literature review reveals differences in research samples between these two competing findings, with the former focusing on government-sponsored firms, whereas the latter, on high-tech firms. Given that the present study's sample is from government-driven high-tech clusters, it is confused whether government *guanxi* is critical to new venture performance.

Second, the study investigates whether contextual factors such as environmental turbulence are contingent on performance implications of *guanxi*. Although previous studies focusing on the Chinese context reveal that some contingencies (i.e., ownership, location, and firm size) may alter the value of *guanxi*, there is an apparent gap in the literature in whether environmental turbulence can be seen as a critical moderator [14]. To answer this question, this study focuses on two typical environmental conditions (institutional turbulence and market turbulence) that may reflect the nature and characteristics of China's economic transition. More specially, it examines their respective moderating effects on the relationship between government *guanxi* (or business *guanxi*) and new venture performance.

The rest of this paper is organized as follows: Section 2 draws on *guanxi* strategy theory to suggest that *guanxi* is a dominant determinant of doing business in China but that environmental turbulence can foster or impede outcomes of different types of *guanxi*. Based on a literature review and a theoretical analysis, the section develops six hypotheses about relationships between *guanxi*, environmental turbulence, and new venture performance. Section 3 describes research sample, data collection method, research model, and measurement method. Section 4 presents the analysis steps and empirical results. Section 5 discusses the research findings, theoretical contributions, managerial implications, limitations, and future research directions, and Section 6 concludes.

2. A Theoretical Review and Hypothesis Development

2.1. Guanxi Strategy Theory

Social network theory, developed by Western management scholars, has been widely applied to investigate the importance of personal or organizational connections in business activities [15,16]. In the context of Chinese management, some scholars also employ social network theory to analyze how personal or organizational connections affect business operations [14,17]. However, general connections can not reflect the nature and characteristics of connection ties in Confucian societies (e.g., Mainland China, Taiwan, and Hong Kong). In this regard, *guanxi* that goes deeper than connection has attracted a great attention from scholars and practitioners [18]. Traditionally, *guanxi* is a deeply ingrained institution that highlights the interrelationships between family members, relatives, friends, and other significant others. Family relations (*qinyuan*), geographic relations (*diyuan*), religious relations (*shenyuan*), business relations (*yeyuan*), and product relations (*wuyuan*) are the most frequent types of *guanxi* that are often used by sociology and management scholars to identify a person's social status. This indicates that *guanxi* traditionally originates from the basis of special roots and refers to personal connections at the individual level.

From the perspective of strategic management, *guanxi* is often regarded as a particular and inimitable strategic resource that can help firms develop and maintain their competitive advantage [19–21]. As mentioned earlier, *guanxi* reflects the Chinese contextual notion and the way that people can do business more effectively and successfully. Therefore, some scholars from both Western countries and China have made efforts since the late 1990s to develop *guanxi* strategy theory to examine the relationship between *guanxi* and firm performance in a more effective manner [22,23]. *Guanxi* strategy theory suggests that building and using *guanxi* connections may help firms strengthen business performance in China's economic transition period [1]. That is because the degree of *guanxi* connections may affect the flow of resources and interactions with the firm-task environment, thereby helping develop a competitive advantage in a rapidly changing business environment [14,24]. Similarly, Su et al. (2003) [25] precisely pointed out that, in comparison to large firms, small- and medium-sized enterprises are more likely to benefit from *guanxi* under scarce resources. Furthermore, they suggested that *guanxi* can be regarded as a strategic tool which can increase the efficiency and effectiveness of doing business in China. In the field of entrepreneurship, Guo and Miller's (2010) [2] work suggested that *guanxi* connections play a significant role across entrepreneurial processes. First, during firm creation, *guanxi* ties with family members and relatives may provide initial funding or psychological support for entrepreneurs [4]. Second, during early firm growth, *guanxi* ties with critical stakeholders such as government officials, business partners, capitalists, and primary customers may help new ventures become more effectively embedded in a network to gain an industrial or social division. Third, during stable firm growth, *guanxi* ties with various individuals and organizations from multiple backgrounds may help new ventures consistently exploit business opportunities and market potential to realize sustainable growth. Su and Sohn (2015) [23] offered additional theoretical perspectives on the role of *guanxi* in entrepreneurship, through which new ventures often obtain important information and critical resources by using their *guanxi* ties with important individuals or organizations. They also emphasized that the mutual trust originating from *guanxi* ties can help new ventures create accessing routines to entrepreneurial resources. In this regard, the present study argues that a utilization of *guanxi* strategy theory may enhance our understanding of how new ventures leverage different types of *guanxi* under different turbulent environmental conditions.

2.2. Government Guanxi, Business Guanxi and New Venture Performance

2.2.1. Government *Guanxi* and New Venture Performance

Studies of Chinese management in the last few decades may convince entrepreneurs and managers that building and maintaining stronger *guanxi* connections with the government and its officials has significant effects on business creation and operation. First, the Chinese government can use its "soft power" to effectively regulate industries and business activities to realize government goals with respect to the economy or society, such as jobs' creation, wealth generation, and economic growth [8]. Second, new ventures need government to provide various supports, such as institutional infrastructure, industrial policies, and even taxation preferences. In this respect, the Chinese government may be a reliable partner and the goals of governments and firms are cooperative rather than competitive.

In addition, recent empirical studies have also asserted the importance of government *guanxi* in new venture performance. For instance, Guo and Miller [2] found that new ventures with good *guanxi* with the government may enhance their ability to access entrepreneurial resources and be more confident in doing business in China. Using a sample of 55 biopharmaceutical high-tech firms in China, Wang and Lestari [26] precisely pointed out that government *guanxi* is positively related to market entry success because the Chinese government "has the authority to approve projects, allocate resources, and arrange financing and distribution." From the resource-based view, Chen et al. [27] suggested that government *guanxi* has a significant effect on information accessibility, thereby influencing new venture creativity and social reputation. In light of the importance of the Chinese government in industrial development and market restructuring, this study deems that new ventures should maintain good *guanxi* connections with government and its officials to obtain more institutional resources or confidence to operate business more smoothly in China. In this regard, the following hypothesis is proposed:

Hypothesis 1. *General speaking, government guanxi has a significant positive effect on new venture performance.*

2.2.2. Business *Guanxi* and New Venture Performance

Precisely speaking, the market of Mainland China is a huge and complex web of business *guanxi* [25]. It indicates that doing business in China requires effective interactions with a particular business network of various stakeholders such as customers, suppliers, partners, and rivals, which is often defined as "business *guanxi*" [10,28]. *Guanxi* strategy theory points out that Chinese businessmen often use *guanxi* to control or influence their business partners because *guanxi* potentially fosters mutual trust for sharing market information, advice, and resources among network members. For instance, keeping good *guanxi* connections with important personals (e.g., top managers of business partners) or organizations (e.g., business partners) may make it more likely to provide industrial divisions and benefits [29]. Similarly, Cao et al. [13] argued that in a common business *guanxi* network, a firm can effectively interact with its business partners "in a particular way at a particular time for a particular price", leading to lower transaction costs and better performance. In sum, previous studies have suggested that investing in and using business *guanxi* can help a firm develop a strategic competitive advantage, ultimately strengthening its performance [30].

For new ventures, their survival and growth are greatly influenced by several important strategic factors such as building business legitimacy [31], looking for primary customers [13], promoting business transactions [32], and obtaining knowledge or technology support [23]. *Guanxi* strategy theory argues that these strategic needs are very closely related to the effective embeddedness of business *guanxi* [1,23]. This is because good business *guanxi* can help new ventures overcome their liability of newness and more effectively embed themselves in the industrial network to benefit from industrial divisions [33]. For example, new ventures can benefit from having good business *guanxi* with primary customers. First, primary customers may provide more targeted and effective advice for new ventures to develop products to better meet customers' needs, exploit market opportunities, or optimize supply chains. Second, primary customers can provide emotional support or confidence for new ventures to do business in an uncertain business environment with a high level of risk [17,34]. Therefore, it is common for new ventures to develop and use good *guanxi* connections with business sectors to do business more successfully when their strategic resources are scarce. In this regard, the following hypothesis is proposed:

Hypothesis 2. *General speaking, business guanxi has a significant positive effect on new venture performance.*

2.3. Economic Transition: Market Turbulence and Institutional Turbulence

Both social network theory and *guanxi* strategy theory point out that the value of *guanxi* (social capital) "varies across distinct environmental conditions" [35]. China's economic transition leads the business environment to experience turbulence in terms of its institutions, markets, and culture [10]. For entrepreneurship, a turbulent environment indicates that new ventures often face massive opportunities and challenges such as rapid changes in customer demands or preferences, institutional policies, and technological innovations [36]. Consequently, this study argues that benefits of *guanxi* are contingent on environmental turbulence. However, some studies [13] have argued that environmental turbulence impedes benefits of *guanxi*, whereas others [1] provide the opposite findings.

Given that government *guanxi* and business *guanxi* are two independent variables of the present study, we argue that institutional turbulence and market turbulence may be two important environmental contingency factors influencing the value of government *guanxi* and business *guanxi*. Therefore, it would be beneficial to take into account environmental turbulence for a better understanding of the nature of *guanxi* in the literature on Chinese management and its impact on doing business in China.

2.3.1. Moderating Effects of Institutional Turbulence

This study posits that institutional turbulence may be an important contingency factor moderating the relationship between government *guanxi* (or business *guanxi*) and new venture performance. Rapid changes in the political system establish many new rules or bring various constraints, which lead new ventures to distribute their finite resources to respond to these changes [36]. A high level of institutional turbulence indicates rapid and uncertain changes in government policies and legal institutions. At this time, the Chinese government and its officials may use "soft power" to have considerable influence on business operations [8]. Therefore, keeping and maintaining stronger *guanxi* connections with the government and its officials may help new ventures obtain institutional resources and enrich the resource base, which can strengthen business performance under a high level of institutional turbulence. However, building and maintaining stronger *guanxi* with the business sector may be counterproductive under a high level of institutional turbulence. That is because developing *guanxi* with primary customers, suppliers, and cooperators requires resource investment so that new ventures will have no enough resources to respond to the institutional changes.

On the other hand, the government tends to provide more service functions and fewer interference functions for business activities under a low level of institutional turbulence. It suggests that legal and institutional systems with respect to industries become stable and developed, indicating that the importance of government *guanxi* connections in doing business is likely to decline, but developing *guanxi* with business sectors may be more crucial for performance creation [10,14]. In this regard, the following hypotheses are proposed:

Hypothesis 3. *Institutional turbulence has a positive moderating effect on the relationship between government guanxi and new venture performance.*

Hypothesis 4. *Institutional turbulence has a negative moderating effect on the relationship between business guanxi and new venture performance.*

2.3.2. Moderating Effects of Market Turbulence

This study posits that market turbulence acts as an important contingency factor moderating the relationship between government *guanxi* (or business *guanxi*) and new venture performance. A turbulent market environment indicates rapid changes in customer demands and preferences [37]. Under a turbulent market environment, new ventures may benefit from developing and maintaining good *guanxi* with business partners. First, having good *guanxi* with primary customers may help new ventures develop products more quickly and accurately to realize a first-mover advantage. Furthermore, existing customers can help new ventures find and establish connections with potential customers and new markets, which may be crucial for the survival of new ventures in a market with a low growth rate [34]. Second, having good *guanxi* with suppliers may help new ventures obtain lower-cost materials with acceptable quality, thereby providing products at lower and more competitive prices. In sum, the value of business *guanxi* in the creation of new ventures increases along with a turbulent market environment.

On the other hand, this study posits that developing and maintaining good *guanxi* with the government and its officials under a turbulent market environment have a negative effect on new venture performance. Previous studies have pointed out that the establishment and development of *guanxi* requires substantial resource investment. However, the resource base of new ventures is weak, so investing their resources in government *guanxi* may be a wrong strategic decision that may impede business performance creation. In addition, resources obtained from the government cannot facilitate or even damage business creation in a turbulent market [38]. In this regard, the following hypotheses are proposed:

Hypothesis 5. *Market turbulence has a negative moderating effect on the relationship between government guanxi and new venture performance.*

Hypothesis 6. *Market turbulence has a positive moderating effect on the relationship between business guanxi and new venture performance.*

3. Methods

3.1. The Sample and Data Collection

New ventures can be defined as small businesses that are invested in by individual(s) or group(s) with the expectation of the business operation bringing in financial or marketing gains for investors or entrepreneurs. It is widely acknowledged that new ventures make important contributions to economic growth and social progress [39]. Previous studies of strategic management have suggested that, in comparison to big and established firms, new ventures often face more severe survival challenges because of resource scarcity [9,39,40]. In this regard, a strategic dilemma regarding how to improve the survival ability of new ventures under the condition of resource scarcity has attracted great attention from scholars and practitioners over a long time. As noted earlier, *guanxi* strategy theory argues that government *guanxi* and business *guanxi* may help new ventures access to institutional or marketing resources and enrich their resource base to develop a competitive advantage [41]. However, contingency theory points out that the value of *guanxi* may be influenced by environmental turbulence [10]. In this regard, a better understanding of the effects of government *guanxi* (or business *guanxi*) on firm performance should take into account the context (ecology) of the organization.

This study conducts a quantitative approach. According to the literature, a questionnaire consisting of seven variables and some important demographic information was constructed, and the English questionnaire was translated into Chinese after some revisions to fit the Chinese context. To ensure smooth survey, two entrepreneurs of new ventures in government-driven high-tech clusters and two professors interested in the *guanxi* strategy and entrepreneurship were recruited to evaluate all items in the questionnaire. Based on their suggestions, some academic terms were replaced with easily understandable ones to help the respondents answer all questions more accurately.

To collect data, several government-driven high-tech clusters (covering Guangdong, Fujian, Zhejiang, Shanghai, and Jiangsu, which consistently made efforts to develop high-tech industries and a private economy in the last decade) were asked for their help in July 2015. Government-driven high-tech clusters were chosen as the investigation setting for two reasons: First, new ventures belonging to these clusters were assumed to accurately describe their connections (*guanxi*) to the government and its officials, which often support or guide them to stimulate local economic growth and technological progress [42]. Second, new ventures in these clusters actively engaged in market competition and industrial divisions and thus could accurately describe their connections (*guanxi*) to the business sector [43].

These clusters provided a list of 550 new ventures with detailed contact information. From December 2015 to May 2016, the Chinese version of the questionnaire was sent to these new ventures to ask for their participation in the survey. To ensure the reliability of firm-level data, we set two criteria. First, each respondent had to be a top manager who could accurately describe the firm's *guanxi* with the government (or the business sector). Second, two top managers of each firm were asked to complete the questionnaire [44]. To avoid common method bias, one manager answered predictor variables (government *guanxi*, business *guanxi*, institutional turbulence, and market turbulence), and the other answered outcome variable (new venture performance). However, they were required to answer control variables (firm age and size). Finally, 152 new ventures and 304 top managers agreed to participate in the survey and returned the questionnaire, including six incomplete responses. The sample size ranged from 5 to 200 employees, averaging 46.8 employees.

3.2. The Research Model

As shown in Figure 1, a research model was used to examine whether government *guanxi* (*guanxi* with the government and its officials) and business *guanxi* (*guanxi* with the business sectors) matter to new venture performance under two typical turbulent environments (institutional turbulence and market turbulence). And, we built an equation to describe the statistical relationships between five variables.

$$NVP = \alpha + \beta_1\,GG + \beta_2\,BG + \beta_3\,IT{\cdot}GG + \beta_4\,IT{\cdot}BG + \beta_5\,MT{\cdot}GG + \beta_6\,MT{\cdot}BG + e, \quad (1)$$

where government *guanxi* (GG) and business *guanxi* (BG) are predictor variables; institutional turbulence (IT) and market turbulence (MT) are moderating variables; new venture performance (NVP) is a dependent variable; and e is the residual of the regression equation. In addition, β_3, β_4, β_5, and β_6 represent interaction effects.

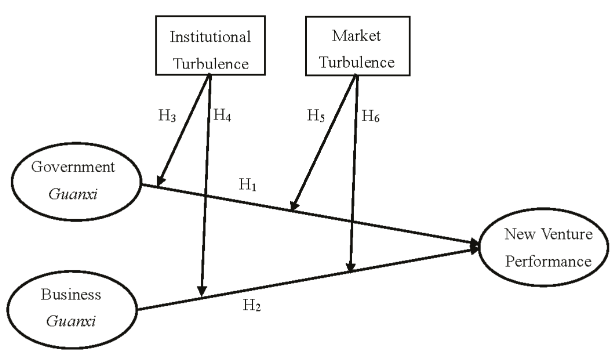

Figure 1. The theoretical model.

3.3. Measures

3.3.1. Government *Guanxi*

The analysis employed Zhang's [45] seven-item scale to measure the nature and extent of government *guanxi*. All items were measured using a seven-point Likert-type scale from 1 (strongly disagree) to 7 (strongly agree). The respondents (top managers) were required to rate the *guanxi* value of their firms with respect to the local government and its officials (see as Table 1).

Table 1. A confirmatory factor analysis, standard estimates, and alpha values (n = 146).

Variable Constructs and Measurement Items	Loading
Government *guanxi* (Zhang, 2010) (α = 0.79; CR = 0.93; AVE = 0.65)	
1. The local government (or its officials) keeps its commitments to our managers and firm.	0.85
2. The local government (or its officials) does justice to our firm.	0.80
3. Our firm and local government (or its officials) trust each other.	0.83
4. Our firm and local government (or its officials) frequently communicate with each other.	0.78
5. If necessary, our firm and local government (or its officials) often provide various assistance to each other.	0.87
6. Our firm and local government (or its officials) often jointly solve some difficulties.	0.82
7. Our firm has good guanxi connections with local government authorities (e.g., government-sponsored banks, science and technology bureaus, industrial and commercial bureaus, and tax bureaus) and their officials.	0.69
Business *guanxi* (Zhang, 2010) (α = 0.76; CR = 0.88; AVE = 0.56)	
1. Primary business partners (e.g., customers, suppliers, and collaborators) consistently keep their commitments to our firm.	0.81
2. Our firm and primary business partners frequently communicate with each other.	0.77
3. Primary business partners have good guanxi connections with top managers of our firm.	0.79
4. Primary business partners often provide useful suggestions on improving the quality of our products.	0.76
5. Primary business partners and our firm often jointly overcome difficulties in product development.	0.67
6. Primary business partners are willing to maintain long-term cooperation with our firm.	0.69
Institutional turbulence (Johanson, 2002) (α = 0.86; CR = 0.87; AVE = 0.62)	
1. The local government acts in a way that leads us to great uncertainty.	0.79
2. It is hard to predict the impact of the political system on the market in this region.	0.81
3. It is difficult to foresee regional institutional changes.	0.82
4. Regional policies are relatively unstable.	0.73
Market turbulence (Jaworski and Kohli, 1993) (α = 0.87; CR = 0.90; AVE = 0.60)	
1. In our kind of business, customers' product preferences change quite a bit over time.	0.82
2. Our customers tend to look for new products all the time.	0.85
3. Our customers are sometimes very price sensitive, but on other occasions, prices are less important.	0.80
4. We are witnessing demand for our products and services from customers who never bought them before.	0.69
5. New customers tend to have product-related needs that are different from those of our existing customers.	0.78
6. We cater to many of the same customers that we used to in the past.	0.68
new venture performance (Anderson and Eshima, 2013) (α = 0.84; CR = 086; AVE = 0.68)	
1. Sales growth	0.81
2. Market share growth	0.84
3. Employee growth	0.82

Notes: KMO (Kaiser-Meyer-Olkin) = 0.85.

3.3.2. Business *Guanxi*

The measurement of business *guanxi* followed a six-item scale also developed by Zhang [45]. All items were measured using a seven-point Likert-type scale ranging from 1 (strongly disagree) to 7 (strongly agree). The respondents were asked to rate their firms' *guanxi* value with respect to primary business partners, including customers, suppliers, and partners (see Table 1).

3.3.3. Institutional Turbulence

The four-item scale from Johanson [46] was used to measure institutional turbulence. The respondents were required to answer the range of change in new policies relevant to their business for the government's role in influencing a special market or industry, even a firm. More specifically, the degree of perceived institutional turbulence in the market was measured using four indicators: the extent to which the local government acts in a way that increases uncertainty; the difficulty in predicting the impact of the political system on the market in the region; the difficulty in foreseeing regional institutional changes; and the certainty of regional policies, particularly S&T and monetary policies. These items were measured using a seven-point Likert-type scale from 1 (strongly disagree) to 7 (strongly agree).

3.3.4. Market Turbulence

Consistent with the literature, the six-item scale from Jaworski and Kohli [37] was used to measure market turbulence. The respondents were asked to describe the degree of perceived market turbulence based on the following factors: the rate of change in customers' product preferences; the rate of change in customers' new needs; the degree of price sensitivity; the ability to exploit new customers; the difference between new customers in product needs; and the ability to meet customer needs. The analysis focused on changes in market demand and customer preferences influencing a firm's market turbulence because these factors influence a firm's attitudes toward the use of its *guanxi* ties to access distinct resources and develop a competitive advantage in uncertain market conditions [44]. These items were measured using a seven-point Likert-type scale from 1 (strongly disagree) to 7 (strongly agree).

3.3.5. New Venture Performance

Three items were used to measure new venture performance. Consistent with the literature, the respondents were asked to address three major financial performance indicators for the last three years: sales growth, market share growth, and employee growth [47]. These three items were measured using a seven-point Likert-type scale 1 (much worse) to 7 (much better). The primary reason why subjective financial performance was used is that new ventures in China generally view objective financial information as a confidential matter and thus try to prevent it from becoming public. In addition, previous studies have shown that subjective financial indicators are more accessible than objective ones and can authentically and effectively reflect new venture performance [40].

3.3.6. Control Variables

Two variables were included as control variables: firm age and size. This is because previous studies have indicated that these two variables have the potential to impact the performance of new ventures [9]. The respondents were required to state the number of years and that of employees since the firm's establishment [47]. To a certain extent, firm age may reflect the degree to which new ventures are embedded in their business network, and firm size may reveal the resource base of new ventures.

3.4. Assessment of Measures

Consistent with the literature, we used AMOS 22.0 and the maximum likelihood estimation to conduct a confirmatory factor analysis (CFA) for assessing the reliability and validity of each construct [48]. Table 1 shows that the proposed five-factor model provided a good fit to the data. In addition, all alpha values exceeded 0.75; all CR (composite reliability) values exceeded 0.85; all average variance extracted (AVE) values exceeded 0.55; and the factor loading of each construct exceeded 0.65, indicating sufficient convergent validity [49].

4. Results

4.1. Analysis Steps

To test the hypotheses about the relationship between government *guanxi* (or business *guanxi*) and new venture performance and examine whether this relationship varied between two typical turbulent environments (institutional turbulence and market turbulence), this study conducted a moderated hierarchical linear regression analysis (MHLRA) [50]. First, two control variables (firm age and size) were used to test their effects on new venture performance. Second, four constructs, namely government *guanxi*, business *guanxi*, institutional turbulence, and market turbulence, were included to test their main effects on new venture performance. Third, product terms representing the interaction between government *guanxi* (or business *guanxi*) and institutional turbulence (or market turbulence) were individually included to test individual moderating effects: Hypotheses 3–6 [51]. In this step, four product terms were produced, namely government *guanxi* × institutional turbulence, government *guanxi* × market turbulence, business *guanxi* × institutional turbulence, and business *guanxi* × market turbulence. Finally, we synchronously added the four product terms to check the robustness of the results.

4.2. Hypothesis Tests and Results

Means, standard deviations, and correlations between all variables in the model test are shown in Table 2. Pearson correlation coefficients between all variables were lower than 0.5 ($p < 0.1$), indicating that multicollinearity was not a serious concern.

Table 2. Means, standard deviations, and a correlation matrix (n = 146) [a,b,c].

	1	2	3	4	5	6	7
1. Firm age							
2. Firm size	0.22 **						
3. GG	−0.11	0.14 *	**0.65**				
4. BG	0.17 *	0.26 **	0.32 **	**0.56**			
5. IT	0.02	0.17 *	0.37 **	−0.08	**0.62**		
6. MT	0.09	0.07	−0.10	0.47 ***	0.05	**0.60**	
7. NVP	0.03	0.09	0.15 *	0.21 **	0.11	0.11	**0.68**
Means	3.25	46.80	5.12	5.23	5.07	5.11	5.29
Standard deviation	0.96	15.47	1.03	0.96	1.16	1.20	1.42

[a] * $p < 0.1$; ** $p < 0.05$; and *** $p < 0.01$. [b] GG = Government *guanxi*; BG = Business *guanxi*; IT = Institutional turbulence; MT = Market turbulence; NVP = New venture performance. [c] Numbers in bold type indicate the square root of the AVE (average variance extracted).

Table 3. Results of a moderated regression analysis ($n = 146$) [a,b].

	New Venture Performance													
	Model 1		**Model 2**		**Model 3**		**Model 4**		**Model 5**		**Model 6**		**Model 7**	
	β	**SE**	**β**	**SE**	**β**	**SE**	**β**	**SE**	**β**	**SE**	**β**		**SE**	
Control Variables														
Firm age	0.03	0.08	0.03	0.07	0.03	0.06	0.03	0.07	0.02	0.08	0.03	0.06	0.03	0.07
Firm size	0.17 *	0.08	0.16 *	0.08	0.11 *	0.07	0.13 *	0.08	0.13 *	0.07	0.14 *	0.07	0.12 *	0.07
Main Effects														
GG			0.23 **	0.07	0.23 **	0.07	0.22 **	0.06	0.21 **	0.07	0.22 **	0.07	0.20 **	0.08
BG			0.45 ***	0.07	0.47 ***	0.07	0.46 ***	0.08	0.42 ***	0.10	0.44 ***	0.09	0.39 ***	0.08
IT			0.17 *	0.06	0.16 *	0.06	0.15 *	0.07	0.16 *	0.08	0.16 *	0.07	0.13 *	0.07
MT			−0.04	0.07	−0.05	0.06	−0.04	0.07	−0.06	0.07	−0.05	0.06	−0.07	0.06
Two-Way Interactions														
GG × IT					−0.08	0.08							−0.07	0.09
GG × MT							−0.13 *	0.07					−0.16 *	0.09
BG × IT									0.01	0.08			0.02	0.08
BG × MT											0.18 *	0.08	0.22 **	0.10
F	1.32 **		4.76 ***		4.56 ***		4.28 ***		4.48 ***		5.67 ***		4.82 ***	
R^2	0.05		0.18		0.17		0.16		0.17		0.22		0.18	
Adjusted R^2	0.04		0.16		0.15		0.13		0.14		0.19		0.16	
ΔR^2			0.13		0.01		0.01		0.01		0.05		0.04	

[a] GG = Government *guanxi*; BG = Business *guanxi*; IT = Institutional turbulence; MT = Market turbulence. [b] * $p < 0.10$; ** $p < 0.05$; *** $p < 0.01$.

Table 3 reports the MHLRA results. As shown in Model 1, new venture performance was not influenced by firm age (β = 0.03, T = 0.35, $p > 0.1$) but related to firm size (β = 0.17, T = 2.47, $p < 0.1$). However, control variables accounted for only 5% of the total variance in outcome variables. Model 2 showed that both government *guanxi* (β = 0.23, T = 3.12, $p < 0.05$) and business *guanxi* (β = 0.45, T = 6.31, $p < 0.01$) had positive effects on new venture performance, providing support for H1 and H2, respectively. Business *guanxi* played a more salient role (0.23 < 0.45) in strengthening new venture performance than government *guanxi*. This suggests that, to some extent, new ventures and their founders should invest more resources in developing and maintaining high-quality *guanxi* connections to the business sectors. This is because resources, information, and technologies obtained from the market are likely to help new ventures embed themselves in the business network and thus build legitimacy for industrial divisions. H3, H4, H5, and H6 considered the moderating effects of two typical environment conditions on performance implications of *guanxi*. According to Model 3, GG × IT had no significant interaction effect (β = −0.08, T = 1.04, $p > 0.1$), providing no support for H3; Model 4 shows that GG × MT had a significant negative interaction effect (β = −0.13, T = 2.07, $p < 0.1$), providing support for H4; Model 5 indicates that BG × IT had no significant interaction effect (β = 0.01, T = 0.2, $p > 0.1$), providing no support for H5; and, according to Model 6, BG × MT had a significant positive interaction effect (β = 0.18, T = 2.62, $p < 0.1$), providing support for H6. The result of the full model (Model 7) was consistent with those of the four separate models, suggesting a high robustness of the research results.

5. Discussion

In China's transition economy, the manner in which different types of *guanxi* can be managed and leveraged more effectively is an emerging topic in the business strategy and entrepreneurship literature. Two pairs of variables (government *guanxi* versus business *guanxi* and market turbulence versus institutional turbulence) potentially reflecting the period and nature of a transition economy were included in the analysis. The purpose of this study is to answer the questions of whether both government *guanxi* and business *guanxi* are related to new venture performance and when they matter to new venture performance in a rapidly changing environment. The results from 146 new ventures belonging to government-driven high-tech clusters suggest that, in general, both government *guanxi* and business *guanxi* can strengthen firm performance. Consistent with the findings of previous studies [2,21,23], the present study also verifies that *guanxi* remains an important strategic asset with a significant effect on doing business in China's transition economy. In addition, the study examines the moderating effects of institutional turbulence and market turbulence on the relationship between government *guanxi* (or business *guanxi*) and new venture performance. The results suggest that a turbulent market environment may weaken the value of government *guanxi* and strengthen the value of market *guanxi*. However, the results reveal no moderating effects of institutional turbulence on direct relationships.

5.1. Findings

The results can be summarized as follows: First, government *guanxi* matters to new venture performance. Previous studies have argued that government *guanxi* may be more important to state-owned enterprises than non-state-owned ones [14]. This study extends the conceptual framework of *guanxi* in the literature by suggesting that government *guanxi* is also crucial for new ventures belonging to government-driven high-tech clusters. The primary reason is that the Chinese government has greater "soft power" (through policies) to regulate the emergence and development of industries during an economic transition period [52]. Similarly, Li et al. [12] argued that in emerging economies such as Russia, Latin American, and China, organizational or personal connections to the government can "substitute for formal institutional support." This suggests that new ventures should establish and maintain formal or informal government *guanxi* to obtain more institutional or policy support from the government, ultimately enriching their resource base for better performance. In addition, stronger government *guanxi* can help new ventures be more confident in doing business in China.

Second, the results verify the significant effect of business *guanxi* on new venture performance. It is widely acknowledged that firms can benefit from their business *guanxi*, including *guanxi* connections to primary customers [10], suppliers [34], and partners [53]. On the one hand, stronger business *guanxi* can help new ventures establish legitimacy and embed in the business network more quickly, ultimately reducing their liability of newness. On the other hand, it can help new ventures obtain resources and information from the business sector and develop various firm-level capacities to strengthen their business performance.

Third, the empirical results indicate that institutional turbulence had no moderating effect on the relationship between government *guanxi* (or business *guanxi*) and new venture performance. A possible explanation may be that, unlike general government policies, those policies concerning government-driven high-tech clusters are relatively stable, and the role of government *guanxi* in firm performance is rarely influenced by institutional turbulence. Another explanation is that there is a time gap between institutional changes and their effects on the business sector. As a result, for new ventures, business *guanxi* may not be sensitive to a turbulent environment, and its role in performance creation may be more sensitive to institutional changes [10]. Therefore, institutional turbulence may not influence the performance value of *guanxi*.

Fourth, the empirical results suggest that market turbulence is an important contingent factor shaping the performance value of *guanxi*. In a turbulent market environment, rapid changes in customer demands, higher price sensitivity, and stronger ability to exploit new customers may result in greater business challenges and opportunities. If new ventures build and maintain stronger *guanxi* connections to the government and its officials in a turbulent market environment, it may reduce their resource investment in the market and thus weaken business performance [10]. By contrast, stronger *guanxi* connections to the business sector may help new ventures exchange resources or information with their primary customers, suppliers, and partners and predict customer and market changes more effectively and quickly in a turbulent market environment, ultimately promoting high-quality products to meet customer demands. This indicates that market turbulence may enhance the performance value of new ventures' stronger *guanxi* connections to the business sector.

5.2. Theoretical Contributions

This study makes several important contributions to the theoretical development of *guanxi* strategy theory. First, the study enriches *guanxi* strategy theory by linking two important types of *guanxi* (government *guanxi* and business *guanxi*) and arguing that, in general, both are crucial for the survival and success of new ventures in China's transition economy. However, the roles of two types of *guanxi* in developing strategic competitiveness are distinct in that they provide different resources for doing business in China [10,54]. Government *guanxi* is more likely to help new ventures obtain political support or institutional confidence in doing business in China, whereas business *guanxi* tends to help new ventures access market-related resources such as market information, technological assets, and even potential customers. Furthermore, this study provides new insights into differences in effects of relationships between business *guanxi* and new venture performance and between government *guanxi* and new venture performance.

Second, the results also have important implications for social network theory about Chinese entrepreneurship and business operations. Although some studies have argued that weaker social ties play a critical role in job hunting [55], the results provide the opposite conclusion and suggest that strong ties may have vital influence on new venture performance. A possible explanation may be that stronger *guanxi* ties in China's transition period may help new ventures create a distinct access routine to obtain social capital, thereby contributing to doing business in China.

Third, this study extends the contingent view that the effect of *guanxi* on new venture performance varies across different turbulent environmental conditions. More specially, two typical environmental conditions (institutional turbulence and market turbulence) were set as contextual factors potentially influencing the performance value of government *guanxi* (or business *guanxi*). In the contingent model, the empirical results suggest that institutional turbulence may not be a moderator of the *guanxi*-performance relationship but that market turbulence may weaken or strengthen the relationship.

5.3. Managerial Implications

The results offer some useful insights into how government *guanxi* and business *guanxi* can be better used in a turbulent environment. First, new ventures can benefit from establishing and developing *guanxi* connections to the government and its officials or to the business sector. To stimulate regional economic growth and technological progress, the local government often provides various institutional support to new ventures. In particular, in comparison to other new ventures, those belonging to government-driven high-tech clusters may be much more likely to obtain such support from the local government [44]. In addition to government *guanxi*, business *guanxi* may help new ventures overcome the liability of newness and obtain important market resources, which play an important role in the success of new ventures.

Second, the results are expected to help entrepreneurs and managers develop more effective policies in response to environmental changes by enhancing different types of *guanxi*. The interaction between business *guanxi* and market turbulence had a positive effect on new venture performance, but that between government *guanxi* and market turbulence had a negative effect. This suggests that new ventures should know that under rapid changes in customer' needs and preferences, they should invest and use business *guanxi* to make appropriate strategic decisions.

Third, the development and utilization of *guanxi* may be dynamic and long-term. It indicates that it is not easy to develop *guanxi* connections with organizations (e.g., business partners and local governments) and people (e.g., managers of other firms and government officials) [56]. Consistent with the findings of Su et al. [25], entering a *guanxi* network is a difficult strategic conundrum for Hong Kong and Taiwan businessmen, although they have the same Chinese culture. In this regard, entrepreneurs creating new businesses in Mainland China should be aware of the importance of investment in developing and utilizing *guanxi* which may provide different types of resources.

5.4. Limitations and Future Research

As all academic research, this study has some limitations that may provide avenues for further research. First, the outcome indicator of this study was self-reported by the respondents because previous studies of Chinese entrepreneurship have suggested that most new ventures consider financial information as confidential and thus keep it from becoming public. Some Western scholars have also argued that objective and subjective indicators have distinct strengths and weaknesses in measuring new venture performance [40]. In this regard, future research on entrepreneurship should employ a better technique to make simultaneous use of objective and subjective indicators in measuring new venture performance. One possible choice for obtaining objective indicators is to ask for government statistical agency or cluster offices and check whether they can give some useful information about new ventures' survival and success.

Second, the present study followed the social network analysis methodology to quantify *guanxi* by measuring strong-weak ties of government *guanxi* (or business *guanxi*) and investigated their main effects on new venture performance. However, *guanxi* reflects "networks of informal relationships and exchanges of favors that dominate business activity through China and East Asia" [24]. More specially, quantifying *guanxi* through a social network analysis proposed by Western scholars may be not the most scientific methodology. In this regard, future research should consider other potential tools to measure *guanxi* more accurately and deeply in the context of China.

The third limitation of this study is that our sample firms are only from government-driven high-tech clusters. Further research should investigate whether both government *guanxi* and business *guanxi* also have positive effects on the survival and success of other types of new ventures such as university spin-offs, corporate spin-offs, independent ventures, and born-globals.

Fourth, three indicators (sales growth, market share growth, and employee number growth) were included in measuring new venture performance. However, government *guanxi* and business *guanxi* may influence different performance indicators. On the one hand, resources provided by government *guanxi* tend to be institutional, such as confidence in doing business and less government interference. On the other hand, resources provided by business *guanxi* tend to be about the market, such as customers making timely payments, low-cost materials, and industrial division benefits [30]. In this regard, further research should empirically tests whether government *guanxi* is more likely to be related to economic performance (such as market share, market growth, and firm size) and business *guanxi* is more likely to influence financial performance (such as return on investment, sales, and profit).

6. Conclusions

Using a survey sample of 146 new ventures in clusters driven by China's local governments, the present study investigates the relationships among government *guanxi*, business *guanxi*, institutional turbulence, market turbulence, and new venture performance. Empirical results suggest that *guanxi* is a necessary but not sufficient condition for doing business in China. This study argues that the creation of good performance through *guanxi* must take into account contextual factors such as environmental turbulence. Overall, the study provides a better conceptual and empirical understanding of the importance of *guanxi* in doing business in China.

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Article

Efficiency Allocation of Provincial Carbon Reduction Target in China's "13·5" Period: Based on Zero-Sum-Gains SBM Model

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Abstract: Firstly, we introduce the "Zero Sum Gains" game theory into the SBM (Slacks-based Measure) model, and establish the ZSG-SBM model. Then, set up 4 development scenarios for the China's economic system in "13·5" (The Chinese government formulates a Five-Year Planning for national economic and social development every five years, "13·5" means 2016 to 2020.) period through two dimensions as economic growth and energy consumption structure, and make the efficient allocation in provincial level of carbon reduction target by using the above ZSG-SBM model based on the China's overall carbon reduction constraint (18%) which is set in "13·5" planning. Finally, we analyze the provincial development path of low-carbon economy by comparing the economic development status with the allocated result of carbon reduction target. Results show that: After the ZSG-SBM model being applied to the efficiency allocation of carbon emission, the input and output indicators of the 30 provinces realize the effective allocation, and the carbon emission efficiency reaches the efficiency frontier. The equity-oriented administrative allocation scheme of government will bring about efficiency loss in a certain degree, and the efficiency allocation scheme, based on the ZSG-SBM model, fits better with the long-term development requirement of low-carbon economy. On the basis of carbon intensity constraint, the re-constraint of energy intensity will force the provinces to optimize their energy consumption structure, thereby enhancing the overall carbon emission efficiency of China. Sixteen provinces' allocation results of carbon reduction target are above China's average (18%) in "13·5" period, all the provinces should select appropriate development path of low-carbon economy according to the status of their resource endowment, economic level, industrial structure and energy consumption structure.

Keywords: ZSG-SBM model; carbon reduction target; efficiency allocation; low-carbon economy

1. Introduction

Greenhouse gases are the source of global warming, and energy conservation and emission reduction has become a global consensus [1–3]. Owing to reconcile the demands of both economic development and energy saving and emission reduction, China's government actively implemented the sustainable development path of low-carbon economy since the global climate conference in Copenhagen, and firstly definitely stipulate the reduction target (17%) of carbon intensity in China's "12·5" Planning. Namely, we would decrease 17% of CO_2 emission on the same level of economic outputs. The China's "13·5" Planning further clearly put forward that the national carbon intensity at the end of 2020 should have an 18% lower than the end of 2015 [4,5]. Visibly, low-carbon economy will be the basic trend of China's economic development in future period. However, a large number of studies have indicated that due to great differences in economic scale, resource endowment, industrial structure and energy consumption structure of China's different provinces, there are great differences in carbon intensity among China's provinces [6–9]. Miao et al. [10] found that setting the same emission reduction target may cause the low efficiency of each province. Therefore, it is necessary to allocate the provincial CO_2 emission reduction target according to the actual situation of provincial carbon intensity. In addition, it has important guiding significance for setting the corresponding economic development planning and industrial structure adjustment strategy.

The following content of this paper is organized as follows. In Section 2, we summarize the literature about this issue. Section 3 discusses the methodology and the data which is used in this paper. Results are calculated in Section 4, respectively. Finally, Section 5 concludes this paper.

2. Literature Review

Carbon emission reduction is an important academic issue concerned by scholars, the relevant research focused on analysis of the evaluation of carbon emission performance, estimation of carbon emission reduction potential and carbon emission reduced cost, so we firstly introduce the related results of existing research in these three aspects.

The research on the performance evaluation of carbon emission was mostly based on Data Envelopment Analysis (DEA) method. DEA was applicable for the efficiency evaluation of complex system which included multi inputs and outputs because of that we didn't need to set the form of the model in advance when using it [11–13]. However, Tone [14] found that the traditional DEA model only estimated the efficiency of each decision making unit, it could not reflect the improvement path of the inefficiency decision making unit, he proposed the SBM model. With the carbon emission problem become more and more prominent in the world, the problem of carbon emission also become the focus academic issue. Yang et al. [15], Zhang et al. [16] and Wu et al. [17] believed that the carbon emission was produced associated with economic outputs, it was the inevitable environmental externality of economic production system. Therefore, they applied carbon emission into the efficiency evaluation model as a "bad output" to construct undesirable SBM model. At present, the undesirable SBM model was widely used in the study about the performance evaluation of carbon emission [18–22]. There were also many research took attention to China's provincial carbon emission efficiency, the basic conclusion was that China's provincial carbon performance were differences, and showed gradually rising space trend from the west to the east areas at present [23,24].

On the basis of the performance evaluation of carbon emission, a large number of domestic and foreign scholars analyzed the China's overall, regional, provincial and industrial carbon emission reduction potential. Du [25], Zhang et al. [26] respectively used undesirable SBM model and non-radial Malmquist index to calculate China's overall and regional carbon emission reduction potential, they found that reduction potential of China's overall and regional carbon emission were great. Li [27] also obtained the similar conclusion, the results showed that the overall carbon emission reduction potential of China reached more than 35%, and it was greater in central and western areas where their economy were relatively backward. The research results about China's provincial carbon emission reduction potential also tend to be same, namely carbon emission reduction potential of central and western provinces were significantly greater than the reduction potential of Beijing, Shanghai, Jiangsu and other economically developed provinces because their economic development level and per capita income were low [28–30]. In addition, the analysis on the industry level, Feng et al. [31], Zhang et al. [22] calculated carbon emission reduction potential of China's power industry and the whole industries. They found different industries had different carbon emission reduction potential.

At present, there were mainly three types of methods for calculating carbon emission reduction cost as bottom-up model, top-down model and mixed model, mainly included the dynamic optimization model [32,33], input-output analysis [34], computable general equilibrium model, mixed model [35,36] and efficiency analysis model [37], and so on. We focused on the relevant literature based on the efficiency analysis model since we also used it in this paper. The theoretical basis of the efficiency analysis model were the dual theory and distance functions, it took the shadow price of carbon emission to represent the marginal cost (opportunity cost) of carbon emission reduction. Maradan et al. [38] and Fāre et al. [39] established the directional distance function to measure the shadow price of CO2 emission, and then calculated the carbon emission reduction cost. Their conclusion was that the carbon emission decreased cost would decrease with the increase of per capita income, and it was significantly higher in low-income countries than in high-income countries. Therefore, economic development level was an important factor affected carbon emission decreased cost, and it may be great differences between all provinces in China due to the heterogeneity in economic development levels.

In conclusion, there were great gaps of carbon performance, carbon emission reduction potential and carbon abatement cost between various provinces in China, averagely distributed the national carbon emission reduction target to all the provinces would inevitably bring the loss of carbon emission reduction efficiency. In addition, performance evaluation of carbon emission, analysis of carbon emission reduction potential and determination of carbon emission reduction cost were the basis of setting carbon emission reduction target. Carbon performance evaluation outlined logic relationship between "economic output, energy consumption and carbon emission" by mathematical model, and calculated current situation of provincial performance of carbon emission [23]. Analysis of carbon emission reduction potential provided the possible direction and path for national carbon reduction policy [40]. Measurement of carbon emission reduction cost was represented the expense for implementation of carbon emission reduction target in each stage. All of them were further service to decision-making problem of setting carbon emission reduction targets [41]. The existing research have provided the theoretical basis and quantitative measurement methods for determining the carbon emission reduction targets, however, determination the carbon emission reduction target in practice was always the total target in national level. Such as, carbon emission reduction target which setting in China's "13·5" and "13·5" Planning. Therefore, the allocation of provincial carbon emission reduction targets in China's "13·5" period from perspective of efficiency had important significance. Therefore, how to allocate national carbon emission target to each province? How to ensure the efficiency in the allocated process? These problems needed to be studied to ensure the realization of above carbon emission reduction target.

There are some problems in the existing research. Such as, the number of articles, which aimed at provincial allocation of carbon emission reduction targets, was few. In addition, performance evaluation of carbon emission, analysis of carbon emission reduction potential and the calculation of carbon emission reduction cost problem were posterior analysis based on historical data, these research were lack of forward-looking results. Therefore, we do the provincial allocation of carbon emission reduction target in China's "13·5" period based on carbon emission reduction targets which setting in China's "13·5" Planning through setting several scenarios and combining the forecast of amount of labor, energy consumption, fixed assets and other inputs and economic outputs in China's "13·5" period. In addition, we calculate the total carbon emissions in China's "13·5" period while determining the national total carbon emission reduction target and setting above scenario hypothesizes, and then make the provincial allocation. Therefore, the summary of provincial carbon emissions is equal to national total carbon emissions, the distribution process is similar to the game theory of "zero sum gains". Therefore, we construct a SBM model based on zero and return (zero sum gains SBM, ZSG-SBM) to allocate provincial carbon emission reduction target in this paper. ZSG-SBM model combines with the traditional SBM model and the thought of "zero sum gains".

3. Methodology and Data

3.1. Output-Oriented SBM

Slacks of input and output of decision making units are the decision variables in SBM model. It intuitively reflects the efficiency improved path of decision making units, and it has significant advantages in efficiency evaluation and resources' efficiency allocation of the economic system while comparing with traditional DEA model [42]. There appeared several SBM models as input-oriented SBM, output-oriented SBM and input-output oriented SBM model [43,44] after Tone [14] firstly proposed the SBM model. In this paper, we take China's provincial carbon emissions as the research object, establish the ZSG-SBM model based on the output-oriented SBM model. Therefore, the following section, we focus on the output-oriented SBM model.

For an economic system which includes m decision-making units $DMU_i(i = 1, \ldots, m)$, each unit has k inputs, l_1 desirable outputs and l_2 undesirable outputs. Its production set T can be represented as:

$$T = \left\{ \left(x, y^g, y^b\right) \middle| \begin{array}{l} x \geq \sum\limits_{i=1}^{m} x_i\lambda_i, y^g \geq \sum\limits_{i=1}^{m} y_i^g\lambda_i, y^b \geq \sum\limits_{i=1}^{m} y_i^b\lambda_i, \\ x_i \geq 0, y_i^g \geq 0, y_i^b \geq 0, \lambda_i \geq 0 \end{array} \right\} \tag{1}$$

Then, according to the modeling ideas of Tone et al. [45] and Du et al. [25]. The output-oriented SBM model based on the undesirable outputs can be expressed as:

$$\begin{array}{rl} \theta_o = & \min 1 - \frac{1}{k}\sum_{k=1}^{K}\left(\frac{s_o^{b-}}{y_o^b}\right) \\ s.t.: & \sum\limits_{i=1}^{m} x_i\lambda_i + s_o^- = x_o, \\ & \sum\limits_{i=1}^{m} y_i^g\lambda_i - s_o^{g+} = y_o^g, \\ & \sum\limits_{i=1}^{m} y_i^b\lambda_i + s_o^{b-} = y_o^b, \\ & \sum\lambda_i = 1, s_o^- \geq 0, s_o^{g+} \geq 0, s_o^{b-} \geq 0, \lambda_i \geq 0 \end{array} \tag{2}$$

In the Formulas (1) and (2), θ_o represents efficiency of decision-making units DMU_o. x, y^g, y^b represent matrix of inputs, desirable outputs and undesirable outputs. $s_o^-, s_o^{g-}, s_o^{b-}$ represent slacks matrix of decision making units. K represents number of undesirable outputs. λ_i is a column vector. In this paper, we only consider the carbon emission as the undesirable output. Namely, $K = 1$. In addition, then, the output-oriented SBM model based on taking carbon emission as the only undesirable output can be expressed as Formula (3) while assuming that: $h_o = \left(y_o^b - s_o^{b-}\right)/y_o^b, (o = 1, \ldots, m)$.

$$\begin{array}{rl} \theta_o = & \min h_o \\ s.t.: & \sum\limits_{i=1}^{m} x_i\lambda_i + s_o^- = x_o, \\ & \sum\limits_{i=1}^{m} y_i^g\lambda_i - s_o^{g+} = y_o^g, \\ & \sum\limits_{i=1}^{m} y_i^b\lambda_i = h_o y_o^b, \\ & \sum\lambda_i = 1, s_o^- \geq 0, s_o^{g+} \geq 0, \lambda_i \geq 0 \end{array} \tag{3}$$

3.2. Output-Oriented ZSG-SBM

(1) Basic principles. In this paper, we take provincial distribution of carbon reduction targets which is specified by China's "13·5 Planning" as the research object. The distribution of carbon emissions among provinces has certain competitive while overall carbon emissions and GDP is determined in China's "13·5" period. Namely, the increase of carbon emissions in one province will cause the reduction of carbon emissions in other provinces. It reflects the "Zero Sum Gains" game theory as the total carbon emissions is unchanged. In this paper, we construct an output-oriented ZSG-SBM model based on "Zero Sum Gains" and traditional output-oriented SBM model, and its basic principle is as shown in Figure 1.

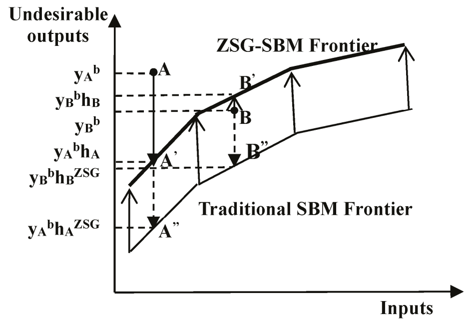

Figure 1. Schematic figure of the undesirable output-oriented ZSG-SBM model.

According to Figure 1, we find that due to make all the decision-making units to realize the efficiency frontier, the output-oriented ZSG-SBM model reallocates the undesirable outputs slacks of inefficiency decision making units based on the evaluation results of the output-oriented SBM model. Namely, we realize distribution of the undesirable outputs in condition of optimal efficiency.

(2) Mathematical model. We assume that DMU_o need to reduce Z unit of undesirable output, and the increase of undesirable output of $DMU_i(i \neq o)$ is z_i. Use $y_o^{b\prime}$ to indicate the undesirable output of DMU_i after distribution, so:

$$\begin{array}{l} y_i^{b\prime} = y_i^b + z_i, \\ Z = \sum\limits_{i=1, i \neq o}^{m} z_i \end{array} \tag{4}$$

According to basic principle of "Zero Sum Gains" theory, we deduce the general form ZSG-SBM model as:

$$\begin{array}{ll} \theta_o = & \min h_o^{ZSG} \\ s.t.: & \sum\limits_{i=1}^{m} x_i \lambda_i + s_o^- = x_o, \\ & \sum\limits_{i=1}^{m} y_i^g \lambda_i - s_o^{g+} = y_o^g, \\ & \sum\limits_{i=1}^{m} y_i^{b\prime} \lambda_i = h_o^{ZSG} y_o^b, \\ & \sum \lambda_i = 1, s_o^- \geq 0, s_o^{g+} \geq 0, \lambda_i \geq 0 \end{array} \tag{5}$$

In Formula (5), h_o^{ZSG} represents efficiency value of DMU_o after efficiency distribution, it reflects the gap between efficiency value of DMU_o after efficiency distribution and the ZSG-SBM frontier. DMU_o needs to reduce Z units outputs to reach the ZSG-SBM frontier, so $Z = f\left(h_o^{ZSG}\right)$. In addition, Z is needed to be distributed among other decision making units, so $y_i^{b\cdots} = f_1(Z) = f_2\left(h_o^{ZSG}\right)$. Therefore, different allocation strategies may bring the different results while we considering the distribution of Z among other decision making units. We choose proportional allocation strategy which was used by Lins et al. [46] and Gomes et al. [47].

(3) Model solving. We distribute Z according to proportion of undesirable output of $DMU_i(i \neq o)$ while using proportional allocation strategy. Namely, $z_i = Z \cdot \left(y_i^b / \sum_{i=1, i \neq o}^{m} \left(y_i^b\right)\right)$ Undesirable output of $DMU_i(i \neq o)$ after distribution is $y_i^{b\cdots} = y_i^b + Z \cdot \left(y_i^b / \sum_{i=1, i \neq o}^{m} \left(y_i^b\right)\right)$. The following Figure 2 shows the relationship between the variables $Z, y_i^b, y_i^{b\cdots}, h_o^{ZSG}$ based on the proportion of distribution strategy.

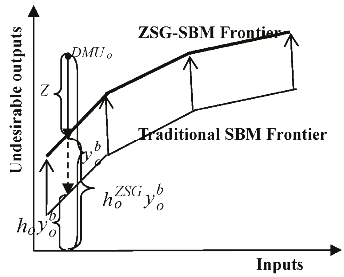

Figure 2. Schematic figure of the undesirable output-oriented ZSG-SBM model in proportional distribution strategy.

According to Figure 2, we find that $Z, y_i^b, y_i^{b\cdots}, h_o^{ZSG}$ meet the following relationship:

$$\begin{aligned} &Z = y_o^b - h_o^{ZSG} y_o^b = \left(1 - h_o^{ZSG}\right) y_o^b \\ &y_i^{b\cdots} = y_i^b + Z \cdot \left(y_i^b / \sum_{i=1, i\neq o}^{m} \left(y_i^b\right)\right) = y_i^b + \frac{\left(1-h_o^{ZSG}\right) y_o^b y_i^b}{\sum_{i=1, i\neq o}^{m}\left(y_i^b\right)} \\ &\quad = y_i^b \left(\frac{\sum_{i=1}^{m}\left(y_i^b\right) - h_o^{ZSG} y_o^b}{\sum_{i=1, i\neq o}^{m}\left(y_i^b\right)}\right) \end{aligned} \tag{6}$$

Then, undesirable output-oriented ZSG-SBM model in proportional distribution strategy is:

$$\begin{aligned} \theta_o = \quad & \min h_o^{ZSG} \\ s.t.: \quad & \sum_{i=1}^{m} x_i \lambda_i + s_o^- = x_o, \\ & \sum_{i=1}^{m} y_i^g \lambda_i - s_o^{g+} = y_o^g, \\ & \sum_{i=1}^{m} \left(\frac{\sum_{i=1}^{m}\left(y_i^b\right) - h_o^{ZSG} y_o^b}{\sum_{i=1, i\neq o}^{m}\left(y_i^b\right)}\right) y_i^b \lambda_i = h_o^{ZSG} y_o^b, \\ & \sum \lambda_i = 1, s_o^- \geq 0, s_o^{g+} \geq 0, \lambda_i \geq 0 \end{aligned} \tag{7}$$

Assume the optimal solution vector of DMU_o in Formulas (3) and (7) are $\left(h_o^*, \lambda_i^*\right)$, $\left(h_o^{ZSG^*}, \lambda_i^*\right)$, then:

$$\begin{aligned} &h_o^* y_o^b = \sum_{i=1}^{m} y_i^b \lambda_i^* \\ &h_o^{ZSG^*} y_o^b = \sum_{i=1}^{m} y_i^b \lambda_i^{'*} \left(\frac{\sum_{i=1}^{m}\left(y_i^b\right) - h_o^{ZSG^*} y_o^b}{\sum_{i=1, i\neq o}^{m}\left(y_i^b\right)}\right) \end{aligned} \tag{8}$$

Azadi et al. [48], Paradi et al. [49] believed that changes of output factors of each decision units in equal proportion didn't affect the reference set of the system frontier in output-oriented SBM model, so:

$$\sum_{i=1}^{m} y_i^b \lambda_i^* = \sum_{i=1}^{m} y_i^b \lambda_i^{'*} \tag{9}$$

Plugging Formula (9) into the Formula (8), we can obtain:

$$\begin{aligned} &h_o^{ZSG^*} y_o^b = h_o^* y_o^b \left(\frac{\sum_{i=1}^{m}\left(y_i^b\right) - h_o^{ZSG^*} y_o^b}{\sum_{i=1, i\neq o}^{m}\left(y_i^b\right)}\right) \\ &namely: h_o^{ZSG^*} = h_o^* \left(\frac{\sum_{i=1}^{m}\left(y_i^b\right) - h_o^{ZSG^*} y_o^b}{\sum_{i=1, i\neq o}^{m}\left(y_i^b\right)}\right) \end{aligned} \tag{10}$$

Formula (10) can be further converted to:

$$h_o^{ZSG^*} = \frac{h_o^* \sum_{i=1}^{m} \left(y_i^b\right)}{\sum_{i=1, i \neq o}^{m} \left(y_i^b\right) + h_o^* y_o^b} \tag{11}$$

Conducting the iterative calculation according to above solution process until all the decision-making units reached the system frontier, namely $h_o^{ZSG^*} = h_o^* = 1$. In addition, the distribution of the output has achieved the optimal efficiency.

3.3. Variables and Data

Similar to the existing research, we choose labor, capital and energy consumption as the inputs, choose GDP as the desirable output, and carbon emission as the undesirable output in this paper. We take distribution of provincial carbon emissions as the research object in China's "13·5" period, and the following calculation involves the relevant data in China's "13·5" period. Therefore, we firstly set the several scenarios about the condition of economic development, energy consumption structure in "13·5" period.

(1) Setting scenarios. In 2015, China's "13·5" Planning stressed the economic growth target by 6.5%~7% during the "13·5" period. Therefore, we set two scenarios for the economic growth level as low speed (6.5%) and high speed (7%). At the same time, a large number of studies showed that the energy consumption structure was an important factor affecting carbon emissions and carbon intensity. Therefore, we also set two scenarios for energy consumption structure as changed and unchanged. Under the condition of unchanged of energy consumption structure, the calculation of provincial energy consumption is based on the coefficient of carbon emission in "12·5" period. However, in the condition of changed of energy consumption structure, we calculate provincial energy consumption in "13·5" period by the decrease constraints of energy intensity (15%) which set in China's "13·5" Planning. Finally, the follow-up study will comprehensively consider all four scenarios.

(2) Indicators and data. Firstly, using the total population of the provinces to represent labor indicators, we calculate it according to average growth rate of provincial population in "12·5" period and the provincial total population at end of 2015. Similar to Li [27], we use the perpetual inventory method to estimate the capital indicators. Combine with the average investment of fixed assets in "12·5" period and the depreciation rate (10.96%), which was calculated by Miao et al. [10] to calculate the provincial capital in "13·5" period. The calculation of energy consumption and GDP indicators is based on the above set of four scenarios. Finally, according to provincial carbon intensity during"12·5" period, the GDP and reduction target (18%) of carbon intensity to push down the carbon emissions indicators during"13·5" period. Through collection and calculation of the data, we obtain the forecast data of inputs and outputs during "13·5" period as shown in Table 1.

Table 1. Predicted data of inputs and outputs of the China's provinces in "13·5" period.

Variables	Situations		Max	Min	Mean	Standard Deviation
Population (ten thousand persons)			11,175.88	613.83	4683.43	2794.83
Capital (hundred million RMB)			254,288.64	14,699.67	93,117.92	58,924.22
Energy (ten thousand tons of coal equivalent)	Rapid	Changed	43,816.88	2620.20	16,247.50	9491.95
		Unchanged	51,549.27	3082.59	19,114.70	11,167.00
	Low	Changed	41,816.45	2500.58	15,505.73	9058.60
		Unchanged	49,195.83	2941.86	18,242.03	10,657.18
GDP (hundred million RMB)	Rapid		98,542.30	3274.41	33,409.74	24,734.41
	Low		88,303.68	2934.19	29,998.44	22,160.63
Carbon (ten thousand tons)	Rapid		83,198.96	3677.94	29,112.10	17,167.94
	Low		74,554.53	3295.80	26,110.99	15,360.57

Data sources: the author sorted and obtained data through collecting initial data from the *China Statistical Yearbook* [50] in 2011–2015, *China Energy Statistical Yearbook* [51] in 2011–2015.

Explanation: due to the lack of energy statistic data in Tibet, we do not include it in the sample. In addition, the data of Capital and GDP indictors are treated by taking 2011 as the base year, the treated indictors are the "average consumer price index" and "average price index of investment in fixed assets" respectively.

4. Results and Discussion

4.1. Estimation of Provincial Carbon Emission Efficiency

According to the Formula (3) and above 4 scenarios, we calculate the carbon emission efficiency of various provinces in China by using Matlab2009a software. Due to limited space, we only take the results of 2020 as an example to show its calculation process (Table 2).

Table 2. China's provincial carbon emission efficiency in 2020 under the above four scenarios.

Provinces	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Beijing	1.0000	1.0000	1.0000	1.0000
Tianjin	1.0000	0.9792	0.9803	0.9069
Hebei	0.5567	0.5550	0.5439	0.4988
Shanxi	0.4544	0.4347	0.4440	0.4072
Neimenggu	0.7499	0.7375	0.7327	0.6720
Liaoning	0.7545	0.7506	0.7371	0.6761
Jilin	0.5757	0.5535	0.5638	0.5218
Heilongjiang	0.5510	0.5273	0.5383	0.4937
Shanghai	1.0000	0.9877	0.9811	0.9088
Jiangsu	1.0000	1.0000	0.9985	0.9919
Zhejiang	0.9657	0.9594	0.9634	0.9509
Anhui	0.6476	0.6281	0.6463	0.6056
Fujian	0.7960	0.7692	0.7920	0.7398
Jiangxi	0.7375	0.6932	0.7362	0.6912
Shandong	0.8901	0.8901	0.8696	0.7976
Henan	0.6639	0.6618	0.6601	0.6465
Hubei	0.6637	0.6596	0.6484	0.5947
Hunan	0.6541	0.6425	0.6391	0.5862
Guangdong	1.0000	1.0000	0.9990	0.9790
Guangxi	0.5775	0.5537	0.5761	0.5396
Hainan	1.0000	1.0000	1.0000	1.0000
Chongqing	0.6127	0.5809	0.5985	0.5490
Sichuan	0.6150	0.6074	0.6009	0.5511
Guizhou	0.6601	0.6230	0.6449	0.5915
Yunnan	0.5504	0.5217	0.5377	0.4932
Shaanxi	0.5878	0.5726	0.5761	0.5301
Gansu	0.5277	0.4994	0.5155	0.4728
Qinghai	1.0000	1.0000	1.0000	1.0000
Ningxia	0.8326	0.8195	0.8182	0.7976
Xinjiang	0.5380	0.5065	0.5256	0.4821

Explanation: Scenario 1, Scenario 2, Scenario 3, Scenario 4 are corresponding to four scenarios four scenarios as high-speed economic growth and energy structure changed, low-speed economic growth and energy structure changed, high-speed economic growth and energy structure unchanged, low-speed economic growth, energy structure unchanged.

The results show that:

(1) In all of the 4 scenarios, the differences of carbon emission efficiency among China's 30 provinces will be great while using the average distribution principle to allocate carbon emission reduction target. The maximum gap will achieve 54.56% between Beijing and Shanxi province.

(2) The efficiency value of Beijing, Hainan and Qinghai province are 1.0000, it shows that the above three provinces are always on the data envelopment frontier, and their carbon emissions, amount of labor, capital, energy consumption and GDP achieve the Pareto optimal state. This is consistent with

the existing literatures. The advantage of Beijing in carbon emission efficiency mainly originated from its strict environmental regulation policy, optimization of its industrial structure and the advanced production technology. In addition, the environmental situation of Hainan province and Qinghai province has been at the forefront in China.

(3) The efficiency of developed eastern provinces, such as Tianjin, Shanghai Jiangsu, Zhejiang, Fujian, Shandong and Guangdong are high, especially in scenario 1, Tianjin, Shanghai, Jiangsu and Guangdong province reach the data envelopment frontier. However, carbon emission efficiency of central, western provinces and the three provinces in Northeast of China where the economic are not so developed were generally low. The main reason may be that the development path of low-carbon economy has been implemented in China for many years, due to the advantage of economic and technical level, the developed provinces such as Beijing, Tianjin and Shanghai have been pioneers in the low-carbon economy and green economy, they also undertake the most stringent constraint target (18%–20%) of carbon emission intensity during China's "12·5" period. All of these laid the foundation for these developed provinces obtaining higher efficiency of carbon emissions in China's "13·5" period, and even more distant future.

(4) Through comparing the calculated results in scenario 1 and scenario 2, scenario 3 and scenario 4. We find that, the greater the economic growth level, the higher the provincial carbon emission efficiency while amount of population and capital scale are fixed. However, the average growth rate of carbon emission efficiency (0.18%) is far lower than the economic growth rate (0.50%), it shows that the effect is poor while seeking the economic growth alone for improving the efficiency of China's provincial carbon emission, we should pay attention to the distribution and matching of labor, capital, energy, carbon emissions and GDP in economic production system. At the same time, through comparing the calculated results in scenario 1 and scenario 3, scenario 2 and scenario 4, we find that the carbon emission efficiency of 30 provinces under the condition of dual constraints as provincial carbon emission intensity and energy intensity constraint are better than the constraint of carbon emission intensity alone. It shows that, on the basis of the constraint of carbon emission intensity, re-constraint of energy intensity will force the provinces to adjust and optimize the energy consumption structure, thus more close to the efficiency data envelopment frontier.

4.2. Allocation of Provincial Carbon Emission Reduction Target

On the basis of measurement of carbon emission efficiency in China's 30 provinces, we calculate the efficiency distribution lines of provincial carbon emission and the change of provincial carbon emission intensity based on ZSG-SBM model through two iterations in all of the above 4 scenarios. The results are shown in Table 3.

According to Table 3, we find that:

(1) In the four scenarios, respectively through iterative calculating by using ZSG-SBM model. The China's provincial carbon emission ZSG-SBM efficiency ($h_o^{ZSG^*}$) are 1.0000 finally. It shows that all the provinces have reached the frontier after efficiency distribution of carbon emission among provinces, and realize the efficient collocation of all the inputs and outputs in 30 provinces.

(2) There are 16 provinces need to further allocated reduce their carbon emissions which include Hebei, Shanxi provinces, and so on. Most of them have low carbon emission efficiency and underdeveloped economic. A part of them are the main industrial provinces of our country, such as the three provinces located northeast China. In these provinces, the high pollution industry accounts for a larger proportion, and the economy are underdeveloped, their environmental processing technology are also backward. Therefore, their carbon emission efficiency is always low. A part of them are the provinces which with good resource endowment, such as Shanxi province. Good resource endowment causes relatively low cost of regional energy resources, then their energy consumption is larger than other provinces, also cause their low carbon emission efficiency. Some of them are the western regions as Gansu, Guangxi province. Due to the backward production technology, the economic production efficiency of these provinces are lowest, their carbon emission efficiency is

low too. Therefore, these provinces should reduce carbon emissions from view of carbon emission efficiency distribution.

Table 3. China's provincial carbon emission ZSG efficiency allocation in 2020 under the above four scenarios.

Provinces	Expected Carbon Emission *(Ten Thousand Tons)*	h_o^{ZSG*} *(Two Iterations)*	Increase/Decrease *(Ten Thousand Tons)*	ZSG-Allocated Emission *(Ten Thousand Tons)*	Expected Carbon Intensity *(Ton/Ten Thousand RMB)*	ZSG-Allocated Carbon Intensity *(Ton/Ten Thousand RMB)*
Beijing	11,907.1339	1.0000	503.5163	12,410.6502	0.3944	0.4111
Tianjin	15,799.9779	1.0000	520.9885	16,320.9664	0.6846	0.7072
Hebei	63,020.5768	1.0000	−2145.8238	60,874.7530	1.5341	1.4819
Shanxi	34,391.1721	1.0000	−2567.6777	31,823.4945	1.9921	1.8434
Neimenggu	27,700.8921	1.0000	245.9345	27,946.8266	1.1260	1.1360
Liaoning	41,181.4770	1.0000	516.6223	41,698.0992	1.0075	1.0201
Jilin	15,807.5487	1.0000	−355.2930	15,452.2557	0.8001	0.7821
Heilongjiang	22,329.9005	1.0000	−715.6735	21,614.2270	1.0585	1.0246
Shanghai	19,153.9380	1.0000	685.8910	19,839.8290	0.5737	0.5942
Jiangsu	45,579.8669	1.0000	1957.5721	47,537.4389	0.4734	0.4938
Zhejiang	27,076.8348	1.0000	945.7960	28,022.6308	0.4687	0.4851
Anhui	25,987.4823	1.0000	−144.4790	25,843.0033	0.8559	0.8511
Fujian	21,653.9327	1.0000	354.9075	22,008.8402	0.6156	0.6257
Jiangxi	17,508.8206	1.0000	179.4990	17,688.3196	0.7770	0.7850
Shandong	81,282.0192	1.0000	2525.5831	83,807.6022	0.9513	0.9808
Henan	35,145.9070	1.0000	−125.8695	35,020.0375	0.7098	0.7073
Hubei	44,868.6001	1.0000	−351.1081	44,517.4920	1.1405	1.1316
Hunan	35,633.3336	1.0000	−194.8119	35,438.5217	0.9158	0.9108
Guangdong	47,970.8513	1.0000	2060.2605	50,031.1118	0.5057	0.5274
Guangxi	21,728.6867	1.0000	−509.7821	21,218.9045	0.9569	0.9345
Hainan	3593.1943	1.0000	154.3211	37,47.5155	0.7217	0.7527
Chongqing	19,923.5496	1.0000	−256.9573	19,666.5924	0.9611	0.9487
Sichuan	42,096.6385	1.0000	−657.7791	41,438.8594	1.0203	1.0043
Guizhou	27,528.2243	1.0000	−266.8916	27,261.3327	1.9592	1.9402
Yunnan	23,692.9654	1.0000	−791.8398	22,901.1256	1.2771	1.2344
Shaanxi	23,425.1758	1.0000	−486.9640	22,938.2118	0.9247	0.9055
Gansu	15,102.7787	1.0000	−570.2329	14,532.5458	1.5651	1.5060
Qinghai	7113.2852	1.0000	305.5026	7418.7878	2.2236	2.3191
Ningxia	7545.0954	1.0000	189.4819	7734.5773	1.9543	2.0034
Xinjiang	27,490.3541	1.0000	−1004.6930	26,485.6612	2.0574	1.9823
Summary	85,3240.2137	--	0.0000	85,3240.2137	0.8714	0.8714

Explanation: Due to limited space, we only list the calculated results under the condition of Scenario 1. If necessary, the author can provide the calculated results of four scenarios.

(3) There are 16 provinces need to further allocated increase their carbon emissions which includes Beijing, Tianjin provinces, and so on. These provinces are mostly developed economy, and located in the eastern area, their carbon emission efficiency are high, such as Beijing and Shanghai. Due to the developed economy, people in these provinces have relatively higher income, and pay more attention and stronger requirement to the living environment. Therefore, these provinces pay more attention to the investment and technology improvement of environmental pollution. All of these cause high carbon emission efficiency in these provinces. A small number of provinces have less secondary industry and good environmental condition, such as Hainan and Qinghai province. The carbon emission efficiency of these provinces are high, these provinces can increase carbon emissions from view of carbon emission efficiency distribution in "13·5" period. Namely, we can reduce the carbon emission constraint target of these provinces.

(4) The last line of Table 3 lists overall total carbon emissions, total carbon emissions after ZSG-SBM distribution and increase or decrease of amount of carbon emissions in 30 provinces based on scenario 1 which corresponding to condition of high-speed economic growth and energy structure changed at end of "13·5" period. The results show that, the increase or decrease amount of total carbon emissions is 0, namely total carbon emission (8532.40 million tons) remain unchanged under the carbon emission intensity constraint in "13·5" period, and overall carbon emission intensity keeps unchanged too. This result reflects the modeling thought of "zero sum gains", namely efficiency distribution of carbon emissions was among provinces based on the overall carbon emission reduction target. Moreover,

results in conditions of scenario 2, scenario 3 and scenario 4 are similar to scenario 1, and we do not repeat them in this paper.

4.3. Analysis of Differences between Efficiency Allocation and Administrative Allocation

In 2016, the "greenhouse gas emission controlling program during 13·5 period", issued by the State Council, determined the carbon emission reduction targets of China's various provinces. Beijing, Tianjin, Hebei, Shanghai, Jiangsu, Zhejiang and Guangdong provinces obtained the largest carbon emission intensity constraint (20.5%). Followed by Fujian, Jiangxi, Henan, Hubei, Chongqing and Sichuan provinces (19.5%). while the carbon emission intensity constraint were 18% in provinces of Shanxi, Liaoning, Jilin, Anhui, Hunan, Guizhou, Yunnan and Shaanxi. Neimenggu, Heilongjiang, Guangxi, Gansu and Ningxia fell by 17%; and finally, the carbon emission intensity constraint of Hainan, Qinghai and Xinjiang were 12%. We compare the differences between ZSG efficiency distribution target and above administrative distribution target of carbon emission intensity in all provinces. The results are showed in Table 4 as follows.

The results show that:

(1) There is large difference between the ZSG distribution target and state administrative allocation target in carbon emission intensity during "13·5" period. There are 15 provinces' ZSG distribution target are lower than their state administrative allocation target which included Beijing, Tianjin provinces. The other 15 provinces are in contrast. It is noteworthy that ZSG distribution target of Hainan and Qinghai province in carbon emission intensity are relatively low. However, their state administrative allocation target are far lower than other provinces due to their well foundation of environmental protection, it causes that their ZSG distribution target are higher than their state administrative allocation target in carbon emission intensity.

(2) In the case of scenario 1, Guangdong, Jiangsu, Beijing and Shanghai obtain the biggest positive differences. These provinces have a high economic development level, and leading environmental pollution treatment technology. The state government give them higher carbon emission intensity reduction target to make them continue to play their advantage, excavate reduction potential, and play an exemplary role in China low-carbon economy transformation process. Xinjiang, Shanxi, Gansu, and Heilongjiang provinces obtain the biggest negative differences. Shanxi province is the largest energy producing and exporting province of China, the good natural resource endowment may cause its low energy cost, and the cost controlling of the enterprises in Shanxi province are more dependent on input of energy resource. Heilongjiang province is China's heavy industry province, and there is a large proportion of polluting industries. Xinjiang and Gansu province are economic backward provinces, and their pollution controlling technology is relatively backward. All of these may be possible explanations for their low carbon emission efficiency. Therefore, they should undertake high responsibility for carbon emissions reduction from the calculated results of "efficiency oriented". However, the administrative allocation mechanism of government was based on "fairness oriented" of provincial carbon emission reduction targets, paid more attention to the status of resource endowment, economic development level and industry structure in these provinces. Therefore, the government appropriate to reduce these provinces' responsibility in carbon emission reduction, thus leading the results of biggest negative differences in these provinces. Carbon emission intensity reduction target allocation through "fairness oriented" is bound to lead efficiency loss in a certain degree. Therefore, the carbon emission reduction target allocation method based on "efficiency oriented" is more satisfy to the concept and requirement of low-carbon economy from the long-term goal of economic development in China. It realizes efficient configuration of labor, capital, energy, GDP and carbon emission of all the 30 provinces, and achieves Pareto optimal of the inputs and outputs.

Table 4. Comparison of provincial ZSG-allocated carbon intensity in 2020 and that in 2015 under the above four scenarios.

Provinces	End of "12·5" Period		Scenario 1			Scenario 3		
	Carbon Intensity in 2015 *(Ton/Ten Thousand RMB)*	Government Decline Range (%)	ZSG-Allocated Carbon Intensity *(Ton/Ten Thousand RMB)*	Decline Range than 2015 (%)	Gap (%)	ZSG-Allocated Carbon Intensity *(Ton/Ten Thousand RMB)*	Decline Range than 2015 (%)	Gap (%)
Beijing	0.4810	20.50	0.4111	14.53	5.97	0.4081	15.16	5.34
Tianjin	0.8349	20.50	0.7072	15.30	5.20	0.7057	15.47	5.03
Hebei	1.8709	20.50	1.4819	20.79	−0.29	1.4785	20.97	−0.47
Shanxi	2.4294	18.00	1.8434	24.12	−6.12	1.8528	23.73	−5.73
Neimenggu	1.3731	17.00	1.1360	17.27	−0.27	1.1372	17.18	−0.18
Liaoning	1.2286	18.00	1.0201	16.97	1.03	1.0166	17.26	0.74
Jilin	0.9758	18.00	0.7821	19.85	−1.85	0.7884	19.20	−1.20
Heilongjiang	1.2909	17.00	1.0246	20.63	−3.63	1.0324	20.02	−3.02
Shanghai	0.6996	20.50	0.5942	15.07	5.43	0.5931	15.22	5.28
Jiangsu	0.5774	20.50	0.4938	14.48	6.02	0.4905	15.05	5.45
Zhejiang	0.5716	20.50	0.4851	15.13	5.37	0.4814	15.78	4.72
Anhui	1.0438	18.00	0.8511	18.46	−0.46	0.8546	18.13	−0.13
Fujian	0.7507	19.50	0.6257	16.65	2.85	0.6247	16.78	2.72
Jiangxi	0.9476	19.50	0.7850	17.16	2.34	0.7884	16.80	2.70
Shandong	1.1601	20.50	0.9808	15.46	5.04	0.9754	15.92	4.58
Henan	0.8656	19.50	0.7073	18.29	1.21	0.7058	18.46	1.04
Hubei	1.3908	19.50	1.1316	18.64	0.86	1.1319	18.62	0.88
Hunan	1.1168	18.00	0.9108	18.45	−0.45	0.9119	18.35	−0.35
Guangdong	0.6167	20.50	0.5274	14.48	6.02	0.5238	15.06	5.44
Guangxi	1.1670	17.00	0.9345	19.92	−2.92	0.9412	19.35	−2.35
Hainan	0.8801	12.00	0.7527	14.48	−2.48	0.7476	15.06	-3.06
Chongqing	1.1721	19.50	0.9487	19.06	0.44	0.9574	18.32	1.18
Sichuan	1.2442	19.50	1.0043	19.28	0.22	1.0046	19.26	0.24
Guizhou	2.3892	18.00	1.9402	18.79	−0.79	1.9543	18.20	−0.20
Yunnan	1.5575	18.00	1.2344	20.74	−2.74	1.2444	20.10	−2.10
Shaanxi	1.1277	18.00	0.9055	19.70	−1.70	0.9092	19.38	−1.38
Gansu	1.9086	17.00	1.5060	21.09	−4.09	1.5232	20.19	−3.19
Qinghai	2.7117	12.00	2.3191	14.48	−2.48	2.3036	15.05	−3.05
Ningxia	2.3834	17.00	2.0034	15.94	1.06	1.9970	16.21	0.79
Xinjiang	2.5091	12.00	1.9823	21.00	−9.00	2.0025	20.19	−8.19

Explanation: Due to limited space, we only listed the compared results under the condition of Scenario 1 and Scenario 3. If necessary, the author can provide the compared results of four scenarios.

(3) We find that using dual constraints of carbon emission intensity and energy intensity will increase the difference between provincial ZSG distribution target and state administrative allocation target in carbon emission intensity while the level of economic development is fixed through comparing the results of the sixth column (scenario 1) and the ninth column (scenario 3) in Table 4. Namely, their gap will increase in conditions of scenario 1 and scenario 3. The possible reason may be that, dual constraints of carbon emission intensity and energy intensity will cause the efficiency frontier moving down while comparing with the single constraint of carbon emission intensity, there are more carbon emissions need to be allocated, thus widening the gap of carbon emission intensity in all the provinces before and after ZSG allocated.

4.4. Analysis on the Development Path of Low-Carbon Economy of All Provinces in "13·5" Period

Development path of low-carbon economy contains two aspects of contents as "economic growth" and "environment friendly". The previous research results show that, due to provincial heterogeneity in resource endowment, energy consumption structure and other factors, it will make huge difference of provincial carbon emission efficiency while average allocated carbon emission reduction target (18%) what set in China's "13·5" Planning to all provinces. Although the "13·5 work planning for controlling greenhouse gas emissions" had adjusted provincial carbon emission reduction targets, but the results in Table 4 show that the adjustment results do not achieve the most optimal configuration to the inputs and outputs in provincial "economic-environment- energy" system. Therefore, we take scenario 1 as an example in following contents. In order to explore the development path of low-carbon economic of all the provinces, we respectively take per capita GDP by 69.70 thousand RMB/person and carbon emission reduction target by 16% as the boundary, divide 30 provinces in China into 4 areas as high per capita GDP low pressure of carbon emission reduction, low per capita GDP low pressure of carbon emission reduction, high per capita GDP high pressure of carbon emission reduction and low per capita GDP high pressure of carbon emission reduction form two dimensions of "economic growth" and "environment friendly". Namely, if the province's ZSG distribution carbon emission intensity decreases by more than 16%, it indicates that the province's carbon emission reduction pressure is high. Results are showed in Figure 3.

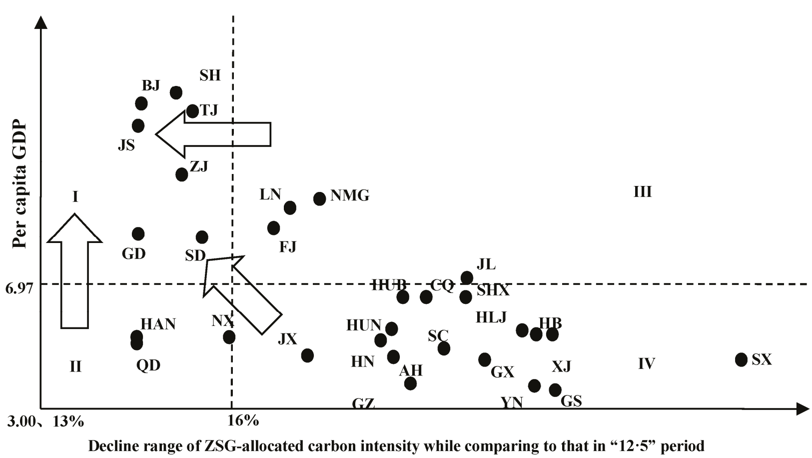

Figure 3. Schematic figure of provinces' CO_2 emission reduction path at end of "13·5" period.

Explanation: BJ-Beijing, TJ-Tianjin, HB-Hebei, SX-Shanxi, NMG-Neimenggu, LX-Liaoning, JL-Jilin, HLJ-Heilongjiang, SH-Shanghai, JS-Jiangsu, ZJ-Zhejiang, AH-Anhui, FJ-Fujian, JX-Jiangxi, SD-Shandong, HN-Henan, HUB-Hubei, HUN-Hunan, GD-Guangdong, GX-Guangxi, HAN-Hainan, CQ-Chongqing, SC-Sichuan, GZ-Guizhou, YN-Yunnan, SAX-Shaanxi, GS-Gansu, QH-Qinghai, NX-Ningxia, XJ-Xinjiang.

According to Figure 3, we find that:

(1) Beijing, Shanghai, Guangzhou and other 7 provinces are located in area I, which indicates that these provinces have high per capita GDP, and their pressure of carbon emissions reduction are relatively low, almost realize the development model of low-carbon economy. These regions should increase the use of wind power, hydropower and other clean energy to further reduce carbon emission intensity, reduced carbon emissions of per unit energy consumption by adjusting the energy consumption structure and optimizing the carbon emission coefficient.

(2) Hainan, Qinghai and Ningxia provinces are located in area II, which indicates that these 3 provinces' pressure of carbon emissions reduction is relatively low. They should focus on enhancing its per capita GDP to transform into the development path of low-carbon economy. Among them, Hainan province can catch the development opportunity on taking part in China's "Sea Silk Road Economic Belt Strategy in 21 Century". Accelerated the development of modern financial services, modern logistics industries. The unique geographical and climatic characteristics of Qinghai and Ningxia provinces create unique advantages and characteristics of their agriculture and husbandry. They are important provinces of China's agriculture and husbandry. Therefore, they should highlight their characteristics of agricultural products and advantages of excellent ecological environment, vigorously developed ecological agriculture and husbandry which are characterized, high efficiency and brand effect. In addition, extend to the upstream industry chain, ensure the supply and sale system operated well through the development and optimization of agricultural products processing industry, further improve the level of economic development.

(3) Provinces which are located in area III have high per capita GDP and high carbon emissions pressure, and they should pay more attention to reduce carbon emissions intensity to realize low-carbon economic development. Among them, Fujian province should full play its area advantage of linking two developed economic areas as the Yangtze River Delta and the Pearl River Delta regions and the coastal area advantage itself. On the one hand, strengthen resource sharing with the Yangtze River Delta, Pearl River Delta regions to promote the third industry agglomeration which included financial services industry. On the other hand, full use of the advantages of offshore wind power, speed up the adjustment of energy consumption structure, reduce the carbon emission intensity. Liaoning province is the main industrial province in China, Neimenggu province is also the major coal exporting province, and these two provinces should focus on the upgrading of the industrial structure, play efforts to reduce the proportion of high pollution and high energy consumption industries.

(4) Provinces which are located in area IV had low per capita GDP and high carbon emissions pressure. Among them, per capita GDP of Hubei, Chongqing, Shaanxi and Jilin provinces are closed to China's overall average per capita GDP. Therefore, these provinces should firstly consider raising their level of local economic development, to close to the area III, and then reduce the carbon emission intensity. However, the per capita GDP of Jiangxi, Hunan, Henan, Anhui, Guizhou and Sichuan provinces are far smaller than China's overall average per capita GDP. They should firstly focus on the reduction of carbon emission intensity, namely, tap their own potential of energy saving and adjust energy consumption structure, close to area II. The Shanxi province which have large proportion of high energy consumption industries due to its resource endowment, it should accelerate the elimination of coal mining, steel and coal chemical industries' overcapacity, pay more attention to reshape the industry structure. Finally, the developing provinces as Guangxi, Yunnan, Gansu and Xinjiang should pay equal attention to both economic development and carbon emission reduction targets, and choose the priority objective according to the actual situation themselves.

5. Conclusions

We establish the ZSG-SBM model in this paper by introducing "zero sum gains" game theory into traditional SBM efficiency measurement model. We then set four kinds of scenarios from the two dimensions of economic growth and energy consumption structure on account of actual situation of economic system in "13·5" period. Then, we carry out the efficiency allocation for China's 30 provinces' reduction targets of carbon emissions intensity by applying the above ZSG-SBM model. Finally, through comparing the efficiency allocated results with the national administrative allocation planning, we explore the development path of China's various provinces' low-carbon economy during "13·5" period. The mainly conclusions of this paper are as follows:

(1) In the four kinds of scenarios, the differences of carbon emission efficiency among China's 30 provinces are great while using the average distribution principle to allocate carbon emission reduction target which is set in China's "13·5" Planning (18%). The carbon emission efficiency of the eastern provinces and the provinces, which have a good environmental situation, are high. Their carbon emission efficiency reaches or is close to the frontier of provincial economic system, while the underdeveloped central and western regions are in contrast. While ZSG-SBM model is applied by efficiency allocation of provincial carbon emissions, the efficiency ($h_o^{ZSG^*}$) of 30 provinces are 1.0000, reaching the efficiency frontier. It indicates that the labor, capital and energy, GDP and carbon emissions of all the provinces realize effective allocation and Pareto optimal.

(2) Due to the heterogeneity of energy resource endowment, economic development level and the existing industrial structure in various provinces of China, at present, the state administrative allocation mechanism on provincial carbon emission reduction targets are mainly based on "fairness oriented". The government should balance many factors as regional economic growth, the improvement of residents' living level while setting provincial carbon emission reduction targets, and ensure the feasibility of these provinces to achieve carbon reduction targets in the short term. However, the administrative allocation method which based on "fairness oriented" may cause efficiency loss to a certain extent, and the efficiency distribution method which based on "zero sum gains" is more satisfied to the requirements of low-carbon economy in long-term economic development. Therefore, the government can cross-use both "fairness oriented" and "efficiency oriented" distribution methods while setting allocation methods of carbon emissions reduction target. It can not only ease the pressure on carbon emission reduction of economic underdeveloped provinces in short term, and also approach the condition as Pareto optimal allocation of the inputs and outputs, ultimately achieving the long term goal of low-carbon economy.

(3) Comparing the calculated results under the conditions of 4 scenarios, we find that: firstly, the carbon emission efficiency of 30 provinces under the condition of dual constraints as provincial carbon emission intensity and energy intensity constraint are better than that are restricted to carbon emission intensity alone. It shows that on the basis of the constraint of carbon emission intensity, constraint of energy intensity will force the provinces to adjust and optimize the energy consumption structure, thus being closer to the efficiency data envelopment frontier. Secondly, using dual constraints of carbon emission intensity and energy intensity will lead to increase the difference between provincial ZSG distribution target and state administrative allocation target in carbon emission intensity while the level of economic development is fixed. The possible reason may be that, dual constraints of carbon emission intensity and energy intensity will cause the efficiency frontier to move down, resulting in more carbon emissions need to be allocated, thus widening the gap of carbon emission intensity in all the provinces before and after ZSG allocated.

(4) Due to the heterogeneity of resource endowment, geographical position, economic development level and the existing industrial structure in various provinces of China, the provinces should choose different development path of low-carbon economy. Beijing, Shanghai and other provinces which located in area I should increase the use of wind power, hydropower and other clean energy to further reduce carbon emissions by optimizing the energy consumption structure. Hainan province in area II should accelerate the development of modern financial services and modern logistics industries. Qinghai and Ningxia provinces also in area II should vigorously develop ecological agriculture and husbandry which are characterized by high efficiency and brand effect, and extend to the upstream industry chain. Fujian province located in area III should give full play to its area

advantage. On the one hand, it should strengthen resource sharing with the Yangtze River Delta, Pearl River Delta regions. On the other hand, take full advantages of offshore wind power and speed up the adjustment of energy consumption structure. Liaoning and Neimenggu provinces should focus on the upgrading of the industrial structure, make great efforts to reduce the proportion of high pollution and high energy consumption industries. Provinces which located in area IV should pay equal attention to both economic development and carbon emission reduction targets, and choose the priority objective according to the actual situation themselves.

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Providing Appropriate Technology for Emerging Markets: Case Study on China's Solar Thermal Industry

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Abstract: Building on a case study of five Chinese solar thermal companies and one association, our study aims to understand how the innovator's choices regarding the use of technology and organizational practices for new product development enable companies to design and diffuse appropriate technology in emerging markets. The study uncovers two critical factors that enhance the appropriateness of technology: redefining the identity of technology and building a local supply system. Our analysis shows that synergic innovation in both architecture and component leads to the appropriate functionalities desired by emerging markets. Moreover, modular design and the building of a local supply system enhance the process appropriateness of technology. Our study provides an empirical basis for advocating going beyond minor adaptations of existing products to creating appropriate technology for emerging markets, and extends our understandings of the upstream process of designing appropriate technology. Moreover, the emphasis on the local supply system reflects a holistic framework for shaping and delivering appropriate technology, expanding the existing research focus on the perspective of the technology itself. Our research also has managerial implications that may help firms tap into emerging markets.

Keywords: appropriate technology; technology identity; local supply system; emerging market; architectural innovation

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1. Introduction

Scholars argue that emerging markets provide important growth opportunities to firms. Specifically, much research considers low-income markets in emerging economies as largely untapped opportunities for viable business ventures [1,2]. Companies that position themselves in these fast-growing markets have significant advantages, as they can capture the most attractive market segments [3]. Furthermore, emerging markets are becoming drivers of fundamental innovation in both products and the business system as a whole. A growing number of companies are initiating successful innovation and entering emerging markets [4,5]. In response to these phenomena, the extant literature has paid attention to innovation in emerging markets from different perspectives [3,6,7].

Recent literature emphasizes that emerging markets are redefining innovation trajectories [8,9]. This is leading to a broader discussion about the applicability of the findings presented by traditional innovation research in emerging market contexts [10]. Therefore, firms need to redesign their innovation strategies for entering emerging markets. Give the unique environments of emerging markets, the "appropriate technology" (AT) movement calls for a consideration of the characteristics of local environments and the appropriateness of the technology provided for local markets [11]. According to Schumacher, technologies appropriate for low-income emerging economies are small-scale, labor-intensive, easy to use and repair, and harmless to the environment [12]. As technologies from developed nations are often too complicated and expensive for customers in emerging markets [13], the AT perspective could help firms identify a new type of innovation appropriate for the specific characteristics and demand features of emerging markets. Meanwhile, as AT requires reconfiguring local manufacturing system [14], it has the potential to enhance local employment and efficient use of local resources. Therefore, AT opens up possibilities of aligning the objectives of firm innovation and sustainable socio-economic development.

This paper chooses AT as the main theme, because AT is a specific kind of innovation that can play vastly increased role in the emerging world such as China [15]. AT emphasizes the important role of demand side factor in inducing innovation. That is, AT calls for innovation based on the different local characteristics and demand features. Such local characteristics and demand features often stimulate new family of innovations which are particularly appropriate for the environment and the low-income consumers in emerging markets. More importantly, AT for emerging economies has the potential to be applied all over the world, known as reverse innovation [9,14]. Therefore, AT is a promising innovation direction that provides new business opportunities. Accordingly, it is interesting to explore how the demand of AT induces new family of innovation, and how companies organize their innovation initiatives to design and deliver AT to align business opportunity and social development.

However, the extant literature on innovation has not paid enough attention to the process of designing and providing appropriate technologies in emerging economies [16]. Some scholars argue that traditional innovation models can be easily used in emerging markets [17,18]. Although some studies discuss the potential of emerging markets as new innovation opportunities [7], the literature focuses on business model innovations for promoting the application of preexisting technologies in emerging markets. Research on the design and diffusion of appropriate technologies in emerging markets is lacking [16]. As a result, the research pays little attention to the upstream processes of innovation in appropriate technologies.

Another research gap is related to the AT concept itself. The definition of AT has been debated since Schumacher (1973) initiated the AT movement [19]. One critique of the AT movement is that, designed for poverty issues, it is not driven by a profitable and sustainable business model [12]. Therefore, the challenge is to align the concept of AT with the broader perspectives of innovation theory to create more flexible and innovative solutions. A review of the relevant literature reveals a paucity of knowledge on this topic.

In response to the arguments above, this study examines how to design and develop appropriate technologies that meet the specific requirement of emerging markets. Given the limited prior theory and empirical research, we use an inductive, multi-case method to examine five solar companies in China's solar thermal system (STS) industry. We focus on the companies' initiatives in technology selection, product design, and production organization, as well as the means by which these companies deliver AT for customers in emerging markets. We identify two primary constructs that underlie the successful design and development of appropriate technologies: redefining the identity of the technology and building a local supply system. Identifying these constructs is a major step forward in our understanding of the upstream process of AT development; thus, our research contributes to the literature on innovation in emerging markets. Our research also has important managerial implications that should help firms design an innovation strategy for tapping into emerging markets.

We focus on China because it is an enormous emerging economy with huge potential purchasing power. The low-income market in China is currently the second-largest after India [20], and it displays the unique characteristics of an emerging market environment, such as a lack of robust infrastructure and weak institutional arrangements. The low-income market in China provides both opportunities and challenges for the study of firm innovation. Furthermore, we study China's solar thermal industry because it is a successful example of designing and developing an AT targeting low-income groups in an emerging market. Solar thermal technology in many countries is not as successful as expected, but it developed very quickly in China, and via a bottom-up pattern, meaning that the technology diffused into low-income areas first and entered the high-end market afterwards. By the end of 2007, China's solar thermal system had an installed capacity of 80.8 GW, far exceeding the 15.9 GW in Europe and the 4.9 GW in Japan [21].

The rest of this paper is structured as follows. First, the paper reviews the extant research on AT and related theoretical perspectives, and presents the research design based on the literature review. Second, the paper analyzes the activities and strategies for designing and developing appropriate technologies in emerging markets based on existing research and a case study on the solar thermal industry in China. Finally, the paper closes with a discussion and concluding remarks.

2. Literature Review

2.1. Innovation for Emerging Market

The unique characteristics of emerging markets pose challenges for firms. Due to income disparities, there are large populations of low-income groups [22], known as the "people at the bottom of the pyramid" (BoP) [1]. Consumers in BoP markets are price-sensitive, with skills too low-level to use products with complicated functionalities [18,23]. Furthermore, due to infrastructure deficiencies, products for such markets need to be robust to harsh environments [24]. As service and repair are not readily available in emerging markets, products suitable for such a context need to be maintainable at the local level [3].

The constraints surrounding emerging markets also affect the kind of technology appropriate for such markets, including financial constraints, limited access to complementary infrastructure, and an insufficient knowledge, information, and skills base [2,25]. Furthermore, due to infrastructure deficiency and institutional voids in emerging economies, firms often need to build entire business ecosystems from scratch [26,27]. Accordingly, products and services need to be redesigned dramatically to meet the specific requirements of emerging markets.

Few studies focus on the upstream processes of innovation of appropriate technologies for emerging markets [28]. To address this gap, we draw on related literature to explain how firms respond to the features of emerging markets and develop products or services with functionalities different from those offered in mainstream markets. Specifically, we draw on research on appropriate technology to examine how to design products appropriate for emerging markets [11]. We also draw on the framework of disruptive innovation to explore how firms respond to demand in BoP markets [29,30].

2.2. Appropriate Technology

Realizing that technology developed in high-income countries was inappropriate for low-income countries, Schumacher (1973) advocated "appropriate technology" (AT), which would be compatible with the income levels and living conditions of low-income groups in emerging economies [11]. According to Schumacher's definition, technologies appropriate for low-income emerging economies are small-scale, labor-intensive, easy to use and repair, and harmless to the environment [12]. Unlike the traditional practice of redesigning existing technologies to lower prices, the concept of AT calls for creating breakthrough innovation. [6] Such technology could improve the economic conditions of those in emerging markets by meeting their demands and developing their capabilities using available resources. The AT view is consistent with the concept of inclusive innovation, as the latter also addresses innovations that create or enhance opportunities to improve the wellbeing of low-income groups in emerging markets [6]. The concept of AT is also unique in emphasizing the small-scale and labor-intensive features of the innovation.

However, the definition of AT has been criticized for decades. Regarding the view of AT as small-scale, labor-intensive, and operated by the local community [11,19], some scholars point out that these standard AT requirements are neither necessary nor easy to achieve [31]. According to their research, the AT movement consigns poor countries to a state of perpetual underdevelopment, whereby low-income groups become locked into the use of unproductive and inefficient technology [32]. Furthermore, the failure of initial AT projects that were not profitable caused people to reconsider the technology selection issue from the perspective of business [33].

Based on the arguments above, some research suggests extending the notion of AT, and integrating advanced Western technology with products or services designed to meet local needs and resource characteristics [34], arguing that AT can be "advanced" and based on modern technology [35]. Thus, advanced technologies should not be considered inappropriate. The recommended objective of AT is to achieve an understanding of new technology and develop innovation and technological capabilities on the basis of such modern technology. Thus, research on AT is converging with research on the technological catching-up and leapfrogging of firms in emerging economies [12]. Accordingly, AT offers an effective way to build indigenous technological capabilities for these firms.

Other scholars suggest a broadened notion of "appropriateness" whereby new technology must be compatible with not only the income level of local users but also the resource availability and existing technology and production model of the local environment [36]. An AT should also be culturally/socially appropriate and compatible with users' norms and routines [37]. Moreover, the literature on the BoP strategy calls for extending the notion of the "appropriateness" of innovations from the technology perspective to include the appropriateness of the business model. The delivery mechanisms in such business models often entail initiatives in local capability building and encouraging partnerships with local organizations [25,38].

Overall, some aspects of the AT philosophy have practical implications, such as building local capabilities related to local contexts. As AT is simple, it enables more people to use the technology and thus enhances capacity development and knowledge accumulation [39]. Thus, AT provides possibilities for positioning a new type of innovation appropriate for the emerging market context. However, critiques of AT also require an extension and further development of the term. In response to the call for an integrated approach that brings together various theories in research conducted in emerging economies [40], our research tries to integrate AT with other perspectives on innovation research. For example, the creation of new markets for BoP groups in emerging markets through the redesign of products and delivery platforms is closely aligned with the concept of "disruptive innovation" [41]. Therefore, integrating related bodies of literature could help us to better understand the mechanism for designing and diffusing AT for emerging markets.

2.3. Disruptive Innovation

Disruptive innovation is a type of innovation that provides performance packages that are not valued by mainstream customers [30]. Despite being inferior to established products in terms of the dimensions valued in mainstream markets, disruptive innovations offer other benefits; for example, they are typically cheaper, simpler, smaller, and sometimes more convenient. Their lower performance makes them unappealing to existing customers, yet they often attract new, less demanding, economy-minded customers. Disruptive innovations first benefit the poorer and less-skilled before shifting upward toward members of higher tiers. With improvements in performance, a disruptive innovation can eventually disrupt mainstream markets [42,43]. A disruptive innovation involves new designs for products, processes, or business models that challenge established value propositions and drastically change the industrial structure. Firms that take on the challenge of developing cheaper, simpler innovations with features customized for low-end markets can experience growth by initially competing against non-consumption. By using under-served markets as the testing ground for refining disruptive innovation and gradually improving their performance, such firms may eventually be able to attack mainstream markets [8].

In emerging economies, new customers with fluid needs and behaviors can be served with new technology in a flexible business context [44]. Thus, emerging economies can provide a great opportunity for disruptive innovation. Given that large populations remain underserved in emerging economies, firms are increasingly realizing growth opportunities by creating disruptive innovations for this niche [45,46]. Such innovations must be easily available, accessible, and affordable; compatible with the user's knowledge base, skills, and culture; and have a relative advantage over existing products [3,47]. The product characteristics must be compatible with their socio-economic context, robust enough for harsh environments, and require only minimum skills for easy use [10,24]. Thus, disruptive innovation provides a feasible way for firms to craft AT for emerging markets.

However, firms in emerging economies need to take the initiatives to exploit the opportunity presented by disruptive innovation [44]. Evaluating the potential of disruptive innovation is difficult [48,49]. Furthermore, serving non-customers who demand different functionalities often requires established firms to change their value and routine dramatically, and to build new processes and capability bases [50]. Such requirements impose challenges on firms attempting to initiate disruptive innovation. As a result, firms need to reengineer traditional innovation processes [29], reallocate resources [51], realign organization structures [52], and instill an organizational culture that can deliver disruptive innovations [49].

All of these findings assist firms in identifying and managing disruptive innovation. However, most of the extant literature focuses on how different types of firms should respond to pre-existing disruptive innovation, while leaving upstream processes of innovation as a black box [13]. While some research tries to explain how to identify candidates for disruptive innovation [51], in-depth studies on the innovation process itself are scarce. Using evidence from the Chinese solar thermal industry, our research tries to bridge this research gap by studying the innovation process that enables firms to develop and diffuse innovation in emerging markets.

Satisfying emerging markets does not require providing stripped-down versions of products for users there. Instead, companies need to provide value-added technologies and products compatible with local contexts [1,53]. Furthermore, companies need to consider innovations beyond the product and technology perspectives, and focus on the total value network. While some models might work well in the context of emerging markets, the unique characteristics of the new environment demand a model re-design. Therefore, we need more research on innovation processes suitable for emerging markets, including not only the design of new product properties but also the building of supply systems compatible with the socio-economic context [25].

The emphasis here is on a contextualized model, incorporating the characteristics of and conditions surrounding emerging markets. The driving of consumption by consumers in emerging markets will trigger a new family of innovations different from those in high-end markets. Moreover, the context of emerging markets is inducing technical change that affects process technologies. For example, small-scale indigenous firms might develop an architectural innovation that relies less on large-scale production. These induced technical changes in processes might also lower entry barriers and facilitate decentralized production models, thus meeting many of the criteria discussed by Schumacher (1973). Most importantly, such technical changes will allow for business-driven participation instead of philanthropy-based sponsorship.

In sum, innovation for emerging markets offers opportunities for extending existing theory on innovation. In-depth analyses of this issue could offer new variables and relationships describing how to design and diffuse innovations appropriate for the context in emerging markets.

3. Methodology

Since our topic is new and unexplored, we follow an exploratory research design [54,55]. Qualitative research, rather than traditional quantitative empirical tools, is particularly useful for exploring implicit assumptions and examining new relationships, abstract concepts, and operational definitions [56,57]. We adopt a multi-case, inductive study to analyze the strategies firms use to develop appropriate technology for emerging markets. An exploratory methodology such as this has been recognized as being particularly useful for researchers interested in examining strategies in emerging economies [58]. In doing so, we hope to facilitate theory-building in this area and the development of constructs for further empirical research.

3.1. Case Selection

The initial research questions provided guidance for this study and helped us to identify meaningful and relevant activities [55]. This study applied the following criteria in selecting the cases. First, the selected cases required innovation activities specific to an emerging market environment and had to provide appropriate products or services specific to emerging market contexts. Second, local firms had to play a dominant role in the industry. Third, the selected cases had to be financially sustainable and scalable (i.e., the business in the case required the potential for large-scale commercialization).

Given the above criteria, the solar thermal industry was selected. To promote the application of solar thermal systems in rural China, a large number of companies in the industry initiate innovation in product design and business models. The solar thermal industry therefore provides a valuable analytic setting for this study.

The case selection processes were carried out iteratively using theoretical sampling for the research participants [54]. The information obtained from the initial data analysis guided decisions on what data to be collected next and where to find them, leading to modifications of interview questions and the selection of the next research participants as we progressed. During this process, the researcher examined the data, looking for new avenues of exploration, unexpected outcomes, and emerging topics. The analysis of the data involved the ongoing iterative processing of transcripts in order to establish patterns in the data. These patterns served as input for the critical analysis, which included reviewing the whole process and structures, evaluating the outcomes, and identifying opportunities to build new constructs. Thus, new construct development emerged from the continuous interplay between the research cycle and the conceptual framework.

The addition of new cases ceases when the researcher reaches theoretical saturation [59]—when many observations have already been considered and consequently the incremental additions of new case to understanding are slight. The developed core concepts saturated after 20 research participants from five solar companies had participated in the study. The five companies are similar in terms of products, so we can explore similar technology development patterns. The cases vary in terms of organization structure and positioning in the industrial chain, so we can compare the effect of different production and innovation diffusion patterns adopted by different companies. We also interviewed the Association for the Application of Solar Thermal Technology (AASTT) to learn more about the background of the industry (see Table 1).

Table 1. Details of the Cases [a].

Company/Organization	Business	Location
HM	Produce solar thermal system	Shandong
LN	Produce solar thermal system and the vacuum tube	Shandong
SL	Produce solar thermal system	Shandong
TH	Produce solar thermal system and the vacuum tube	Beijing
TY	Produce solar thermal system	Jiangsu
AASTT	Coordinate and guide the development of the industry	Beijing

Note: [a] The company names are substituted with codes for consideration of secrecy.

3.2. Introduction of the Solar Thermal Industry in China

Development of China's solar thermal system (STS) industry began in the 1980s. Solar thermal systems are used to heat water for households and other places that use hot water. Competing with electric- and gas-based water heaters, STS can meet the normal demand for hot water at low cost, with low local infrastructure requirements.

Solar thermal systems have been targeted mainly at low-income families in rural areas and small towns. Chinese solar firms have been active in technological innovation, production modes, and delivery pattern design to promote the diffusion of STS in the targeted markets. Since the 1990s, China's STS market has grown very fast. For example, annual production grew from 500 thousand m^2 in 1991 to 13 million m^2 in 2004, with an average annual growth rate of over 28% [60] (see Figure 1). By 2004, the cumulative installations of STS in China (more than 60 million m^2) accounted for over 70% of the global market. China now has the largest STS market in the world.

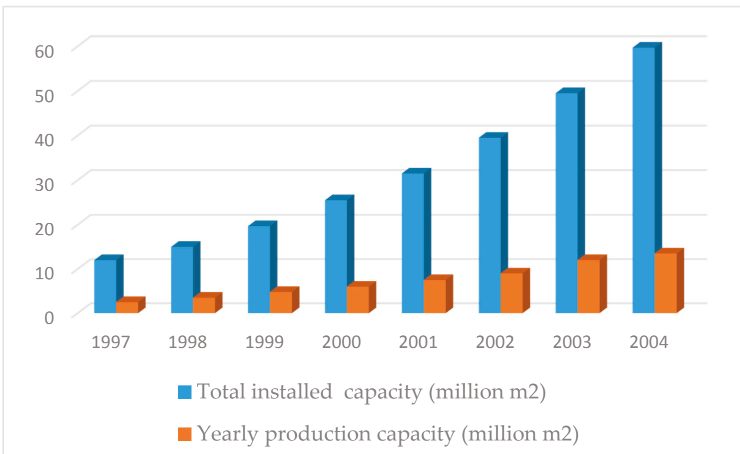

Figure 1. Total installed and yearly production capacity (million m^2) of STS in China by year. Sources: Li (2005) [22].

Three types of STS are used in China: STS with evacuated tube collectors, STS with flat plate collectors, and STS with combined storage collectors [60]. Among these, STSs with flat plate collectors are introduced from abroad, while STSs with evacuated tube collectors are developed by Chinese universities and companies. The flat plate STS dominates the market outside China, but STS with evacuated tube collectors is the leader in China. The flat plate STS cannot operate well in China's rural areas, where water pressure is unstable. Moreover, the core component of the flat plate STS, the flat plate, is made of heavy metal, which makes the product very expensive for most low-income Chinese families. In response to this problem, Chinese solar companies are working with universities to redesign the STS to make it fit local conditions.

In 1984, Tsinghua University invented the technology of "magnetron sputtering gradient aluminum-nitrogen/aluminum sun selective absorption coating", which made the production and commercialization of STS with evacuated tubes possible. Subsequently, researchers at Tsinghua University improved the quality of the evacuated tubes and started to promote the diffusion of the technology and cultivate the Chinese solar thermal industry [61].

The evacuated tube is made of glass, a locally available low-cost material. Therefore, the evacuated tube STS is much cheaper than the flat plate STS. Most importantly, TH, a leading solar company, has simplified the STS architecture. The new architecture is mainly comprised of evacuated tubes with absorption coating to assimilate heat from sun, a water tank to store water and maintain heat, water pipes to connect the evacuated tubes with the water tank, and a supporting structure for installation in a flat field or on top of a building. This simplification has lowered the price of evacuated tube STS dramatically.

The product properties of the evacuated tube STS are considered appropriate for meeting the demand of the low-income groups in rural areas. With the spread of production technology and the maturation of the industrial system, many small and medium-sized enterprises (SMEs) were set up in most provinces to provide local solutions. As a result, the market shares of the evacuated tube STS rose from 35% in 1997 to 88% in 2004. The evacuated tube STS became the dominant product in the Chinese market. China's evacuated tube STS is now benefitting the world, as Chinese solar companies are starting to export the technology and products to other countries.

The development of this evacuated tube STS industry provides a good opportunity to study how the solar companies design and diffuse AT in a complex context in which the social setting and environment differ from those in advanced economies. To simplify, we use "STS" to refer to the evacuated tube STS henceforth.

3.3. Data Collection and Data Analysis

Using data triangulation [55], we collected data from multiple sources, including interviews with solar firms, archival materials (e.g., reports of the International Energy Agency and the AASTT), and published papers on STS in China. This multiple data-source approach guarantees the validity of our findings. Following the triangulation principle, we asked multiple interviewees the same question and compared their answers. We also established a reference memo based on the archival and public materials collected during and after the field studies. We used this information to crosscheck first-hand data from the field studies in order to minimize biases caused by the interviewees' subjectivity and the retrospection bias.

Data collection involved several overlapping steps [55]. Beginning in 2012, two research assistants conducted an exhaustive search for existing cases and other archival information on the application of solar thermal technology in China's rural markets. In addition, from 2012 to 2013, companies were selected for further in-depth analysis, which included collecting archival material and, where possible, contacting key informants. Concurrent with the collection and analysis of the archival materials and case studies, interviews and discussions were held with managers of the solar companies. Extensive discussions were also held during this period with companies involved in the rural solar thermal business. Data collection occurred for years until our research reached theoretical saturation [59].

The data analysis includes onsite case analysis and synthesized cross-case analysis. The two phases are intertwined. When collecting and classifying materials from each case study, we also started to analyze, examine, compare, conceptualize, categorize, and code the qualitative data. When the field study in one case was finished, we conducted initial analyses of it. Every new field study and analysis was based on prior field studies. After having analyzed five cases, we went through all the original material again; at the same time, we compared the coding results of the cases with each other, summarized them a second time, and formulated the cross-case data coding results.

This study used grounded theory to deal with the coding process, which allowed us to go back and forth between the data and the emerging theoretical arguments [59]. First, the research group developed a narrative account of the findings by chronologically ordering the raw data, including quotations from interviews, documents, annual and committee reports, and field notes. To reinforce our understanding of the events as reflected in the emerging narrative, the research group checked the accounts with a set of informants from different companies. We used Nvivo 8.0 to accomplish this analysis. Our coding scheme built a map of the activities of different companies, paying particular attention to the variety of practices the companies engaged in to design and diffuse AT.

Second, we adopted a three-step coding procedure to analyze the narrative material [62]. The first step involved the creation of first-order codes and categories. The research group used Nvivo to keep track of the emerging categories and to view similarly coded texts simultaneously, which helped us manage the large amount of data. Following the procedures suggested by Miles and Huberman [63], the first categorical codes provided descriptive labels for the different sorts of activities that we observed. The codes were largely built upon the vocabulary of the interviewees. Once codes were named and categories developed, the research group returned to the data to check for categorical fidelity. During this process, we either corrected a category or reconceptualized it when the revisited data did not fit it well.

The second step involved axial coding [62], wherein the research group compared the first-order codes with one another to clarify themes and to create second-order constructs. This was an inductive, recursive process through which we identified a set of more abstract, theory-rich constructs. The axial coding was done by individual researchers as well as jointly by the research team. The team met numerous times to create constructs and assess the categorical fidelity of the emerging codes. These iterative discussions helped to refine the code base and to delimit the emerging theory [64,65].

Finally, in the third step, the research group identified important dimensions from the sets of second-order constructs. Next, we generated alternative theoretical frameworks to make sense of how these constructs related to one another and to the literature. Then, we worked through the relevant insights each one provided. We consolidated these available factors into two broad theoretical dimensions: "redefining technology identity" and "building local supply system". The theoretical dimensions resonated with the data and provided further analytic guidance in elaborating how to provide AT for emerging markets.

Figure 2 provides an overview of our analysis process, showing the first-order codes, second-order constructs, and the aggregate theoretical dimensions in our analysis.

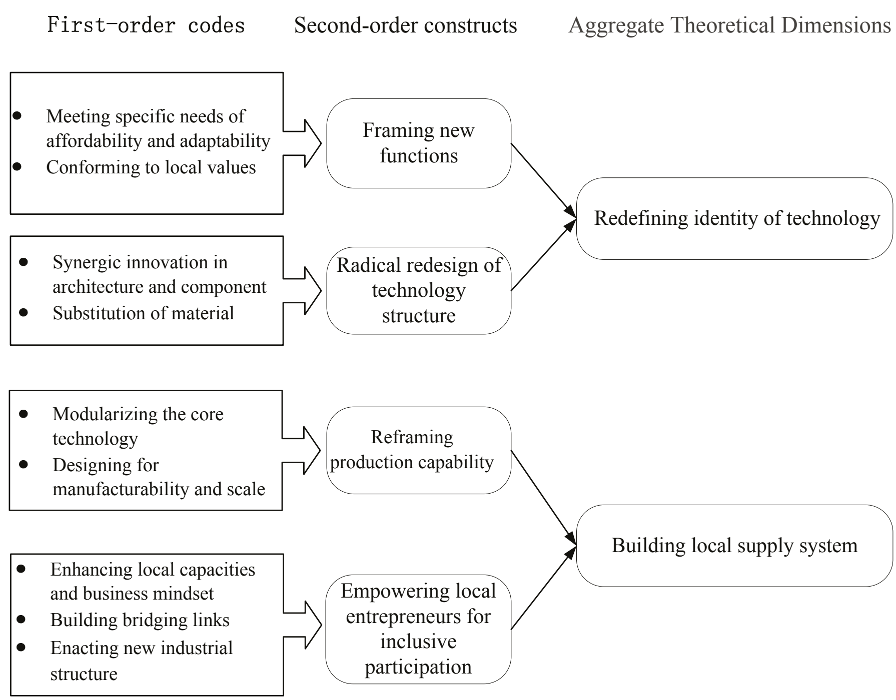

Figure 2. Coding process for obtaining the theoretical dimensions.

4. Analysis and Findings

Our analysis explores the resonance between the views and experiences of the companies and abstractions characteristic of the AT literature. Our analysis revealed two broad themes: "redefining the identity of technology", related to the property of the technology itself, and "building a local supply system", related to the process domain of the technology. These emerged from our data structures and were embedded in the case scenarios. Here, we do not discuss the data analysis process in detail but only briefly report our cross-case analyses findings. We illustrate them with typical quotations from the original interview transcripts, in the same order as the three coding steps. We present our analysis in this section to develop a provisional model of providing AT in emerging markets.

4.1. Redefining the Identity of Technology

Building on the concept of *the identity of technology* set out by Faulkner and Runde (2009), our initial findings point to the "dual" nature of technology, wherein the identity of a technology is the combination of its technical properties and its use or function [66]. Based on this argument, the appropriateness of technology is defined by two dimensions: appropriate function and appropriate technical properties. "Appropriate function" means that the usage of the technology should satisfy the specific characteristics and user requirements of emerging markets. This covers how the technology will be or may be used for the users' needs and markets. "Appropriate technical properties" refers to the built-in structure, technical performance, and the phenomenological properties that give the technology its "shape" [67]; this means that the technology should possess the physical structures, characteristics, and capabilities required to perform the functions concerned. The adequacy of the two dimensions reflects the appropriateness of a technology. Thus, we obtain two second-order constructs: "framing new functions" and the "radical redesign of technical properties".

4.1.1. Framing New Functions

The first set of activities consists of framing and providing new product functions that match the specific characteristics of emerging markets and provide perceived value for the targeted users. This second-order construct aggregates two first-order codes: "meeting specific needs of affordability and adaptability" and "conforming to local values". Our analysis highlights the latter first-order code, as functional assignments should be understood as social rules [66].

How a new product is designed in terms of new product functions is critical to its acceptance among the targeted users [24]. Consistent with the extant research, our analysis finds that the functions most valued by emerging markets are those compatible with the context and the specific demand features of the users [10,37]. From a product perspective, this translates to demand for new product functions, such as affordability and adaptability under harsh condition [3,68]. In maximizing value for customers in rural areas, the solar companies focus their innovation efforts on meeting the specific requirements there. For example, due to the deficiency of gas, electricity, and other infrastructure in rural areas, rural users in China cannot use hot water to bathe most of the year. The solar thermal system, which needs only water and sunlight, provides an alternative for them. In addition, the solar thermal products imported from Western countries would not work well due to the unstable water pressure in many rural areas. In response, the Chinese solar system replaces automated control with manual operation to enable it to work well in rural areas. One company told us the following:

> *Electricity- and gas-driven water heaters are too expensive in rural areas, and STS exported from western companies (the flat-panel-based one) cannot work well in rural areas due to water pressure problem. These products above are like expensive cars which can only run on highways, but not on village roads. Our product works well even on mountain roads. It can be used wherever there is water.*
>
> —Vice president of TH

Furthermore, in emerging markets, users' economic activities often interweave with social and emotional development [38,69]. As a result, the solar companies integrate local norms and values into their product designs to create a tight blend of emotional and economic value for users. Aligning products with local values and traditions is appropriate from a local perspective, as it enables the users to integrate new technology with their traditional values. For example, the STS incorporates simple-to-use features, and it does not require consumers to change their lifestyle. Such initiatives enhance the attractiveness of the product. Thus, a new assignment of functions spreads by being adopted by large groups of users [66], as one informant told us:

> *We tell rural users: "Without boilers and electricity, [the STS] costs you only very little money, and it can make you live a decent life like city people." They like this.*
>
> —Market Supervisor of HM

4.1.2. Radical Redesign of Technical Structure

This set of activities emerging from our analysis suggests that changes in function are precipitated by innovation in technical structure. This second-order construct aggregates the first-order codes "synergic innovation in architecture and component" and "substitution of material".

To provide the functions mentioned above, the solar companies radically redesigned both the architecture and the components of the product simultaneously. Due to the unique context and characteristics of emerging markets, slightly modifying components in existing products is not a viable strategy [16]. Instead of making trivial adaptations to an existing product, the solar companies redesign the product dramatically through innovation in both architecture and components, including using new components and reconfiguring the architecture that integrates them [70]. TH, a leading company engaged in technological collaboration with a leading university in China, redefines the architecture of STS, making it much simpler than the architecture adopted by Western countries. The new architecture mainly comprises evacuated tubes with absorption coating to assimilate heat from the sun, a water tank to store water and maintain heat, water pipes to connect the evacuated tubes with the water tank, and a supporting structure for installation in a flat field or on top of a building. Substantial reengineering in architecture simplified the product, and provided the unique functions desired by emerging markets.

Furthermore, consistent with the call for frugal use of resources in emerging markets [7], the solar companies tried to maximize the use of abundantly available low-cost resources to provide basic functions at a low price. While evacuated tubes, the core components of STS imported from abroad, are made of heavy metal, the Chinese solar companies used glass to produce the evacuated tubes. The use of glass instead of heavy metal makes the product much cheaper than those imported from abroad. An informant illustrated this point:

> *We use glass to produce the evacuated tube, the core component of our STS, instead of the heavy metal used by Western companies. This innovation lowered the costs dramatically, thus making our product much cheaper than the flat-panel-based product provided by Western companies. However, our product has some disadvantages. For example, the product cannot endure high water pressure. But it can operate well with caution in rural areas, and it is cheap and affordable for normal rural families* . . . *Besides, the product uses only sunlight to heat the water, and the operation cost is very low. Therefore, it is widely used in many villages.*
>
> —President of TH

The adoption of the principles of synergic innovation in both architecture and component provides a logical low-cost option for offering the required functions with an innovative technical structure. Moreover, the simplification of the architecture and the substitution of the materials lower the cost of manufacturing significantly, thus enabling a price dramatically lower than that of the comparable product.

Thus, we have identified two dimensions that redefine the identity of technology in ways that enhance its appropriateness. The solar companies accomplished this redefinition by radically changing both the function and the technical structure of their product. In doing so, they changed the identity of STS as appropriate technology for rural users in China.

Furthermore, scholars argue that the AT production technique is important [71], positing that the "appropriateness" of technology includes compatibility with the local resource availability and production model [36]. This broadened notion of AT points to the fixity between process and product technologies [72], whereby a given product is associated with a given process (production technique). In line with this perspective, our findings highlight a second category of activities that are related to the AT process domain.

4.2. Building a Local Supply System

This category concerns the process appropriateness of technology. We focus on two questions: (1) what kind of production technique is efficient in providing AT? (2) How do companies make it happen? Addressing the controversial arguments about the "small-scale" and "labor-intensive" characteristics of AT [12,19], our analysis reveals that the production techniques of AT are not necessarily small-scale or labor intensive. Instead, the appropriateness of a production technique is dependent on resource availability and the existing production mode. That is, AT requires a fit between production techniques and technical structure, as well as between production techniques and local resource characteristics. Based on this logic, our analysis identifies two sets of activities: "reframing production capacity" and "empowering local entrepreneurs for inclusive participation".

4.2.1. Reframing Production Capacity

This second-order construct that emerged from our analysis highlights the activities the solar companies adopted to redefine the production technique that fits both the technical structure of the technology and local resource characteristics. This construct aggregates two first-order codes: "modularizing the core technology" and "designing for manufacturability and scale".

Its strong manufacturing capacity enables China to make products with a high performance–price ratio [73]. Under conditions of resource shortage, the capability to leverage these alternative capacities and resource endowments may become critically important for building appropriate production techniques. In line with this philosophy, the solar companies incorporate modularity in the architecture of STS to simplify the production process. LN, a leading solar company, integrates the parts required for STS into a set of basic modules, and keeps the "architecture", "interfaces", and "standards" stable [74]. Thus, the technology and knowledge of the key component (e.g., the evacuated tube) are embedded into modular systems. Accordingly, the subsequent production process is characterized by standardized assembly and installation, requiring only low technological capabilities. Producing STSs requires only some related structural knowledge and the purchase of modularized components. Thus, the leading solar companies have lowered entry barriers, helping local manufacturing capacity participate in the value chain.

The reframing of production techniques also involves the simultaneous consideration of cost, speed, and scale. By reconfiguring the architecture and using alternative materials and modular designs, the solar companies aim to make manufacturing as simple as possible and to achieve low product prices. Moreover, the modularity of core components enables a separation between capital- and labor-intensive processes. The leading companies provide modularized components with capital-intensive manufacturing and R&D investment to update technologies in the component. Meanwhile, for the downstream activities, the leading companies can initiate collaborative partnerships with local entrepreneurs or small- and medium-sized enterprises (SMEs) to empower a low-cost production model. Many local entrepreneurs and SMEs, acting as satellite units of the leading solar companies, purchase modularized components from the leading companies and assemble and distribute the final product to meet local needs. An informant from the solar association told us the following:

> *LN* [a leading solar firm] *just produces and sells the evacuated tube, and let hundreds and thousands of SMEs produce the final product for local needs. They* [the SMEs] *know the local context well and know what functionalities are needed. Therefore, they can assemble different components to match local demands. Besides, they know how to sell the product.*

The new low-cost assembly model is labor-intensive, with very low break-even points. Therefore, local entrepreneurs or SMEs need to operate in local areas to provide local solutions, with no need for a scale economy. The labor-intensive model, which is popular in emerging market environments [13,39], has become part of the solar industry. Meanwhile, modularity allows leading companies to provide standard modules with common features, thereby enhancing the scale economy for their capital-intensive business. Thus, the leading solar companies integrate large-scale manufacturing and labor-intensive processes into their value chain to balance low cost, speed, and scale.

4.2.2. Empowering Local Entrepreneurs for Inclusive Participation

Our analysis reinforces the argument that the diffusion of AT is interwoven with local entrepreneurship [75,76]. The technology improvement discussed above lowers the skill requirements in the production process and lowers entry barriers for local entrepreneurs. However, in an emerging economy with limited resources, entrepreneurial activities are often hindered by resource constraints and shortages of entrepreneurship [11]. In response to this problem, the solar companies initiate various activities to empower local entrepreneurs to participate in the industrial chain. Our analysis generated the construct of "empowering local entrepreneurs for inclusive participation", highlighting the activities the solar thermal companies adopted to expand the local productive opportunity space through which local entrepreneurs can participate in the solar thermal industrial chain [77,78]. This second-order construct aggregates three first-order codes: "enhancing local capacity and business mindsets", "building bridging links", and "enacting a new industrial structure".

In the early stages of the solar thermal industry, the leading companies initiated various activities to promote the diffusion of product knowledge and manufacturing technology within the industry, including training, technology transfer, and local development programs. The knowledge sharing and the abovementioned activities set up the knowledge and technology foundation for the explosive growth of the industry. For example, TH told us the following:

> *We realized that one company could not promote the industry to grow quickly enough. Therefore, we* [the company] *started to train others to join the industry since 1980s. We initiated lots of training programs for those interested in the solar thermal industry, and taught them the principles of our technology and taught them how to produce STS. We even helped some of the trainees set up their factories. Many CEOs in the solar industry had once been trainees of our programs.*

"Enhancing the business mindset" is related to the cognitive process of empowerment. Cognitive structures often shape and articulate conceptions of value and constitute shared templates that facilitate the adoption of similar patterns [77]. Isolated from sources of knowledge from the outside world, people in an emerging economy often cannot cognitively perceive opportunities to develop their own business. In response, the leading solar companies start by providing training and demonstrating the economic potential of the STS. They also urge potential entrepreneurs to think beyond existing cognitive patterns and visualize possibilities to create value from existing productive opportunities or expand spaces for entrepreneurial opportunity. These activities enhance the sense-making capability of local entrepreneurs and motivate them to seize the productive opportunities within the solar thermal industry and build up local capacity. At the same time, solar companies also provide value-added advisory services and training programs to help local entrepreneurs build their business. For example, training programs for local entrepreneurs and factory building assistance help some regions to build up local manufacturing infrastructure and institutions critical for local business.

The second first-order code explains the social dimension of empowerment. This code points out that empowerment comes from building bridging links among local entrepreneurs, solar businesses, and other external parties. The use of "bridging links" stems from "bridging social capital" in the research on social capital [79], which refers to peripheral ties that tend to be high in unique resources and low in closure [80]. The solar companies set up "working stations" within rural areas to increase the structural diversity of local networks. These working stations act as ties that bridge the community to both the solar companies and other resources needed to create local businesses. Such links help to connect entrepreneurs with fragmented local resources, thus changing the local entrepreneurs' cognition and attitudes to the entrepreneurial opportunities within the solar thermal industry. The bridging links enhance the flow of information and other resources, increase the productive opportunity space, and provide channels of access to business capabilities.

The empowerment activities of solar thermal companies enable a growing number of local entrepreneurs to set up SMEs and integrate the existing manufacturing capacity into the solar thermal industrial chain. Thus, the leading solar companies enable a new industrial structure: they provide a modularized component with capital-intensive manufacturing, whereas local SMEs act as satellite units of the leading companies, assembling and distributing the final product to meet local needs. The industrial chain and the relationship among companies in the industry are reconceptualized by reconciling constraints and resource endowments in a local context. The collaborative partnership between leading solar companies and local SMEs creates locally sustainable innovation ecosystems, allowing better solutions for different market tiers.

We have identified a set of initiatives that the solar companies undertook to build up local supply systems for STS. Our analysis highlights the importance of appropriate production techniques and production modes in providing AT. The redesign of the technology breaks from the mass production process and radically recombines it to match the characteristics of local resources. Meanwhile, the leading solar companies empower local entrepreneurs and other resources to join the value chain, thus leveraging the available local resources. The participation of local entrepreneurs and low-cost manufacturing capacity actively contributed to the attractiveness of STS by lowering costs and adding local content to the product. The SMEs are embedded in the local community and have a better understanding of local contexts than large companies have. Therefore, they could provide tailored products to meet local demand quickly and flexibly. Furthermore, the leading companies could co-design products with local SMEs, who understand local needs, and provide the required functionality. For example, the simple-version STS with only the basic functions of hot water heating and bathing could meet the basic needs of low-income families that require cheap and easy-to-use products.

In fact, before the emergence of a large population of SMEs, TH and HM used another vertically integrated production model: the companies covered the whole value chain. Neither of them could provide the functionalities required by rural users at affordable prices. Although HM attempted to cultivate the market, the product was not adopted as quickly as expected. After LN initiated the modularization of core components, local SMEs started to enter the solar industrial chain and provide low-price products with different functionalities to meet different market tiers. Thereafter, the STS was considered appropriate technology for rural areas and was adopted quickly by rural users. The following illustrates the importance of the innovation mentioned above:

> *With the leading companies producing and selling the core components of the product, there emerged thousands of SMEs entering the solar thermal industry. Afterwards, solar thermal companies are founded by local entrepreneurs in almost every province, providing local solutions for the rural areas. The emergence of these SMEs has greatly accelerated the diffusion of STS in the rural market.*

—An analyst in AASTT

5. Discussion

This study explores how companies can provide AT in emerging markets. By investigating how Chinese solar companies make their product fit the specific features and conditions of Chinese rural consumers, our case study enables a move away from abstraction toward a grounded knowledge of the factors that enhance the appropriateness of technology. These factors are uniquely important in the context of emerging markets due to their unique demand characteristics and resource conditions.

Two broad themes characterized the efforts to design and diffuse AT in emerging markets. First, redefining the identity of technology in both functions and technical structures might be necessary to ensuring a good fit between supply and demand. The technology needs to be radically redesigned to fit the demand features of emerging markets. Second, the building of local supply systems is critical to enhancing the process appropriateness of technology. Companies need to reconfigure their production techniques to fit the emerging market-specific characteristics of available resources, as well as identify, build on, and leverage local capacity to develop and diffuse AT. We elaborate on the contributions of our research below.

First, our findings reinforce the argument that calls for a radical redesign of technology to fit emerging markets [16,38]. Minor adaptations of existing products represent a change in the function of a technology within a preexisting technical structure. Our analysis suggests that this "same-technical structure–different function" form of technological change cannot fit the context of emerging markets. Specific demand contexts in emerging markets decide the features of technology that are considered appropriate. The technology must meet certain technical requirements and local users' needs, and closely match local conditions. As shown in our case study, the flat plate STS, which is introduced from abroad, cannot meet the specific needs for affordability and adaptability in China's rural areas. In response, the solar companies radically redesign both the core components and the architecture of STS, and develops the evacuated tube STS to provide the functionalities required by rural consumers. Our analysis highlights the importance of a radical redesign of the "adequate pair" of the identity of technology—the functions and the technical structure—for emerging markets [67]. When existing technology cannot adequately meet local demands such as affordability criteria, or when poor infrastructure renders the existing technology less effective, radically reframing the functions of the technology becomes necessary. As the new functions required by emerging markets are radically different from those in developed markets, radical change in technical structure is needed. Thus, our analysis illustrates that exploring AT in emerging markets consists of knowing what kind of technical structure is needed and what it can do (i.e., its functions). This finding extends the research by providing more in-depth insights into the upstream process of designing AT.

Second, in terms of technical structure, our findings illustrate that the principle of synergic innovation in architecture and components provides a logical low cost option to create AT. Redesigning core components with the use of abundant local material enables frugal use of local resources. Meanwhile, architectural innovation—new combinations of component technologies—achieves the price-performance package required by local consumers. Thus, a substantial redesign of both core components and the architecture, as well as frugal use of local resources, provides the performance packages demanded by users in emerging markets. As architectural innovation is difficult to discern, such innovation suggest a more disruptive market environment [48,81]. Our research speaks to and provides an empirical path to continue the conversations about going beyond minor adaptations of existing products to creating AT for emerging markets.

Third, our analysis reveals that a modular design yields not only cost savings but also the flexibility to customize products that meet the requirements of users in emerging markets. A modular design treats a product as a set of separable modules with "architecture", "interfaces", and "standards" unchanged [74]. Such architecture enables production techniques that combine capital-intensive manufacturing and labor-intensive assembly. As a result, local SMEs can initiate labor-intensive and low-technique assembly of subsystems, resulting in a low-cost model. This decomposition of production enables large companies to leverage the low-cost labor-intensive assembly process to provide the required price performance. Furthermore, modularity provides a platform on which a wide range of alternative functions could be added to serve multiple needs and income segments [16]. Thus, in emerging economies with resource constraints, modularity allows for scalability and flexibility, and enables the coevolution of the product, local resources, and markets.

As illustrated by our case study, critical redesign of the technology (i.e., modularization of the core components, standardization of the production process and deskilling of the production process) makes it possible to manufacture STS locally and scale up quickly in a short timeframe. Therefore, in places with local manufacturing capacities, innovations in product architecture that enable the participation of local manufacturing capacity can create a new production mode. This new mode not only creates a low-cost and flexible technological supply system but also enables the addition of local content to local solutions, thus contributing to affordability and other functionalities valued by consumers in emerging markets [10].

Fourth, our findings illustrate the importance of empowering local entrepreneurs to participate in local supply systems. The exploitation of local entrepreneurs and existing manufacturing capacities to provide AT reduces costs. However, the context in which many entrepreneurs in emerging markets operate often features resource constraints such as poor access to education and other knowledge sources. Isolated from the resources required to realize entrepreneurial opportunities, entrepreneurs in such contexts need to be empowered in order to identify and exploit productive opportunities [77]. Our analysis shows that leading companies empower local entrepreneurs in terms of two dimensions: cognitive empowerment and relational empowerment. While the redesign of technology expands the productive opportunities within the solar thermal industry, cognitive empowerment and relational empowerment improve entrepreneurs' alertness, awareness, and mindfulness for entrepreneurial activities [82]. For example, the leading solar companies initiate various bridging links with both local entrepreneurs and other partners and enhance knowledge sharing among the partners, thus connecting fragmented resources and entrepreneurs and enabling local entrepreneurs to build up SMEs to pursue low-cost innovations for local users. These empowering activities maximize the leverage of available resources such as local entrepreneurs and existing manufacturing capacities. Our findings reinforce ongoing arguments on the frugal use of local resources in crafting AT [83].

Our fifth finding relates to the new industrial structure that provides local solutions. Due to the heterogeneity of culture, traditions, and economic behavior among people in different regions, markets in emerging economies are fragmented and diverse [84]. It is difficult and economically inefficient for large companies to serve all these heterogeneous markets by themselves. On the other hand, local entrepreneurs, empowered by the leading companies, are better suited to provide localized solutions to fit local conditions and needs. Considering the comparative advantages of the two sides, the partnership among the leading companies and the local entrepreneurs is an effective strategy for balancing the serving of local needs and operational scale [27,85]. This study reinforces this argument and shows that the leading companies can build on and leverage existing entrepreneurs and labor-intensive manufacturing capacities to create more appropriate products for local users. This new industrial structure lowers costs throughout the whole industrial chain. For example, shipping semi-assembled modules to satellite factories saves transportation costs. Moreover, the participation of local entrepreneurs and related low-cost manufacturing capacity actively contribute to the attractiveness of STS by lowering costs and adding local content to the product.

The partnership mentioned above creates a new industrial structure with distributed systems that maintain both the scale capability of the large companies and the flexibility of the local entrepreneurs [8,27]. This finding supports the view that AT may not necessarily be only small-scale and labor-intensive [39]. The requirement for small-scale and labor-intensive techniques set out by traditional AT research [11,12] does not fit the recent progress in production techniques seen in many emerging markets. Rather, our analysis reveals that companies can radically redesign their technology with modern knowhow to enable new production techniques that can combine capital-intensive techniques with labor-intensive processes. This finding extends the notion of AT in the dimension of "process appropriateness": AT requires production techniques that fit the characteristics of local resources and the existing modes of local production, and it can integrate modern capital-intensive technology and labor-intensive processes.

6. Conclusions and Managerial Implications

Our study represents an attempt to explore how companies develop and diffuse AT in emerging markets. Overall, the results are in line with the extant literature on AT and the research on innovation in emerging markets [12,86]. Building on existing research, our study provides an in-depth look at the upstream process of developing AT with a more diverse repertoire of methods. Our analysis suggests that developing and diffusing AT in emerging markets will require the following initiatives: (1) radically redefining the identity of technology in terms of both functions and technical structure to meet local needs; (2) synergic innovation in architecture and components to improve the price-performance ratio; (3) simplifying the product technology through modularized design to enable a low-cost production mode; and (4) empowering local entrepreneurs to enable the frugal use of resources and enacting a new industrial structure to balance scale and local requirements.

Our findings have managerial and policy implications for companies and governments in emerging markets. First, AT requires that companies integrate demand perspective into their innovation process. Companies need to understand the unique context and characteristics of the environment in emerging markets in order to understand and explore the basic functionalities of AT. For example, the unique affordability, acceptability, and availability criteria of emerging market customers can be a starting point for designing AT. Another example is the infrastructure deficiencies and the constraints surrounding emerging markets, which might help determine the kind of technology that is appropriate for them. Companies need to maintain an open learning orientation that enables learning from unfamiliar settings and spotting transformational consumer needs; and cultural sensitivity that enables deep examination of different contexts.

Second, companies that can produce techniques appropriate for low income users can dominate these markets. Companies should identify a distinct new family of innovations, which are particularly appropriate for low-income operating environments and low-income consumers. It is essential to redesign the overall concept of the products, with respect to components, structure and efficient use of local resources. Companies need to reconfigure the innovation process to combine the deeper understanding of unpredictable product usage scenarios, the focus on local sustainability (local materials, local skills, local culture), and the leveraging of any available resources. A radical redesign of technology in both architecture and components—with the simultaneous considerations of cost reduction, local adaptation, speed, and scale—is needed to meet the elevated requirements for appropriate technology. This will probably require that companies in emerging markets be tasked with seeking opportunities to realize the redesign locally, rather than focusing on limited adaptations of imported product designs.

Third, rather than the technology becoming an end in itself, creating markets and encouraging economic activities are ways to enhance the effectiveness of appropriate technology. Therefore, companies need to pay attention to the building of local manufacturing and supply system necessary for the sustainable growth of appropriate technology and foresight about the future directions of this technology. As illustrated in our research, collaborating with local partners is an effective path to build the ecosystem for appropriate technology. China possesses outstanding capacity for producing low-cost and high-performance physical products, led by its strong manufacturing capacity and the availability of a low-cost and high-quality labor force. Leveraging and integrating existing capabilities and resources such as low-cost assembly capacities is an effective way to enter emerging markets such as China. Therefore, large companies need to develop alliances with local players in order to tap into local knowhow and the environment to develop and diffuse AT. Moreover, tapping into local partners' low-cost processes and learning routines may enable large companies to integrate a low-cost, labor-intensive model in their value chain. Networks of local entrepreneurs could also assist large companies in building or tapping into local supply chains for procuring local inputs and raw materials at low costs.

Fourth, the energy industry is considered one of the most active fields for appropriate technology. As AT requires the use of technology and materials that are environmentally, economically, culturally and socially suitable to the location in which they are implemented, it provides a feasible solution of aligning the objectives of firm innovation, social development and sustainability. Policy makers should take actions to maximize the rate at which these new vintages of innovation take place in many emerging countries. A sound public policy can create a well-functioning innovation infrastructure that raises AT output on a sustainable basis. Policies that harmonize efforts, facilitate partnerships across sectors, can result in a superior generation, exchange and transfer of related knowledge, and take AT from conception to deployment and widespread adoption. The policy instruments should be based on the principles of achieving wider impact, greater outreach, and deeper involvement of all stakeholders. To leverage the managerial and organizational efficiency, manufacturing capabilities, market knowledge, technical and industrial expertise and risk taking capability of the companies, public policy should have provisions to encourage businesses to adopt commercially sustainable business models involving AT.

7. Limitations

Although this study uses case studies and a theoretical sampling approach consistent with grounded theory, the sample's composition from a single industry limits the generalizability of the conclusions. Future studies using cases from more industries, as well as empirical studies with large samples, are necessary to extend our findings.

Another limitation arises from the main context, China. The second-order constructs in Sections 4.1.1 and 4.1.2 are related to the availability of existing industrial skills, manufacturing capacity, and entrepreneurs in China. It remains unclear whether similar patterns can be discovered in other BoP regions with significantly different contexts. Studies comparing among different regions would be worth conducting to verify the validity of the findings in different contexts.

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The Influence of Household Heterogeneity Factors on the Green Travel Behavior of Urban Residents in the East China Region

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Abstract: A questionnaire survey was conducted with 1475 urban residents in the east region of China to explore the impact of household heterogeneity factors on the green travel behavior of urban residents. The green travel behavior was divided into practice-based and promotion-based green travel behavior, and the results showed that variables including gender, age, educational background, household monthly income, amount of cars, professional status, positional tiers and housing ownership were correlated with both of the two types of green travel behavior significantly. Variables that included having elderly family members or not, having children or not, and position level were only correlated with practice-based green travel behavior significantly. Moreover, the study found that the variables female, elderly and young, highly educated, low-income, low professional status, low positional tiers, low positional status, house-renting, not having elderly family members or children and having fewer cars had a significantly positive impact on green travel behavior.

Keywords: household heterogeneity factors; urban residents; green travel behavior

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1. Introduction

With the rapid expansion of urbanization and urban mechanization, Chinese car ownership is growing in intensity and, thus, a series of problems, such as urban road traffic congestion, transport energy consumption and urban air pollution, are becoming prominent issues. Niu's investigation data in Chinese new-type urbanization report indicate that, in cities with populations above a million in China, the traffic capacities of over 80% of the road segments and 90% of the road crossings have reached their limits [1]. Moreover, traffic congestion is no longer a metropolitan phenomenon, with regions of middle and small cities having more serious congestion than the larger cities including Beijing, Shanghai, and Guangzhou [2]. At present, Chinese traffic fuel consumption accounts for one-third of the national total fuel consumption, and according to predictions, petroleum consumption for transport, which accounts for 55%–60% of the national total petroleum consumption, will be the largest sector by the year 2020 [3]. Of all passenger transport modes, including car, public bus, civil aviation and railway, the energy consumption of the car is the greatest and this is increasing progressively year by year [4]. Now, with a leap in car ownership, the huge amount of exhaust fumes from cars has become one of the main sources of urban air pollution. Based on the 2013 IEA (International Energy Agency) report, CO_2 emissions from the transport sector account for 8.4% of total CO_2 emissions from fuel combustion in China. The road transport sector accounts for 81.3% of all transport sectors in China, a proportion that is higher than the global average and continues to increase gradually [5]. At the same time, with the transformation of travel structure, the CO_2 emissions from cars are the highest proportion of all passenger transport modes and this proportion has increased from 51% in 2000 to 82% in 2011 according to the research results of Wang and Liu [6]. On the other hand, carbon monoxide, hydrocarbon, oxynitride and solid suspended particulate matter generated by motor vehicle exhaust emission are very hazardous for human health and even life-threatening. This is because the range of motor vehicle exhaust emission is 0.3–2 meters, similar to the range of human respiration. Motor vehicle exhaust emission directly stimulates human respiratory system, skin and eyes [7].

Based on socioeconomic development status, the State Statistics Bureau on 13 June 2011 divided the Chinese mainland into four economic areas: the eastern region, central region, northeast region, and western region. The economic development levels of different economic areas vary greatly, with the eastern region having the highest economic development level and the highest population and distribution of cities. The east China region includes 10 provinces and cities: Beijing, Tianjin, Hebei, Shanghai, Jiangsu, Zhejiang, Fujian, Shandong, Guangdong, and Hainan. The amount of private car ownerships of the 10 provinces and cities in the east China region accounts for more than 50% of the national total, and this amount has increased by about 20% annually in recent years [8]. Based on the 2015 transportation analysis report of major cities in China, on a national scale, the urban traffic congestion of east China region is the most serious, and seven of the ten most congested Chinese cities belong to the east China region [9]. Moreover, based on the Chinese PM2.5 space-time distribution diagrams published in the Chinese Journal of Nature drawn by the research group of Yale-NUIST Center on Atmospheric Environment, the east China region is the most serious region in haze, the PM2.5 index of the Beijing-Tianjin-Hebei region, especially, is staying at a high level all year round [10]. In other words, compared with other regions in China, the traffic congestion, carbon emissions and air pollution of the east China region are more serious due to the higher amount of car owners.

To solve the above problems, China is appealing to the public to implement green travel. Green travel, which could reduce the travel energy consumption and pollution, had been brought into the 13th Five Year Plan after the 12th Five Year Plan. Meanwhile, the above data indicate that there is a realistic significance to research how the government guides urban residents of the east China region into implementing green travel. Urban residents are the key subjects of the implementation of green travel; that is, the development of green travel is inseparable from the residents' participation. Recently, many scholars have paid close attention to the relationship between green travel behavior and the individual, as the subject of household consumption, but relatively few studies are focused on the impact of household heterogeneity factors on green travel behavior. Therefore, this article aims to investigate the impact of household heterogeneity factors on urban residents' green travel behavior, to provide some relevant basis and policy suggestions for the government to guide urban residents' green travel behavior to normalization.

2. Literature Review and Research Hypothesis

2.1. Literature Review

The concept of green travel came from the idea of green transport, but does not have a unified or clear definition. As a manifestation of green consumerism, green travel is a new type of travel idea from the individual realization that the environmental problem is in the context of an environmental crisis. Green travel aims to guide residents to choose travel modes which use low-energy, are energy efficient, low polluting, and balance efficiency with fairness, and are a benefit to the sound development of the city and the citizen. Therefore, as an environmental behavior, green travel behavior is a conscious effort made in order to avoid or solve environmental problems [11,12]. Thus, this article defines urban residents' green travel behavior as a conscious effort action, in the context of considering the harmonious development of people, society and environment; that is, to do effort consciously to reduce the energy consumption and pollution in their own or others' travel.

This article combines the characteristics of green travel to classify green travel behavior into two types: practice-based and promotion-based [13–15]. Practice-based green travel behavior is a physical daily practice, an adjustment behavior that is initiatively exercised (adjusting existing travel mode to green travel mode). In other words, practice-based green travel behavior is a direct curtailment and adjustment behavior, such as taking public transport instead of driving or taking taxi. Promotion-based green travel behavior is a lobbying operation between residents, or a behavior where residents take an active part or suggest others take part in green travel behavior relevant to an organization or activities. In other words, promotion-based green travel behavior can be viewed as an interpersonal interaction behavior, such as persuading the people around to take more public transport instead of driving or taking taxi. Practice-based green travel behavior is an immediacy behavior, whereas promotion-based green travel behavior may not be, but it can prompt the occurrence of green travel behavior to some extent.

According to the purpose of the trip, various travel behaviors can be divided broadly into two types: daily local travel and tourism travel. In view of the frequency and seriousness of environmental air pollution, only daily local travel is the focus of this article.

The majority of recent research results indicate that sociodemographic characteristics are significant contributors that impact on environmental behavior [16–18]. As a type of environmental behavior, green travel behavior is also affected significantly by sociodemographic characteristics [19,20]. Factors that are considered sociodemographic characteristics mainly included gender, age, graduation, income, family structure and size. For example, Golob and Hensher found that demographic characteristics have significant impact on travelers' environmental protection behavior; in other words, environment friendly travel behavior varied in demographic characteristics, and those travelers who are female, under 30 years old and over 50 years old, with high educations and incomes, and with low car ownership are more willing to participate in environment friendly travel behavior [21]. Specifically, gender was a significant influencing factor of green travel behavior. Prillwitz and Barr investigated urban residents' daily travel behavior and found that females were favoring green travel more than males [22]. Simma and Axhausen studied the commuting behavior of Australian residents, and their results showed that males wanted to own a car more than females, while females were more willing to choose walking or public transportation than males [23]. Polk's research indicated that the frequency of car use by Swedish women was significantly less than for Swedish men, and the intention to reduce car usage by Swedish women was stronger than for Swedish men [24]. Age was also considered a significant influencing factor of green travel behavior. The research results of Plaut demonstrated that those under 25 years old showed a higher propensity for non-motorized travel [25]. The study of Klineberg et al. [26] and Singh [27] showed that younger age groups gave higher attention to ecological environmental problems and a higher implementation rate of pro-environmental behavior and had a social responsibility in consuming behavior with sustainable development. However, some studies have pointed out that older age groups may pay more attention to recycling and find it easier to implement sustainable consuming behavior [28,29]. In terms of the relationship between educational background and green travel behavior, most studies showed that residents' green travel behavior was proportional to their educational background. Golob and Hensher [21] and Plaut [25] found that travelers with a college diploma and above were more willing to participate in pro-environmental travel behavior. Ma and Liao surveyed urban residents' low-carbon trip situation in Xi'an, and their results showed that, if residents received suitable guidance and realistic conditions, the higher the educational background the residents possessed, the greater was the frequency of their low-carbon trips because the residents with a higher education owned a stronger ability of accepting new ideas and a sense of social responsibility [30]. Generally speaking, residents' standard energy consumption is proportional to their income and this view had been verified by most scholars [31,32]. However, the higher energy consumption level caused by a higher income did not influence residents' implementation of green travel behavior. Based on data from international social surveys, Franzen and Meyer verified that the attention on the environment by the individual or the nation was proportional to their income or level of affluence [33]; Prillwitz and Barr also verified this result [22]. Some studies have demonstrated that the individual's occupation has a significant impact on his or her environmental behavior [34]; for instance, Liu found that people with a higher social position were more inclined to adopt green consumption [35]. Some studies have also demonstrated that residents who own their property could significantly influence their energy consuming behavior, specifically, residents who owned their property were more inclined to invest in energy efficiency, while residents who did not own their property were more inclined to change their behavior to reduce their energy consumption [36]. Through verifying the relationship between residents' housing and their energy saving behavior on home heating and oil consumption, Painter et al. found that housing was the fourth most important variable for differentiating whether the resident is an energy-efficient person [37]. Family scale and structure directly influence energy consumption, and household energy consumption generally increases as the amount of family members increases [38]. Prillwitz and Barr investigated residents' daily travel behavior, and their results showed that 58% of families did not have children in the group that preferred green travel, and the greater the amount of children in a family, the lower the rate in which they preferred green travel [22]. At the same time, car ownership was also considered a key factor influencing green travel behavior by the majority of scholars. Through surveying the residents of 13 communities in England, Susilo et al. found that the rate of residents choosing cycling or public transport would decrease greatly if residents owned one or more private cars [39]. Plaut indicated that the more private cars residents owned, the higher the intention of residents to choose motorized travel [25], and Golob and Hensher verified that travelers with fewer private cars were more willing to participate in pro-environmental travel behavior [21].

However, a few scholars have queried the relationship between social demographic variables and environmental behavior, and believe that this relationship was not stable [40,41]. In investigating environmental protection by organization members, Marcinkowski considered age, gender, date of birth, educational status, occupation, socioeconomic status, political view point, youth residence and hometown size as social demographic variables and used these variables to predict environmental behavior. He found that the variables contributed little in predicting environmental behavior [42]. Both Scheiner's investigation of German residents' travel modes from 1976 to 2002 [43] and Hjorthol's investigation of Norwegian residents' travel modes from 1992 to 2005 [44] showed that the influence of gender on travel mode chosen fell off rapidly, in other words, there was no significant difference between males and females in the area of travel mode choice. Some studies indicate that there was no significant correlation between education and green travel behavior; however, some studies found a negative correlation; for instance, Singh found that the implementation rates of socially responsible consumer behavior of those people with a higher education were lower [27], and Böhler et al. pointed out that the group with a higher educational background were more inclined to choose motorized travel [31]. In addition, some studies demonstrate that there was no significant correlation between income and green travel behavior; however, some studies found a negative correlation; for instance, Samdahl and Robertson found that the environmental awareness of low income residents was noticeably higher than the social average level [45], and both Singh [27] and Wang [29] found that low income residents were more inclined to implement recycling consumption behavior and socially responsible consumer behavior. The majority of studies have demonstrated that there was no significant relationship between residents' occupations and their environmental behavior [46]. Overall, scholars believed that social demographic variables did not have a significant impact on green consuming behavior [27,47].

In conclusion, although the existing literature on the relationship between social demographic characteristics and green travel behavior has obtained uncertain results, the definitions of specific factors and mechanisms of social demographic characteristics are not always consistent because of differences in regional cultures and social economic development. Furthermore, the existing research on green travel behavior focuses on Europe and the United States and other developed countries, and research that is focused on Chinese urban residents is relatively deficient, so the social demographic characteristics of urban residents' green travel behavior in the Chinese context remains to be verified.

Family is the major factor of the urban residents' life. Family structure, size, income, educational background and occupation and social status all influence the residents' travel mode, and restrain the social and economic boundaries of the travel mode choice [48,49]. Therefore, this article takes household heterogeneity factors as the research perspective, not only focusing on demographic variables, and this could describe the essential characteristics of urban residents' green travel behavior more accurately to some extent.

2.2. Research Hypothesis

Based on a literature review, combined with the family characteristics and travel modes and habits of Chinese urban residents, this article points out that the household heterogeneity influencing factors of urban residents' green travel behavior include gender, age, educational background, occupation, household monthly income, housing ownership, whether there are elderly members over 60 years old in the family, whether there are children under 12 years old in the family, and the amount of private cars. According to the literature and expert suggestion, the relationship between the occupation and social status should be considered; this article measures occupation by professional status, positional tiers, and positional status. Furthermore, this article adopts the information of householder to denote residents' statistical characteristics such as gender, age, educational background, and occupation. The research hypotheses discussed above are summarized in Table 1.

Table 1. Research hypothesis.

Number	Research Hypothesis
H1	Green travel behavior is different for men and women
H2	Green travel behavior is different for various age ranges
H3	Green travel behavior varies depending on educational background
H4	Green travel behavior varies depending on family monthly income
H5	Green travel behavior varies with various positional status
H6	Green travel behavior varies with various professional status
H7	Green travel behavior varies with various positional tiers
H8	Green travel behavior is different for different housing types
H9	Green travel behavior shows significant variations by whether there are elderly people over 60 years old in the family
H10	Green travel behavior shows significant variations by whether there are children under 12 years old in the family
H11	Green travel behavior varies depending on the amount of private cars

Note: Green travel behavior includes practice-based green travel behavior and promotion-based green travel behavior.

3. Research Method and Data Sources

3.1. Research Method

To collect the basic data, this article has adopted a questionnaire survey, a method widely used in research fields such as environmental behavior, energy usage and consuming behavior. Firstly, we designed the initial scale of this study based on existing studies, and combined with expert advice and results of interviews with representative residents. According to Chinese urban residents' usual travel and green travel, the initial scale of this article was amended for localization. Next, through small sample pre-research which was designed to find possible problems and test the validity of the scale, the initial scale was amended to the formal scale. The formal scale included three parts comprised of 20 items: statistics of household heterogeneity factors, statistics of urban residents' current travel modes, and the measurement of green travel behavior.

The design of items for household heterogeneity factors was mainly obtained from the China Statistical Yearbook and correlational researches of environmental behavior from international and national studies. The current situation of urban residents' travel modes was measured by census of urban residents' major transportation in daily travel. The items for green travel behavior were mainly designed and measured using scales from established international and national studies (Smith-Sebasto and D'Costa [14], Qu and Pan [50], Pan [51], Wang [52], and Yang [53]), the related information on the Chinese official website of green travel [54], and the official website of green travel foundation of China Association for NGO Cooperations [55]. To combine these data with the actual characteristics of Chinese urban residents' green travel behavior, the items were localized, amended, and redesigned. The green travel behavior section covered two areas: practice-based green travel behavior and promotion-based green travel behavior (totally covering six items). Of which, three examples of practice-based green travel behavior were presented, such as taking more public transport instead of driving or taking taxi. Similarly, three examples of promotion-based green travel behavior were presented, such as persuading the people around to take more public transport instead of driving or taking taxi. The answers were given on a five-point scale: rarely, sometimes, half the time, mostly, and very often. Using these examples, the green travel behavior characteristics of every respondent were determined.

3.2. Data Sources

Urban residents of the east China region (which included the following ten provinces or cities: Beijing, Tianjin, Hebei, Shanghai, Jiangsu, Zhejiang, Fujian, Shandong, Guangdong, and Hainan) were regarded as the subjects of this questionnaire survey. The questionnaires were distributed in a month-long field study from 10 November 2015 to 10 December 2015, and network research was also used. The Internet-based questionnaires were sent by online questionnaire survey platform, and by email using various methods with the assistance of schoolmates, colleagues, friends, and relatives. Finally, 1300 field questionnaires were issued, and 1082 field questionnaires and 614 network questionnaires were regained. According to the screening principle of no item-missed and no same value for eight items in succession [56], 901 valid field questionnaires and 574 valid network questionnaires were regained with an 86.97% effective rate and 77.06% recovery rate. The city distribution of questionnaire data is shown in Table 2.

Table 2. The city distribution of questionnaire data.

Province/City	Valid Questionnaires	Proportion
Beijing	104	7.05%
Tianjin	236	16.00%
Hebei	96	6.51%
Shandong	340	23.05%
Jiangsu	314	21.29%
Shanghai	89	6.03%
Zhejiang	105	7.12%
Fujian	69	4.68%
Guangdong	65	4.41%
Hainan	57	3.86%
Total	1475	100.00%

3.3. The Test of Reliability and Validity

Cronbach's α coefficient of SPSS 22.0 was used in this article to test the reliability of the green travel behavior scale. The results showed that the scale design had high reliability because the Cronbach's α coefficient of the green travel behavior scale was 0.774, and the Cronbach's α coefficient of each item was between 0.729 and 0.755. The Cronbach's α coefficient was not improved after an item was deleted, and the overall correlation coefficient and the multiple correlation square coefficient of each item was over 0.3. The validity of green travel behavior scale was tested by exploratory factor analysis and confirmatory factor analysis, successively. Before the exploratory factor analysis, Kaiser–Meyer–Olkin

(KMO) and Bartlett test were conducted and the results showed that the KMO value was greater than 0.7 and the chi-square value of Bartlett test was larger and statistically significant, thus the scale was suited for factor analysis (Table 3).

Using the principal component analytical method and maximizing the deviations orthogonal rotation, and according to the retrieval standard that the eigenvalue is greater than 1, two common factors were extracted from green travel behavior and their total square deviation probability was 68.72%, which was relatively high. At the same time, the load value of each index item on its own factor was greater than 0.5 and on other factors were less than 0.5, this indicated that the green travel behavior scale in this article had a good convergent validity and discriminant validity. Next, confirmatory factor analysis was done by Lisrel 8.70, and the results showed that all goodness-of-fit indexes met the requirements of ideal values, and the factor loadings of the two potential factors of green travel behavior on its own index items all met the traditional requirement that the factor loading was greater than 0.4; that is, the dependent variable scale had a good construct validity.

Table 3. The test results of reliability and validity.

Variables		Items	Cronbach's α Coefficient	KMO Value	Bartlett Test	Sig.
Green travel Behavior	Practice-based green travel behavior	3	0.750	0.707	2973.060	0.000
	Promotion-based green travel behavior	3	0.778			

The results also showed that there was a correlation between the two common factors of green travel behavior, so a second order model was built to verify the existence of the high order, and also to verify the rationality of the classification mode of green travel behavior. As shown in Figure 1, compared with the first order model, the dependent variable second order model is more concise, and the factor loading of each first order factor is greater than 0.5. This result indicates that the second order model of green travel behavior is rational, and the classification mode of green travel behavior is rational, in other words, green travel behavior can be well explained by practice-based green travel behavior and promotion-based green travel behavior.

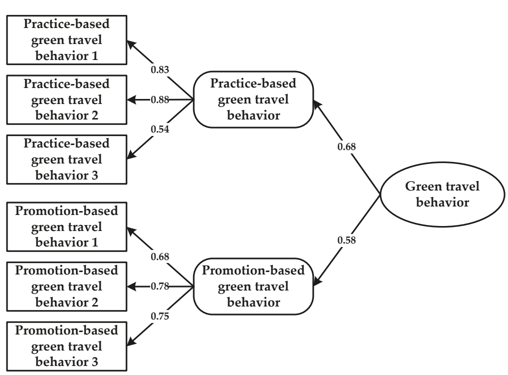

Figure 1. Path analysis of the second order model of the green travel behavior scale.

4. Result Analysis and Discussion

In this article, we used independent-samples *t*-test to analyze the difference in practice-based and promotion-based green travel behavior by gender, housing type, whether the family has elderly members over 60-years old, and whether the family has children under 12-years old. The results are shown in Table 4. In addition, we used one-way analysis of variance to compare practice-based with promotion-based green travel behavior by age, educational background, family monthly income, positional tiers, professional status, positional status, and the amount of private cars. The results are shown in Table 5.

Table 4. Variance analysis of green travel behavior on household heterogeneity factors based on independent-samples *t*-tests.

Variables and Attributes		Practice-Based Green Travel Behavior		Promotion-Based Green Travel Behavior	
		Significance	Mean Value	Significance	Mean Value
Gender	Male (738, 50.0%) Female (737, 50.0%)	0.000	3.372 3.637	0.005	3.244 3.389
Housing type	Property owned (1100, 74.6%) Property not owned (375, 25.4%)	0.000	3.387 3.850	0.003	3.272 3.445
Family members over 60-years-old	Yes (575, 39.0%) No (900, 61.0%)	0.000	3.390 3.577	0.067	3.258 3.354
Family members under 12-years-old	Yes (732, 49.6%) No (743, 50.4%)	0.000	3.244 3.389	0.054	3.267 3.365

Note: Mean value refers to the mean value of similar respondents' self-reports of their implementation situation of green travel behavior (1 = rarely, 2 = sometimes, 3 = half the time, 4 = mostly, 5 = very often).

As shown in Table 4, practice-based and promotion-based green travel behaviors show significant variations by gender, which conforms to the theoretical assumption in this article. The comparative analysis results of average values show that the frequency of practice-based green travel behavior for females (3.637) is higher than for males (3.372), as well as promotion-based green travel behavior (females 3.389 > males 3.244). This result is in accord with the conclusions of Golob and Hensher [21] and Prillwitz and Barr [22]. In terms of practice-based green travel behavior, as shown in Figure 2, the statistical results of urban residents' travel modes indicate that males prefer non-green travel modes such as private car and taxi, while females prefer green travel modes such as public transport, bicycle/electric bicycle, and walking. This statistical result is consistent with the result of Simma and Axhausen [23]. The reason could be that males pay more attention to efficiency, such as speed and comfort level, and females pay more attention to the cost and energy conservation in most cases [57]. In terms of promotion-based green travel behavior, compared to males, females are more willing to participate in green travel correlated activation and are willing to suggest or persuade others to implement green travel behavior. The reason may be that, in the Chinese context, females seem to engage in small group activities, such as shopping and chatting, more frequently than males, and it is easier to recommend joint activities with others in a small group [34].

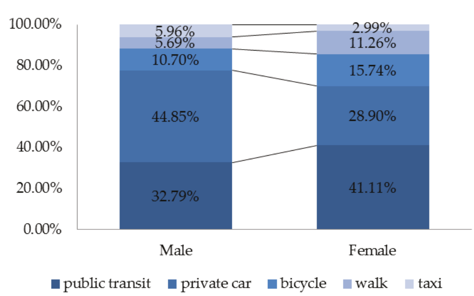

Figure 2. Proportions of different travel modes by gender.

As shown in Table 4, practice-based and promotion-based green travel behaviors show significant variations by housing type, which conforms to the theoretical assumption in this article. The comparative analysis results of average values show that the frequency of practice-based green travel behavior of the group with house ownership (3.850) is higher than the group who do not have house ownership (3.387); similar results were obtained with promotion-based green travel behavior (house ownership 3.445 > do not have house ownership 3.272). This result is in accord with the conclusions of Black et al. [36] and Painter et al. [37]. In terms of practice-based green travel behavior, as shown in Figure 3, the statistical results of urban residents' travel modes indicate that the proportions of green travel modes, such as public transit, cycling and walking, in the group who do not own their houses are apparently higher than the group who own their houses. The proportion who have private cars is apparently higher for those with house ownership than for those who do not. The reason for this may be that job and life stability and family economic strength of the house ownership group are higher than the group who do not have house ownership in most cases, as a consequence, the group who own their houses is more likely to own a private car [35]. In terms of promotion-based green travel behavior, compared to the group who do not own their houses, the group who have housing ownership is more willing to participate in green travel correlated activation and is willing to suggest or persuade others to implement the green travel behavior that they practice.

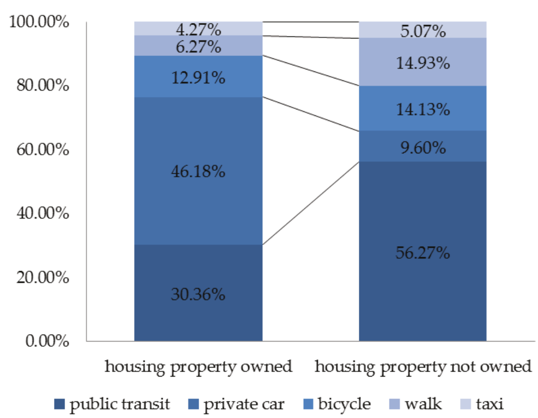

Figure 3. Proportions of different travel modes by house ownership.

As shown in Table 4, only practice-based green travel behavior shows significant variation when a family has elderly members or children, which partially conforms to the theoretical assumption in this article. The comparative analysis results of average values show that the frequency of practice-based green travel behavior of the group who do not have elderly family members or children (3.577, 3.389) is higher than the group who has elderly family members or children (3.390, 3.244). This result is in accord with the conclusions of Prillwitz and Barr [22] and Aydinalp et al. [38]. As shown in Figure 4, the statistical results of urban residents' travel modes indicate that the proportions of green travel modes such as public transit, cycling and walking in the group who do not have elderly family members or children are apparently higher than the group who do, while the proportion of private cars in the group who have elderly family members or children is apparently higher than the group who do not. Through our questionnaire survey, we knew that one of the reasons why many families buy private cars is to make travelling with the elderly or children easier. Perhaps this is the reason why the frequency of practice-based green travel behavior is relatively low for the families who have elderly members or children.

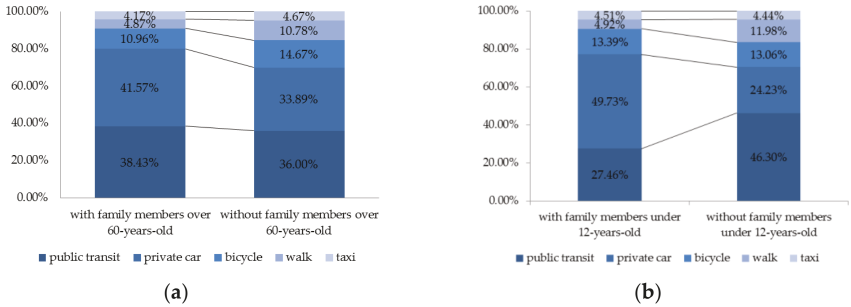

Figure 4. Proportions of different travel modes by family structure. (**a**) Denotes the family structure that whether there are elderly people over 60 years old in the family; (**b**) denotes the family structure that whether there are children under 12 years old in the family.

Table 5. Variance analysis of green travel behavior on household heterogeneity factors based on one-way analysis of variance.

Variables and Attributes		Practice-Based Green Travel Behavior		Promotion-Based Green Travel Behavior	
		Significance	Mean Value	Significance	Mean Value
Age	Under 18 years (6, 0.5%)	0.000	4.111	0.017	3.222
	18–30 years (797, 54.0%)		3.690		3.380
	31–45 years (487, 33.0%)		3.246		3.220
	46–60 years (160, 10.8%)		3.281		3.242
	Over 60 years (25, 1.7%)		3.920		3.653
Educational background	Junior high school or less (45, 3.1%)	0.002	3.704	0.025	3.163
	Senior high school (158, 10.7%)		3.291		3.095
	Junior college (270, 18.3%)		3.410		3.312
	Bachelor (732, 49.6%)		3.528		3.357
	Above bachelor (270, 18.3%)		3.627		3.367
Family monthly income (Yuan)	Less than 4000 (169, 11.5%)	0.000	3.953	0.000	3.548
	4000–6000 (335, 22.7%)		3.695		3.214
	6000–8000 (257, 17.4%)		3.715		3.463
	8000–10,000 (293, 19.9%)		3.373		3.358
	10,000–30,000 (322, 21.8%)		3.215		3.222
	30,000–100,000 (59, 4.0%)		3.000		3.209
	100,000 or more (40, 2.7%)		2.700		2.867
Amount of private cars	0 (520, 35.3%)	0.000	3.969	0.013	3.414
	1 (736, 49.9%)		3.342		3.271
	2 (192, 13.0%)		2.948		3.276
	3 or more (27, 1.8%)		2.938		2.951
Positional status	None (1224, 83.0%)	0.003	3.550	0.152	3.324
	Family-level (171, 11.68%)		3.349		3.207
	Department-level (34, 2.3%)		3.098		2.971
	Stall or Bureau level (18, 1.2%)		3.074		3.407
	Provincial or ministerial-level (28, 1.9%)		3.560		3.429
Professional status	None (828, 56.1%)	0.000	3.586	0.003	3.296
	Primary (244, 16.5%)		3.526		3.295
	Intermediate (282, 19.1%)		3.457		3.482
	Sub-senior (85, 5.8%)		3.035		3.020
	Senior (36, 2.4%)		2.963		3.324
Positional tiers	None (299, 20.3%)	0.000	3.699	0.005	3.495
	Junior staff (561, 38.0%)		3.668		3.282
	Front-line manager (284, 19.3%)		3.524		3.324
	Middle manager (253, 17.2%)		3.225		3.196
	Senior manager (78, 5.3%)		2.778		3.239

Note: Mean value refers to the mean value of similar respondents' self-reports of their implementation situation of green travel behavior (1 = rarely, 2 = sometimes, 3 = half the time, 4 = mostly, 5 = very often).

As shown in Table 5, practice-based and promotion-based green travel behaviors show significant variations by age, which conforms to the theoretical assumption in this article. The comparative analysis results of average values show that the frequency of green travel behavior of the middle-aged group (31–45 years and 46–60 years) is the lowest, and the youth and the elderly are relatively higher. This result is in accord with the conclusions of most scholars [25–29]. In terms of practice-based green travel behavior, as shown in Figure 5, the statistical results of urban residents' travel modes indicate that the middle-aged group prefers to choose private cars as their travel mode, and the reason may lie in their relatively stable social status and family incomes. The youth and the elderly prefer public transit, and the rate by which they choose private cars is relatively low. The reason may lie in their values, incomes, and travel attributes. In terms of promotion-based green travel behavior, the frequencies by youths under 30-years old and the elderly over 60-years old are relatively higher than the middle-aged group. The reason may be that, in the Chinese context, youths are more vigorous than the middle-aged group, and are more receptive to new things, and are more likely to participate in public activity, while the elderly are more frugal, and more likely to give others advice according to their experiences [34,58].

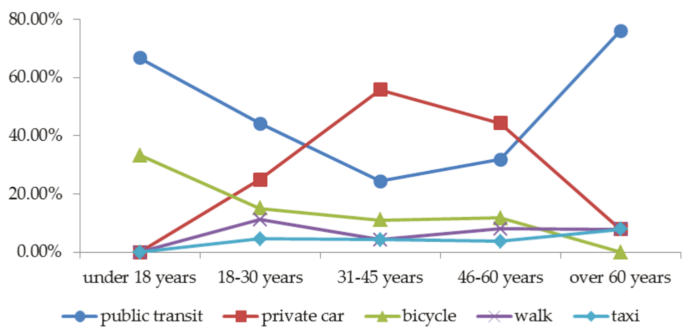

Figure 5. Proportions of different travel modes by age.

As shown in Table 5, practice-based and promotion-based green travel behaviors show significant variations by family monthly income, which conforms to the theoretical assumption in this article. The comparative analysis of average values shows that the frequency of urban residents' green travel behavior decreases with the level of family monthly income. This result is inconsistent with the research results of some developed countries [22,33], but is in accord with the research results of India [27] and China [29]. As shown in Figure 6, the statistical results of urban residents' travel modes indicate that the proportion of private car usage increases with the level of family monthly income, while the proportion using public transport and bicycles decreases with monthly income. The reason may be that, with the increase of income level, buying a private car will be affordable and a necessity for most families, especially young families.

As shown in Table 5, practice-based and promotion-based green travel behaviors show significant variations by educational background, which conforms to the theoretical assumption in this article. The comparative results of average values show that the frequency of urban residents' green travel behavior increases with their educational background level, except for junior high school or less. This result is in accord with the conclusions of Golob and Hensher [21] and Plaut [25]. The frequency of practice-based green travel behavior of the group with a junior high school degree or less is the highest, and that of promotion-based green travel behavior is also relatively higher than with other groups, and the reason may lie in the small sample size. As shown in Figure 7, the statistical results of urban residents' travel modes indicate that the relationship between the proportion of public transit and urban residents' educational background level is a "U"-shaped curve, and the proportion of public transit in the group with a junior college level is the lowest. While the relationship between proportion of private car and urban residents' educational background level is a "converse-U"-shaped curve, and the proportion of private cars in the group with junior college level is the highest. The reason may be that urban residents' behavior could be influenced by other factors, such as the urban residents' environmental awareness and income, while the environmental cognition and environment protection consciousness will increase with their educational background level, as well as their income. However, the influences of environmental awareness and income on green travel behavior are the opposite.

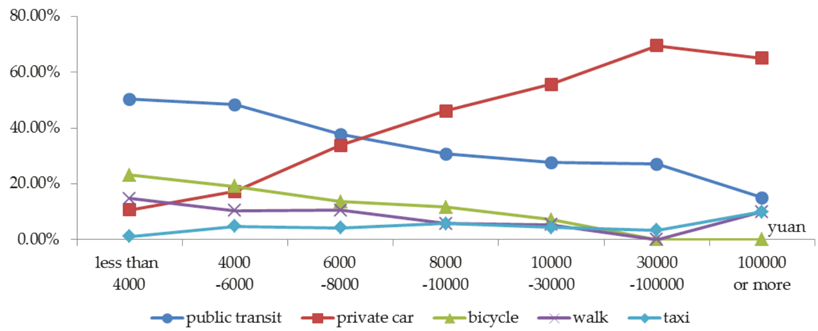

Figure 6. Proportions of different travel modes by family monthly income.

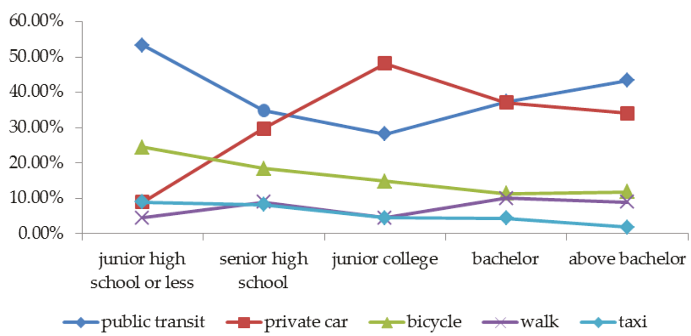

Figure 7. Proportions of different travel modes by educational background.

As shown in Table 5, practice-based and promotion-based green travel behaviors show significant variations by the amount of cars owned by the family, which conforms to the theoretical assumption in this article. The comparative analysis results of average values show that the frequency of urban residents' green travel behavior can decrease with the amount of cars owned by the family. This result is in accord with the conclusions of Golob and Hensher [21] and Plaut [25] and Susilo et al. [39]. As shown in Figure 8, the statistical results of urban residents' travel modes indicate that the proportion of private car usage increases with the amount of cars owned by the family, while the proportion of other travel modes decreases with the amount of cars owned by the family.

As shown in Table 5, practice-based and promotion-based green travel behaviors show significant variations by professional status and positional tiers, only practice-based green travel behavior shows significant variation by positional status, which partially conforms to the theoretical assumption in this article. The comparative analysis results of average values show that the frequency of urban residents' practice-based green travel behavior can decrease with their positional status, and the frequency of urban residents' practice-based and promotion-based green travel behavior can decrease with their professional status and positional tiers. This result is inconsistent with the conclusions of Liu [35] and Curtis [46]. As shown in Figure 9, the statistical results of urban residents' travel modes indicate that the proportion of private car usage increases with their positional status, professional status, and positional tiers, while the proportion of public transit, cycling and walking decreases with their positional status, professional status, and positional tiers. The reason may be that urban residents' income could increase with their positional status or professional status or positional tiers in most cases, while the rate of owning a private car also could increase with their income in most cases. It should be pointed out that some errors may exist in the above results because of the small sample size of the provincial and ministerial levels in the positional status and senior professional status.

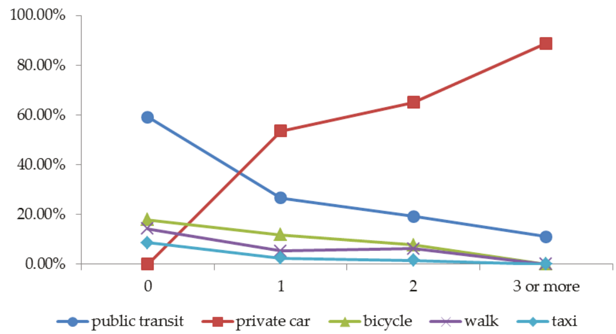

Figure 8. Proportions of different travel modes by the amount of private cars.

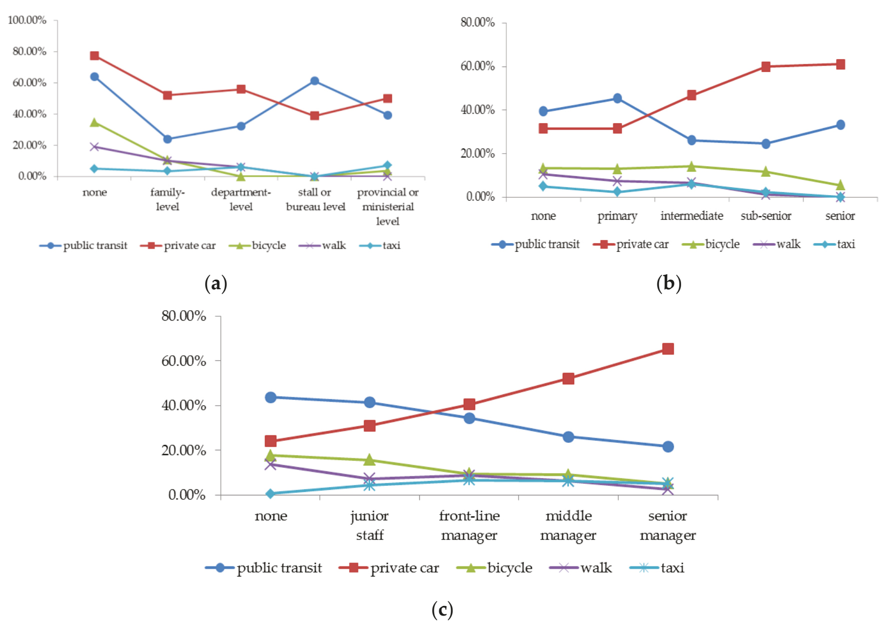

Figure 9. Proportions of different travel modes by positional status, professional status and positional tiers. (**a**) Denotes positional status; (**b**) denotes professional status; (**c**) denotes positional tiers.

5. Conclusions and Policy Implications

In conclusion, this study shows that both practice-based and promotion-based green travel behavior shows significant variation by household heterogeneity factors. In practical terms, females, the elderly and the young, highly educated, low income, low professional status, low positional tiers, low positional status, house-renting, no elderly family members or children, and having fewer cars has a significantly positive impact on green travel behavior. Therefore, according to the questionnaire survey statistical results, this article proposes the following policy changes to enhance public participation and initiative in green travel behavior.

(1) Pay attention to females, the young and the elderly, and attach importance to their strong characters and functions in formulation and implementation of green travel behavior guiding policies. In China, females are the main consumer of their family and the main educator of their children in most cases, so females could have a significant influence on the consumption views of their family and children. In most cases, the young are information-rich, are quick to accept new things, will positively participate in social activities, and are the main force of future family consumption. In China, respect and honor of the elderly is a traditional virtue, so the thoughts and behaviors of the elderly could have significant influence on the thoughts and behaviors of other family members. The results of this study indicate that the implementation frequency of females, the young and the elderly is relatively high. For this reason, and in order to make better use of guiding policies, relevant departments should pay attention to those groups as key breakthrough and target groups in the formulation and implementation of green travel behavior guiding policies.

(2) Pay attention to the positive impacts of educational background on green travel behavior. The results of this study indicate that there is a positive correlation between the frequency of green travel behavior and urban residents' educational background; in other words, the implementation frequency of urban residents' green travel behavior can increase with educational background. Therefore, relevant policymakers should take into account publicity channels and contents of green travel behavior in the process of receiving and implementing education in order to increase urban residents' environmental awareness.

(3) Guide urban residents' consumption views correctly, and cultivate and enhance urban residents' green travel cognition. In order to increase the comfort level of life, most urban residents will increase their consumption level with their income. One of those manifestations is buying one or more private cars, and the private car has become the second biggest demand of the family after housing. The results of this study indicate that there is a negative correlation between the implementation frequency of green travel behavior and urban residents' family income and the amount of private cars. To promote the development of green travel does not mean to limit urban residents' travel consumption but to guide urban residents to establish low carbon consumption in order to avoid excessive and luxury consumption.

(4) Emphasize guiding the house-renting group in order to accustom them to green travel behavior. In our samples, the house-ownership group accounts for 75 percent and the house-renting group accounts for 25 percent. Our statistical results show that the implementation rate of the house-renting group is significantly higher than that of the house-ownership group. In China, buying a house is a rigid demand of a family, and the present house-renting group may own their own property eventually. Perhaps the relatively high implementation rate of green travel behavior by the house-renting group may be limited by the family's current economic capabilities, but if the house-renting group could be actively guided by relevant policy makers, and their environmental protection awareness cultivated, their temporary green travel behavior is likely to be normalized and accustomed imperceptibly.

(5) Guide green travel behavior of the group who live with the elderly or children. It is a traditional virtue in China to respect the elderly and take good care of children, and one of the original intentions of buying private cars by many families is to make travel easier for the elderly or children. Our research results show that, as independent travelers, the implementation rate of the elderly is relatively high. However, as family members, the elderly or children can decrease the implementation rate of green travel behavior by the head of the household. Therefore, the relevant policy makers should guide green travel behavior of those groups who live with the elderly or children by utilizing incentive measures, and cultivate low-carbon awareness and low-carbon consumption patterns by increasing publicity channels and contents.

We have observed a number of limitations in this study. Although our research samples involved urban residents of ten provinces or cities in the east China region, there is discrepancy in the quantities of research samples among different provinces or cities. Therefore, it is recommended that future research should enrich and extend the research samples to improve the universality of the research conclusion. Second, this study was based upon the urban residents' self-reports of their implementation situation of green travel behavior rather than upon field observations. Self-reports may produce social desirability bias, which could affect the authenticity of the results. Therefore, it is recommended that future research should use more survey methods to collect data, such as long-term field observations supplemented by interviews. However, despite these limitations, this explorative research has helped us to further the study of implementation situation and influencing factors of urban residents' green travel behavior.

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Conflicts of Interest: The authors declare that they have no conflict of interest.

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Scheduling Optimization of Home Health Care Service Considering Patients' Priorities and Time Windows

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Abstract: As a new service model, home health care can provide effective health care by adopting door-to-door service. The reasonable arrangements for nurses and their routes not only can reduce medical expenses, but also can enhance patient satisfaction. This research focuses on the home health care scheduling optimization problem with known demands and service capabilities. Aimed at minimizing the total cost, an integer programming model was built in this study, which took both the priorities of patients and constraints of time windows into consideration. The genetic algorithm with local search was used to solve the proposed model. Finally, a case study of Shanghai, China, was conducted for the empirical analysis. The comparison results verify the effectiveness of the proposed model and methodology, which can provide the decision support for medical administrators of home health care.

Keywords: home health care; mathematical programming; scheduling optimization

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1. Introduction

At present, as China faces the issue of the rapidly aging population and increasing of chronic diseases, the reduction of hospitalization costs becomes more and more urgent in China. Home health care has shown its potential possibilities in China as the new service model. It provides continuous effective health care that patients could obtain in hospitals; meanwhile, it also decreases the average hospitalization rate and saves the corresponding medical expenses. During the last decade, as a proven and useful method for reducing hospitalization costs, home health care service has experienced a significant growth in the USA and many European countries. Unlike the hospital health care services, home health care service providers (community hospitals, home care companies, etc.) can offer door-to-door services, such as family bed services, palliative care and day care services, which can improve patient satisfaction by breaking through the limit of fixed locations and optimizing the utilization of medical resources. Home health care services have a great significance as they could meet the clinical and psychological care demands in a personal environment of high quality services and save medical and social resources for conventional hospitalization.

The gap between the need for health care services and the capabilities of current Chinese health care resources is still immense, and the aging population makes the problem even worse. As the world's most densely-populated country, China's population was equivalent to 18.47% of the total world population as of 25 January 2017, based on the latest United Nations estimates. However, according to the report from China Daily, the medical resources of China only accounted for about three percent of the world's medical resources. In recent decades, China's demographic landscape has been thoroughly redrawn by unprecedented population changes, and the problem of a rapidly aging population has become more severe. The elderly population has grown substantially, and its share has reached about 10.5% of the total population in China. In particular, 80%–90% of the elderly population suffered from various chronic diseases, which has brought about the tremendous pressure on pension funds. According to China's elderly population and the aging career statistics in 2015, the elderly aged 60 years and older increased to 212 million, accounting for 15.5% of China's total population, which was significantly higher than the ratio in the traditional standard aging society (10%). Meanwhile, the pension services have been comprehensively increased, including pension beds, day care institutions and meal-aid services. It can be seen that these kind of medical and pension services serving the community and family would play important roles in health care in the aspects of relieving pension pressure, easing the tension between limited medical resources and increasing medical needs and improving the quality of pension and health care services.

Most studies in China focused on the qualitative description of home health care services while paying little attention to resource management or scheduling optimization in family medical care. Actually, despite a vast range of prospects in home health care services, as well as its application and development in China, relevant management optimization methods designed to make the operation of home health care more reasonable and effective are still scarce. Compared with the traditional service industry, home health care service has its own features, as well as troubles in scheduling management.

In the resource management and scheduling of home health care service, we should take various uncertain factors such as the uncertain demand, stochastic traveling time and high randomness of service time into account. In addition, there are many real constraints (time windows limit, care service priority, service consistency, workload balance, and so on). The factors mentioned above bring difficulties and challenges to home health care service management and scheduling compared with the traditional hospitalization. Therefore, it is necessary to explore research on scientific management and scheduling optimization methods to solve the problems of high randomness and a dynamic environment by taking the features of a structural network into consideration.

According to the existing research of home health care, combined with practical difficulties and features, this paper focuses on the scheduling optimization of home health care service by considering patients' priorities and time windows.

The rest of this paper will be organized as follows. A literature review is presented in Section 2. Section 3 describes the scheduling optimization model. The genetic algorithm with local search is provided in Section 4. Section 5 provides the empirical analysis and relevant results. Finally, the conclusion will be given in Section 6.

2. Literature Review

Many scholars have conducted research in the application of home health care. Chahed et al. [1] pointed out that resource planning is very important in the operation of home care organizations by properly managing human and physical resources so as to avoid the flow or the progress from poor efficiency, medical delay and low-quality service. Eveborn et al. [2,3], Bertels and Fahle [4], Thomsen [5] and Bennett and Erera [6] studied a program of human resources in home care, but they did not consider the consistency of medical service requirement. Bard and Purnomo [7,8] developed an integer programming model for the problem of scheduling nurses by using the branch and bound algorithm, the column generation method and the Lagrangian relaxation technique. Belien and Demeulemeester [9] integrated the scheduling of nurses and the operating room and solved it by the column generation method. Punnakitikashem et al. [10] established a scheduling model that involves nurses' favor and medical contraction. Hertz and Lahrichi [11] proposed a two-stage mixed programming model to distribute medical resources. Brunner et al. [12,13] made a plan of physicians' flexible scheduling. In order to make arrangements in advance, many researchers established a stochastic patients' scheduling programming model to examine patients' situations [14–25]; however, most of those studies ignored the characteristics of the home care system.

Borsani and Matta [26] proposed a human resource scheduling model of home health service in 2006. In 2009, Kergosien [27] proposed the home health care problem and extended the multiple traveling salesman problem. The article considers time windows (ti ∈ [ei, li], the earliest and the latest starting time of service i), personnel continuity and other restrictions. Bachouch and Hajri-Gabouj [28] proposed the optimal task assignment model for home health service in 2010. Although the article has taken into account the factors and key constraints, such as balancing the workload of nurses, job skills and time windows of the working day (for full-time nurses), it does not consider the condition of cost minimization. A brief summary of the related literature is shown in Table 1.

Table 1. The research summary of home health care scheduling.

Article	Decision Type	Objective	Factors Considered	Model	Solution Technique
Lanzarone et al. [29]	Human resource planning in home care	Optimize service quality of human resources	Some variables and unpredictable event	Stochastic model	Markov chain
Triki et al. [30]	Periodic home health care planning	Minimize the total cost of transportation during each time period	The adherence to the care plan while optimizing the routes	One two-stage mathematical formulation	The tabu search and a Mixed-Integer Programming (MIP)-based neighborhood search method
Liu et al. [31]	Vehicle routing problem with delivery and pickup and time windows in home health care	Improve the quality and health service at their homes	Medical logistics vehicle scheduling problem in home care	Two mixed-integer programming model	Heuristic algorithms, a genetic algorithm (GA) and a tabu search (TS) method
Liu et al. [32]	Weekly home health care logistics optimization problem	Minimize the maximal routing costs of the week	Time window constraints of patients and precedence constraints	Periodic vehicle routing problem (PVRP) model	Tabu search and different local search schemes
Cappanera and ScutellÒ [33]	Scheduling and routing optimization to home care for a weekly planning horizon	Balance the operator utilization	The assignment and the scheduling in the planning horizon	Integer linear programming (ILP) model	Cplex 12.4
Koeleman et al. [34]	Optimal patient and personnel scheduling policies for home care	Optimal control policy	Family medical human resource configuration, staff scheduling, family health service facilities	Markov decision process	Successive over-relaxation (SOR) algorithm
Hiermann et al. [35]	Multimodal home health care scheduling problem	Determine efficient multimodal tours	Staff and customer satisfaction	Mathematical modeling	Meta heuristics, simulated annealing hyper-heuristic

In addition, Ran Liu et al. [36] proposed a periodic vehicle routing problem, so as to reduce the total scheduling cost. Rasmussen et al. [37] provided the crew scheduling problem of home care based on preference-based visit clustering and temporal Dependencies. This article mainly focused on how to allocate the home health medical staff for patients in home visits to improve the overall service level. Apparently, more work needs to be done for the above proposed problem in the article. Cappanera and ScutellÒ [38] provided the optimization problem of home care model generation. In order to optimize the home care service, it also proposed that in the allocation of home care medical staff, factors such as the capacity constraint of compatibility should be considered, and the home visiting for patients should be included in the scheduled route. Matta et al. [39] simulated the home care service centers from the perspective of operation management and discussed the operational framework of home health service and the hierarchical structure of the operation management decision. Yalcindag et al. [40]

studied the problems of the assignment of medical staff and route scheduling in home care service and discussed how to solve the problems of personnel assignment and route scheduling though two-phase approaches while proving continuous (long-term) service. The purposes of this article were to explain the reasonability of these two different approaches and apply them to the doctor-seeing procedures for the assumption of a single region. Specially, the above mentioned article focused on the interaction between personnel assignment and routes. The assignment output results were included in the route scheduling inputs. During the personnel assignment, the mathematical programming model (MPM) and two different policies were used to balance the workload. Moreover, the route problem was solved by the travelling salesman model (TSM). However, this article did not consider the route scheduling problem if the selected place was much smaller. Lanzarone et al. [29] provided a patient stochastic model to support human resource planning of home care service. This article provided a nursing path for the patient of the stochastic model, which offered the main variable data prediction on the basis of the historical data of the home care structure. Nevertheless, both continuous (long-term) care service and workload balance still need further improvement. Nickel et al. [41] provided the problems of medium-term or long-term planning to support the home care service and discussed how to make medium-and-short-term plans (e.g., optimal weekly plan) by combining common heuristic algorithm and constraint model (CHACM) based on the historical data. However, it is necessary to support the research topic by using the actual data. Lanzarone et al. [42] provided the problem of operations management for home care service and discussed how to balance the workload of the medical staff by selecting the mathematical programming model (MPM) of a specific category. This model took some features, such as continuous services, skills of the medical staff and geographic areas of the home health service into consideration. However, considering that the patient demands are either stochastic or certain, the stochastic patient demands cannot be satisfied in the above article. Yuan et al. [43] provided the home care time arrangement and route scheduling problems under random service time. The article minimized the travel cost and the predicted tardiness penalty by establishing a stochastic programming model (SPM) and suggested that the branch and bound method (BBM) could solve the problem.

Akjiratikarl et al. [44] adopted the particle swarm optimization (PSO)-based algorithm to solve the home care worked scheduling problem. Duque et al. [45] presented a decision support system for the home care service planning problem by considering the service level and travelling distance. Braekers et al. [46] provided the method of the trade-off of cost and service level and formulated a bi-objective scheduling problem. Rest and Hirsch [47] presented a model for daily scheduling of a real-world home health care problem. Redjem and Marcon [48] developed a heuristic method for solving caregivers' routing of home care services. Yalçındağ et al. [49] adopted a data-driven methodology for estimating uncertainties in traveling times so as to solve the patient assignment problem. Mankowska et al. [50] presented a model for the routing and scheduling problem of home health care by considering interdependent services. Trautsamwieser and Hirsch [51] provided a model for optimizing the daily nurse scheduling of home care services. Nguyen and Montemanni [52] presented two mixed integer linear programming models to solve the home care services planning problem. Addis et al. [53] discussed how to deal with uncertainty factors by adopting the cardinality-constrained method for the health care optimization problem.

This study aims to carry out more extensive research by considering several real situations based on the existing articles. The primary model and calculation method are presented in Section 3.

3. The Scheduling Optimization Model

3.1. Problem Definition

At present, home health care in Shanghai, China, mainly relies on the family doctor studio in community health care service centers. A family doctor studio is equipped with 2–3 general medical practitioners, who would provide medical care according to patients' appointments. The types of services are divided into family beds and health records. On average, a doctor may visit 10–15 families that have signed health care service contracts with family doctors. According to the "Guiding Opinions on Promoting the Contractual Healthcare Services from Family Doctors" issued by the State Council of China, the home health care services are regulated based on health care contracts. Residents and families shall choose a team of family doctors to sign the health care service agreements, in which the content, manner and time limit of the contractual health care services, as well as the responsibilities, rights and obligations of both parties and other relevant matters have been clearly defined. In principle, the contractual health care service is valid in a one-year term. When the original contracts expire, residents and families can choose to extent the contracts or change health-care providers. After the completion of the medical care for all patients, the service personnel will return to the family doctor studio.

Therefore, this scheduling problem can be abstracted as a multiple traveling salesman problem (MTSP). MTSP is defined as: "there are n nodes and m traveling salesmen, who start working from a particular starting point. After the salesmen have visited the destinations, they come back to the starting point. The goal is to find such an amount of access paths, which satisfy the requirements that each salesman can visit a place only once in order to minimize the total cost" [54]. This paper aims to construct a model with time windows to solve the personnel scheduling problem of home health care services.

3.2. Mathematical Programming Model

One of the common problems in home care service is how to schedule the medical staff and arrange their routes to minimize the travel cost, as well as service cost. This paper attempts to establish a route scheduling model to solve this problem.

The model is constructed based on the following basic assumptions:

(1) Only one type of service is required by each patient per time;
(2) The time that it takes the doctors to reach any two patients respectively is the same;
(3) Service will be started immediately after the medical staff arrive at the patients' homes;
(4) Medical staff are enough to meet all demands.

Subscripts:

i represents the previous service-required place (departure place);
j represents the next service-required place (destination) ($i, j \in P = \{0, 1, \ldots, n\}$;
0 represents the service center;
h represents the medical staff ($h = 1, \ldots, H$);
k represents the type of service ($k = 1, \ldots, K$);

Parameters:

$c1_{ij}$ represents the travel cost from place i to place j to provide service to patients;
$c2_{hk}$ represents the cost for medical staff h to provide the k-th service;
t_{ij} represents the travel time from service center i to service-required place j;
τ_j represents the execution time of the service required by the j-th patient;
w_i represents the required waiting time of the service personnel arriving at service nodes early;
e_i represents that patient i can accept the earliest starting time;
l_i represents that the patient can accept the latest starting time, which constitutes the time window requirements of the provision of each patient service;
S_i represents the time that the medical staff take to reach service-required place i, and $S_1 = e_1$;
D_i represents the time that the medical staff take to leave service-required place i; $S_i \in [e_i, l_i]$, $D_i = \max\{A_i + \tau_i, e_i + \tau_i\}$, in which e_i represents the earliest starting time accepted by the i-th patient; l_i represents the latest starting time accepted by the i-th patient;

y_{jhk} represents whether the service k can be provided by the medical staff h for the service-required place j (0: no, 1: yes), and y_{jhk} is the input parameter;

r_{ij} represents whether the service-required place j has priority over the service-required place i (0: yes, 1: no), and r_{ij} is the input parameter that can be determined in advance;

Decision Variables:

$$x_{ijhk} = \begin{cases} 1 if\ the\ medical\ staff\ h\ who\ provides\ service\ k\ passes\ the\ places\ (i,j) \\ 0 otherwise \end{cases}$$

The mathematic model is given as follows:

$$\min \sum_{i\in P}\sum_{j\in P}\sum_{h\in H}\sum_{k\in K}(c1_{ij}+c2_{hk})x_{ijhk} + \sum_{i\in P}\sum_{h\in H}P_i(s_i) \tag{1}$$

The constraints are given as follows:

$$\sum_{j\in P}\sum_{h\in H}\sum_{k\in K}x_{ijhk} = 1 \qquad \forall i \in P\backslash\{0\} \tag{2}$$

$$\sum_{i\in P}x_{ijhk} - \sum_{i\in P}x_{jihk} = 0 \forall j \in P\backslash\{0\}, k \in K, h \in H \tag{3}$$

$$\sum_{j\in P}\sum_{k\in K}x_{0jhk} = 1 \qquad \forall h \in H \tag{4}$$

$$\sum_{j\in P}\sum_{k\in K}x_{j0hk} = 1 \qquad \forall h \in H \tag{5}$$

$$\sum_{i\in Q}\sum_{j\in Q}\sum_{h\in H}\sum_{k\in K}x_{ijhk} \le |Q| - 1 \forall Q \subseteq P\backslash\{0\}, k \in K, h \in H \tag{6}$$

$$w_j = max(e_j - s_i - t_{ij},\ 0) \forall j \in P\backslash\{0, \mathrm{i}\} \tag{7}$$

$$\sum_{i\in P}\sum_{h\in H}\sum_{k\in K}x_{ijhk}(s_i + t_i + t_{ij} + w_j) = s_j \quad \forall j \in P\backslash\{0, \mathrm{i}\} \tag{8}$$

$$P_i(s_i) = p \times w_i + q \times max(s_i - l_i,\ 0) \tag{9}$$

$$x_{ijhk} \le y_{jhk} \qquad \forall i \in P, j \in P\backslash\{0\}, k \in K, h \in H \tag{10}$$

$$D_i + t_{ij} + t_j \le r_{ij}D_j \qquad \forall i \in P, j \in P\backslash\{0\} \tag{11}$$

$$s_i \in [8, 18] \qquad \forall i \in P \tag{12}$$

$$x_{ijhk} \in \{0, 1\} \forall i, j \in P, k \in K, h \in H \tag{13}$$

Formula (1) in the purposed model is to minimize the travel cost (C1), service cost (C2) and penalty cost and fully meet all patients' demands at the same time.

Constraint (2) represents that each patient should be serviced by medical staff exactly once.

Constraint (3) represents that the medical staff must leave immediately after reaching one service-required place.

Constraints (4) and (5) represent that the medical staff only can leave and return to the service-required place once, respectively.

Constraints (6) denotes the sub-tour elimination constraint.

Constraints (7)–(9) represent the time window constraint.

Constraint (7) calculates the required waiting time of the service personnel arriving at the service nodes early.

Constraint (8) gives the time of delivery service personnel arriving at each demand point.

Constraint (9) calculates the penalty of the medical staff if they arrived early or late at the demand points, in which p is the penalty coefficient of arriving early and q is the penalty coefficient of arriving late.

Constraint (10) represents that the medical staff can offer visiting services only if he or she is a licensed qualified health care professional.

Constraint (11) is the time window restriction, which restricts the earliest departure time at each service-required place for the medical staff. Priority *r* represents that the medical staff must leave for the service-required place with higher priority to provide service. The priority levels in the analytical approach of this paper are identified and determined by the seriousness of the patients' conditions. In other words, we ensure that patients with more serious conditions are accorded higher priority in medical treatment. Specifically, we divide patients into two categories with different priorities: emergency patients and non-emergency patients. Emergency patients are the top priority compared to non-emergency patients. If the serious conditions of emergency patients are equivalent, the priority classes are comprehensively determined based on factors, such as the appointment time of patients, the location of patients and the medical resources of health care service centers. The priority levels of non-emergency patients are usually determined by the appointment time of patients.

Constraints (12) and (13) represent the value ranges of the variables.

4. The Genetic Algorithm with Local Search

The proposed model in this paper is the variation of a multi-traveling salesman problem. If we relaxed the constraint of patients' priorities, the problem of "scheduling optimization of home health care service considering patients' priorities and time windows" will turn into the "multiple travelling salesman problem (MTSP) with time windows" [55]. Since the traveling salesman problem (TSP) with time windows has been proven to be a strongly NP-hard problem [56,57], we can concluded that the problem for our research is also NP-hard. Namely, "under the assumption of the $P \neq NP$, we cannot find an algorithm which can get the optimal solution in polynomial time." Although the optimal solution can be obtained by the exact algorithm, its running time is exponentially complex. Therefore, the improved genetic algorithm can be used to solve the constructed model during the large-scale solution.

The genetic algorithm is a kind of random search method, which is based on the survival of the fittest and evolved from the biological world. Goldberg summed up a basic genetic algorithm, and its structure is simple, which is the basis of other genetic algorithms and the prototype [58]. A population-based algorithm enhanced with a local search structure is applied to the research problem in this paper for the following three reasons: first, the method of the hybrid genetic algorithm (HGA), which integrates GA (the global optimization algorithm) with local search (the local optimization), has been adopted by many scholars to solve the problem of home health care [59–62]; second, compared to the tabu search/path-relinking (TS/PR), the method of HGA requires shorter computational time to solve the problem, but it obtains solutions with lower quality in the same computational time limit [63–66]; third, the problem proposed in this paper is mainly to meet the time requirements of families in health care services, which can be solved by the method of HGA [49,67]. However, considering the advantages of TS/PR, we would try to adopt TS/PR to deal with the research problem in our future research to further improve the quality of solutions.

This paper refers to the basic genetic algorithm with local search, and the constructed iterative process is shown in Figure 1.

Algorithm: Genetic algorithm with local search (HGA) for home care serivce scheduling

Main Procedure

Step 1 *Initialization*

Input parameters: population size *ps*, stopping criteria T_{max} and so on

Generate initialization population using heuristic and random method

Calculate fitness and give ranking

Make the diversity of the population

Step 2 *Selection Operator*

Select chromosomes using the roulette selection operators P_1 and P_2

Step 3 *Crossover Operator*

Apply crossover strategy for the chromosomes to get two offsprings C_1 and C_2

Step 4 *Local search and mutation*

If Generate a random number (0,1) is less **than** q, then execute local search.

If the fitness can not be changed for 5 generations, **then** execute mutation operator.

Step 5 *Procedure termination and output*

Meet termination conditions/Output the best solution

Figure 1. The general framework of the hybrid genetic algorithm (HGA).

Several main procedures can be given as follows:

(1) The population structure and chromosome coding:

The first step is to initialize the population of chromosomes, and the key problem is how to encode the chromosomes. In order to solve the MTSP problem using the genetic algorithm, the general method is converting MTSP to the TSP problem; that is, the virtual symbol is added for coding.

Assume that Point 0 represents that there is no demand for the health service center of home care service staff, while points 1, ..., n represent that there are 1, ..., n demand points for the m-th service personnel to visit. Then, a total of $m - 1$ virtual symbols are to be set, respectively, $n + 1$, ..., $n + (m - 1)$. Each virtual symbol appearing in the medical personnel access path indicates that the medical staff return to the health service center to form a loop. Figure 2 represents the chromosome encoding. Specifically, the first medical staff would return to the health service center after visiting Point 2 and then Point 1; the second medical staff would return to health service center after visiting Point 6, Point 4 and then Point 5.

2	1	n + 1	6	4	5	n + 2	…	n

Figure 2. The chromosome encoding.

During the coding, we need to pay attention to avoid the problem of medical staff working overtime, as well as the ordinary sub-path of the situation, that is, the medical staff did not visit any demand points directly before they return to the health service center. In the programming, the fitness of these two cases will be set to the maximum value to eliminate such a chromosome.

(2) Selection operator:

The selection operator is used to reproduce the individuals who have a high degree of adaptability from the old population to the new population. The target of this model is to minimize the cost; therefore, the fitness function $f(x) = 10/Z$ is used for the fitness of the chromosome.

The roulette selection operator is used in this paper [68]. It uses the proportion of each individual's fitness to determine the probability of its future generations. The execution of a selection operator is like spinning the wheel to select a chromosome. In addition, the best individual elitist preservation strategy is considered in this paper [69], which is selected on behalf of the population to the highest degree of individual and directly copied to the offspring. It ensures the best individual smoothly enters into the next generation and thereby speeds up the convergence of the population and improves the efficiency of the algorithm.

(3) Crossover operator:

The relevant crossover strategy is adopted in this paper [70–72], which can increase the population diversity without changing any certain part's order of its parent. This method will speed up the algorithm convergence. The specific steps are given as follows:

Randomly select A code from Parent Generation B; keep them in the corresponding location of the Filial Generation A. In order to ensure that two of the same chromosome can cross to produce different offspring, we consider switching the third part of Parent Generation A with the first part of Parent Generation B. After that, the rest of the parts of Filial Generation A can be selected from Parent Generation B in order (skip existing codes), and the selection of Filial Generation B is one in the same way.

- Before crossing:

  Parent Generation A: 872,139 | **546**

  Parent Generation B: **983** | 567,142
- After crossing:

  Filial Generation A: 721,546 | **983**

  Filial Generation B: **546** | 983,712

(4) Local search and mutation:

The local search is adopted with a fixed probability in HGA. If a generated random number (0, 1) is less than q, then the local search will be executed. The two-opt exchange will be used for local search; more detailed information can be found in [73–76]. The two-opt exchange for our research is executed in the case of a single route by replacing two of its arcs in the tour using two other arcs [77,78]. For example, let us assume that there is a single route consisting of many demand nodes with a given order for one health care service center, and the $\{(p, p+1); (q, q+1)\}$ is traversed in this order, which forms a crisscross [79]. The two-opt exchange will eliminate the crisscross of the arcs $(p, p+1)$, $(q, q+1)$ by replacing them with (p, q), $(p+1, q+1)$ to reconnect a new route [80]. The same method can be used for multiple different routes for the local search. Especially, if the fitness cannot be changed for 10 generations, then the system will execute the mutation operator. For mutation operation, the multiple exchange mutation operator is adopted. We randomly select two parts from the chromosomes, then exchange the gene from the two parts and repeat the process a few times.

(5) Terminate evolution conditions:

Considering that the genetic algorithm is an iterative process, we must set the appropriate termination of the evolution conditions to terminate the algorithm. When the algorithm meets the termination conditions set, individuals who have the largest fitness during the evolutionary process will be given as the optimal solution, and the calculation will be terminated.

In this paper, we set up the following two termination rules:

(1) It has reached the predefined evolution generations, namely 3000 generations.
(2) The best individual of the population cannot obtain more improvements in 200 consecutive generations.

5. Empirical Analysis

5.1. The Analysis of the Calculation Results

In order to verify the proposed model, the Yichuan sub-district located in eastern Putuo district, Shanghai, China, is used for empirical analysis, which has 1.12 square kilometers with about 26,900 households and 87,800 residents. There are 20 neighborhood committees in this sub-district. In the numerical examples, we assume that the Yichuan street community health service centers are equipped with five home health care providers, who need to provide 30 patients with family beds or health archive services. The red dots in Figure 3 represent the home health service-required places in this paper to study the home health care assignment problem of Yichuan sub-district, Shanghai, China.

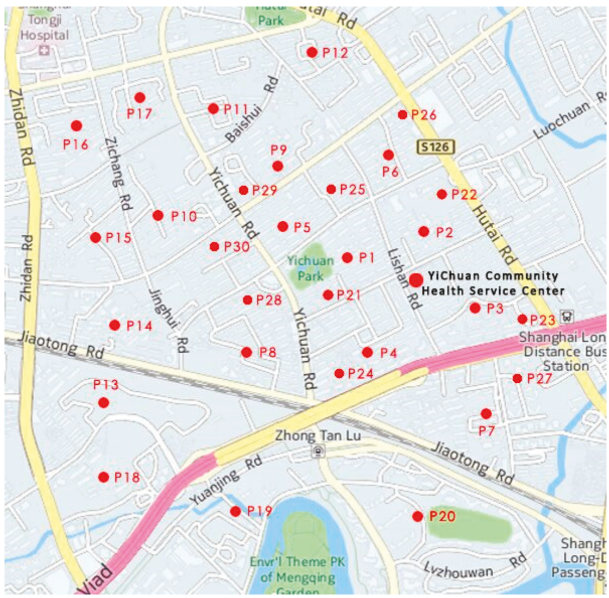

Figure 3. Yichuan road street area and the distribution of community health service centers. ***Note:*** P in the figure denotes the demand point in the Yichuan road street area.

This paper takes the Yichuan Sub-district Community Health Service Center (a first-level medical institution) as the service center to provide home health care services. This center has convenient service stations. These stations can supply guiding services, medical advice, business information consultation and other handy services for the patients initiatively. Meanwhile, those patients who are unable to move freely or have special needs can be paid home visits though telephone appointments and can be provided with all kinds of visiting services, such as hospital beds and medical tests at home.

This paper assumes that the certain service demand of each service-required place can be processed centrally within a certain period of time. There are five medical staff in the service center, of which, the mastered skills are summarized in Table 2.

Table 2. Relevant data of service staff.

Service Staff	Mastered skills
h1	Home Treatment
h2	Home Treatment, Health Record
h3	Hospital Bed at Home
h4	Hospital Bed at Home
h5	Hospital Bed at Home, Health Record

The parameter settings for the model and algorithm are listed in Tables 3 and 4. The first dataset of five medical staff in Table 2 and the positions of health care service demands (P1–P30, the 1st demand point to the 30th demand point) in Figure 3 are provided by the Yichuan Sub-district Community Health Service Center, Shanghai, China; whereas the second dataset is generated randomly. Specifically, the exact location of each patient is randomly sampled in the selected district from a normal distribution with the mean and standard deviation, respectively. The number of medical staff is also randomly generated based on the small-scale (A.3.3–A.5.45), medium-scale (B.3.50–B.8.80) and large-scale (C.9.90–C.12.120) instances.

Table 3. Parameter setting for the model.

Parameter	Value
The service hours for hospital bed at home (k1) (hour)	0.5
The service hours for health record (k2) (hour)	0.3
travelling speed (km/h)	8
Unit travel costs (RMB/km)	2
The penalty coefficient for early arrival	1
The penalty coefficient Late arrival	2

Table 4. Parameter settings for the algorithm.

Parameter	Value
The size of population	500
The probability of crossover	0.5
The probability of mutation	0.5
Termination generation	3000

Using Eclipse IDE to make a Java program running on Windows 7 operating system, it takes 2.4 s to reach the results. The optimal results of route scheduling can be obtained (shown in Table 5 and Figure 4).

In order to further verify the proposed model, we assume that there are three care givers and 50 patients in the Yichuan Sub-district Community Health Service Center, Shanghai. We also use the same Java program to run this model. The optimal results of route scheduling are shown in Table 6, and the time windows of each node are presented in Table 7.

Table 5. The calculation results.

Route	Node i	Node j	Service Personnel	Service Type
P0→P20(K1)→P24(K1)→P19(K1)→P18(K1)→P28(K1)→P8(K1)→P0	0	20	h1	k1
	20	24	h1	k1
	24	19	h1	k1
	19	18	h1	k1
	18	28	h1	k1
	28	8	h1	k1
	8	0	h1	k1
P0→P2(K1)→P26(K1)→P6(K1)→P27(K1)→P7(K1)→P0	0	2	h2	k1
	2	26	h2	k1
	26	6	h2	k1
	6	27	h2	k1
	27	7	h2	k1
	7	0	h2	k1
P0→P3(K1)→P4(K1)→P1(K1)→P0	0	3	h3	k1
	3	4	h3	k1
	4	1	h3	k1
	1	0	h3	k1
P0→P12(K2)→P11(K2)→P14(K2)→P13(K2)→P15(K2)→P21(K2)→P25(K2)→P22(K2)→→P23(K2)→P0	0	12	h4	k2
	12	11	h4	k2
	11	14	h4	k2
	14	13	h4	k2
	13	15	h4	k2
	15	21	h4	k2
	21	25	h4	k2
	25	22	h4	k2
	22	23	h4	k2
	23	0	h4	k2
P0→P9(K1)→P5(K1)→P16(K1)→P17(K1)→P10(K1)→P29(K1)→P30(K1)→P0	0	9	h5	k1
	9	5	h5	k1
	5	16	h5	k1
	16	17	h5	k1
	17	10	h5	k1
	10	29	h5	k1
	29	30	h5	k1
	30	0	h5	k1

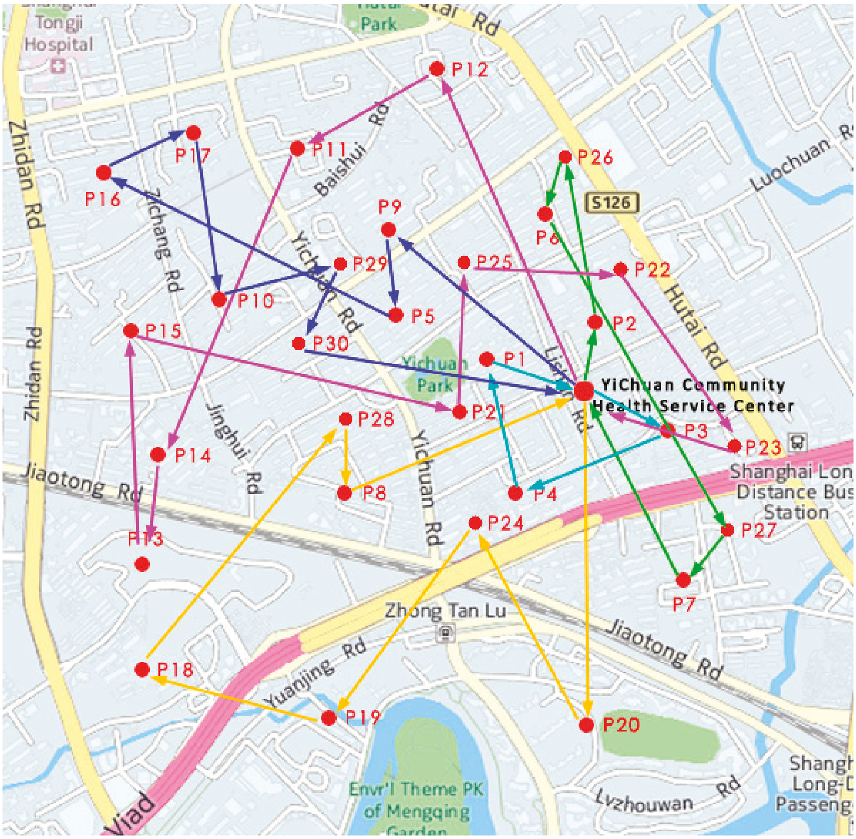

Figure 4. The schematic diagram of the optimal result for route scheduling.

Table 6. The optimal results of route scheduling.

The Target	Results
Final generation	2904
Minimum cost	48.0
Route 1	P0→P22(K1)→P1(K1)→P21(K1)→P15(K1)→P16(K1)→P36(K1)→P34(K1)→P43(K1) →P8(K1)→P49(K1)→P17(K1)→P35(K1)→P37(K1)→P10(K1)→P30(K1)→P26(K1) →P6(K1)→P32(K1)→P5(K1)→P28(K1)→P13(K1)→P38(K1)→P0
Route 2	P0→P18(K1)→P45(K1)→P33(K1)→P44(K1)→P14(K1)→P48(K1) →P19(K1)→P4(K1)→P42(K1)→P11(K1)→P31(K1)→P12(K1)→P2(K1)→P3(K1)→P0
Route 3	P0→P9(K1)→P25(K1)→P23(K1)→P47(K1)→P46(K1)→P24(K1)→P41(K1)→ P50(K1)→ P27(K1)→P7(K1)→P40(K1)→P20(K1)→P39(K1)→P29(K1)→P0

Table 7. The time window of each node.

Route	Node	Earliest Starting Time	Latest Starting Time	Service Personnel	Service Type
Route 1	P22	8	11	h1	k1
	P1	8	11	h1	k1
	P21	8	12	h1	k1
	P15	8	11	h1	k1
	P16	9	12	h1	k1
	P36	8	12	h1	k1
	P34	10	16	h1	k1
	P43	8	12	h1	k1
	P8	9	12	h1	k1
	P49	12	15	h1	k1
	P17	10	13	h1	k1
	P35	13	17	h1	k1
	P37	13	16	h1	k1
	P10	10	14	h1	k1
	P30	13	16	h1	k1
	P26	12	15	h1	k1
	P6	9	15	h1	k1
	P32	15	18	h1	k1
	P5	10	16	h1	k1
	P28	14	17	h1	k1
	P13	13	17	h1	k1
	P38	14	17	h1	k1
Route 2	P18	10	14	h2	k1
	P45	8	11	h2	k1
	P33	9	15	h2	k1
	P44	9	15	h2	k1
	P14	8	12	h2	k1
	P48	10	14	h2	k1
	P19	12	15	h2	k1
	P4	9	15	h2	k1
	P42	13	17	h2	k1
	P11	12	15	h2	k1
	P31	14	17	h2	k1
	P12	13	16	h2	k1
	P2	14	17	h2	k1
	P3	15	18	h2	k1
Route 3	P9	10	13	h3	k2
	P25	10	14	h3	k2
	P23	9	12	h3	k2
	P47	10	13	h3	k2
	P46	9	12	h3	k2
	P24	10	13	h3	k2
	P41	10	16	h3	k2
	P50	10	16	h3	k2
	P27	13	16	h3	k2
	P7	10	16	h3	k2
	P40	9	15	h3	k2
	P20	13	17	h3	k2
	P39	15	18	h3	k2
	P29	15	18	h3	k2

The minimum cost and the algebraic relationship are shown in Figure 5. As shown in Figure 5, the cost of the first generation is as high as 9262 due to the high time-windows penalty. After 15 generations of evolution, a sharp drop appears in the cost. The cost fluctuation tends to be stable at the 77th generation, and we obtained the optimal solution at the 2904th generation. The convergence of the experiment proved that it is feasible to adopt the genetic algorithm to solve this issue.

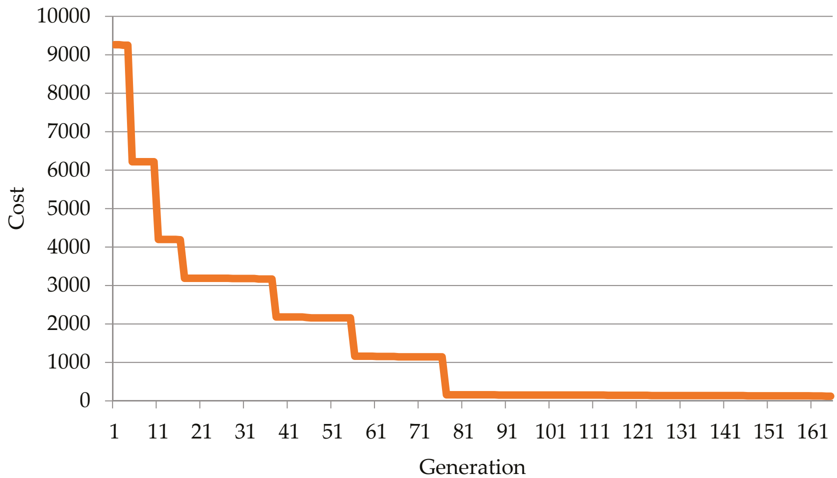

Figure 5. The convergence trend for evolution.

In the analysis of the paramedics arrival time for each demand point, we can find that no medical staff's arrival time go beyond the latest starting time, which means that the model ensured the travel arrangements in accordance with the time window constraints of the maximum extent, effectively improving patient satisfaction; indicating the reliability of algorithm.

5.2. Comparisons of Schedules' Quality

At present, most scheduling of home health care service was performed by manual operation, which is time-consuming and cannot produce better results. Additionally, commercial optimization software (like the Cplex solver) can obtain the best solution with small-scale demand points. In order to further verify the proposed model and algorithm, we compare the scheduling quality by considering different demand points of home care service based on two main criteria: cost and time [81]. The performances of the three methods (HGA, GA and Cplex) were compared using the same datasets. Each method is experimented on 20 times. The average calculation results are regarded as the final results. The mean computation times (min), recorded for Cplex, GA and HGA, are given in Figure 6.

As shown in Figure 6, we can see that the average calculating time of HGA is less than those of the methods of GA and Cplex for small-scale demand points. Especially, with the increasing demand points, the average calculating time of HGA is relatively stable; meanwhile, there is a sharp surge in the average calculating time of Cplex. In addition, when the demand points are more than 40, Cplex would not obtain any results.

The average error with different demand points is shown in Figure 7.

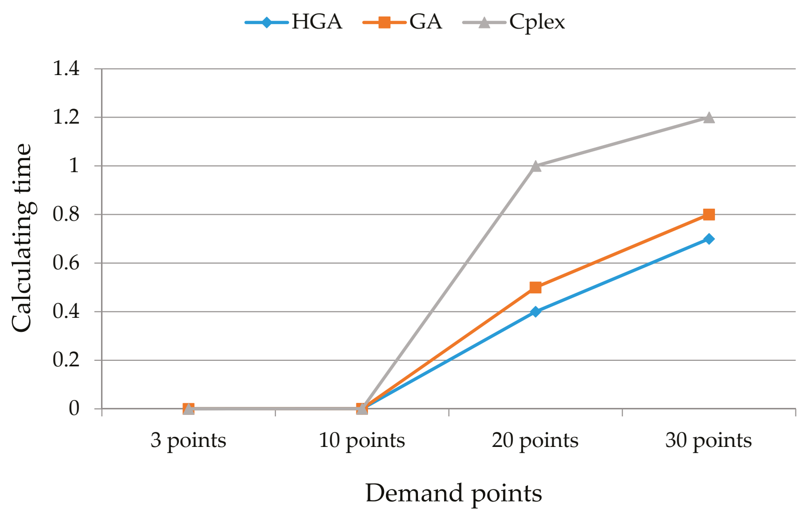

Figure 6. The average calculating time of different methods with three home health care providers.

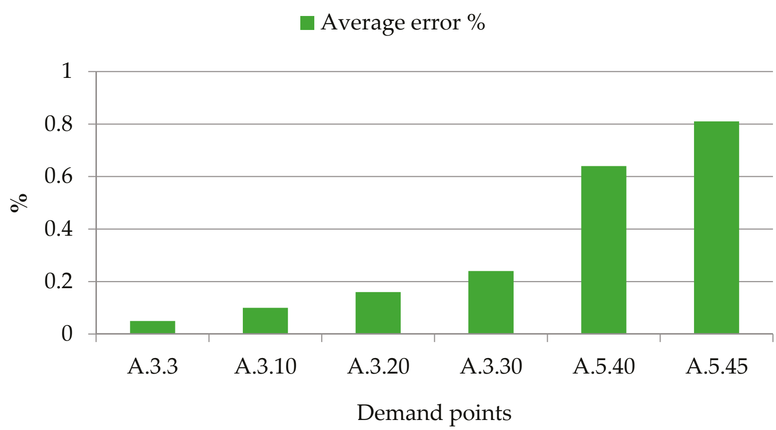

Figure 7. The average error with different demand points.

The group (instance A.3.3–A.5.45) in Figure 7 represents the small problem instances with 3–45 patients. A.3.3 means that there are three care givers and three patients and one health care center. From Figure 7, we can see that the maximum average error for all of the groups for small problem instances is less than 0.81%. For the medium-sized instances (from B.3.50–B.8.80) and the large-sized instances (from C.9.90–C.12.120), Cplex cannot give the solution. As shown in Table 8, the calculation results of HGA are superior to GA under any circumstance. The average error is smaller than the standard GA. Therefore, the proposed model and HGA can be validated.

Table 8. The comparisons of the calculation results of different algorithms.

Instance	Cplex	GA	HGA
B.3.50	-	50 ± 0.61	48 ± 0.23
B.5.60	-	69 ± 0.45	66 ± 0.18
B.6.70	-	76 ± 0.39	71 ± 0.22
B.8.80	-	96 ± 0.27	88 ± 0.14
C.9.90	-	123 ± 0.28	102 ± 0.23
C.10.100	-	165 ± 0.51	122 ± 0.45
C.12.120	-	188 ± 0.42	141 ± 0.29

Currently, the dispatch of medical staff is fulfilled by manual scheduling. On the one hand, it cannot avoid the occurrence of inevitable errors; on the other hand, reasonable scheduling is hard to attain because the demand is random and uncertain. When the health care service demand is high, patient wait time would be longer, and the emergency patients would not obtain timely medical treatment. The model constructed in this paper considers the time windows of patients (the shortest and longest time limitations). The solution results can meet the requirements of patients on the medical service time. In particular, the model considers the priority levels of different patients, so that it could effectively arrange the order of medical treatment. In this way, patients' priority levels (prioritization) are determined by the seriousness of the patients' conditions, and the patient wait time can be effectively improved, which is conducive to improve the patient satisfaction. To summarize, the optimization method of this paper can improve patient wait time and patient satisfaction degrees and, thus, help save medical cost due to delayed treatment. Patient satisfaction is an important and commonly-used indicator for measuring the quality in health care. Although patient satisfaction is multi-dimensional [82–84], four indexes are usually used to measure the patient satisfaction in home health care [85]: response time, patient wait time, service quality and service price. In general, response time is affected by factors, such as the level of convenience in contact and the number of medical staff. Patient wait time, a quality indicator of home health care service, is influenced by location planning of home health care service centers, as well as the dispatch of medical staff. Service quality in home health care is affected by levels of health care workers and the degree of advancement of medical equipment. Service price is influenced by the pricing scheme or the price specifications regulated by the government.

6. Conclusions

Under the constraint of scarce medical resources, home health care can offer convenient and effective medical services to the elderly and other special groups with less investment. In addition, reasonable arrangements for nurses and their routes not only can reduce input costs, but also can improve the degree of patient satisfaction. In order to solve this problem, this paper conduct research on the scheduling optimization problem of home health care. The proposed model can optimize the scheduling of home health care staff, and the genetic algorithm with local search was used to solve this model. In addition, some uncertainties of services and traveling time should be considered in the further study. In particular, how to establish a stochastic programming model to find the most effective solutions to the problem will be an important research direction.

Notably, it is also necessary to compare the home health care system vs. the hospital system for a period of time to comprehensively analyze the advantages and disadvantages of the home health care system. Although there are several comparisons in the literature between the home health care system and the hospital system, more detailed comparisons are still needed to provide policy implications for the development of home health care. For instance, Benbassat and Taragin [86] found that the home health care system can reduce readmissions and improve the care quality with less expenditure. Starfield and Shi [87] considered effectiveness, costs and equity for home health care and found that better health and lower overall costs of care could be achieved by home health care. Bruce et al. [88]

found that "poor medical and functional status for the patient" is the major disadvantage of home health care compared to the hospital system. In this paper, we mainly focus on the improvement of the efficiency, as well as the quality of home health care based on the proposed model and methodology. In order to test the effectiveness of the proposed model, we conducted a survey about the implementation effect of the optimization method and found that the home care system can reduce the care cost and improve patient satisfaction by providing more efficient and convenient services. Considering the big data requirements, we will try to compare the home health care system vs. the hospital system for a period of time in our future research.

In addition, we would like to consider more factors, such as the workload of the medical staff, in order to balance the time window constraints and the optimal allocation of health care personnel using the improved intelligent optimization algorithm [89,90] according to the actual needs of the situation [91,92] in the future research.

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Moderating Effects of Trust on Environmentally Significant Behavior in Korea

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Abstract: To treat environmental problems and to seek sustainable development, voluntary and cooperative efforts, which is really against the traditional mentality with the emphasis on the individual competitive optimization, became the key to maintain the sustainability of complex social and ecological systems. To understand the cooperative and voluntary individual's environmentally significant behavior (ESB), this paper focuses on the role of trust, and assesses the effect of trust on the relationship between existing factors and ESB. A structural equation model (SEM) is constructed to estimate the moderating effects of trust on ESB in Korea. We found that people with a negative view on strict environmental regulations do not exhibit ESB and thus nudge policies could be much more effective than the forceful measure. It is noteworthy that public private partnership, as a kind of optimal trust, should be more promoted in the environmental protection policies.

Keywords: environmentally significant behavior (ESB); public private partnership (PPP); trust; structural equation model (SEM); Korea

1. Introduction

The core characteristics of the modern society manifested in science, technology, industrial capitalism, market economy, and bureaucratic society are indebted to the "enlightenment mentality". The mentality linked with our modern values and consciousness makes us believe that we can handle social problems through scientific and technological methods advanced with economic development [1]. Unfortunately, this instrumental mentality has been equally applied to the method of dealing with environmental problems that threaten our future survival. However, technological advancement itself is not sufficient to solve modern environmental problems such as natural resource depletions and global climate change [2]. These problems, which are embedded in a combination of complex social-ecological systems with multiple subsystems and internal variables within these subsystems, demand collaborative governance where resource users participate in developing rules and norms for managing the resources [2,3]. Policy solutions with one-size-fit-all recommendations are likely to fail to achieve environmental sustainability without voluntary and cooperative participation from the public.

The importance of the involvement of citizens in environmental policy is related to the growing challenge faced by government in terms of handling environmental problems. Environmental problems characterized by multiple stakeholders and scientific uncertainty make it harder for government to determine levels and methods of regulations [4]. As a response, scholars turn their attention to citizens' involvement in promoting environmental conditions. They argue that the promotion of environmentally significant and responsible behavior can draw on collaborative environmental governance, which is an alternative to the failures of top-down methods of government regulations [5].

As such, there is a growing interest in individuals' environmentally significant behavior (ESB) ranging from reduced consumption to the purchase of energy-efficient products [6,7]. ESB involves changes in environmental practices and lifestyles that lead to positive consequences of the environment. However, despite the positive implications of ESB, one that hinders further facilitating the behavior is related to the public nature of ESB. That is, rational and self-interested individuals are less willing to endure inconvenience from reducing consumption and paying more for environmentally friendly goods for the sake of promoting such common goods as the environment. Rather, individuals want to merely enjoy benefits from ESBs without paying their own costs [8–10]. So this challenge raises the following questions: how can ESB be facilitated? Why some individuals engage in this environmentally responsible behavior and others do not? This study pays special attention to trust and its moderating effects on ESB. Researchers from diverse academic fields have examined the factors affecting on ESB. Most of these studies focused on environmental values and psychology and socio-demographic factors. Recently, several scholars pay attention to trust as a means to understanding environmental behavior [11–14]. However, these studies are mainly conducted in western contexts and thus their results and implications may not be applicable to Asian contexts.

Thus, this study focus on the moderating effects of trust on the relationships between existing factors and ESB using the National Survey of Environmental Behavior conducted in South Korea (hereafter Korea). It constructed a structural equation model to estimate the moderating effects.

2. Theoretical Review and Hypotheses

2.1. The Concept of ESB

Environmentally significant behavior (ESB) involves individuals' voluntary and proactive behavior toward allocating and managing environmental resources in a socially sustainable manner and goes beyond present regulatory requirements, thereby playing an important role in promoting environmental sustainability. Recently, ESB has received increasing attention from scholars as a feasible and practical complement to regulatory regimes in dealing with nontraditional environmental issues such as climate change; that is, those issues characterized by weak regulatory regimes and environmental leadership based mainly on some disagreement over methods for addressing them and the level of responses [4].

ESB is defined by its impact and intention [6]. The former describes the extent to which the individual's environmental behavior is altered to address environmental change either directly or indirectly. Direct environmental impacts of individuals are introduced by practicing sustainability in their everyday lives, including reductions in material consumption and pollution-causing activities. In addition, environmental enhancement can be achieved indirectly by shaping the context in which decisions that affect the environment are made [6,15]. Individuals can influence public policies that are directly or indirectly associated with the environment by participating in the policymaking process. For example, policies concerning the local transport and waste management infrastructure can affect patterns of behaviors such as personal travel and waste disposal [16]. Similarly, diverse market provision systems may influence individuals' attitude on environmental-friendly consumption.

In addition, individuals can engage in ESB with the intention to affect the environment. This environmental intention can trigger an individual to take environmental action, but it does not necessarily lead to actions with environmental impacts [6]. For example, individuals may report their willingness to make "green" purchases and engage in other pro-environmental behaviors, but such intentions often fail to translate into actual behaviors. The discrepancy between environmental intentions and behaviors has been widely discussed [6,17].

With the definition of ESB, it can be classified into four coherent subtypes based on a two-by-two table as shown in Table 1. The vertical dimension distinguishes between inactive behaviors describing environmental intentions and active ones that lead to some action producing an environmental impact. The horizontal dimension focuses on domains in which individuals' environmental behaviors, ranging from private to public, occur. First, behaviors in the private sphere involve actions that directly cause environmental impacts by shifts in personal lifestyles that practice "voluntary simplicity" either dramatically or incrementally. Such behaviors entail the personal curtailment of consumption (e.g., water and meat) and the use/purchase of environmentally friendly products [6,18]. Second, behaviors in the public sphere involve actions that cause environmental impacts indirectly through the public domain, including participation in the public policymaking process through various means such as environmental protests, environmental petitions, and donations to environmental organizations [6]. Combining these two dimensions, the present study classifies four types of ESBs: no active ESBs in the private sphere, no active ESBs in the public sphere, active ESBs in the private sphere, and active ESBs in the public sphere. The study pays special attention to active ESBs in the private sphere, including personal constraints on consumption (PCC) and personal green consumerism (PGC). Recently, both policymakers and scholars have recognized these two types of ESBs as important for environmental sustainability. Without drawing on individuals' voluntary efforts to change their unsustainable level of consumption, any initiatives involving policies and technologies are likely to fail.

Table 1. Types of ESB.

	Private Sphere	Public Sphere
No Action (Intention)	Provide support for using green products (e.g., willingness to pay higher prices for "green" products)	Provide support for environmental policies (e.g., willingness to pay higher environmental taxes and the acceptance of environmental regulations)
Action	1. Personal constraints on consumption (PCC; e.g., less meat, less water, and less driving)	1. Environmental citizenship (e.g., environmental petition and donated to environmental organizations)
	2. "Green" consumerism (e.g., using/purchasing energy-efficient products)	2. Environmental activism (e.g., active participation in environmental organizations and demonstrations)

Note: This table is adjusted based on Stern (2000) [6]. ESB: Environmentally significant behavior.

In response to the recent popularity of environmentalism, majorities of Koreans agree the need for ESB and are willing to practice it. However, there is a considerable gap between environmental willingness and actual environmental actions [19]. According to the report of the Korea Environmental Industry and Technology Institute (2010) [20], about 88.4% of the people agree on the necessity of environment-friendly living, while 64.5% think that environment-friendly products are too expensive and only 37.9% are living with an environmentally friendly lifestyle. Recently, as a means to promote ESB by individuals, Korean government has been introducing voluntary environmental programs, including "carbon point system", "green mileage system", and "carbon cashback system." These programs provide financial incentives (redeemable points or gift certificate) to people who save electricity, water, and gas as well as purchase eco-friendly products.

2.2. Theoretical Perspectives of ESB and Hypotheses

In an attempt to understand pro-environmental behavior, psychological perspectives have focused primarily on internal and psychological factors, including environmental values, beliefs and attitudes and related them to environmental behavior [21–25]. These studies were fundamentally based on a linear model suggesting that environmental knowledge leads to environmental attitudes (environmental awareness and concern), which in turn gives rise to pro-environmental behavior [26]. Although a variety of studies have been conducted to analyze ESB based on this early model, they have lacked explaining mechanisms of how environmental attitude shape behavior. To fill this gap, Ajzen and Fishbein [27] introduced a theory of planned behavior in which environmental behavior is predicted by a complex structure of individual behavior involving behavioral intention, attitudes, social pressures, and behavioral beliefs and normative beliefs. Furthermore, building upon Ajzen and Fishbein's model, Hines, Hungerford and Tomera [28] did a meta-analysis of 128 research studies on pro-environmental behavior and suggested factors linked with environmental behavior, including knowledge of issues, knowledge of action strategies, locus of control, attitudes, verbal commitment, individual sense of responsibility, and situational factor.

From economic perspectives, economists understood environmental behaviors as a private provision of public good [25]. The general assumption of this perspective is that individuals will maximize his/her own utility and benefits and thus are more likely to be free riders than participate in provision of public goods. However, this economic perspective cannot explain individuals' voluntary effort to provide public goods [29]. This gap is filled by another perspective that goes beyond the economic perspective, suggesting that voluntary environmental behavior is driven by "warm glow" altruism [30] and morality [31]. According to Andreoni [30], people who have warm glow altruism will contribute to the private provision of public goods because they feel rewarded by the act of giving, such as donation or pro-environmental behavior [25,30]. Similarly, Brekke et al. [31] argue that individuals' utility from charitable activity is motivated by moral reason rather than self-interest [29,31]. In their moral-based model, people have their own moral ideal and would make voluntary contribution to their ideal.

Despite the divergent understanding about environmental behavior, literature generally converges on factors that influence ESB. They include (1) New Environmental Paradigm (NEP) [32–34]; (2) Environment-Economy Trade-off (EET) as a perception of relationship between economic growth and environmental conservation [35,36]; (3) Environmental Knowledge (EKN) [21,37,38]; (4) Pro-social Behavior (PSB) [6,39–41].

2.3. The New Environmental Paradigm

Fundamental issues of environmental behavior research are about individual's value and/or concern for the environment [41–44]. Values are generally conceptualized as important life goals or standards that function as guiding principles in life [44,45]. Especially, in relation to environmental problems, values may play an important role in solving these problems [43]. Several studies revealed that the stronger individuals have new environmental values, the more likely they are to engage in environmental responsible behavior [44,46]. As a value-based approach, Stern et al. (1995) [47] proposed a causal model of environmental concern to examine the relationship between values and environmental behavior, and they used the New Environmental Paradigm (NEP) scale suggested by Dunlap & Van Liere (1978) [32] as measures of environmental concern. The New Environmental Paradigm (NEP) is focusing on measurement of people's views on the relationship between human and environment, so it has been used as a tool to measure general environmental concern [33,48]. And these studies using NEP revealed that person with a higher environmental concern is more likely to act in a pro-environmentally manner [44,49]. Therefore, we hypothesize that:

H1: *Individuals with a stronger level of NEP are more likely to show ESB.*

2.4. Environment-Economy Trade-Off

The relationship between environmental protection and economic growth has been an ongoing debate [50–52]. This environment-economy dichotomy indicates the level of perception toward the impact of environmental protection and economic development. On one hand, individuals with a stronger perception toward an economy-environment trade-off are less likely to undertake ESB. This is largely due to the perceived costs involved in environmental behavior and their subsequent influence on economic well-being [53,54]. On the other hand, individuals who perceive the positive relationships between environmental protection and economic development are more likely to support environmental policies and thus voluntarily undertake environmental behavior. Similarly, those with environmental value putting environmental conservation over economic growth have a greater tendency to adopt ESB. Therefore, we develop the following hypotheses:

H2: *Individuals with a stronger level of perception toward a positive relationship between environmental protection and economic development are more likely to show ESB.*

2.5. Environmental Knowledge

Researchers insist that an individual's environmental behavior is highly dependent on his/her environmental knowledge [21,55]. According to Fryxell & Lo (2003, p. 45) [56], environmental knowledge can be defined as "a general knowledge of facts, concepts, and relationships concerning the natural environment and its major ecosystems." Similarly, Laroche et al. (2001) [57] approached a concept of environmental knowledge as individual's ability to identify or define a number of symbols, concepts, and patterns of behavior associated with environment. In other words, environmental knowledge involves what people know about the environment, key relationships leading to environmental aspects or impacts, an appreciation of "whole systems", and collective responsibilities necessary for sustainable development [41]. In general, therefore, it is considered that environmental knowledge has a positive impact on pro-environmental behavior. Kaiser & Fuhrer (2003) [58], Mobley et al. (2010) [59], and Oğuz et al. (2010) [60] revealed that people who have sufficient knowledge about environmental issues and problems are more likely to behave in an eco-friendly manner. Thus, we developed the following hypothesis:

H3: *Individuals with a greater level of environmental knowledge are more likely to show ESB.*

2.6. Prosocial Behavior

Another approach to analyzing factors affecting ESB is based on the models of altruism, empathy, and prosocial behavior [26]. Prosocial behavior is defined as any voluntary behavior that results in benefits for other persons [61,62] and explained well by norm-activation theory of altruism [6,63,64]. This theory considers environmental behavior as a function of social norms, personal norms, and awareness of consequences. In the same vein, Stern, Dietz & Kalof (1993) [65] and Mostafa (2009) [66] found that prosocial behavior (or altruism) has a positive influence on pro-environmental behavior. Oppositely, individuals with a stronger level of selfish and competitive orientation are less likely to act ecologically [67]. Therefore, we hypothesize that:

H4: *Individuals with a strong level of prosocial propensity are more likely to show ESB.*

2.7. Trust as a Moderating Factor

Trust is generally built upon the accumulation of social and institutional relations [68–71]. It can help lubricate social friction and promote cooperation, particularly in the areas where collective actions are needed, including economic development, democratic [68,71,72] and environmental governance [73,74]. The focus of scholars in this field has focused two primary dimensions, including social trust and institutional trust [71,72,75–77]. First, social trust primarily results from continued social interaction between and among individuals and has a social property for facilitating cooperation. Individuals with a greater level of social trust are more likely to pursue the common good than their counterparts. This behavioral tendency is related to the fact that these individuals tend to believe that the members of the community will cooperate and work towards the protection of the common good. Second, institutional trust describes trust towards public institutions, including government and nonprofit organizations [78]. Individuals with a higher level of institutional trust are more likely to behave more responsibly with the environment than their counterparts. This is largely because these individuals tend to believe that public institutions are credible and executes environmental policies in a reliable manner handling the environmental problems [77,79,80]. Also, trust promotes citizens' participation in social networks involving organized social groups function as channels to facilitate the flow of information and knowledge and thus increase the level of awareness on environmental issues [77]. This aspect is well documented in local urban development contexts. Therefore, we hypothesize that:

H5: *The effects of NEP, EEP, EKN, and PSB on ESB will be different between the group with high level of trust and the group with low level of trust.*

3. Research Methodology and Model Description

3.1. Data

We used data from the National Survey of Public Environmental Behavior conducted in South Korea in the spring of 2012. The survey considered a random sample of 5000 residents drawn from a national panel developed by a survey firm, and the panel proportionally represented the population of major cities. The questionnaire was circulated by e-mail and by a covering letter addressed to the name of each head of household listed in the panel directory. A total of 5000 individuals were originally targeted, and a total of 1085 responses were obtained after excluding 60 for incomplete data (a 21.7% response rate).

3.2. Variables Measures

Private-sphere ESB was measured in two ways. First, it was measured by separate measures in two dimensions: (1) PCC (less meat, less water, and less driving) and (2) PGC (the use of energy-efficient bulbs, the use of energy-efficient electronic devices, and recycling). Each measure was evaluated based on a five-point Likert-type scale ranging from "strongly disagree" (1) to "strongly agree" (5). Pfeffer and Stycos used similar measures to estimate ESB [7].

For the independent Variables, the new environmental paradigm (NEP) is the underlying worldview and mind-set that people have toward the environment and emphasizes harmonious interactions between humans and nature [32]. This perspective emphasizes that earth can support only a limited number of people with its limited resources. It reflects a shift in people's environmental perspective from the "dominant social paradigm", which suggests the power of humans over the environment and natural resources and thus seeks unlimited economic growth [33] (p. 178). The items for measuring the NEP were adapted from Dunlap and Van Liere [32], and Dunlap et al. [33]: (1) "The balance of nature is very delicate and easily upset by human activities", (2) "The earth is like a spaceship with only limited room and resources", and (3) "We are approaching the limit of the number of people the earth can endure."

The environment-economy trade-off (EET) focuses on the negative perception toward a relationship between environmental protection and economic prosperity. EET was measured by asking the extent to which the respondent agreed with the following three statements [81]: (1) "Environmental regulations have a negative impact on the economy", (2) "Environmental regulations have a negative impact on employment", and (3) "Individuals are worse off by environmental regulations."

Environmental knowledge (EKN) indicates the level of knowledge that people have of causes of major environmental issues such as global warming. It was measured by five items to assess the respondent's knowledge of primary causes of global warming, including (1) pollution from firms, (3) the use of fossil fuels, and (5) the destruction of tropical forests. Previous studies have generally verified the significant positive effect of EKN on the progressive environmental behavior of individuals [82], which suggests that cognitive factors such as EKN can be an important prerequisite for the development of environmental behaviors [83].

Pro-social behavior (PSB) was measured by asking the respondents to indicate the extent to which he or she agreed with the following statements: (1) "Sometimes I give change to beggars", (2) "From time to time I contribute money to charities", and (3) "From time to time I volunteer for community service." The items of all independent variables were measured based on a five-point Likert-type scale ranging from "strongly disagree" (1) to "strongly agree" (5).

For the moderating variables, first, trust could be measured by an additive index of multiple modes of trust: generalized trust, trust in government institutions/programs, and trust in civil society organizations. Generalized trust was measured by asking the respondent to indicate the extent to which he or she thought that most people can be trusted. Similarly, trust in government institutions was measured by the response to the statement "Generally speaking, I would say that government institutions, including government agencies, the National Assembly, and courts, can be trusted." Finally, trust in civic society organizations was measured in a similar way.

Gender was a nominal variable. The respondent was coded as 1 if male and 0 otherwise. Household income was an ordinal variable and measured using gross household income before taxes. Those respondents indicating an income less than 12 million won (Korean) were coded as 1, those with an income between 12 and 24 million won as 2, those with an income between 24 and 36 million won as 3, an income between 36 and 60 million won were coded as 4, and those an income above 60 million won as 5.

For other descriptive characteristics of the variables, age could be the first ordinal variable. This variable was not designed as a continuous variable because asking to indicate age can be culturally sensitive and even inappropriate for some people, particularly for females and older individuals. Therefore, a direct question may induce no response. For the coding scheme, those respondents indicating their age to be less than 18 were coded as 1; those between 19 and 24, as 2; those between 25 and 34, as 3; those between 35 and 44, as 4; those between 45 and 54, as 5; and those above 55, as 6. Home ownership was a nominal variable. The respondent was coded as 1 if he or she was a homeowner and 0 otherwise. Marital status was a nominal variable. The respondent was coded as 1 if he or she was married and 0 otherwise. Educational attainment was an ordinal variable. The respondents were asked to indicate the highest level of education completed in 2009. Those respondents with a middle school degree were coded as 1; high school graduates, as 2; college graduates, as 3; and those with a graduate degree or higher, as 4. Religiosity was an ordinal variable measured by the frequency of attending religious services. Those respondents attending religious services more than once a week were coded as 4; those attending approximately once a week, as 3; those attending approximately once a month, as 2; those attending only on major religious holidays, as 1; and those who did not attend religious services, as 0. Based on these variables, our research framework for empirical analysis is as shown in Figure 1.

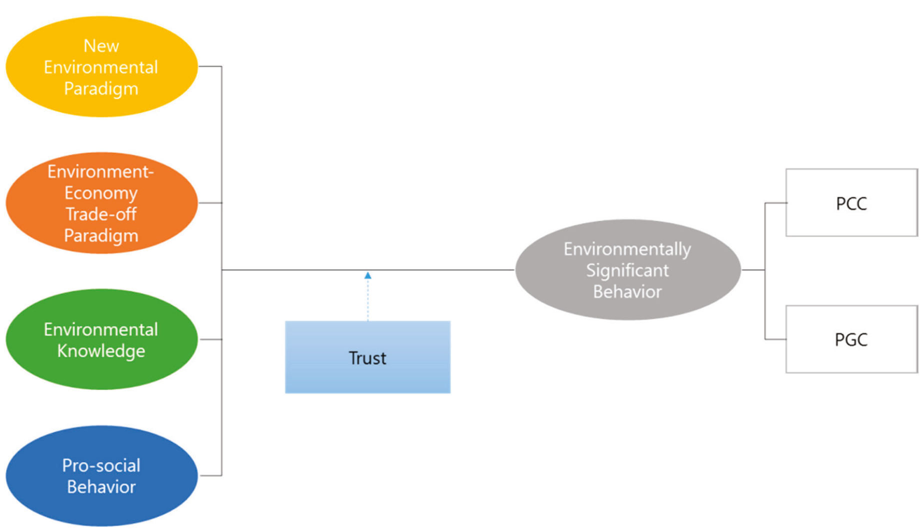


Figure 1. Research framework.

3.3. Research Methodology

In this study, to examine the factors affecting ESB, and to assess the moderating effects of trust, gender, and income, we utilize a multi group analysis of SEM. All the questions based on the arguments of the hypotheses on the variables, a five-point Likert-type scale is used for evaluation ranging from "strongly disagree" (1) to "strongly agree" (5). Prior to our assessment, we conducted reliability analysis and confirmatory factor analysis (CFA) about the total survey items using the maximum likelihood estimation procedure, and reconstructed items based on the results of CFA. Reliability analysis is a method for estimating the consistency of measured items by utilizing the value of Cronbach's α. And through CFA, which is used to test whether measured items of model are consistent with latent variables using covariance, we could understand the construct validity and appropriateness of the measurement model.

A general regression model has limitations in that it cannot reflect functional relations between each variable, because all dependent variables are treated as one group and trapped into one linear regression equation. In addition, in the presence of multi-collinearity or endogeneity problems, it is not possible to make accurate prediction so that regression analysis is conducted by cutting off correlations between variables through various assumptions and constraints. However, SEM can be used to analyze the validity of the research model and the causal relationship between variables empirically, which cannot be estimated by regression analysis. In other words, this method has the characteristics of general regression analysis, and is possible to conduct simultaneous estimation about correlations between variables. The method also has the advantage of reflecting measurement errors into the analysis of model validity.

The main study purpose is to identify the moderating effects of trust, for which it is appropriate to use multiple group analysis to estimate different effects of moderating variable by using the characteristics of SEM. First of all, therefore, this study estimates the validity and causal relation of measurement model. And then, to examine the moderating effects of trust, gender, and the level of income, we divide all samples into two groups; trust is divided by the average point (3 point) of measured items, gender is classified as male and female group, and income level is categorized into higher and lower groups with a cut-off of 36 million won. Based on these, we employ an unconstrained (or free) model which does not impose restrictions that relations between latent variables are differ from the effects of moderating variable and equality constrained model which assume that the sizes of relations between variables are equal to each other. We then analyze the moderating effects of three variables by conducting $\chi 2$ difference test between the two models. Data analysis is carried out by SPSS 18.0 (IBM, Armonk, NY, USA) for windows and AMOS 18.0 software (IBM, Armonk, NY, USA).

4. Empirical Results and Implications

4.1. Demographic Characteristics of Participants

The demographic characteristics of the full sample are shown in Table 2. The table presents the distribution of respondents by gender, age, income level, marital status, home ownership, educational attainment, religion, and occupation.

Table 2. Descriptive statistics.

Variables	Items	Frequency	Ratio	Variables	Items	Frequency	Ratio
Gender	Male	510	47.0%	Religion	None	502	46.3%
	Female	575	53.0%		Protestantism	252	23.2%
Age	From 19 to 24	193	17.8%		Catholic	110	10.1%
	From 25 to 34	204	18.8%		Buddhism	209	19.3%
	From 35 to 44	270	24.9%		Others	12	1.1%
	From 45 to 54	260	24.0%	Participation in religion activity	None	600	55.3%
	over 55	158	14.6%		Only at religious feast	138	12.7%
Income Level	Less than 12 million won	129	11.9%		Once a month	76	7.0%
	12–24 million won	189	17.4%		Once a week	167	15.4%
	24–36 million won	228	21.0%		Twice a week (or more)	104	9.6%
	36–60 million won	354	32.6%	Occupation	Unemployed	50	4.6%
	over 60 million won	185	17.1%		Housewife	193	17.8%
Home Ownership	Yes	605	55.8%		Student	154	14.2%
	No	480	44.2%		Self-employed	110	10.1%
Marital Status	Yes	691	63.7%		Public official	51	4.7%
	No	394	36.3%		Business worker	450	41.5%
Educational Attainment	Middle school	24	2.2%		Profession	54	5.0%
	High school	342	31.5%		Man of religion	3	0.3%
	University	635	58.5%		Retired	20	1.8%
	Graduate school (or more)	84	7.7%	Total/Response Rate		1085	100%

4.2. Reliability and Validity Analysis

Prior to testing the moderating effects of trust, gender, and income level on ESB, CFA was performed to assess the reliability and validity of the measurement model. In this study, the proposed measurement model consists of four latent constructs, i.e., NEP, EET, EKN, and PSB. These factors are measured by their respective multiple indicator variables, and are allowed to inter-correlated. The results of CFA indicate that the measured model fits the observed data well enough (Results of CFA on standard model: GFI = 0.927, AGFI = 0.904, CFI = 0.905, IFI = 0.906, RMR = 0.048, RMSEA = 0.064.), but there were items for which the standardized regression weights are less than 0.5. Thus, we removed these items, and performed CFA on the modified model. According to the results of CFA on the modified model, all factor loadings are significant and all standardized regression weights are more than 0.5 (see Table 3).

Table 3. Standardized factor loading of modified model items.

Items	Estimate	Factor Loading	*t*-Value	Items	Estimate	Factor Loading	*t*-Value
NEP3←NEP	1.000	0.519	fixed	EKN2←EKN	0.970	0.758	23.264 ***
NEP2←NEP	1.193	0.734	14.193 ***	EKN1←EKN	0.970	0.738	22.706 ***
NEP1←NEP	1.184	0.728	14.169 ***	EKN4←EKN	0.828	0.591	18.199 ***
EEP3←EEP	1.000	0.793	fixed	EKN5←EKN	0.938	0.684	21.082 ***
EEP2←EEP	1.081	0.877	26.913 ***	PSB3←PSB	1.000	0.671	fixed
EEP1←EEP	0.976	0.761	25.224 ***	PSB2←PSB	1.345	0.909	12.831 ***
EKN3←EKN	1.000	0.751	Fixed	PSB1←PSB	0.726	0.506	13.514 ***

*** Statistically significant at 99%.

In addition, the goodness-of-fit index (GFI = 0.974), the adjusted goodness-of-fit index (AGFI = 0.961), the normed fit index (NFI = 0.960), the incremental fit index (IFI = 0.974), and the root-mean-square residual (RMR = 0.019) of the modified model met the recommended threshold levels, so we could argue that this modified model is better than the standard model. On the basis of CFA, we named the selected items as NEP, EEP, EKN, and PSB. We also performed reliability analysis on each item, and found no problems with the reliability of the scales because the values of Cronbach's α are more than 0.7 in all items except for NEP (Cronbach's α of NEP = 0.681, see Table 4).

Table 4. Survey items and Cronbach α after Confirmatory Factor Analysis (CFA).

Variables	Items	Cronbach α
New Environmental Paradigm (NEP)	The environment can be easily destroyed by human activities.	0.681
	The earth has limited physical space and resources.	
	The world's population has reached a critical point which the earth can sustain.	
Environment-Economy Trade-Off Paradigm (EET)	Strict environmental regulation has a negative effect on the economy.	0.850
	Environmental regulation has a negative effect on personal employment.	
	Strict environmental regulation damages individuals.	
Environmental Knowledge (EKN)	Air pollution of a manufacturing business or another industry	0.829
	Driving a car	
	Use of fossil fuel (coal or oil) by an electric power company	
	Use of home appliances (electric heater, laundry machine, refrigerator)	
	Destruction of tropical forest	
Pro-Social Behavior (PSB)	I give money to beggars.	0.706
	I contribute money to charity.	
	I volunteer at voluntary organizations or local communities.	
Trust	Generally speaking, I would say that most people can be trusted.	0.731
	Generally speaking, I would say that government institutions, including government agencies, the National Assembly, and court can be trusted.	
	Generally speaking, I would say that government programs can be trusted.	
	Generally speaking, I would say that civil society organization can be trusted.	
Environmentally Significant Behavior (ESB)	I normally try to cut down on eating meat for environmental reasons.	0.712
	I normally try to use less water when showering or bathing.	
	I normally try to use energy-efficient light bulbs.	
	I normally try to purchase energy-efficient appliance such as hot water heaters, refrigerators, and dish washers.	
	I normally try to drive less.	
	I normally try to recycle.	

4.3. Results of the Standard Structural Model

The basic SEM of this study is the relationship between NEP, EET, EKN, PSB, and ESB. We conducted covariance structure analysis by constructing the paths of each factor, targeting a total of 1085 respondents, and we used the maximum likelihood method, which is known to be consistent and asymptotically efficient when estimating the parameters of large samples [84]. Before analyzing the basic model, we tested the skewness and kurtosis of each variable, and the results satisfy the conditions for a normal distribution (skewness was less than 2, and kurtosis was less than 4). Table 5 shows the goodness-of-fit of the basic measurement model, but we draw the modified model by reducing the relations between non-significant variables to secure the appropriateness of the research. The model was modified by using a modification index (MI), but some parts were revised based on the theoretical basis. The goodness-of-fit index (GFI = 0.938), adjusted goodness-of-fit index (AGFI = 0.919), and the root-mean-square residual (RMR = 0.036) of the basic model met the recommended level, but all indices of the modified model were much better.

Table 5. Goodness-of-fit of the measurement model.

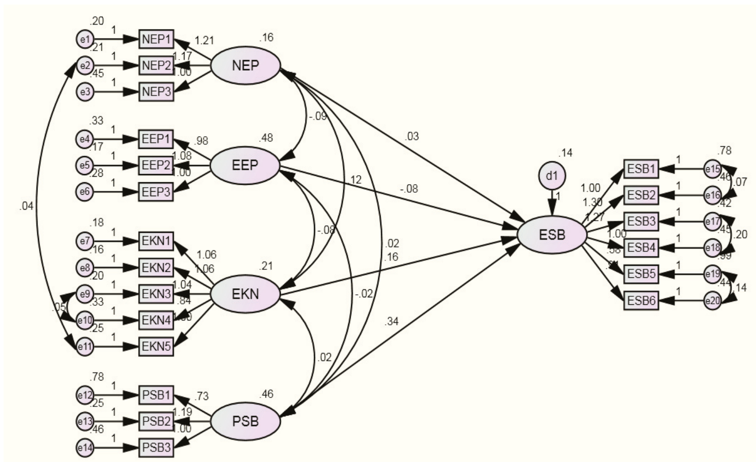
Goodness-of-Fit	Absolute Fit Index					
	d.f.	**χ^2**	**χ^2/d.f.**	**GFI**	**RMR**	**RMSEA**
Standard	-	-	5	0.9	0.05	0.05
Basic	160	658.35	4.115	0.938	0.036	0.054
Modified	155	410.05	2.645	0.963	0.029	0.039
	Incremental Fit Index					
	TLI	**NFI**	**IFI**	**CFI**		
Standard	0.9	0.9	0.9	0.9		
Basic	0.914	0.907	0.928	0.928		
Modified	0.955	0.942	0.963	0.963		
	Parsimonious Fit Index					
	AGFI	**PNFI**	**PGFI**			
Standard	0.9	Model comparison	Model comparison			
Basic	0.919	0.764	0.715			
Modified	0.95	0.769	0.711			

The χ^2 statistic is the basic estimator for evaluating goodness-of-fit, and we can make the conclusion that the model is suitable when the χ^2 statistic is low and the p-value of χ^2 is high. However, the χ^2 statistic varies with the size of the sample so that other alternative indices should be considered with it [85]. In general, a RMSEA (root-mean-square error of approximation) value less than 0.10 is considered a good fit, and a value less than 0.05 is considered a very good fit. The GFI (goodness-of-fit index), adjusted goodness-of-fit index (AGFI), and NFI (normed fit index) better than 0.90 are considered as a good fit [86]. Therefore, we adopted the modified model for the final analysis.

The results of the analysis about the effects of NEP, EET, EKN, and PSB on ESB are shown in Table 6. First, the effect of NEP on ESB was not significant, although the sign was positive (β_NEP = 0.028). Therefore, Hypothesis 1, "the higher the individual level of NEP is", the more he or she acts in an environmentally friendly manner, was rejected. This result corresponds with Wiidegren's findings that personal norms have a greater impact on ESB than NEP [87]. Through the years, Korean citizens have experienced major events including the four-river project, green growth policy, or Japan's disaster of the Fukushima nuclear accident, and their concerns and awareness about the environment have highly increased. In accordance with this trend, the respondents reacted positively to the questionnaires related to NEP, but, in reality, this value or paradigm cannot be converted into ESB yet. Second, Hypothesis 2, "an individual with a negative view on strict environmental regulations will not exhibit ESB", predicts a negative path from EET to ESB. The results showed that the path from EEP to ESB was significant (β_EEP = −0.114, $p < 0.01$), supporting Hypothesis 2. Although citizen's values about the environment have been heightened recently, when the two values, economic growth and environmental conservation, oppose each other, they might still place more weight to economic aspects. Likewise, the person who is more concerned about economic benefits rather than the regulation for environmental protection may not control their consumption activity, or may not use energy efficient or eco-friendly products.

Table 6. Results of the Standard Model.

H	Path	Estimate	β	S.E.	*t*-Value	Result
H1(+)	NEP→ESB	0.032	0.028	0.070	0.457	Reject
H2(−)	EEP→ESB	−0.076 ***	−0.114	0.026	−2.899	Accept
H3(+)	EKN→ESB	0.157 ***	0.157	0.057	2.728	Accept
H4(+)	PSB→ESB	0.337 ***	0.498	0.037	9.180	Accept



Note: *** indicate significance at the 1% levels.

Third, in this study, the level of EKN is measured by questions about the main reasons for environmental pollution and global warming. According to the result, EKN had a positive effect on ESB, and the path coefficient was significant (β_EKN = 0.157). In other words, the higher the individual level of EKN, the more he or she will save environmental resources and use eco-friendly products. This result coincides with the argument of Burgess et al. [88] (p. 1447), that knowledge about the environment may affect the consciousness about environmental problems, and further that this consciousness may draw pro-environmental behavior. Thus, Hypothesis 3 was accepted. Fourth, among the four latent variables in this study, PSB had the most significant effect on ESB and the sign was positive (β_PSB = 0.498). Generally, the person who seeks self-interest and acts based on selfishness tends to emphasize his or her own outcomes, and has lower concerns about the environment. In addition, the studies dealing with the value-basis of environmental beliefs and behavior revealed that the individuals who strongly subscribe to values beyond their self-interests, such as self-transcendent, pro-social, altruistic, or biospheric values, are more likely to engage in pro-environmental behavior [46,89,90]. The present study result agrees with all of these studies, and Hypothesis 4, “the person who has pro-social propensity will exhibit ESB”, was accepted.

4.4. Results of the Moderating Effects of Trust

We performed a multiple group analysis to estimate the moderating effects of trust on ESB. Multiple group analysis is a method to test the difference of path coefficients between two groups [85] (p. 467). In this study, respondents were split into two groups based on their trust. Respondents with a high level of trust were placed in the high trust group (*n* = 478), whereas respondents with a low level were classified into the low trust group (*n* = 607). We estimated the significance of the difference between the two groups by comparing the χ^2 statistics of the cross-group equality constraint model and the unconstrained model. If there are meaningful differences between them, we could argue for the moderating effects of trust on the relations between NEP, EET, EKN, PSB, and ESB. The significance of the difference between the two models can be identified by the χ^2 variation. When a change of the degree of freedom is 1, we could judge that the result is statistically significant at the 0.05% significance level if the variation of χ^2 is larger than 3.841 [85] (p. 472). In addition, standardized path coefficients can be used for deciding the relative importance of the coefficient, but it is impossible to compare coefficients of each sample when the samples are separated. Thus, unstandardized path coefficients are used for comparing each group in multiple group analysis [85] (p. 274).

Table 7 presents the results of the moderating effect of trust. On the whole, the goodness-of-fit indices met the recommended level (GFI = 0.951, NFI = 0.922, IFI = 0.963, CFI = 0.963, RMSEA = 0.027). First, moderating effect of trust was identified in the causal relations between NEP and ESB (the variation of χ^2 = 4.072). But when separating the moderating effect of trust between a higher trust group and a lower trust group, the effect was significant only for the lower trust group ($p < 0.1$, $coef_{NEP} = 0.180$), not for the higher trust group. In higher trust group, trust is embedded in the values and norms of the group members; it is natural for them to expect cooperation and compliance with rules. Basically, trust is not rare and found relatively easy and can used as it needs for promoting cooperation. In this situation, the moderating effect of trust is not likely to draw on environmentally responsible behavior. On the contrary, for the lower trust group, trust is rare and essential commodity to bring back cooperation among a member of people. So trust is an essential ingredient for people to act in a manner pursuing common goals. Thus, it is more likely to observe the moderating effect of trust on the relations between NEP and ESB.

Table 7. Moderating effects of trust on ESB.

Independent Variable	**Dependent Variable**	**Trust**		**Unconstrained Model χ^2(d.f. = 310)**	**Constrained Model χ^2(d.f. = 311)**	**$\Delta\chi^2$(d.f. = 1)**
		Low (*N* ='607)	**High (*N* = 478)**			
All Variables (Constrained)				563.692	574.772 (d.f. = 314)	11.08 ** (d.f. = 4)
NEP	ESB	0.180 *	0.097	563.692	567.764	4.072 **
EEP		−0.079 **	−0.067 *	563.692	563.746	0.054
EKN		0.019	0.293 ***	563.692	569.538	5.846 **
PSB		0.387 ***	0.247 ***	563.692	566.996	3.304

Regression weights of this table are non-standardized estimates. GFI = 0.951, NFI = 0.922, IFI = 0.963, CFI = 0.963, RMSEA = 0.027. *, **, *** indicate significance at the 10%, 5%, and 1% levels, respectively. According to the result of the multi-group analysis, χ^2 of the unconstrained model is 563.692, and χ^2 of the equally constrained model for all variables is 574.772, so the difference between the two models is 11.08. A standard value of χ^2 at the 0.05 significance level (d.f. = 4) is 9.488, implying that there is a significant difference.

Second, the moderating effect of trust also existed in the relationship between the level of EKN and ESB (the variation of χ^2 = 5.846). For the low trust group, the path coefficient of EKN on ESB was not significant, but, for the high trust group, the path coefficient had a strongly positive effect at the 0.01 significance level ($coef_{EKN} = 0.293$). Combining these results, person with low trust may act in an eco-friendly manner according to their subjective value rather than EKN which is acquired from other experiences. On the other hand, those with a high level of trust may behave in an environmental friendly manner based on the knowledge about environment rather than their own value. Meanwhile, there were no moderating effects on the paths from EET and PSB to ESB because the χ^2 variations were lower than 3.841, but the effects of each variable were the same in the high- and low trust groups. That is, those with a negative view about rigorous environmental regulation do not seem to exhibit ESB, and those who acted pro-socially also behave in an environmental friendly manner regardless of the level of trust.

In addition to the analysis of the moderating effect of trust, we tested the effects of gender and income level. The items for ESB are composed of how much do they control their private consumption, and how often do they use eco-friendly products. Therefore, we established hypotheses to investigate whether the characteristics of ESB vary with gender and income level by H6, "the effects of NEP, EEP, EKN, and PSB on ESB will differ depending on the gender", and H7, "the effects of NEP, EEP, EKN, and PSB on ESB will differ depending on the level of income". According to the results, however, the moderating effect of gender on ESB was not significant. Only the path of EET had a significant difference between males and females (χ^2 variation = 4.564), and the EEP of women had a more negative effect on ESB than men's (see Table 8).

Table 8. Moderating effects of gender on ESB.

Independent Variable	Dependent Variable	Gender		Unconstrained Model χ^2(d.f. = 310)	Constrained Model χ^2(d.f. = 311)	$\Delta\chi^2$(d.f. = 1)
		Male (*N* = 510)	Female (*N* = 575)			
All Variables (Constrained)				610.566	616.353 (d.f. = 314)	5.787 (d.f. = 4)
NEP	ESB	0.008	0.047	610.566	610.642	0.076
EEP		−0.017	−0.129 ***	610.566	615.130	4.564 **
EKN		0.203 **	0.101	610.566	611.351	0.785
PSB		0.341 ***	0.322 ***	610.566	610.626	0.060

Regression weights of this table are non-standardized estimates. GFI = 0.946, NFI = 0.917, IFI = 0.957, CFI = 0.957, RMSEA = 0.030. **, *** indicate significance at the 5%, and 1% levels, respectively.

In the next analysis, the level of income had no moderating effect on the relations between all latent variables and ESB. In other words, the χ^2 variations between the cross-group equality constraint model and the unconstrained model of all latent variables were lower than 3.841. Hence, we conclude that the moderating effect of income level was not significant for the relationships between NEP, EET, EKN, PSB, and ESB. Thus, Hypothesis 7 was rejected (see Table 9).

Table 9. Moderating effects of income on ESB.

Independent Variable	Dependent Variable	Income Level		Unconstrained Model χ^2(d.f. = 310)	Constrained Model χ^2(d.f. = 311)	$\Delta\chi^2$(d.f. = 1)
		Male (*N* = 510)	Female (*N* = 575)			
All Variables (Constrained)				576.113	581.075 (d.f. = 314)	4.962 (d.f. = 4)
NEP	ESB	0.166	−0.047	576.113	578.240	2.127
EEP		−0.092 **	−0.055 *	576.113	576.607	0.494
EKN		0.033	0.238 ***	576.113	579.101	2.988
PSB		0.376 ***	0.300 ***	576.113	576.954	0.841

Regression weights of this table are non-standardized estimates. GFI = 0.948, NFI = 0.920, IFI = 0.961, CFI = 0.961, RMSEA = 0.028. *, **, *** indicate significance at the 10%, 5%, and 1% levels, respectively.

5. Conclusions

It is generally recognized that government cannot handle environmental problems effectively without assistance from the public. The involvement of citizen in environmental policies through reduced or green consumption is necessary to maintain and promote sustainability. In this research, we focus on the moderating effect of trust on the relationship between existing factors and ESB. In addition, we tested the effects of gender and income level as moderator variables on ESB.

The main findings could be summarized as follows. First, the effect of NEP on ESB was not significant, and this result agrees with previous arguments that personal norms have a greater impact on ESB than on NEP. This might reflect the situation that agreement with the NEP items becomes the rule rather than the exception, but this agreement may not be changed into ESB. Second, the result indicates people with a negative view on strict environmental regulations do not exhibit ESB.

This means that those who are concerned more about economic benefits than about the regulation for environmental protection may not control their consumption activity, or may not use eco-friendly products. Third, EKN had a positive effect on ESB, and this result agrees with the previous discussion that knowledge about environment may affect the consciousness about environmental problems, and further that this consciousness may draw pro-environmental behavior. Fourth, those who participate in voluntary organizations and contribute to charities are more likely to exhibit ESB. This result coincides with arguments that the individuals who strongly subscribe to values beyond their self-interests, that is, self-transcendent, pro-social, altruistic or biospheric values, are more likely to engage in pro-environmental behavior.

We also estimated the moderating effects of trust, gender, and income level on the relations between NEP, EEP, EKN, PSB and ESB. According to the results, the moderating effects of trust were identified in the causal relations between NEP, EKN and ESB. First, trust functioned as moderator only for a lower trust group, not a higher trust group. For a higher trust group, trust is a highly embedded value and practiced among and between the group members and thus does not occupy any special place for the role as a moderator for ESB. On the contrary, trust for a lower trust group can play a special role in moderating ESB because of its rarity as an essential ingredient for fostering ESB. Therefore, people in a lower trust group are more likely to behavior in an environmentally responsible manner. In addition, there were no moderating effects on the paths from EET and PSB to ESB across two groups. Finally, we tested the moderating effects of gender and income level and the results showed that these factors had no moderating effects in general. Especially, income level did not have a significant effect as a moderator for ESB. The possible reason may be related to voluntary programs, including "carbon point", "green mileage", and "carbon cashback", that Korean governments have initiated. These programs have provided financial incentives to individuals who provide environmentally responsible behavior through saving energy and water. This financial incentive may weaken the effect of income for ESB. There was a significant difference between the genders on the path of EET to ESB, and EEP of women had more negative effect on ESB than men's.

These results have some implications. First, the empirical results suggesting the moderating effects of trust on ESB is particularly relevant to low-trust societies like Korea and raise the questions about the methods of promoting trust. We suggest separate but complementary processes of fostering trust in the society. First, social trust can be developed by increasing social interactions and communications. Civic society organizations can play an important and active role into this area. They encourage citizens to engage in civic discussions and volunteering activities. Second, institutional trust underlying trust in public institutions and legal frameworks can be strengthened by providing formal and equitable arrangements for facilitating cooperation between government institutions and various segments of society. The role of government would particularly be important in this area.

As for the limitations of this study, it is related to variable measurements. Variables, including environmental values, EKN, and trust are highly abstract concepts that require multiple dimensions and the measurements we used in this research may not the best to represent the concepts. Thus, there may be possible measurement errors. In addition, the study is limited to evaluating private environmental behavior addressing personal consumption and purchase. Future study may want to investigate public environmental behavior describing citizens' participation in environmental policy processes through environmental petition and donation.

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Empirical Study of China's Provincial Carbon Responsibility Sharing: Provincial Value Chain Perspective

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Abstract: Against the background of global warming, China has vowed to meet a series of carbon emissions reduction targets and plans to launch a national carbon emissions rights trading market by 2017. Therefore, from the provincial value chain perspective, using input-output tables from China in 2002, 2007, and 2010, this study constructs models to calculate the CO_2 emissions responsibility of each province under the production, consumption, and value capture principles, respectively. Empirical results indicate that Shandong, Hebei, Jiangsu, Guangdong, and Henan bear the most responsibility for CO_2 emissions under the three principles in China, while Hainan and Qinghai have the least responsibility. However, there is a great difference in the proportion of carbon emissions responsibility for each province during the same period under different principles or different periods under the same principle. For consumption-oriented areas such as Beijing, Tianjin, Zhejiang, Shanghai, and Guangdong, the production principle is more favorable, and the consumption principle is more beneficial for production-oriented provinces such as Hebei, Henan, Liaoning, Shanxi, Inner Mongolia, and Shaanxi. However, the value capture principle strikes a compromise of the CO_2 emissions responsibility of each province between the production and consumption principles, and it shares the CO_2 emissions responsibility based on the actual value captured by each province in the provincial value chain. The value capture principle is conducive to the fair and reasonable division of CO_2 emissions rights of each province by sectors, as well as the construction of a standardized carbon emissions rights trading market.

Keywords: carbon responsibility sharing; production principle; consumption principle; value capture principle; provincial value chain

1. Introduction

The State Council issued the "13th Five-Year" program to control greenhouse gas emissions on October 2016, which proposed that CO_2 emissions per unit GDP (Gross Domestic Product) should be cut by 18% from the 2015 levels by 2020. Additionally, the national carbon emissions rights trading market will be launched by 2017. It means that all provinces will be included in a trading system to achieve the carbon reduction targets. Therefore, it is critical to determine the reasonable shares of carbon emissions responsibilities and rights. If one divides the carbon emissions reduction responsibility and carbon emissions rights totally in accordance with the principles of production, consumption, or some shared responsibility based on production and consumption principles, it may involve issues such as fairness and efficiency. In addition to promoting the coordinated development of economic growth in China, the separation of production and consumption places implies inter-provincial carbon emissions transfer. Moreover, the great differences in the provincial economic development levels, industrial structures, and natural conditions and other economic development conditions may result in different capacities to bear the carbon emissions reduction responsibility among provinces. Therefore, from the perspective of the provincial value chain, this study makes use of the economic link directly and indirectly among sectors in input-output tables, and tracks the value captured by all participants in the production chain and the amount of carbon emissions, thus allocating their corresponding carbon emissions reduction responsibilities in accordance with their abilities. This is propitious to determining reasonable carbon emissions reduction measures, scientifically allocating carbon emissions reduction responsibilities, and providing theoretical support for the realization of carbon emissions reduction targets and the establishment of a carbon emissions trading system.

Domestic and foreign scholars conducted a series of studies on the principles of carbon emissions responsibilities. The earliest is the principles of historical responsibility and fairness, which were first put forward in the World Climate Conference. These principles state that countries that consumed atmospheric space in the past which caused climate change should now bear moral responsibility. No generation can discharge too much greenhouse gas without compensating for it. However, these principles depend on the data of the environmental resources consumption around countries or regions over the years. The lack of historical data makes it difficult to accurately measure their emissions responsibilities, coupled with the opposition of most developed countries, resulting in the failure of adoption (Wang and Huang, 2011) [1].

With the refinement of the global production division, some scholars compartmentalize the international CO_2 emissions responsibility from the production, consumption, and income sides. They have proposed four basic principles to divide the global carbon emissions reduction responsibility: the principles of production, consumption, shared responsibility, and income liability. Since the 1997 Kyoto Protocol, the principle of production has become the basic principle of international climate policy and international negotiations. It advocates that "the responsibility for carbon emissions should be borne by the producer". The international transfer of production activities optimizes the allocation of resources and promotes the economic growth, technological progress, employment, and social welfare of production places. Thus being a "beneficiary" of international trade, these countries should bear more responsibility for carbon emissions reduction. This means that under the production principle, the Parties to the Kyoto Protocol bear the corresponding emissions reduction responsibility for carbon emissions that are directly generated by production within their borders. However, its fairness has been questioned. Schaeffer and Sa, 1996 [2], Tolmasquim and Machado, 2003 [3], and Csutora and Vetőné mózner, 2014 [4] have argued that this principle is not conducive to emerging countries and may lead to plight in climate policy negotiations. Moreover, this territorial principle does not include the carbon emissions generated during transportation and is more likely to generate "carbon leakage" (Pan et al., 2008) [5].

In order to compensate for the shortcomings of the production principle, academic circles have focused on the consumption principle. The consumption principle argues that countries with low environmental regulation in free trade have cost advantages in regards to pollution-intensive products, causing the transfer of pollution-intensive industries in countries with high environmental regulation, and resulting in transfer-in countries becoming the pollution shelter of transfer-out countries, (Copeland and Taylor, 1994; Ederington, 2007) [6,7]. These countries should be responsible for CO_2 emissions. Wyckoff and Roop, 1994 [8] argued that a country can achieve its goal of reducing its domestic emissions by outsourcing production and increasing imports. Thus, the diversification of consumption products and the reduction of pollution emissions increase the social welfare of outsourced countries, and the consumption principle of "the responsibility for carbon dioxide emissions should be borne by the consumer" shall be held (Munksgaard and Pedersen, 2001) [9]. Although the consumption principle can effectively solve the "carbon leakage" and "carbon transfer" problem as opposed to the production principle, it is unfair to those economically developed countries that have more consumption than production, such as the United States and Japan (Peters, 2008) [10]. Therefore, it is difficult to accept allocating carbon responsibility under either the production or consumption principles. As the stakeholders of carbon emissions responsibility and economy, both the production and consumption principles are difficult at reflecting fairness. Therefore, the principles of shared responsibility and income have been gradually recognized by scholars.

The principle of shared responsibility refers to the fact that producers and consumers share the pollution and emissions caused by production in light of some rules. Many scholars have studied the principle of shared responsibility mainly from three aspects: (1) theoretical research on the principle of shared responsibility (Bastianoni et al., 2004; Lenzen, 2005; Lenzen et al., 2007) [11–13]; (2) the application of the shared responsibility principle in dividing carbon emissions responsibility caused by international trade, such as Csutora and Vetőné mózner, 2014 [4] and Peng et al., 2016 [14]; (3) the application of the shared responsibility principle in the carbon emissions responsibility for a certain country, for example, Zhang, 2012 [15] and Chang, 2013 [16] applied the principle of shared responsibility to study the division of carbon emissions responsibility for China's various sectors. Ferng, 2003 [17] constructed a framework for estimating the carbon liability of a country or districts from the perspective of the interest principle and the ecological deficit, and analyzed the data of Taiwan from 1996. Andrew and Forgie, 2008 [18] used input-output analysis to study the greenhouse gas emissions responsibility of New Zealand under the principles of production, consumption, and shared responsibility, and found that compared with traditional production or consumption principles, the principle of shared responsibility was more likely to be accepted. Lenzen and Murray, 2010 [19] established a framework for quantifying the responsibility for downstream carbon footprints and the structural path analysis model (SPA), which was applied to analyze the division of carbon emissions responsibility in Australia. The principle of shared responsibility offsets the shortcomings of the principles of production and consumption. However, as stakeholders, producers and consumers achieve a mutually acceptable shared responsibility, and this plight may occur in global climate negotiations.

Based on the supply perspective, the principle of income responsibility uses the Ghosh model of input-output to measure the direct and indirect pollution emissions caused by the initial supply, that is, the downstream perspective. In contrast, the consumption principle views the upstream perspective, which uses the Leontief inverse matrix in the input-output model to measure direct and indirect pollution emissions caused by the final demand. Lenzen and Murray, 2010 [19] pointed out that the existing studies from the downstream perspective that track the carbon footprint were fewer, mainly due to the lack of a clear definition of downstream responsibility. Therefore, under the definition of upstream and downstream responsibilities, they took the Australian industry as an example and analyzed its carbon footprint. Marques et al., 2011 [20] studied the carbon emissions embodied in trade from the downstream perspective. Marques et al., 2012 [21] also proposed "income liability" to measure the carbon responsibility of countries from the downstream perspective. Marques et al., 2013 [22] further studied the geographical isolation between the place of international trade income and the place of carbon emissions from the principle of income responsibility in the downstream perspective. Zhang, 2015 [23] studied the carbon emissions responsibility and made a comparative analysis using the inter-provincial input-output model of China under the principles of production, consumption, income responsibility, and four shared responsibilities.

In summary, extant research on the principles of shared carbon emissions responsibility has focused on the principles of production, consumption, and shared responsibility. Due to carbon emissions transfer and carbon leakage between the provinces in China, there are significant differences in the value captured by each province from the provincial production value chain. Therefore, it is reasonable to divide the amount of carbon emissions by the value captured by each province and sector in the production value chain. Currently, there has been little work to investigate the carbon emissions responsibility among all the provinces based on the combination of input-output methods, shared responsibility ideas, and the provincial value chain perspective. Zhang and Wei, 2016 [24] put forward the value capture principle which not only contains "shared responsibility", but also includes "beneficiaries should pay for carbon emissions" and "those who are capable shall pay". It is more reasonable for all participants to allocate emissions under the value capture principle. It also provides theoretical support for the development of fair and reasonable inter-provincial environmental policies and emissions reduction policies.

From the provincial value chain perspective, based on the input-output tables of China from 2002, 2007, and 2010, this study constructs models to calculate the amounts of CO_2 emissions responsibility of each province under the principles of production, consumption, and value capture, respectively. This will provide support for dividing the carbon emissions responsibility, building carbon emissions trading systems, and meeting the carbon reduction commitments for China's provinces.

The remainder of this paper is organized as follows. Section 2 discusses the materials and methods. Section 3 states the study results and discussion. Section 4 presents the conclusions.

2. Materials and Methods

2.1. Data Preparation

The 30-province and 30-sector inter-provincial input-output tables (2002, 2007, and 2010) of China were obtained from the Chinese Academy of Sciences Research Center on Fictitious Economy and Data Science (http://free.xiaze.com). These tables include the 30 major provinces in China, excluding Hong Kong, Macau, Taiwan, and Tibet. This study merged the five categories of final demands (rural residents' consumption, urban residents' consumption, government consumption expenditure, fixed capital formation, and inventory increase) in the input-output table into one category. In other words, the final demands of all provinces are a column vector. Also, the element structure of the value added is not taken into account in this study, therefore the value added is only a row vector (as shown in Table 1).

Table 1. Inter-provincial Environmental Input-Output Table in China.

		Intermediate Demands				Final Demands				Exports	Total Outputs
		P1	***P2***	···	***Pn***	***P1***	***P2***	···	***Pn***		
Intermediate inputs	*P1*	Z_{11}	Z_{12}	···	Z_{1n}	f_{11}	f_{12}	···	f_{1n}	E_1	X_1
	P2	Z_{21}	Z_{22}	···	Z_{2n}	f_{21}	f_{22}	···	f_{2n}	E_2	X_2
	⋮	⋮	⋮	⋱	⋮	⋮	⋮	⋮	⋮	⋮	⋮
	Pn	Z_{n1}	Z_{n2}	···	Z_{nn}	f_{n1}	f_{n2}	···	f_{nn}	E_n	X_n
Imports		M_1	M_2	···	M_n						
Value-added		V_1	V_2	···	V_n						
Total inputs		X'_1	X'_2	···	X'_n						
CO_2 emissions		C_1	C_2	···	C_n						

Note: *P1* represents the first province, *P2* is the second province, ... , *Pn* is the nth province.

With reference to the method proposed by Zhang, 2015 [23], we estimated the carbon emissions of different provinces and sectors. The concrete steps are as follows: firstly, the energy consumption data for China's provinces in 2002, 2007, and 2010 were obtained from the China Energy Statistical Yearbook (in 2003, 2008, and 2011) (http://free.xiaze.com). The industrial energy consumption by sectors were obtained from the provincial Statistical Yearbook, and the energy consumption data of agriculture and services were from the "comprehensive energy balance table" for the provinces published by the China Energy Statistical Yearbook. Secondly, the collected data were compiled into the energy consumption data of the 30 sectors for the 30 provinces in China. The carbon emissions factors of various fuels were calculated with reference to IPCC (Intergovernmental Panel on Climate Change). Finally, the amount of major fossil fuels consumed by each province and sector were multiplied by the corresponding carbon emissions factors to calculate the CO_2 emissions from the 30 provinces by the 30 sectors in China. The amount of CO_2 emitted from the 30 provinces by 30 sectors was divided by the total output of each province by its sectors, and then the carbon emissions coefficient of each province by each sector was obtained, that is, the amount of CO_2 emissions per unit of output from each province by each sector.

The matrices in Table 1 are defined as follows: $\mathbf{Z_{ij}}$ is the intermediate demand matrix from Pi to Pj, and its dimension is $m\times m$; f_{ij} is the final demand vector from Pi to Pj, and its dimension is $m\times 1$; X_i and E_i are the total output vector and the export vector of Pi, respectively, and their dimensions are $m\times 1$; M_i, V_i, and C_i are imports, value added, and CO_2 emissions vectors of Pi, respectively, and their dimensions are $1\times m$. The superscript (′) indicates that the vector or matrix is transposed.

2.2. Model Specification

The equilibrium relationship of the row direction in Table 1 is:

$$X_{mn\times 1} = \begin{bmatrix} X_1 \\ X_2 \\ \vdots \\ X_n \end{bmatrix}_{mn\times 1} = \begin{pmatrix} Z_{11} & \cdots & Z_{1n} \\ Z_{21} & \ddots & Z_{2n} \\ \vdots & & \vdots \\ Z_{n1} & \cdots & Z_{nn} \end{pmatrix}_{mn\times mn} \begin{bmatrix} 1 \\ 1 \\ \vdots \\ 1 \end{bmatrix}_{mn\times 1} + \begin{pmatrix} f_{11} & \cdots & f_{1n} \\ f_{21} & \ddots & f_{2n} \\ \vdots & & \vdots \\ f_{n1} & \cdots & f_{nn} \end{pmatrix}_{mn\times n} \begin{bmatrix} 1 \\ 1 \\ \vdots \\ 1 \end{bmatrix}_{n\times 1} + \begin{bmatrix} E_1 \\ E_2 \\ \vdots \\ E_n \end{bmatrix}_{mn\times 1} \quad (1)$$

If the direct consumption coefficient matrix is $A_{ij} = \frac{Z_{ij}}{uX'_j}$, where u is a $m\times 1$ column vector. Then Equation (1) can be written in the form of a matrix:

$$X = AX + F + E \quad (2)$$

Among them, X, F, and E are the total output, the final demand, and the export matrix of all provinces by sectors, and A is the direct consumption coefficient matrix of each province by each sector. According to Equation (2), the total output of each province by its sectors can be expressed as:

$$X = (I - A)^{-1}(F + E) = B(F + E) \quad (3)$$

In Equation (3), B is the Leontief inverse matrix, i.e., the complete demand coefficient matrix. The main difference among the three principles (production, consumption, and value capture) is that the CO_2 emissions are divided differently. In fact, the CO_2 emissions are due to changes in the total output caused by changes in the final demands of each province by its sectors. To divide the CO_2 emissions responsibility, we explore the different paths in which the final consumption causes changes in the total output (we only consider the changes of total output and the corresponding CO_2 emissions caused by the domestic final demands, regardless of export demands):

$$X_{ij,k} = \begin{bmatrix} X_{1,ij,k} \\ X_{2,ij,k} \\ \vdots \\ X_{n,ij,k} \end{bmatrix}_{mn\times 1} = B_{mn\times mn} \begin{bmatrix} 0 \\ 0 \\ \vdots \\ f_{ij,k} \\ \vdots \\ 0 \end{bmatrix}_{mn\times 1} \quad (4)$$

In the above formula, $X_{ij,\,k}$ is the total output of all provinces by sectors caused by the final demand of Pj to sector k of Pi, and its elements $X_{p,\,ij,\,k}$ represent the total output of the pth province caused by the final demands of Pj supplied by sector k of Pi, and its dimension is $m\times1$. p is in the range of $1,\cdots,n$.

The production principle states that "the producer should be responsible for carbon emissions". Then according to Equation (4), the amount of CO_2 emissions of the pth province and each province, which are caused by the final demands of Pj supplied by sector k of Pi, are expressed as:

$$Y^{s}_{p,ij,k} = c_p X_{p,ij,k} \tag{5}$$

$$Y^{s}_{ij,k} = \sum_{p=1}^{n} Y^{s}_{p,ij,k} = \sum_{p=1}^{n} c_p X_{p,ij,k} \tag{6}$$

c_p is the CO_2 emissions coefficient vector of the pth province by sectors, and its dimension is $1 \times m$, and $c_p = C_p/X_p{}'$, $p = 1,2,\cdots,n$.

If the amount of CO_2 emissions of the pth province is caused by the final demands of all provinces supplied by all sectors, then under the production principle, the responsibility of CO_2 emissions that the pth province should bear can be calculated by:

$$Y^{s}_{p} = \sum_{i}^{n}\sum_{j}^{n}\sum_{k}^{m} c_p X_{p,ij,k} = c_p \sum_{i}^{n}\sum_{j}^{n}\sum_{k}^{m} X_{p,ij,k} \tag{7}$$

However, the consumption principle states that "the consumer should be responsible for carbon emissions". Then, under the consumption principle, Pj should be responsible for the amount of CO_2 emissions from all provinces caused by the final demands of Pj. According to Equations (4) and (5), the formula for calculating the CO_2 emissions responsibilities of Pj ($j = 1,2,\cdots,n$) can be expressed as:

$$Y^{c}_{j} = \sum_{p}^{n}\sum_{i}^{n}\sum_{k}^{m} c_p X_{p,ij,k} \tag{8}$$

where the sign is the same as that of Equation (5), and p represents the pth province. For ease of understanding, Equation (8) can be converted to:

$$Y^{c}_{p} = \sum_{j}^{n}\sum_{i}^{n}\sum_{k}^{m} c_j X_{j,ip,k} \tag{9}$$

The value capture principle proposed by Zhang and Wei, 2016 [24] concluded that the responsibilities of CO_2 emissions caused by the final demands of all provinces by sectors should be allocated in accordance with the value added for economic activity participants. Then, from Equation (4), the total output of all provinces by sectors caused by the final demands of Pj supplied by sector k of Pi can be obtained, if it is multiplied by the corresponding value-added rate, and the amount of value added to each province by each sector from the whole economic activity can be determined. The specific equation is as follows:

$$\varphi_{p,ij,k} = v_p X_{p,ij,k} \tag{10}$$

In Equation (10), v_p represents the value-added rates vector of the pth province by sectors, its dimension is $1 \times m$, and $v_p = V_p/X_p{}'$, $p = 1,2,\cdots,n$.

The purpose of the value capture principle is to divide the responsibilities of CO_2 emissions in accordance with the proportions of the value added that is captured by the economic activity participants. Meanwhile, the sum of the value added to all provinces by sectors caused by the final demands is equal to its final demands. Then we can obtain the sharing ratio of the carbon emissions responsibilities for each province by sectors, caused by the final demand:

$$\psi_{p,ij,k} = \frac{\varphi_{p,ij,k}}{\sum\limits_{p=1}^{n} \varphi_{p,ij,k}} = \frac{v_p X_{p,ij,k}}{\sum\limits_{p=1}^{n} v_p X_{p,ij,k}} = \frac{v_p X_{p,ij,k}}{f_{ij,k}} \tag{11}$$

In combination with Equations (6) and (11), the amounts of CO_2 emissions that the pth province should be responsible for in the CO_2 emissions caused by the final demands of Pj supplied by sector k of Pi are:

$$Y^v_{p,ij,k} = \psi_{p,ij,k} Y^s_{ij,k} = \psi_{p,ij,k} \sum_{p=1}^{n} Y^s_{p,ij,k} = \psi_{p,ij,k} \sum_{p=1}^{n} c_p X_{p,ij,k} \tag{12}$$

When we divide the responsibility of CO_2 emissions caused by the final demands of all provinces by sectors, the responsibility of the CO_2 emissions that the pth province should bear are:

$$Y^v_p = \sum_{i}^{n} \sum_{j}^{n} \sum_{k}^{m} Y^v_{p,ij,k} = \sum_{i}^{n} \sum_{j}^{n} \sum_{k}^{m} (\psi_{p,ij,k} \sum_{p=1}^{n} c_p X_{p,ij,k}) \tag{13}$$

3. Results and Discussion

In this section, we use the above-stated Equations (7)–(9), and (13) to measure the CO_2 emissions responsibility for China's provinces under the principles of production, consumption and value capture, respectively, in 2002, 2007, and 2010. The specific results are as follows.

3.1. Dynamic Analysis of CO_2 Emissions Responsibility under the Three Principles

Figure 1 shows that under the principle of production in 2002, 2007, and 2010, Shandong and Hebei bear the most carbon emissions responsibility. They account for 7% of the country's total carbon emissions, showing an upward trend throughout the study period. Hainan and Qinghai bear the least responsibility, accounting for less than 0.5% of the total carbon emissions, and showing a downward trend. First, due to their geographical locations, Shandong and Hebei may have become the transfer of the production bases of Beijing and Tianjin, and Hainan and Qinghai have less industrial production activities. Second, Henan, Shanxi, and Jiangsu and other places closer to Shandong and Hebei bear more responsibility for carbon emissions. Dynamically, the share of carbon emissions in the Beijing-Tianjin region (Beijing and Tianjin), Shanxi, Jilin, Heilongjiang, and the eastern coastal areas (Shanghai, Jiangsu, and Zhejiang) shows a rapid decline, while Hebei, Inner Mongolia, Liaoning, Guangdong, and Guangxi and the central region of Henan, Hunan, and Jiangxi and other places show an upward trend.

Figure 2 illustrates that under the principle of consumption, the most carbon emissions responsibility switches from Hebei in 2002 (7.34%) to Shandong in 2007 and 2010 (9.61% and 8.36%), followed by Guangdong and Jiangsu, accounting for 6%–7%. Qinghai and Hainan are the least responsible provinces for carbon emissions, and their ratios are below 1%. Dynamically, the share of carbon emissions in Beijing, Hebei, Shanxi, Heilongjiang, Guangxi, and Hainan and other places show a rapid decline. Tianjin, Inner Mongolia, Liaoning, Jilin, Zhejiang, Shandong, and Guangdong have a more substantial increase in their proportion and the other regions indicate a narrow range of fluctuations.

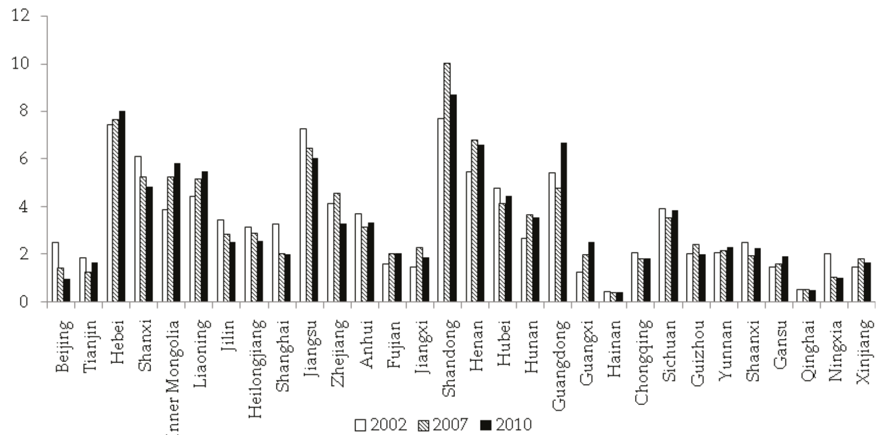

Figure 1. The proportion of all provinces in total CO_2 emissions under the production principle (unit: %).

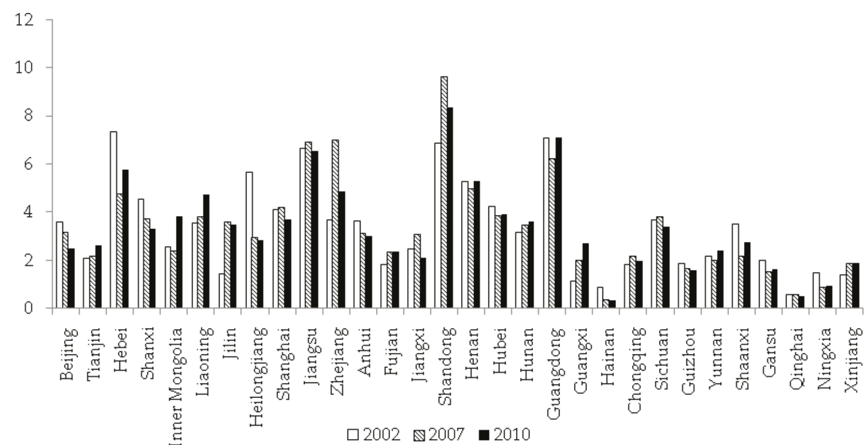

Figure 2. The proportion of all provinces in total CO_2 emissions under the consumption principle (unit: %).

Figure 3 demonstrates that under the principle of value capture, Shandong has the most carbon emissions responsibility of the country's total carbon emissions in 2002, 2007, and 2010, accounting for 7.79%, 10.46%, and 9.42%, respectively. Second, Jiangsu is charged with more carbon emissions responsibility, but its share of carbon emissions displays a downward trend, from 7.65% to 6.84%. During the entire study period, Guangdong and Hebei account for more than 6% of the total carbon emissions. Relatively speaking, Qinghai and Hainan have less responsibility for carbon emissions, with their share below 0.5%. On the whole, Beijing, Shanxi, Heilongjiang, Shanghai, Jiangsu, and Ningxia show a rapid decline in the proportion of total carbon emissions. Inner Mongolia, Liaoning, Shandong, Henan, and Guangxi have a more substantial increase in their proportions and other regions display a narrow range of fluctuations.

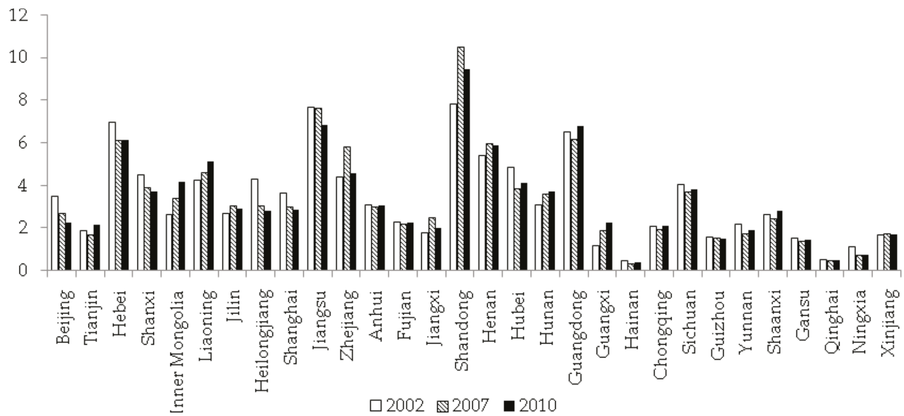

Figure 3. The proportion of all provinces in total CO_2 emissions under the value capture principle (unit: %).

The comparative analysis of the carbon responsibility of the same province under different principles indicates that the home market effect is ubiquitous in the provinces (the home market effect means that products produced by the province are consumed by the province, and the value is also attributed to the province). It is not obvious for the change in the main carbon emissions responsibility under the different principles, concentrating on Shandong, Hebei, Jiangsu, Guangdong, and Henan. However, the differences are obvious for the carbon responsibility of the provinces under the different principles and years. Taking Guangdong as an example, Figures 1–3 display that during the whole study period, the carbon responsibility under the principle of production is less than that under the value capture principle and the latter is less than that under the principle of consumption. Similar results are found for Beijing, Tianjin, Zhejiang, Shanghai, and other places. It is clear that the allocation of the carbon reduction responsibility under the principle of production is more favorable for these consumption-oriented provinces. For Hebei, Henan, Liaoning, Inner Mongolia, and Shanxi, the carbon emissions responsibility under the production principle is greater than that under the value capture principle, and the latter is greater than that under the consumption principle, indicating that the consumption principle is easily accepted by these provinces. For Shandong, Jiangsu, Shaanxi, and Hunan, the carbon emissions responsibility under the principle of value capture is greater than that under the principles of production and consumption. For Gansu, Guizhou, and Anhui, the carbon emissions responsibility under the principle of production is greater than that under the principle of consumption, and the latter is greater than that under the principle of value capture.

Overall, the different principles of responsibility have different interests for different provinces. Compared to the provinces' existing economic development in Figure 4, that is, the contribution to GDP, we can conclude that the provinces' emissions reduction capacity is quite different. In general, carbon responsibility under the principle of value capture is in accordance with economic capabilities. This is because the use of the value capture principle to share the carbon emissions responsibility can be accepted by the provinces, with strong fairness. It also enables the provinces to have the ability to reduce emissions and improve the emissions reduction efficiency.

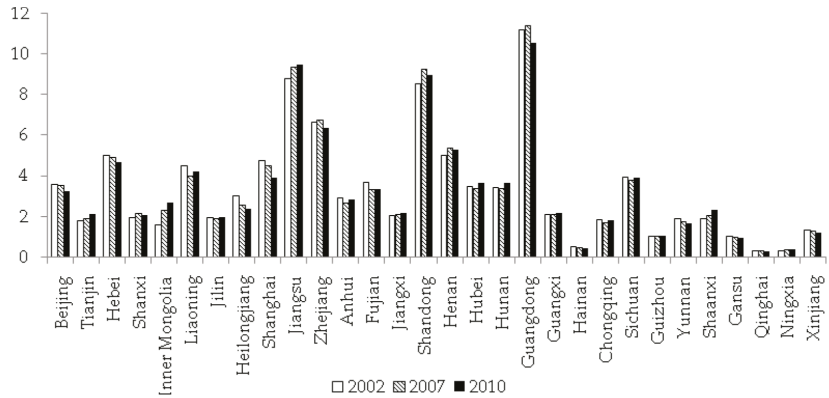

Figure 4. The ratio of each province in total GDP in China in 2002, 2007, and 2010 (unit: %).

3.2. Dynamic Comparative Analysis of CO_2 Emissions Responsibility of Each Province under the Three Principles

In order to perform a dynamic comparative analysis, we calculate the relative change rates of consumption-based emissions to production-based emissions, value capture-based emissions to production-based emissions, and value capture-based emissions to consumption-based emissions for each province respectively in 2002, 2007, and 2010.

3.2.1. A Comparison between the Principles of Consumption and Production

Figure 5 indicates that compared to the production principle, Hainan has the highest change rate, reaching 1.04 under the consumption principle in 2002. Hainan is one of the provinces with the least carbon emissions responsibility. However, under the consumption principle, its responsibilities have increased by 1.04 times compared to that under the production principle. This may result from Hainan's dependence mainly on tourism and agriculture to develop its economy with its relatively backward industrial level. In addition, Hainan is a province where consumption exceeds production. So it is obvious that adopting the consumption principle would increase its carbon emissions. Additionally, in 2002, compared to the production principle, the consumption principle increased the carbon emissions responsibility of some provinces, such as Heilongjiang, Jiangxi, Beijing, Guangdong, and Shanghai. On the other hand, it decreased the carbon emissions responsibility of Jilin, Inner Mongolia, Shanxi, Shandong, and Jiangsu. Other provinces have nearly the same responsibility for carbon emissions under the two principles. In 2007, the carbon emissions responsibility of Beijing, Shanghai, Tianjin, Zhejiang, and Guangdong increased obviously, while that of Inner Mongolia, Hebei, Guizhou, Shanxi, and Henan decreased significantly. In 2010, Shanghai, Beijing, Tianjin, and Zhejiang had a palpable increase in responsibility of carbon emissions, while Inner Mongolia, Shanxi, Hebei, and Henan had reduced responsibility.

It can be concluded that during the whole study period, compared with the production principle, the consumption principle has greatly increased the carbon emissions responsibility of Beijing, Shanghai, Tianjin, Guangdong, etc., and has lowered the liability of Inner Mongolia and Shanxi, which are rich in coal resources. However, this conclusion is not static. Taking Zhejiang and Jilin as examples, in 2002, their consumption-based emissions were lower than their production-based emissions, but in 2007 and 2010, we find that their consumption-based emissions were higher than their production-based emissions. Also, in 2002, Hainan's consumption-based emissions were higher than their production-based emissions. Along with the "Strong Industrial Province" slogan and the implementation of the "big enterprises enter, large projects led" development strategy, Hainan has achieved a leap-forward development and its industry has become an important force for its economic development. Thus, its consumption-based emissions are less than production-based emissions in 2007 and 2010.

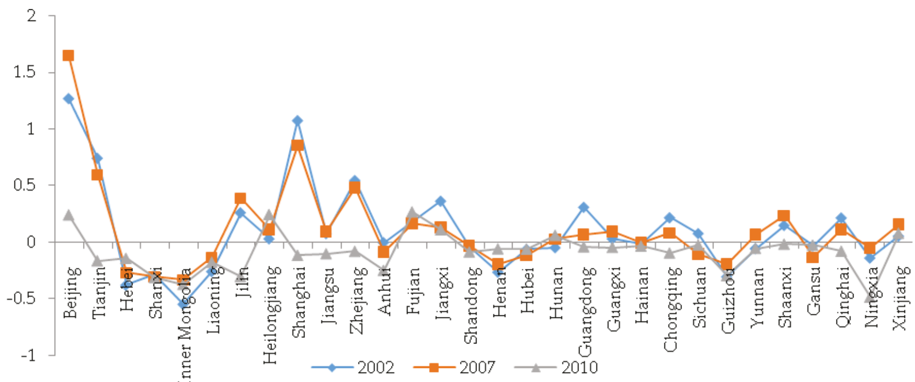

Figure 5. The dynamic comparison of the CO_2 emissions of each province under the principles of consumption and production. The vertical axis represents the rate of change, i.e., (CO_2 emissions under the consumption principle − CO_2 emissions under the production principle)/CO_2 emissions under the production principle.

3.2.2. A Comparison between the Principles of Value Capture and Production

Figure 6 reveals that in 2002, compared to the production principle, Fujian, Beijing, Heilongjiang, Jiangxi, Guangdong, Xinjiang, Hunan, Shanghai, and Shandong have significantly increased their carbon emissions responsibility under the principle of value capture, while Ningxia, Inner Mongolia, Shanxi, Jilin, and Guizhou have significantly reduced their carbon emissions responsibility. Similarly, in 2007, Beijing, Shanghai, Zhejiang, Tianjin, Guangdong, Shanxi, Heilongjiang, and Shandong have significantly increased their carbon emissions responsibility under the value capture principle, while Ningxia, Inner Mongolia, Shanxi, Jilin, and Guizhou have significantly reduced their carbon emissions responsibility. In 2010, compared to the production principle, Beijing, Shanghai, Zhejiang, Tianjin, Shanxi, Jilin, Chongqing, Jiangsu, and Shandong have significantly increased their carbon emissions responsibility, but Ningxia, Inner Mongolia, Shanxi, Hebei, and Henan have significantly reduced their carbon emissions responsibility under the value capture principle.

Therefore, during 2002–2010, compared to the production principle, the value capture principle has greatly increased the carbon emissions responsibility of consumption-oriented provinces such as Beijing, Shanghai, Tianjin, Guangdong, and Zhejiang, but has also lowered the responsibility of production-oriented provinces such as Inner Mongolia, Shanxi, Henan, and Hebei. For the production-oriented provinces, compared with the production principle, they are more inclined to the value capture principle. This means that pollution-intensive industries and low value-added industries in Beijing, Tianjin, Shanghai, Guangdong, and Zhejiang have been transferred, and then these provinces have obtained high added value from research and development. If the production principle is adopted to divide the carbon emissions responsibility, it will reduce the fairness and emissions reduction efficiency. Therefore, compared with the production principle, the value capture principle is more fair and efficient.

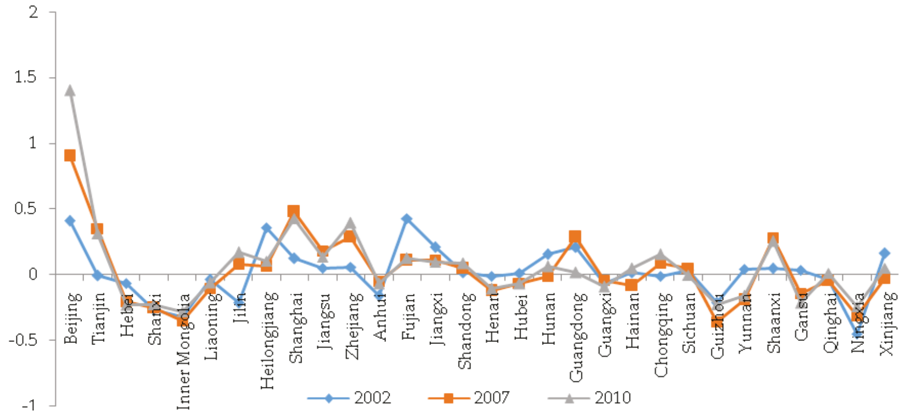

Figure 6. The dynamic comparison of CO_2 emissions of each province under the principles of value capture and production. The vertical axis in represents the rate of change, i.e., (CO_2 emissions under the value capture principle − CO_2 emissions under the production principle)/CO_2 emissions under the production principle.

3.2.3. A Comparison between the Principles of Value Capture and Consumption

Figure 7 indicates in 2002, relative to the consumption principle, the responsibility of carbon emissions for Jilin, Fujian, Xinjiang, Liaoning, Zhejiang, Jiangsu, Shandong, Guangxi, and Inner Mongoliain significantly increased under the value capture principle, while it has sharply reduced for Hainan, Jiangxi, Shanxi, Ningxia, Heilongjiang, Tianjin, Shanghai, Guangdong, and Beijing. Similarly, in 2007, the responsibility of carbon emissions for Inner Mongolia, Hebei, Liaoning, Henan, Shandong, Shanxi, and Heilongjiang increased, while it reduced for Shanghai, Yunnan, Ningxia, Tianjin, Beijing, Zhejiang, and Guangdong. In 2010, the responsibility of carbon emissions for Shandong, Shanxi, Henan, Inner Mongolia, Hebei, and Jiangsu had obvious increases, but significantly reduced for Shanghai, Yunnan, Tianjin, Ningxia, Guangxi, and Jilin.

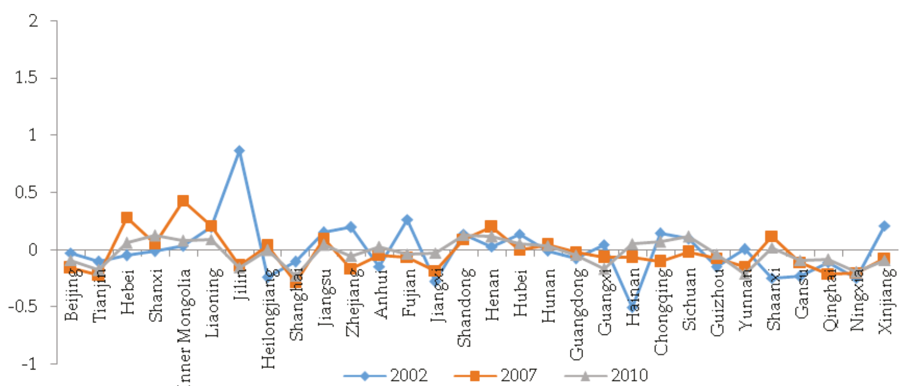

Figure 7. The dynamic comparison of CO_2 emissions of each province under the principles of value capture and consumption. The vertical axis represents the rate of change, i.e., (CO_2 emissions under the value capture principle − CO_2 emissions under the consumption principle)/CO_2 emissions under the consumption principle.

It is to be found that, relative to the consumption principle, the value capture principle greatly increased the carbon emissions responsibility of production-oriented places such as Shandong, Inner Mongolia, Jiangsu, Henan, and Hebei, but lowered the responsibility of high-consumption areas such as Shanghai, Tianjin, Beijing, and Guangdong. At this time, if the consumption principle is adopted, Shanghai, Tianjin, Beijing and Guangdong would not agree. These places insist that consumption leads to the economic growth of provinces depending on industrial production to stimulate economic development. The consumption principle states that "The responsibility for carbon dioxide emissions should be borne by the consumer". Thereby the efficiency of the emissions reductions would be sharply reduced. Additionally, the division of carbon emissions responsibility in accordance with the value capture principle will ease the tense relationship between producers and consumers.

In summary, taking Figures 5–7 for comparison, for most provinces, the relative change rates of value capture-based emissions to production-based emissions and value capture-based emissions to consumption-based emissions are both less than the relative change rates of consumption-based emissions to production-based emissions in 2002, 2007, and 2010. These conclusions indicate that the value capture principle is more eclectic than the consumption principle and the production principle. Different from the production principle and the consumption principle, the value capture principle divides the amount of carbon emissions from domestic production activities in keeping with the amount of value captured by each province by sectors in the production value chain. It is more equitable and more likely to be accepted by all responsible participants.

3.3. Sector Analysis under the Value Capture Principle

According to the empirical analysis of Section 3.1, it can be seen that the main provinces of carbon emissions responsibility under the principle of value capture in 2002, 2007, and 2010 are Shandong, Jiangsu, Hebei, Guangdong, and Henan. As a result, in this section, we provide a detailed analysis of the sector allocations of the five major carbon-depleting responsibilities.

Table 2 shows that carbon emissions responsibilities for Shandong, Jiangsu, and Guangdong are mainly distributed in other services (30) and construction (24), accounting for 10% to 20%. The rapid development of the service stimulates economic growth and promotes the transfer of industrial structure. The value captured by other services in the inter-provincial value chain is relatively large, so the carbon responsibility is relatively large. Similarly, there is an intimate linkage between the construction and the steel, cement, and mining sector and other sectors. In the production chain derived from the value chain, construction has a larger value, causing a large commitment to the carbon emissions reduction. Second, non-metallic mineral products, agriculture, chemicals, and chemical products contribute to the carbon emissions responsibility in Shandong, Jiangsu, and Guangdong. For the Hebei province, the primary carbon responsible sectors are other services, construction, basic metals, and agriculture. Other services, non-metallic mineral products, and agriculture have always been the main contributors of carbon emissions in the Henan province.

From the data above, we can see that other services, construction, non-metallic mineral products, agriculture, and chemicals and chemical products are the main carbon responsibility sectors for Shandong, Jiangsu, Hebei, Henan, and Guangdong. This means that the production activities of the provinces are connected through the inter-provincial value chain. China should allocate carbon emissions responsibility to specific sectors according to the principle of the value capture. For the common main carbon emissions responsibility sectors, the provinces can learn from each other and cooperate with each other to achieve the sectors' carbon emissions reduction targets. It is also notable that the food and beverage sector is the main carbon offset responsibility sector in Shandong, and in Henan it is the mining of coal. The provinces should put forward specific carbon emissions reduction responsibility schemes according to the province's own situation. For example, to complete the carbon emissions reduction responsibility for the food and beverage sector in Shandong, it can not only adopt technical optimization to reduce the carbon emissions intensity of the production process, but can also pay a certain cost through the carbon emissions trading system to buy carbon emissions rights for lower carbon responsibility of the provinces or lower carbon emissions sector in the province.

Table 2. The sector distribution of the major carbon responsibility provinces under the value capture principle (%).

Province	2002	2007	2010
Shan-dong	30(15.7); 24(14.1); 1(10.5); 6(7.3); 12(7.2); 26(6.6); 16(6.5); 13(4.8); 22(4.4); 3(4.4)	30(13.5); 24(9.8); 16(7.1); 12(6.4); 1(6.4); 13(6.3); 25(4.8); 6(4.4); 22(4.1); 14(4.0)	30(14.3); 24(10.1); 12(7.0); 16(6.9); 1(6.7); 26(6.1); 6(5.4); 25(5.4); 14(4.8); 13(4.2)
Guang-dong	30(18.6); 24(14.3); 22(8.1); 25(6.3); 1(6.3); 26(5.1); 13(4.8); 15(4.8); 12(4.5); 27(3.8)	30(18.3); 24(11.9); 22(8.9); 12(6.4); 13(6.1); 26(5.9); 1(4.9); 25(4.8); 15(4.0); 18(3.9)	30(18.9); 24(11.9); 22(7.7); 12(5.5); 25(5.3); 26(4.9); 13(4.4); 18(4.0); 1(3.9); 17(3.5)
Jiangsu	30(16.0); 26(11.7); 24(11.5); 12(8.2); 22(7.0); 1(5.9); 13(4.8); 16(4.5); 14(4.4); 25(3.4)	30(19.0); 24(12.0); 14(8.1); 12(7.7); 16(7.2); 26(5.6); 18(4.9); 1(4.3); 22(4.3); 25(3.8)	24(13.8); 30(13.6); 16(8.1); 12(6.7); 18(5.8); 26(5.7); 14(5.6); 22(4.8); 25(4.5); 17(4.4)
Hebei	30(11.0); 24(9.6); 1(9.6); 14(9.4); 25(8.8); 13(7.1); 16(5.7); 22(5.2); 12(5.1); 26(5.0)	30(16.4); 14(11.1); 1(8.7); 24(8.5); 25(7.5); 22(6.3); 13(4.9); 16(4.8); 12(4.2); 26(3.9)	30(14.2); 14(10.5); 24(8.7); 25(8.0); 1(7.3); 4(6.8); 22(5.5); 26(5.5); 12(5.0); 2(4.2)
Henan	13(12.3); 1(10.7); 30(9.2); 24(9.0); 22(7.8); 25(6.7); 2(5.0); 26(4.9); 16(4.7); 12(3.6)	30(11.3); 1(9.1); 13(9.0); 24(7.5); 14(6.6); 25(6.2); 16(5.3); 22(5.1); 6(4.9); 26(4.8)	30(11.5); 13(9.9); 1(8.1); 24(7.9); 16(7.1); 2(6.5); 14(5.8); 6(5.6); 26(5.1); 12(5.0)

Note: The numbers in brackets in Table 2 represent the percentage of carbon emissions, and the numbers outside the brackets are the sector codes. The meanings of the sector codes are defined as follows. 1: Agriculture; 2: Mining of coal; 3: Mining of oil and gas; 4: Mining of metal; 5: Mining of nonmetal; 6: Food and beverage; 7: Textile; 8: Wearing apparel, dressing, and dyeing of fur; 9: Wood and product of wood; 10: Paper and products for culture, education, and sports;11: Refined petroleum products, coking products, and coal gas and coal gas products; 12: Chemicals and chemical products; 13: Nonmetallic mineral products; 14: Basic metals; 15: Manufacture of fabricated metal products; 16: Machinery; 17: Transport equipment; 18: Electrical machinery and apparatus; 19: Communications, computer, and other electronic equipment and apparatuses; 20: Instruments, watches, and clocks; 21: Other industrial activities; 22: Production and distribution of electricity and heat; 23: Steam and hot water supply; 24: Construction; 25: Transportation and warehouse; 26: Wholesale and retail; 27: Hotels and restaurants; 28: Leasing and commercial services; 29: Research and experiments; 30: Other service activities.

4. Conclusions

For China, an accurate accounting of CO_2 emissions responsibility of each province by sectors is the basis for the fair and equitable distribution of carbon emissions rights, and the complete start of the carbon emissions rights trading market and the rational development of provincial environmental policy. The method of accurately allocating CO_2 emissions responsibility for each province by sectors has become the focus of scholars and policy makers. Due to carbon emissions transfer, carbon leakage, and other issues between the provinces in China, there are significant differences in the value captured by each province from the domestic production value chain. It is reasonable to divide the amount of carbon emissions from the domestic production activities in keeping with the amount of value captured by each province and sector in the production value chain. Consequently, from the provincial value chain perspective combined with input-output methods and the sharing responsibility ideology, based on the input-output tables of China in 2002, 2007, and 2010, this study constructs models to calculate the CO_2 emissions responsibility of each province under the three principles, respectively. The empirical results are compared and analyzed from the vertical and horizontal directions. The main conclusions are as follows:

On the whole, under the production, consumption, and value capture principles, the provinces that bear the most responsibility for CO_2 emissions in China are Shandong, Hebei, Jiangsu, Guangdong, and Henan, while those with the least responsibility are Hainan and Qinghai. However, there is a great difference in the proportions of carbon emissions responsibility for each province during the same period under different principles or different periods under the same principle. For provinces such as Beijing, Tianjin, Zhejiang, Shanghai, and Guangdong, the proportion of CO_2 emissions liability under the production principle is less than that under the value capture principle, and the latter is less than that under the consumption principle. In other words, it is more advantageous for these economically developed and consumption-oriented areas to share CO_2 emissions responsibility in accordance with the production principle. The consumption principle is more beneficial for these production-oriented provinces such as Hebei, Henan, Liaoning, Shanxi, Inner Mongolia, and Shaanxi. However, the value capture principle strikes a compromise of the CO_2 emissions responsibility of each province between the production and consumption principles, and it shares the CO_2 emissions responsibility based on the actual value captured by each province in the provincial value chain. From the sector analysis, other services, construction, non-metallic mineral products, agriculture, and chemicals and chemical products are found to be the main carbon responsibility sectors for Shandong, Jiangsu, Hebei, Henan, and Guangdong.

According to the above analysis, this study argues that the value capture principle can be used to apportion CO_2 emissions responsibility of each province by the sectors in China, so that the CO_2 emissions responsibility of each province by its sectors is matched with its value captured from the provincial value chain. On this basis, Chinese policymakers should divide the carbon emissions rights for various provinces by the sectors in China fairly and rationally, establish an open carbon emissions database and a standardized national carbon emissions rights trading market, and build a platform for online transactions and information sharing, so that the participants of transactions are able to timely understand the supply and demand situation of the carbon emissions rights of each province by its sectors. In addition, to effectively achieve the carbon emissions reduction targets as soon as possible, we can proceed from the following points: for one thing, for the common sectors of the major responsible sectors of the carbon emissions responsibility in all provinces, it is necessary to strengthen the sharing and exchange of experience in carbon reduction among the provinces and break down the barriers in inter-provincial trade and competition. For another, the low-capacity, high-energy, high-emission, but inefficient sectors should be removed, while production technology and emissions reduction technology should be improved.

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