sustainability

The Metabolism of Islands

Edited by
Simron Jit Singh, Marina Fischer-Kowalski and Marian Chertow

Printed Edition of the Special Issue Published in *Sustainability*

www.mdpi.com/journal/sustainability

MDPI

The Metabolism of Islands

The Metabolism of Islands

Editors

Simron Jit Singh
Marina Fischer-Kowalski
Marian Chertow

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

Editors
Simron Jit Singh
University of Waterloo
Canada

Marina Fischer-Kowalski
University of Natural Resources and Life Sciences (BOKU)
Austria

Marian Chertow
Yale University
USA

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

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

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

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

ISBN 978-3-0365-0936-5 (Hbk)
ISBN 978-3-0365-0937-2 (PDF)

Cover image courtesy of Sophia Bourdanou.

© 2021 by the authors. Articles in this book are Open Access and distributed under the Creative Commons Attribution (CC BY) license, which allows users to download, copy and build upon published articles, as long as the author and publisher are properly credited, which ensures maximum dissemination and a wider impact of our publications.
The book as a whole is distributed by MDPI under the terms and conditions of the Creative Commons license CC BY-NC-ND.

Contents

About the Editors

Simron Jit Singh is Professor at the University of Waterloo, Canada. He is one of the pioneers of socio-metabolic research on small islands. As an industrial ecologist, he tracks material and energy flows through island systems: what and how much resources are locally produced, imported, transformed, used, stocked, and discarded. His research aims to inform science and policy on ways small islands can achieve resource and energy security in addition to meeting social and economic goals while building system resilience against the impacts of climate change. He is the founder and lead of the research program "Metabolism of Islands", Chairs the inaugural board of "Island Industrial Ecology", and leads the working group "Metabolic Risk on Islands" within the Emergent Risks and Extreme Events (Risk-KAN), a joint initiative of Future Earth, Integrated Research on Disaster Risk (IRDR), and the World Climate Research Programme (WCRP).

Marina Fischer-Kowalski is Professor Emeritus, founder and long-term Director of the Institute of Social Ecology, Vienna. She led development of the concept of "social metabolism" along with the widely used metric for material and energy flows to complement economic accounting. She has received numerous national and international awards, for example, the Austrian State Award for Arts and Sciences (2015) and the Austrian Ministry of Science Award for transdisciplinary sustainability research (2016) and became an Honorary Citizen of the Municipality of Samothrace, Greece, for her provision of scientific support to its sustainability pathway (2012). The University of Klagenfurt awarded her its Ring of Honour (2017). In 2017, she received the prestigious Society Prize of the International Society for Industrial Ecology for outstanding contributions to the field.

Marian Chertow is Professor of Industrial Environmental Management at the Yale School of Forestry and Environmental Studies and Director of the Center for Industrial Ecology. She is also appointed at the Yale School of Management and the National University of Singapore. Her research and teaching focus on industrial ecology, business/environment issues, circular economy, waste management, and urban sustainability. Her research has championed the study of industrial symbiosis involving geographically based exchanges of materials, energy, water, and wastes within networks of businesses globally. In 2019, she received the highest recognition of the International Society for Industrial Ecology, its Society Prize, for her outstanding contributions to the field.

PRIME MINISTER

GRENADA

FOREWORD

Islands have been portrayed for a long time as victims of global development and climate change. That narrative is now rapidly changing. The urgency faced by island governments have put "resilience" and "self-reliance" at the forefront of their national policies. Utilizing innovation in energy, industry, technology, infrastructure, finance, and global partnerships, islands are poised to become leaders in climate action and sustainability.

Island communities comprise almost a tenth of the global population, and utilize one-sixth of the Earth's surface, including surrounding oceans. The share of island nations in the United Nations membership is almost a quarter, giving them a strong voice in international decisions. Recent scholarship has highlighted the astounding adaptability of island communities. They demonstrate that "islandness" is not a barrier, rather a strength that draws from its unique geography, culture, traditions, and history.

Grenada's own National Sustainable Development Plan (2020 – 2035) prioritizes climate resilience, robust infrastructure, and resource security. As such, this book is very timely. It offers a compelling paradigm rooted in systemic thinking to address resource-use and infrastructure challenges faced by small islands. The authors provide valuable insight in understanding island risk and resilience from a metabolic perspective. Through several island cases, they articulate concepts and tools that can be very effective in island policy-making.

Some of the editors and authors of this book are active scholars in the research program "Metabolism of Islands" (MoI). Grenada was an early collaborator in MoI through the efforts of Dr. John Telesford of the T.A. Marryshow Community College. Previous publications from the MoI team have found its way into our National Sustainable Development Plan (NSDP), and in the Grenada Solid Waste Management Authority's (GSWMA) planning agenda.

Henceforth, it is my pleasure to write the Foreword to the first collection of articles that will serve as a foundation for the emerging field of "island industrial ecology". We hope that this research will influence wider policy that can transform the position and perception of small island states from vulnerable victims of global development and environmental change, to resilient nations that control their own futures.

Keith C. Mitchell (Dr. the Right Honourable)
Prime Minister of Grenada

Messages and testimonials for “Metabolism of Islands”

Islands are often at the frontier of environmental kickbacks for an ill-designed and exploding social metabolism that the UNEP-IRP is trying to document and ultimately to tame. As the panel’s Co-chair, I welcome this book for documenting the risks and portraying local efforts to finding ways out.

Janez Potočnik
Co-Chair, UNEP’s International Resource Panel (IRP), and recipient of the United Nations’ 2013 Champions of the Earth Award

----

By combining an industrial ecology approach with the context and systems operating on small islands, this book brings us closer to understanding how sustainability works in the real world, and how this might be applied to our global island.

James E. Randall
UNESCO Chair in Island Studies and Sustainability
University of Prince Edward Island, Canada

Metabolism of islands is a timely and fresh perspective on these small, open, and vulnerable economies. The principles of ecological economics embedded in this framework provide an instructive framework of how we as islanders can live, work, and recreate in a more sustainable and resilient manner.

Senator Crystal Drakes, Government of Barbados
Economist and Foresight Sustainability Strategist

We welcome this book that provides a comprehensive picture of the ecological and social risks and of sustainable development prospects on islands. We are also grateful to the editors who played an important role as scientists who advise us.

Carlota Marañon Marquina
Founding President, “Sustainable Samothraki”

This book offers a unique perspective to island scholarship and policy, challenging island governments to think systemically for building resilience.

Vincent Sweeney
Head, Caribbean Sub-Regional Office
United Nations Environment Programme (UNEP)

sustainability

Editorial

Introduction: The Metabolism of Islands

Simron Jit. Singh [1,*], Marina Fischer-Kowalski [2] and Marian Chertow [3]

1 School of Environment, Enterprise and Development (SEED), University of Waterloo Environment, Waterloo, ON N2L3G1, Canada
2 Institute of Social Ecology (SEC), University of Natural Resources and Life Sciences (BOKU), 1190 Vienna, Austria; marina.fischer-kowalski@boku.ac.at
3 Yale School of Forestry and Environmental Studies, Yale University, New Haven, CT 06511, USA; marian.chertow@yale.edu
* Correspondence: simron.singh@uwaterloo.ca

Received: 10 November 2020; Accepted: 13 November 2020; Published: 16 November 2020

Abstract: This editorial introduces the Special Issue "Metabolism of Islands". It makes a case why we should care about islands and their sustainability. Islands are hotspots of biocultural diversity, and home to 600 million people that depend on one-sixth of the earth's total area, including the surrounding oceans, for their subsistence. Today, they are on the frontlines of climate change and face an existential crisis. Islands are, however, potential "hubs of innovation" and are uniquely positioned to be leaders in sustainability and climate action. We argue that a full-fledged program on "island industrial ecology" is urgently needed with the aim to offer policy-relevant insights and strategies to sustain small islands in an era of global environmental change. We introduce key industrial ecology concepts, and the state-of-the-art in applying them to islands. Nine contributions in this Special Issue are briefly reviewed to highlight the *metabolic risks* inherent in the island cases. The contributors explore how reconfiguring patterns of resource use will allow island governments to build resilience and adapt to the challenges of climate change.

Keywords: island metabolism; island sustainability; island industrial ecology; socio-metabolic research; metabolic risk; socio-metabolic collapse

---

1. Why Care about Islands?

On 23 September 2017, five days after Hurricane Maria ravaged the small island nation of Dominica, Prime Minister Roosevelt Skerrit boldly announced to the 72nd UN General Assembly his goal of rebuilding the country as the world's first climate resilient nation. Only six months later, with financial support from Canada and the U.K., the *Climate Resilience Execution Agency for Dominica* (CREAD) was launched. By the end of 2018, Dominica had passed its *Climate Resilience Act* [1]. Dominica's urgency for a sustainability transformation and to build resilience to the impacts of climate change is a concern increasingly shared by most small island states and island communities around the world.

According to *Island Conservation*, there are ~465,000 islands in the world [2], of which some 80,000 are inhabited by approximately 600 million people, or 8.5% of the global population [3]. Islands comprise 5.3% of the earth's terrestrial area, and if we include the surrounding oceans, this amounts to one-sixth of the earth's total area on which island communities depend [4]. Thus, islands are home to rich and rare biodiverse systems. Harboring 20% of all plant, bird and reptile species found globally, islands are biodiversity hotspots; 7 out of 10 coral reef concentrations, and 12 of 18 centers of marine endemism surround islands. Islands are, therefore, conservation frontiers, with a third of the world's conservation areas being on islands [5,6].

In addition to a thriving biodiversity, islands have for millennia been at the crossroads of human culture–nature interactions, that have forged new forms of social expression. As a result, diverse island cultures have evolved [7,8]. They have developed from the days of the wind-propelled long and arduous journeys where ships anchored at islands to replenish supplies or to enter into trade, to the times of colonial and slave trade, to more recent times where a significant portion of island populations are living and working abroad. Given such dynamic histories, regions such as the Caribbean, Oceania, and the Pacific, are referred to as the microcosms of the Earth, with multiple ethnicities, languages, and ideologies [9].

Today, islands are severely threatened, and are on the frontlines of climate change. With less than 1% of greenhouse emission, island communities contribute the least to climate change; yet they remain the most impacted [10–12]. They have become sites of compound events and multiple risks. With fragile economies and ecosystems, the ability for small island economies to withstand the shocks caused by climate-induced extreme weather events are limited, and losses tend to be disproportionate, relative to the size of the island economy. The 2017 hurricane season, for example, resulted in severe losses relative to GDP in Sint Maarten (797%), the British Virgin Islands (309%), and Dominica (259%) [13], with the economic costs of recurring disasters only increasing over time [14–17]. Even in the much less exposed Mediterranean Sea, an extreme weather event of so far unknown intensity in 2017 washed away part of the central medieval town on the small island of Samothraki [18].

Besides their exposure to the increasing frequency and intensity of extreme weather events, most islands suffer from resource shortages, are import dependent, have undiversified exports, and some degree of brain drain [19]. The Caribbean region, for example, is the most tourism-reliant region in the world, with its countries importing up to 90% or more of its food and energy needs and construction materials. Caribbean nations are among the top 20 countries in the world with the highest migration rates of those having a post-secondary education with severe impacts on the local labor market [5,20–24]. Practices such as concentrated infrastructure development along the coast (coastal squeeze), population growth and drift to main centers, poor waste management, land-and-ocean degradation, and centralized energy systems are additional stressors on small islands [25].

In an era of climate urgency, islands will need to undergo a transformation to sustainability, where all citizens can enjoy a high quality of life at the lowest environmental cost. This will require a fundamental shift in the way small islands respond to problems and the way they conceive island development. Policy responses to challenges such as extreme weather events, resource insufficiency, international debt, brain drain, and waste are inevitably tackled independently, and on a narrow time-frame [26]. Links amongst these problems are often poorly understood, and the solution to one is frequently at the expense of another. To monitor progress towards sustainability and guide the development of innovative solutions, systemic approaches need to be adopted [27,28].

That said, few systemic studies exist for small islands that study the linkages between societal resource use, derived benefits, and environmental impact. This represents a significant knowledge gap with respect to understanding island sustainability which, in turn, inhibits effective policy. This volume is a step in addressing this critical gap. Through the nine contributions in this book, we not only highlight some of the pressing sustainability challenges on islands from a systems perspective, but also aim to provoke further research on the "metabolism of islands" and pave the way for a full-fledged research program on "island industrial ecology"—a program with the aim to offer policy-relevant insights and strategies to sustain small islands in an era of global environmental change.

2. Towards a Metabolism of Islands: Clarifying Core Concepts

"Metabolism" is a biological concept that refers to the chemical conversion and breakdown of organic matter to sustain reproduction. Analogous to biological metabolism, any given society organizes material and energy flows through their natural environment (or through imports with other societies) for their sustenance and reproduction. Some materials and energy become waste (outflows), while the rest of the flows are net additions to "material stocks" (or built environment). This process of organizing and reproducing material stocks and flows by society is referred to as *social metabolism* [29] (Figure 1).

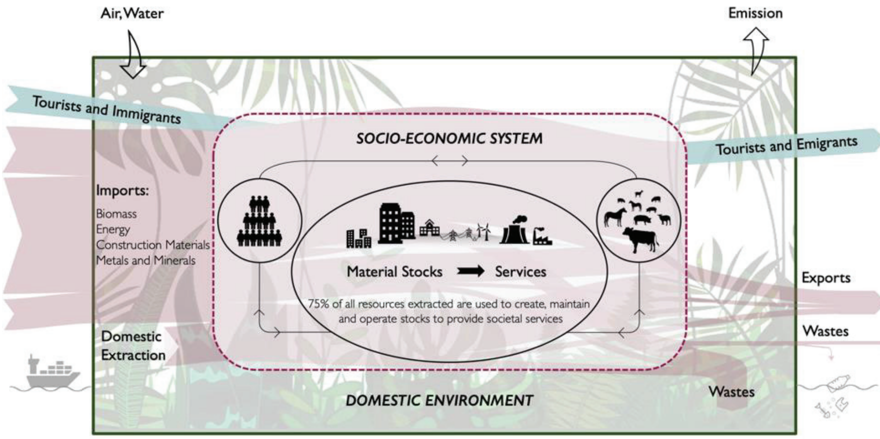

Figure 1. Specific combinations of material stocks and flows contribute to the system's exposure to risk (metabolic risk) and its ability to provide essential services.

Material stocks (or simply "stocks") provide critical societal services such as housing, food, energy, transport, health, and education. As economies develop, they stimulate the demand for *essential services* that are provided by the stocks and hence, they are viewed as the material basis of societal well-being. The larger the stocks, the greater the flows required to maintain and reproduce these stocks, creating a feedback loop, referred to as the *material stock–flow–service* (SFS) nexus [30]. The quantity and composition of resource throughput in a socioeconomic system characterizes its *metabolic profile* and is indicative of the pressure an economy exerts on the environment.

Just as metabolism influences a person's body, the process of *social metabolism* influences the natural environment by altering land-and-sea-use (by mining, urbanization, fishing, and agriculture) and, over time, causes pressure on ecosystems, the atmosphere and bio-geo-chemical cycles [31]. Climate disruptions, sea-level rise, hurricanes, and possibly even pandemics are examples of ecosystem *dis*-services, against which society needs to adapt and protect itself by altering existing patterns of *social metabolism*.

As such, specific combinations of material stocks and flows can become a *metabolic trap* and contribute to the system's exposure to risk, which we refer to as the *(socio-)metabolic risk* [32]. The IPCC [33] defines risk as "the potential for adverse consequence", that results from the "interaction of vulnerability (of the affected system), its exposure over time (to the hazard), as well as the (climate-related) hazard and the likelihood of its occurrence" (p. 557). Maladaptive practices such as reliance on imports for basic needs, centralized energy systems, coastal squeeze, or population drift can increase metabolic risks on islands. Systems that exhibit high metabolic risks are inherently vulnerable to shocks and disruptions, and to impacts of climate change.

A *(socio-)metabolic collapse* is an adverse outcome for systems that embody high metabolic risk, where the system's ability to organize its *social metabolism* is severely compromised. It signals the crossing of a threshold or *tipping point* that is often irreversible. Reaching a tipping point can be due to a biophysical (e.g., overuse of natural resources causing an ecological disaster), or social phenomenon (out-migration due to lack of services or jobs on an island causing a demographic shift), or a combination of both [34]. In the case of small islands, a metabolic collapse can be rapid, such as disruptions from hurricanes, or slow from gradual depletion of resources, or sea-level rise. Reconstruction following an adverse event, such as a hurricane, comes with large fiscal and environmental costs and can increase the metabolic risk if rebuilding actions are maladaptive.

Research presented in this volume illustrates the complex interactions in the stock–flow–service nexus. In analyzing the metabolism of islands, the 35 authors conducted *socio-metabolic research* (SMR), a research tradition within *industrial ecology* (IE) for systematically studying the biophysical stocks and flows of material and energy associated with societal production and consumption. SMR offers crucial insights to develop strategies to reconfigure and reduce societies' use of natural resources that are compatible with ecological boundaries, while also providing essential services to reach social thresholds [28].

3. Brief Overview of Socio-Metabolic Research (SMR) on Islands

The first known socio-metabolic research (SMR) on an island was for Nämdö in the Stockholm archipelago, Sweden, that analyzed energy and food flows [35]. Subsequently, Singh et al. [36] conducted a full material and energy stock and flow account for Trinket Island (India) that portrayed the changing metabolic profile of an indigenous society affected by development programs from the Indian state. The same case was later compared to the rise in material and energy consumption caused by excessive aid following the 2004 Asian tsunami [37,38]. Most SMR on islands have focused on "flows". Some have considered all material and energy throughput, while others have emphasized specific (problematic) materials or sectors of interest. Prominent examples of "flow" studies are Iceland and Trinidad and Tobago [39], Malta [40], the Philippines [41], Cuba [42], and Hawaii [43]. Flow studies with a focus on specific materials or sectors are: biomass flows for Jamaica 1961–2015 [44], e-waste for five Caribbean countries [45], plastics and packaging material on Trinidad [46], disaster waste on St. Martin [47], material and energy use in the tourism sector on Grenada [48] and on Menorca, Spain [49], solid waste on Grenada [50], and the metal–energy–construction materials nexus in New Caledonia [51].

Interest in material stock research is relatively recent, hence, stock accounts for islands are still very rare. Tanikawa et al. [52] estimated the loss in material stocks following the earthquake and tsunami in Japan, and conducted a stock account for construction materials for Japan for the period 1945 and 2010 [53]. Symmes et al. [54] conducted the first spatially explicit material *stock–flow* analysis in the Caribbean, focusing on Grenada's metabolism of construction materials, their distribution across the different sectors of the economy, and the potential impacts from sea-level rise. Noll et al. [55] analyzed the stock–flow relationship for the Greek island of Samothraki between 1971 to 2016, with a focus on construction materials, including inflows, as well as the construction and demolition waste generated. Merschroth et al. [56] estimated the loss in stocks in Fiji due to sea-level rise and global warming. Bradshaw et al. [57] explores the first material *stock–service* relationship for any island (Antigua and Barbuda) with consequences for island tourism under sea-level rise scenarios. Stock analysis on islands is extremely important, both from a perspective of total resource requirements over time, but also to identify infrastructure vulnerability (or *metabolic risks*) and resulting loss of societal services during and after a crisis.

4. Contributions in This Volume

The nine contributions in this volume cover a wide range of application of socio-metabolic research, from flow accounts, to stock analysis, and their relationship to services in space and time. Marian Chertow and colleagues (Chapter 1) analyze material flows for the archipelago of Hawaii and their scale interactions for five nested layers (or *holons*). They argue for a multi-level material flow analysis or a "holarchic" approach to island metabolism to better identify drivers of resource use at multiple scales and associated sustainability challenges.

Bahers and colleagues (Chapter 2) utilize a nexus approach, analyzing the nodes of interdependence for metal, energy, and construction mineral flows on the island of New Caledonia. The authors examine how extractive activities impact resilience and metabolic sustainability on a small remote island. To understand scale interactions and power relations, they apply the idea of "territorial metabolism" to conduct a material flow analysis of New Caledonia, combining biophysical analysis with the political decision-making that impacts resource flows.

Fischer-Kowalski et al. (Chapter 3) illustrate how islands can serve as real-world laboratories to promote sustainability. The authors conduct socio-metabolic research in a transdisciplinary setting on the Greek island of Samothraki to pave the way for the island to become a member of UNESCO's World Network of Biosphere Reserves. They argue that the transformation of local agriculture, as well as infrastructure, is critical for the island's sustainability. However, a collaborative process with stakeholders is essential to maximize social, economic, and environmental outcomes.

In Chapter 4, Dominik Noll and colleagues focus on biomass flows in the context of livestock overgrazing on Samothraki (as in Chapter 3). They show the degradation of the local ecology through focusing on ever-increasing livestock numbers incentivized by the European Union's Common Agriculture Policy (CAP). The case of Samothraki presented here reveals the complex interaction between environmental, economic, and social factors at an island level.

Chapters 5 and 6 focus on island waste. Shah et al. (Chapter 5) highlight the limitations of islands to absorb large volumes of waste produced because of high imports and associated packaging materials. Using the case of Trinidad and Tobago in the Caribbean, the authors identify three temporal phases and describe the efforts, reactions, drivers, and circumstances to deal with plastics and packaging materials. This work contributes to our understanding of the institutional factors that shape the search for solutions to the wicked problem of island waste metabolism.

Popescu and colleagues (Chapter 6) analyze stocks and disaster waste flows after hurricane Irma devastated the Caribbean French municipality of Saint Martin in 2017. They ask whether shocks such as this helped sustainably transform the island's waste management system. In answering this question, the authors focused on the intensity of waste flows, the spatial structure of metabolism and the actors and techniques that determine metabolic dynamics. They argue that islands urgently need to develop strategies for recovering, recycling, and reusing disaster waste as part of resilience building efforts.

Chapters 7 and 8 analyze material stocks in Antigua and Barbuda and in Fiji, respectively. Bradshaw and colleagues (Chapter 7) use Geographic Information System (GIS) techniques to quantify and locate the material stocks for Antigua and Barbuda in the Caribbean. The authors show how tourism would be most impacted under a 1- and 2-m sea-level rise scenario, given that most of the infrastructure is along the coast. By linking stocks with services, this research uncovers the complexities that connect environmental and economic vulnerabilities on an island, and the need for better infrastructure and spatial planning to enhance system resilience.

Similarly, Merschroth et al. (Chapter 8) adopt IPCC sea-level rise scenarios for the years 2050 and 2100 to estimate the amount of material stocks that will be inundated with sea-level rise in Fiji. The authors combine GIS-based digital inundation analysis with material stock analysis to reveal the hidden vulnerabilities with respect to spatial and infrastructure planning in Fiji. They show that by 2050 and 2100, some 4.5% and 6.2% of all existing buildings in Fiji will be inundated, which is equal to 40% of new construction each year.

In Chapter 9, Bogadóttir takes a long view to investigate the interrelations between social metabolism and socio-ecological sustainability in the Faroe Islands. She shows the importance of localizing food production that will foster food security, food sovereignty and biocultural diversity. Drawing from the Faroese experience, she describes their traditional food practices as "quiet sustainability" that contributes to local food security. She argues that such local practices should be considered real alternatives to import-based consumption, and so deserve a place in sustainability discourses.

The collection of articles in this volume suggest that islands have "methodological utility" [43]. They have the potential to pave the way for sustainability education, research, and practice. Islands are systems with clearly delineated boundaries and are, therefore, excellent geographies for socio-metabolic research. They offer numerous educational stories and lessons. Islands experience feedback rapidly (whether positive or negative), and consequences are more pronounced on small islands than on a mainland, prompting learning and immediate corrective action. There is also the aspect of urgency, especially since the impact of global environmental change on small islands is disproportionate and grips them in a spiral of increasing metabolic risk. Restructuring patterns of resource use, both for stocks and flows, will allow island governments to build resilience and adapt to the challenges of climate change. Small islands, therefore, urgently need to overcome systemic impasses to achieve their full competitive and equitable human development potential. Islands as potential "hubs of innovation" are uniquely positioned to be leaders in sustainability and climate action, therefore, in this journey, "island industrial ecology" and socio-metabolic research can certainly play an important role in helping islands achieve that status.

Author Contributions: Conceptualization, writing—original draft preparation, S.J.S.; writing—review and editing, M.C. and M.F.-K. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Acknowledgments: The authors thank Elham Mohammadi for her help in redrawing Figure 1 in this manuscript.

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

References

1. Bardouille, P.; Scaife, C. A Best Practice in the Making? How Dominica is Building the World's First Climate Resilient Nation. Available online: https://nextbillion.net/dominica-first-climate-resilient-nation/ (accessed on 8 July 2020).
2. Island Conservation. Why Islands? Islands are Biodiversity Hotspots. Available online: https://www.islandconservation.org/why-islands/ (accessed on 10 November 2020).
3. Baldacchino, G. *The Routledge International Handbook of Island Studies: A World of Islands*; Routledge: London, UK, 2018.
4. Ellsmoor, J. Island Innovation. Available online: http://eepurl.com/gw3ENX (accessed on 10 November 2020).
5. UN-OHRLLS. SIDS in Numbers. Climate Change Edition 2015. Available online: http://unohrlls.org/sids-in-numbers-climate-change-edition-2015/ (accessed on 8 July 2020).
6. Butler, R. The top 10 most biodiverse countries. Available online: https://news.mongabay.com/2016/05/top-10-biodiverse-countries/ (accessed on 10 November 2020).
7. Hong, S.-K. Biocultural diversity conservation for island and islanders: Necessity, goal and activity. *J. Mar. Isl. Cult.* **2013**, *2*, 102–106. [CrossRef]
8. Pungetti, G. Islands, culture, landscape and seascape. *J. Mar. Isl. Cult.* **2012**, *1*, 51–54. [CrossRef]
9. UNESCO. *Islands as Crossroads: Sustaining Cultural Diversity in Small Island Developing States*; Curtis, T., Ed.; UNESCO: Paris, France, 2011; Available online: https://unesdoc.unesco.org/ark:/48223/pf0000190899 (accessed on 10 November 2020).
10. IPCC. Impacts of 1.5 °C Global Warming on Natural and Human Systems (Chapter 3). In *Global Warming of 1.5 °C Special Report*; Intergovernmental Panel on Climate Change (IPCC): Geneva, Switzerland, 2018; Available online: https://www.ipcc.ch/sr15/chapter/chapter-3/ (accessed on 1 June 2020).
11. UNDP. Small Island Nations at the Frontline of Climate Action. 2017. Available online: https://www.undp.org/content/undp/en/home/presscenter/pressreleases/2017/09/18/small-island-nations-at-the-frontline-of-climate-action-.html (accessed on 8 July 2020).
12. Thomas, A.; Schleussner, C.-F.; Kumar, M. Small island developing states and 1.5 °C. *Reg. Environ. Chang.* **2018**, *18*, 2197–2200. [CrossRef]
13. CRED; UNISDR. Economic Losses, Poverty & Disasters: 1998–2017. 2018. Available online: https://www.undrr.org/publication/economic-losses-poverty-disasters-1998-2017 (accessed on 5 July 2020).
14. IMF. *Caribbean Small States—Challenges of High Debt and Low Growth*; International Monetary Fund: Washington, DC, USA, February 2013; Available online: https://elibrary.imf.org/view/IMF007/28058-9781498342261/28058-9781498342261/28058-9781498342261.xml (accessed on 8 July 2020).
15. Institute for International Law of Peace and Armed Conflict. World Risk Index 2019. Available online: https://reliefweb.int/sites/reliefweb.int/files/resources/WorldRiskReport-2019_Online_english.pdf (accessed on 3 July 2020).

16. United Nations Office for the Coordination of Humanitarian Affairs. Natural Disasters in Latin America and the Caribbean. 2020. Available online: https://reliefweb.int/sites/reliefweb.int/files/resources/20191203-ocha-desastres_naturales.pdf (accessed on 3 July 2020).
17. CRED. Centre for Research on the Epidemiology of Disasters International Disaster Database. 2020. Available online: https://www.emdat.be/ (accessed on 3 July 2020).
18. Fischer-Kowalski, M.; Löw, M.; Noll, D.; Petridis, P.; Skoulikidis, N. Samothraki in Transition: A Report on a Real-World Lab to Promote the Sustainability of a Greek Island. *Sustainability* **2020**, *12*, 1932. [CrossRef]
19. Deschenes, P.J.; Chertow, M. An island approach to industrial ecology: Towards sustainability in the island context. *J. Environ. Plan. Manag.* **2004**, *47*, 201–217. [CrossRef]
20. Docquier, F.; Lohest, O.; Marfouk, A. Brain Drain in Developing Regions (1990–2000); Presented at the Social Science Research Network, Rochester, NY, USA, July 2005; IZA Discussion Paper No. 1668. Available online: https://ssrn.com/abstract=761624 (accessed on 17 June 2020).
21. Mishra, P. *Emigration and Brain Drain: Evidence from the Caribbean*; IMF: Washington, DC, USA, 2006.
22. FAO. *FAO's Work with Small Island Developing States. Transforming Food Systems, Sustaining Small Islands*; FAO: Rome, Italy, 2019; p. 40.
23. Scott, D.; Hall, C.M.; Gössling, S. Global tourism vulnerability to climate change. *Ann. Tour. Res.* **2019**, *77*, 49–61. [CrossRef]
24. WTTC. Economic Impact Reports. *World Travel and Tourism Council.* 2020. Available online: https://wttc.org/Research/Economic-Impact (accessed on 9 July 2020).
25. IPCC. Climate Change 2014: Mitigation of Climate Change. Fifth Assessment Report. Intergovermental Panel on Climate Change (IPCC). 2014. Available online: https://www.ipcc.ch/report/ar5/wg3/ (accessed on 8 July 2020).
26. Petzold, J.; Magnan, A.K. Climate change: Thinking small islands beyond Small Island Developing States (SIDS). *Clim. Chang.* **2019**, *152*, 145–165. [CrossRef]
27. Saxena, A.; Qui, K.; Robinson, S. Knowledge, attitudes and practices of climate adaptation actors towards resilience and transformation in a 1.5 °C world. *Environ. Sci. Policy* **2018**, *80*, 152–159. [CrossRef]
28. Haberl, H.; Wiedenhofer, D.; Pauliuk, S.; Krausmann, F.; Müller, D.B.; Fischer-Kowalski, M. Contributions of sociometabolic research to sustainability science. *Nat. Sustain.* **2019**, *2*, 173–184. [CrossRef]
29. Fischer-Kowalski, M.; Weisz, H. The Archipelago of Social Ecology and the Island of the Vienna School. In *Social Ecology: Society—Nature Relations across Time and Space*; Haberl, H., Fischer-Kowalski, M., Krausmann, F., Winiwarter, V., Eds.; Springer International Publishing: Cham, Switzerland, 2016; pp. 3–28.
30. Haberl, H.; Wiedenhofer, D.; Erb, K.-H.; Görg, C.; Krausmann, F. The Material Stock–Flow–Service Nexus: A New Approach for Tackling the Decoupling Conundrum. *Sustainability* **2017**, *9*, 1049. [CrossRef]
31. Steffen, W.; Richardson, K.; Rockström, J.; Cornell, S.E.; Fetzer, I.; Bennett, E.M.; Biggs, R.; Carpenter, S.R.; de Vries, W.; de Wit, C.A.; et al. Planetary boundaries: Guiding human development on a changing planet. *Science* **2015**, *347*, 736–747. [CrossRef] [PubMed]
32. Singh, S.J. Natural Hazards and Complex Disasters. In *The International Encyclopedia of Anthropology*; Callan, H., Ed.; John Wiley and Sons: Hoboken, NJ, USA, 2021.
33. IPCC. Glossary—Global Warming of 1.5 °C. 2018. Available online: https://www.ipcc.ch/sr15/chapter/glossary/ (accessed on 10 November 2020).
34. Petridis, P.; Fischer-Kowalski, M. Island Sustainability. The Case of Samothraki. In *Social Ecology: Society-Nature Relations across Time and Space*; Haberl, H., Fischer-Kowalski, M., Krausmann, F., Winiwarter, V., Eds.; Springer International Publishing: Cham, Switzerland, 2016.
35. Sundkvist, Å.; Jansson, A.; Enefalk, Å.; Larsson, P. Energy flow analysis as a tool for developing a sustainable society—A case study of a Swedish island. *Resour. Conserv. Recycl.* **1999**, *25*, 289–299. [CrossRef]
36. Singh, S.J.; Grünbühel, C.M.; Schandl, H.; Schulz, N. Social Metabolism and Labour in a Local Context: Changing Environmental Relations on Trinket Island. *Popul. Environ.* **2001**, *23*, 71–104. [CrossRef]
37. Singh, S.J.; Haas, W. Complex Disasters on the Nicobar Islands. In *Social Ecology. Society-Nature Relations across Time and Space*; Haberl, H., Fischer-Kowalski, M., Krausmann, F., Winiwarter, V., Eds.; Springer: Dordrecht, The Netherlands, 2016.
38. Singh, S.J.; Fischer-Kowalski, M.; Haas, W. The Sustainability of Humanitarian Aid: The Nicobar Islands as a Case of 'Complex Disasters'. In *The Asian Tsunami and Post-Disaster Aid*; Reddy, S., Ed.; Springer: Singapore, 2018.

39. Krausmann, F.; Richter, R.; Eisenmenger, N. Resource Use in Small Island States. *J. Ind. Ecol.* **2014**, *18*, 294–305. [CrossRef]
40. Conrad, E.; Cassar, L.F. Decoupling Economic Growth and Environmental Degradation: Reviewing Progress to Date in the Small Island State of Malta. *Sustainability* **2014**, *6*, 6729–6750. [CrossRef]
41. Martinico-Perez, M.F.G.; Fishman, T.; Okuoka, K.; Tanikawa, H. Material Flow Accounts and Driving Factors of Economic Growth in the Philippines. *J. Ind. Ecol.* **2017**, *21*, 1226–1236. [CrossRef]
42. Eisenhut, S.M. National Material Flow Analysis. Dipl, Uniwien, Wien, 2009. Available online: http://othes.univie.ac.at/3530/ (accessed on 26 September 2020).
43. Chertow, M.R.; Graedel, T.E.; Kanaoka, K.S.; Park, J. The Hawaiian Islands: Conceptualizing an Industrial Ecology Holarchic System. *Sustainability* **2020**, *12*, 3104. [CrossRef]
44. Okoli, A. Socioeconomic metabolism of Biomass in Jamaica in the Context of Trade and National Food Security: A time series biophysical analysis (1961–2013). Master's Thesis, University of Waterloo, Waterloo, ON, Canada, 2016.
45. Mohammadi, E.; Singh, S.J.; Habib, K. Electronic waste in the Caribbean: An impending environmental disaster or an opportunity for a circular economy? *Resour. Conserv. Recycl.* **2020**, *164*, 105106. [CrossRef]
46. Shah, K.U.; Niles, K.; Ali, S.H.; Surroop, D.; Jaggeshar, D. Plastics Waste Metabolism in a Petro-Island State: Towards Solving a 'Wicked Problem' in Trinidad and Tobago. *Sustainability* **2019**, *11*, 6580. [CrossRef]
47. Popescu, R.; Beraud, H.; Barroca, B. The Impact of Hurricane Irma on the Metabolism of St. Martin's Island. *Sustainability* **2020**, *12*, 6731. [CrossRef]
48. Telesford, J.N. Strategic Sustainability and Industrial Ecology in an Island Context, with Considerations for a Green Economy Roadmap: A Study in the Tourist Accommodation Sector, Grenada. Ph.D. Thesis, Robert Gordon University, Aberdeen, Scotland, UK, 2014.
49. Marcos-Valls, A.; Kovacic, Z.; Giampietro, M.; Kallis, G.; Rieradevall, J. Isolated yet open: A metabolic analysis of Menorca. *Sci. Total Environ.* **2020**, *738*, 139221. [CrossRef] [PubMed]
50. Elgie, A.R.; Singh, S.J.; Telesford, J.N. You can't manage what you can't measure: The potential for circularity in Grenada's waste management system. *Resour. Conserv. Recycl.* **2021**, *164*, 105170. [CrossRef]
51. Bahers, J.-B.; Higuera, P.; Ventura, A.; Antheaume, N. The 'Metal-Energy-Construction Mineral' Nexus in the Island Metabolism: The Case of the Extractive Economy of New Caledonia. *Sustainability* **2020**, *12*, 2191. [CrossRef]
52. Tanikawa, H.; Managi, S.; Lwin, C.M. Estimates of Lost Material Stock of Buildings and Roads Due to the Great East Japan Earthquake and Tsunami. *J. Ind. Ecol.* **2014**, *18*, 421–431. [CrossRef]
53. Tanikawa, H.; Fishman, T.; Okuoka, K.; Sugimoto, K. The Weight of Society Over Time and Space: A Comprehensive Account of the Construction Material Stock of Japan, 1945–2010. *J. Ind. Ecol.* **2015**, *19*, 778–791. [CrossRef]
54. Symmes, R.; Fishman, T.; Telesford, J.N.; Singh, S.J.; Tan, S.-Y.; Kroon, K.D. The weight of islands: Leveraging Grenada's material stocks to adapt to climate change. *J. Ind. Ecol.* **2020**, *24*, 369–382. [CrossRef]
55. Noll, D.; Wiedenhofer, D.; Miatto, A.; Singh, S.J. The expansion of the built environment, waste generation and EU recycling targets on Samothraki, Greece: An island's dilemma. *Resour. Conserv. Recycl.* **2019**, *150*, 104405. [CrossRef]
56. Merschroth, S.; Miatto, A.; Weyand, S.; Tanikawa, H.; Schebek, L. Lost Material Stock in Buildings due to Sea Level Rise from Global Warming: The Case of Fiji Islands. *Sustainability* **2020**, *12*, 834. [CrossRef]
57. Bradshaw, J.; Singh, S.J.; Tan, S.-Y.; Fishman, T.; Pott, K. GIS-based Material Stock Analysis (MSA) of Climate Vulnerabilities to the Tourism Industry in Antigua and Barbuda. *Sustainability* **2020**, *12*, 8090. [CrossRef]

Publisher's Note: MDPI stays neutral with regard to jurisdictional claims in published maps and institutional affiliations.

© 2020 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (http://creativecommons.org/licenses/by/4.0/).

sustainability

MDPI

Article

The Hawaiian Islands: Conceptualizing an Industrial Ecology Holarchic System

Marian R. Chertow [1,†], Thomas E. Graedel [1,†], Koichi S. Kanaoka [1,*,†] and Jooyoung Park [2,†]

[1] Center for Industrial Ecology, School of Forestry and Environmental Studies, Yale University, New Haven, CT 06511, USA; marian.chertow@yale.edu (M.R.C.); thomas.graedel@yale.edu (T.E.G.)
[2] Graduate School of Energy and Environment (KU-KIST Green School), Korea University, Seoul 02841, Korea; jy_park@korea.ac.kr
* Correspondence: koichi.kanaoka@yale.edu
† These authors contributed equally to this work.

Received: 24 February 2020; Accepted: 8 April 2020; Published: 13 April 2020

Abstract: The Hawaiian Islands form a holarchic system with at least five nested layers (holons) at increasing spatial scales: from a single enterprise to cities, to individual islands, to the archipelago (the group of islands), and to the global resource base that connects them all. Each holonic layer operates individually but is also linked to holons at lower and higher levels by material input and output flows. An integrated study of the holarchic system allows us to explore the value of applying this concept to industrial ecology. We present examples from a multi-level material flow analysis combining a large quantity of material and energy flow data for Hawaii from the five holarchic levels. Our analysis demonstrates how a holarchic approach to the study of selected interacting systems can reveal features and linkages of their metabolism not otherwise apparent and can provide a novel basis for discovering material, energy, and societal connections.

Keywords: holarchy; holon; industrial ecology; material flow analysis; social metabolism

---

1. Introduction

Industrial ecologists have established material flow analysis (MFA) as a premier tool for assessing the metabolism of human society. While an MFA can be a highly effective tool for optimizing resource allocation, researchers can easily overlook the relationships between a system under study and other related systems. Failing to understand the interdependencies of systems could lead to sub-optimal decision making when considering broader system boundaries for analyses. One such example is the shock in global automobile production following the 2011 earthquake in Japan, which revealed to many major automakers that parts of their upstream supply chains depended on a pigment produced by only one factory in the world, near Fukushima. Automakers could have hedged their supply chain risks if they had a full understanding of how their networks of lower-tier suppliers (lower-level systems) integrated with networks that include higher-tier suppliers (higher-level systems). The current framework for MFA works well at helping researchers identify opportunities for optimizing systems at a single system level but is not well suited for optimizing material flows across nested systems interacting with one another. One idea to address this limitation is to approach MFA using the holarchy framework. The holarchy concept aims to examine systems holistically by acknowledging the systems nature of the modern material-based society.

The holarchy framework was proposed by Koestler [1] as an alternative to hierarchy in recognizing the semi-autonomous characteristic of components of biological and social systems, including organizations, organisms, and cells. Each of these entities is considered a holon since each is a complex system with operational and managerial independence wherein each system is seeking to optimize objectives at its respective holarchic level [2]. As such, a holon is simultaneously a part and a whole in itself and arises from the collaboration of its complex sub-systems and super-systems. This framework has been commonly applied to information systems of intelligent manufacturing systems [3–5] and of supply chain management systems [6–8] and, more recently, to energy systems such as microgrids [9]. Holarchy has also been used to analyze the means for improving the resilience of social-ecological systems [10,11], including how to alleviate congestion, ineffective distribution of resources, and environmental pollution in cities [12]. Holarchy was introduced to industrial ecology by the works of Kay [13] and Spiegelman [14] to study socio-economic systems as self-organizing, holarchic, open (SOHO) systems.

It is widely recognized that quantifying the material flows into and from a jurisdictional region such as a city or country is not a simple matter. The challenge is one of data availability, which could result from (1) a simple lack of effort in data collection, (2) data collected but in insufficient detail for the intended purpose, or (3) the difficulty of monitoring flows across porous jurisdictional boundaries. In principle, a promising way of addressing the data challenge is by focusing on islands, which have clearly defined physical boundaries and, often, a small number of locations (ports, airports) where material flows need to be monitored [15]. The methodological utility of island boundaries was, of course, recognized by Darwin in his studies of finches in the Galapagos Archipelago. A nice summary of his work is given by Grant and Estes [16]. Examples of island-based MFAs that demonstrate this efficacy include those of Singh et al. [17], Lenzen [18], Krausmann et al. [19], Nielsen and Jørgensen [20], and Cecchin [21].

Anthropogenic activities on islands become segments of economies larger and smaller. In this vein, the sum of human activities on Planet Earth related to material flows represents the sum of flows into and from Earth's regions. The regional flows are those related to cities, industries, and other activities, extending down to smaller entities. Nonetheless, it is not easy to demonstrate the features of a modern, multi-level material system. Islands may provide a potential end-run around this challenge because island archipelagoes are themselves generally self-contained and are also connected with their individual islands (a lower level) and with flows to and from continental and global systems (higher levels).

An archipelago and its connections form an example of a holarchy, or what engineers call a system of systems [2] and ecologists call a panarchy [22,23]. In such a system, a higher-level holon is, in part, a result of activities of holons below it in the hierarchy. Similarly, an upper-level holon may constrain the behaviors of lower-level holons. One can, therefore, picture a material flow holarchy ranging from the lowest level holon to the highest level holon defined in this paper as (1) an industrial activity on an island by one or more enterprises, (2) a city on the island that contains that industrial activity, (3) the island itself, (4) the archipelago of which the island is part, and (5) the planet that contains the archipelago. The holarchy framework can also be applied to conceptualize non-island socio-economic systems.

In practice, a holarchic study in industrial ecology would consist of the collective examination of material flow accounts of a particular holon and its lower- and higher-level holons which form a holarchy (Figure 1). This article synthesizes research by faculty and graduate students from the Yale School of Forestry and Environmental Studies and explores some of the benefits and challenges of examining material flows for Hawaii using the holarchy framework. The material flow accounts presented in this study were not compiled with the idea of holons in mind, but it subsequently occurred to us that the islands were part of a holarchic system. Our previous objective had been to compare material flows on islands that were each a political unit (typically a county) of the same state, Hawaii, thereby allowing us to examine variations in metabolism while controlling for differences in the regulatory system. Because of limitations in scope and data availability, the results are indicative rather than comprehensive, revealing some of the challenges and achievements of applying the holarchic perspective within industrial ecology. The value of the activity is that it demonstrates the potential of a holarchic approach to MFA, and thereby encourages further research based on that perspective.

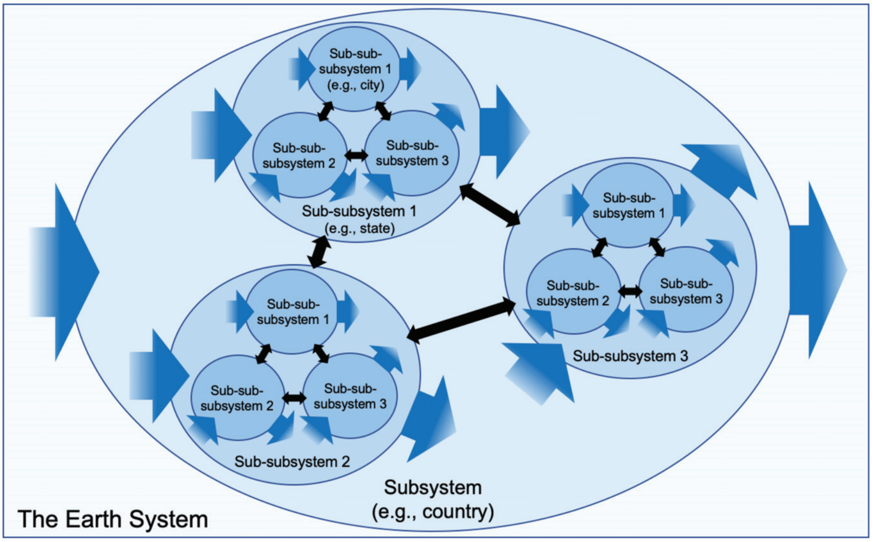

Figure 1. Conceptual diagram of a holarchic system for integrated material flow analyses. The entire Earth system and each circle denote individual holons, and their borders represent system boundaries for individual material flow analyses. Holarchic levels are indicated by shades of blue. Black arrows represent flows of materials between holons in the same holarchic level, and blue arrows represent flows between holarchic levels.

2. Materials and Methods

The Hawaiian Island Archipelago consists of six principal islands (Figure 2) and a number of smaller, largely uninhabited islands. During the years 2006–2013, faculty and graduate students from the Yale School of Forestry and Environmental Studies conducted projects related to quantifying and analyzing flows of materials through the islands, organized by authors of the present study. MFAs, energy analyses, and targeted studies of various kinds were conducted for a selection of industries, cities, and islands in the archipelago [24–47]. These activities were pursued with diverse analytic aims in mind, with the result that the individual studies were interesting and useful, but the sum of the studies did not comprise a fully integrated specification of the interlinked material flows related to the Hawaiian Archipelago. Nonetheless, the results provide examples of metabolism at the different holarchic levels, thereby enabling us to demonstrate the potential value of a complete holarchic evaluation centered on anthropogenic flows of materials.

The analysis in the present work is directed at the five-level holarchy shown in Figure 3. As the holarchy framework views each holon as a semi-autonomous system, our study treats each holon as an individual system of analysis, effectively constructing a tiered system of MFAs consisting of multiple levels connected by material input and output flows. We present the multi-layer analysis of material flows by providing examples of standalone MFAs for holons drawing on our previous works (see the Supplementary Materials for additional examples of such MFAs). The compiled material flows are compared across individual holons to yield insights that are not apparent when examining each holon in isolation.

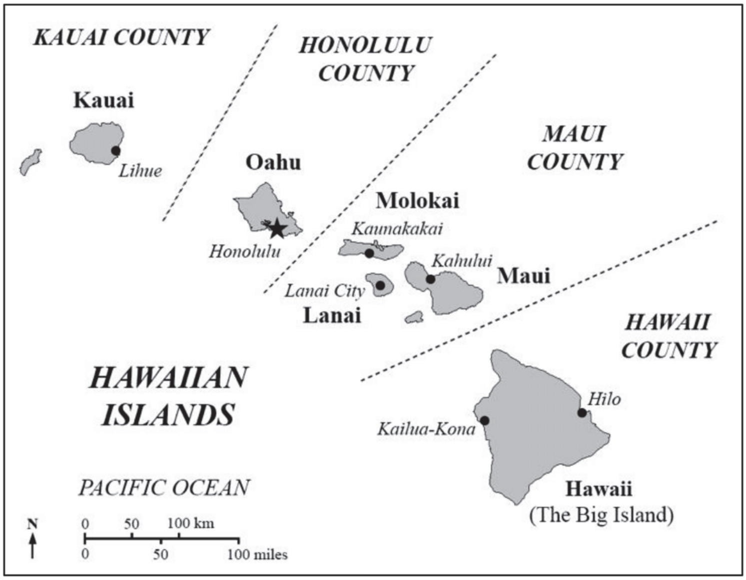

Figure 2. The Hawaiian Archipelago, picturing the six islands under study and several principal cities.

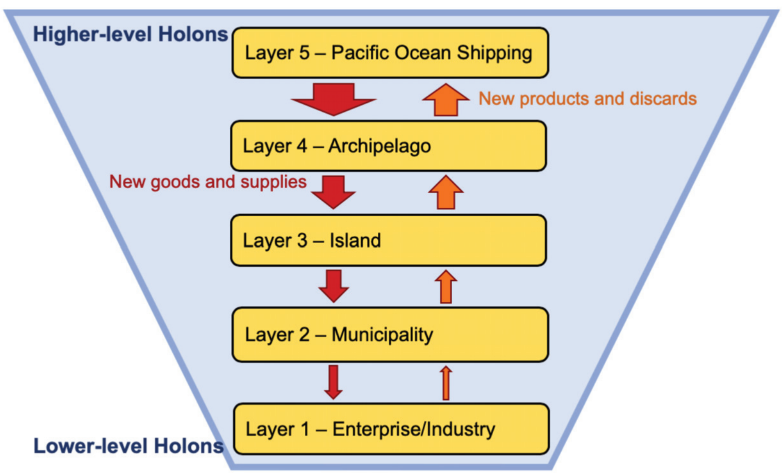

Figure 3. The Hawaiian Islands holarchic system. Arrows represent material flows between holarchic levels. Lower-level holons are nested within higher-level holons. Flows between higher-level holons are larger than those between lower-level holons. In addition, flows from higher to lower holons are depicted as larger than those from lower to higher holons to indicate that material stocks in Hawaii are gradually increasing over time as island infrastructure is further developed.

The material flow accounts at each holarchic level were compiled based on Eurostat's methodology for economy-wide material flow accounts (EW-MFA; see the Supplementary Materials for the compiled material flow data) [48]. Imports and exports for each holon were calculated using data on inbound and outbound ocean shipments by port from the U.S. Army Corps of Engineers Waterborne Commerce Statistics Center [49]. The accounts for domestic extraction drew primarily on state-level harvest and mining data from the U.S. Department of Agriculture's National Agricultural Statistics Service [50] and the U.S. Geological Survey's National Minerals Information Center [51]. State-level material accounts were disaggregated to the island and municipality levels based on information including the distributions of crop area, retail sales, population, and man-hours worked in mines, provided by the State of Hawaii Databook [52], a publication of the State of Hawaii's Department of Business, Economic Development and Tourism (DBEDT), the U.S. Census Bureau's Economic Census [53], and the U.S. Department of Labor's Mine Safety and Health Administration [54], among others. For analyses of island and industry-level holons, data from these sources were enhanced by in-person interviews conducted in Hawaii by Yale graduate students and by personal communication with individuals at local organizations. Apparent consumption, or formally direct material consumption, is calculated as the sum of used domestic extraction and imports, minus exports.

Material shipments by air are not accounted for in this study. Approximately 98% of imports to Hawaii were ocean deliveries [37], and this ratio was assumed to be similar for exports. Therefore, values for ocean shipments were treated as all shipments in the calculations. Furthermore, the terms "import" and "export" are used in this document to describe inbound and outbound material flows for a defined system as used by Eurostat [48] and do not strictly indicate international flows. Imports and exports for the entire State of Hawaii can be calculated from port-level data because all ocean shipments to and from the Hawaiian Islands pass through Oahu [37]. Our analysis does not include unused extraction, indirect flows, or sectoral disaggregation of material flows. We present the results of MFAs for individual holons by holarchic level in order of increasing spatial scale and explore their relationships.

3. Results

3.1. Holon Level 1: The Macadamia Nut Industry on the "Big Island"

Among the significant industrial sectors in the Hawaiian Archipelago is the macadamia nut industry on Hawaii Island (hereafter termed the "Big Island" to avoid confusion). One macadamia nut factory processed 14.1 Gg of macadamia nuts in 2005 (Figure 4). The processing plant's operations relied on very few island imports relative to its direct material inputs (island export-import ratio of 3.4 by mass). The facility derived 60% of its power from an on-site generator that burned 660 Mg of discarded macadamia nut shells and another 20% from 130 Mg of waste fuel oil. Water was extracted from two deep wells on the property, and the nuts were grown primarily in orchards adjacent to the factory, minimizing the distance for material transport. Other industries could, of course, be analyzed in the same way, depending on the availability of data and the purpose of the analysis.

The material flows for individual facilities could be effectively characterized by conventional MFAs for enterprise-level holons. However, these analyses alone do not inform how the quantified flows relate to flows for a city, an island or county, and other higher-level holons. Whole island data show that 25.6 Gg of macadamia nuts were harvested on the Big Island in 2005, so the factory processed over half of all macadamia nuts collected on the island in that year. Such a comparison for a single material may be simple and interesting, but much more data are required to make robust assessments about the overall relationships between material flows for an individual enterprise (or industry) and aggregate flows for higher-level holons. For example, the relative contributions of the factory's material flows to the total flows for the State of Hawaii remain unaddressed. This knowledge gap may be filled, however, by utilizing results from other holarchic levels, as shown in the following sections.

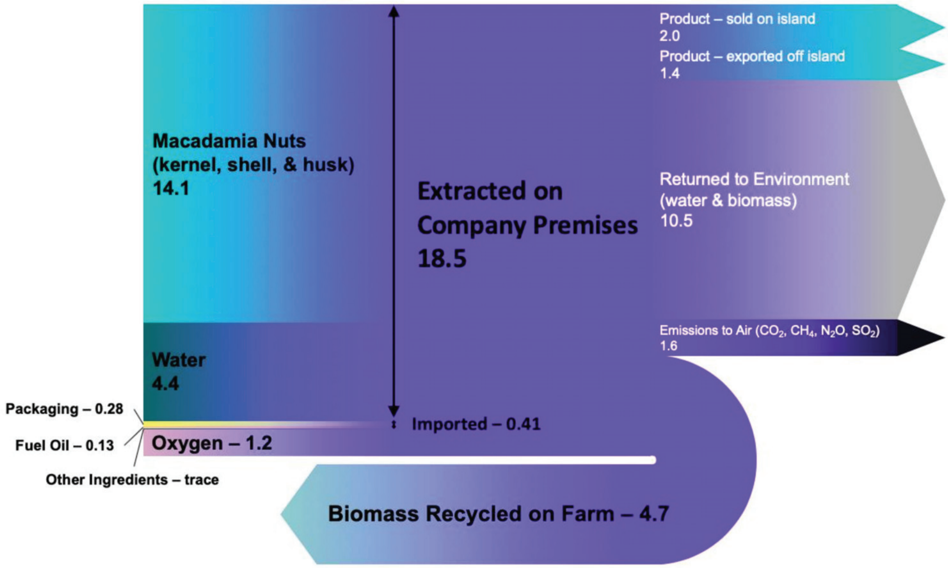

Figure 4. Material flow analysis for a macadamia nut processing plant on the Big Island in 2005. The units are Gg a^{-1}. Based on Houseknecht et al. [40].

3.2. Holon Level 2: Municipalities on the Big Island: Hilo and Kona

The example holon for level 2 is a municipality. As part of our study, the students conducted MFAs to examine the social metabolism of Hilo and Kona, the two principal urban centers on the Big Island. In this study, Hilo's spatial extent is defined as the Hilo Census Designated Place (CDP), and Kona's extent is defined as the collection of Kailua, Kahaluu-Keauhou, Kalaoa, Holualoa, and Honalo CDPs, based on extensive consultation with geographers and the County of Hawaii planning departments (Although Kona and Hilo are known as the largest municipalities on the Big Island, neither has municipal boundaries per se. It is typical in Hawaii that the more populous islands are designated as counties and are unincorporated. With no official boundaries, a geographical carving out of CDPs had to be created for both Hilo and Kona to conduct the comparison properly, specifically in connection with National Science Foundation grant #0948781 ULTRA-Ex Award. "Human-Nature Interactions in an Urbanized Island Setting: Hilo and Kailua-Kona, Hawaiʻi as Model Socio-Ecological Systems."). The macadamia nut factory lies outside of our system boundaries for Hilo and Kona. Because more than one example of a municipality holon was addressed, it was possible to compare the two results, as shown in Figure 5.

Significant differences are seen across Hilo and Kona in imports, exports, and domestic extraction. The resident population of Hilo was approximately 20% greater than that of Kona in 2009 [52], but the direct material input to Hilo was 43% greater than that of Kona. One reason for this disparity was Hilo's fossil fuel imports, which were 87% greater than that of Kona. On the other hand, there were several materials that had larger flows for Kona than those for Hilo. Notably, Kona imported, locally extracted, and consumed a larger amount of biomass, for grazing and for food and agricultural products. The larger imports and domestic consumption of biomass may partially be explained by Kona's greater focus on the tourism industry. Interestingly, Kona extracted more biomass, even though Hilo had 13 times more water than the dry, tourism-oriented Kona [26]. Construction minerals accounted for 44% of direct inputs to each municipality, and almost all were used within the cities. Together, the two municipalities consumed 350 Gg of fossil fuels and utilized 1,350 Gg of construction minerals. While separate MFAs for holons at the same holarchic level allow for some comparisons, no claims with respect to higher-level holons could be made without MFA results for higher-level holons, as was the case with the macadamia nut factory.

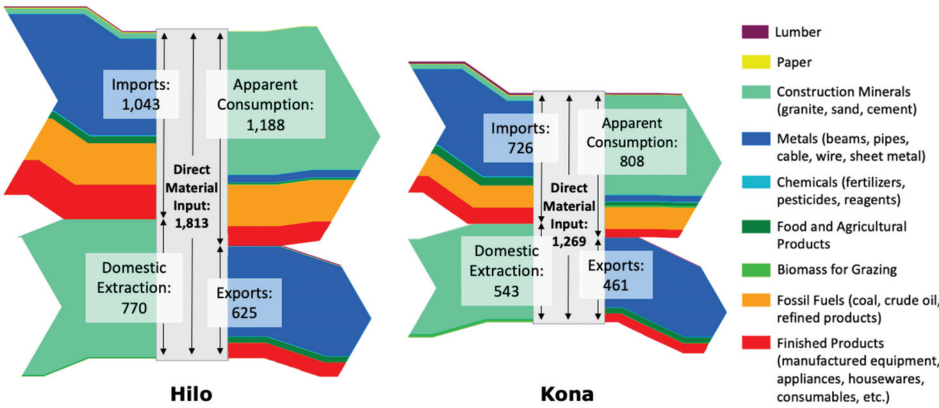

Figure 5. Material flows (Gg a^{-1}) for the Big Island communities of Hilo (left) and Kona (right) in 2009, excluding water. Data from Chertow and Seto [27].

3.3. Holon Level 3: The Big Island

The example holon for level 3 is an island. An MFA that was completed for the Big Island is shown in Figure 6. The economy of the island was evenly dependent on imports and local extraction in 2009, with the direct material input equaling 5,080 Gg. Fossil fuel imports amounted to 580 Gg, of which 99% was consumed on the island. Construction minerals were the largest material flow, equaling 40% of direct inputs. Practically all non-metallic mineral inputs were consumed on the island. Approximately 72% of the direct material input, a larger ratio compared to Hilo and Kona, was consumed on the Big Island as a whole. This difference is mainly a result of the large local extraction of biomass for grazing on the island.

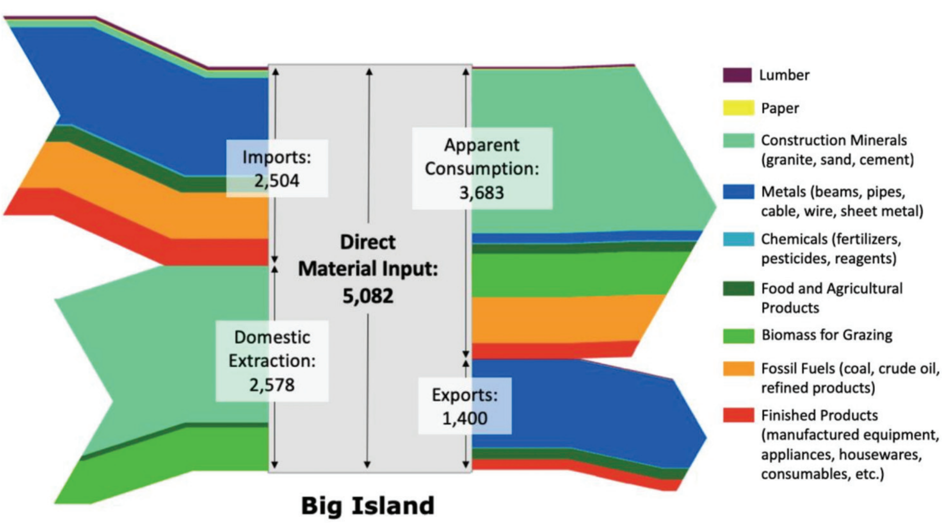

Figure 6. Material flow analysis for the Big Island (Gg a^{-1}) for year 2009, excluding water. Data from Chertow and Seto [27].

A comparison of material flows for Hilo and Kona with that of the entire island reveals that while almost half of the island's population resided in Hilo and Kona [52], the two municipalities together accounted for the use of 61% of fossil fuels and 66% of construction minerals consumed on the entire island. Furthermore, the quantity of biomass extracted in the two municipalities combined was practically insignificant for the island overall (0.9% of local extraction and 0.4% of the direct material input to the Big Island).

Thus, comparing the metabolism of Hilo and Kona with that of the entire island illustrates that much of the island exhibited characteristics of a more rural economy. With MFA data for multiple holarchic levels, researchers may be able to make practical approximations of material flows for holons with data gaps. For example, subtracting Hilo and Kona's quantities for local extraction of food and agricultural products from the total extraction of food and agricultural products on the Big Island yields the result that the distribution of extracted food and agricultural products was 3.9 Gg in Hilo, 4.4 Gg in Kona, and 58.7 Gg across the entire rest of the island. This distribution would have been missed from solely an island-level MFA or a comparison of Hilo and Kona. The estimation technique is not directly applicable to our dataset because the flows for Hilo and Kona were derived together with those for the rest of the island by applying allocation factors to island-level flows (based on ratios of cropland area, building permits, product sales, etc.). The approach would have been practical, however, if the domestic extraction of biomass for Hilo and Kona were calculated using cropland area and granular crop yield estimates, which vary widely by section of the island. It could also be useful in cases where material flow data are documented for a higher-level holon (e.g., island or county) and only for some nested, lower-level holons (e.g., city).

With approximate data for the extraction of food and agricultural products on the rest of the Big Island, comparisons could be made with the macadamia nut factory. The quantity of macadamia nuts processed by the factory accounts for roughly a quarter of food and agricultural products extracted on the island, excluding Hilo and Kona, and a fifth of all food and agricultural products extracted on the island overall. This comparison also shows, however, that even an enterprise such as the macadamia nut factory contributed less than 1% of the total domestic extraction and the direct material input for the Big Island.

3.4. Holon Level 4: The Hawaiian Archipelago

The example holon for level 4 consists of the six most populous islands of the Hawaiian Archipelago, which account for the vast majority of material flows for the State of Hawaii. Figure 7 illustrates the overall material flows for the state, revealing the archipelago holon's metabolic profile to be very different from that of the Big Island holon. The State of Hawaii had a direct material input of 24.8 Tg in 2007, split evenly between domestic extraction and imports, similar to the Big Island. Unlike the Big Island, however, 94% of the direct material input to the state was consumed within the archipelago system.

Construction minerals were the most prominent materials for domestic extraction and apparent consumption for the archipelago holon. The flows of fossil fuels for the entire state were much larger than for the Big Island holon in absolute terms and in relation to other materials for imports, exports, and apparent consumption. Further analyses of material flows for island-level holons revealed that over two-thirds of all fossil fuel imports are consumed on Oahu. The distribution of fossil fuel consumption among the islands was in line with the population distribution, although there also appeared to be a decrease in consumption per capita with islands with higher population densities. This trend was similar for other material flows as well.

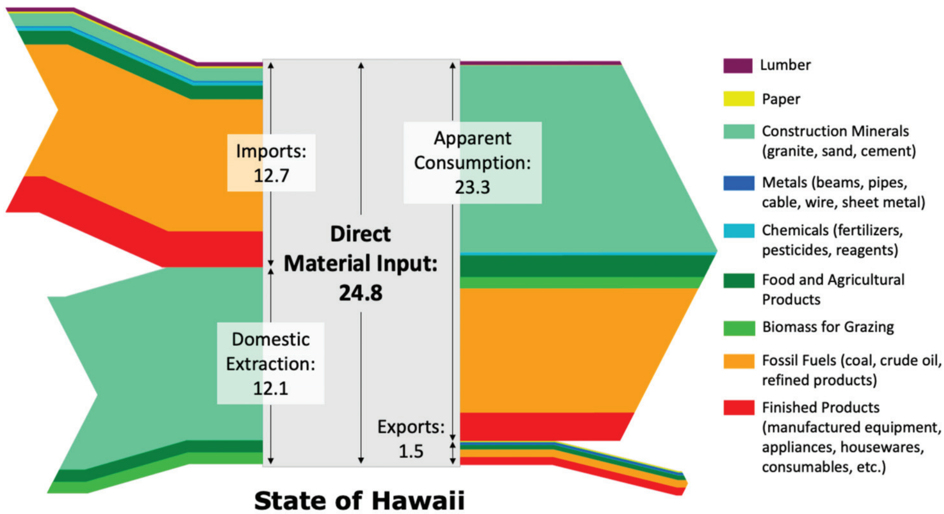

Figure 7. Material flow analysis for the State of Hawaii (Tg a^{-1}), 2007. Based on Famely et al. [37] and Kanaoka [55].

The quantities for the state's exports may appear to be small when considering that the Big Island's exports alone were comparable to those of the entire state. The comparison of MFAs for the archipelago-level and island-level holons revealed that 46% of all of Hawaii's ocean shipments (sum of imports and exports) were intrastate (inter-island) shipments by mass, mostly consisting of metals. This result is in agreement with figures from a study by the Hawaii DBEDT [56]. For the archipelago holon, fossil fuel was a significant export, translating to 6% of imported fossil fuels. Much of the exported fossil fuels consisted of naphtha, a solvent and feedstock for plastics, for which no significant market exists in Hawaii [57].

3.5. Holon Level 5: Pacific Ocean Shipping

The available data for material flows to and from the Hawaiian Archipelago do not permit us to fully reconstruct the material interactions between the archipelago and the planet. One particular material flow, however, can be accessed, plotted, and studied: the flows of petrochemical fuels to the Hawaiian Archipelago from the world's major oil-producing regions (Figure 8).

As in the example of automobile paint in the introduction, conceptualizing the global supply chain for petrochemical fuels as a holon could help understand the dependence of lower-level holons on the holarchic system. As we have noted, petrochemical fuels constitute the most significant direct material input to the State of Hawaii by mass (Figure 7). Because Hawaii has no proven crude oil reserves, the use of petrochemicals on the islands has been completely dependent on imports. The total quantity of imported liquid fuels remained around 50 million barrels per year between 1992 and 2009 (Figure 8). While almost half of the liquid fuel imported to Hawaii in 1992 was from the continental U.S. (i.e., Alaska), that ratio was reduced to 2% by 2009. The energy system at the heart of Hawaiian society has thus become significantly more reliant on material flows from foreign nations than was the case a half-century ago.

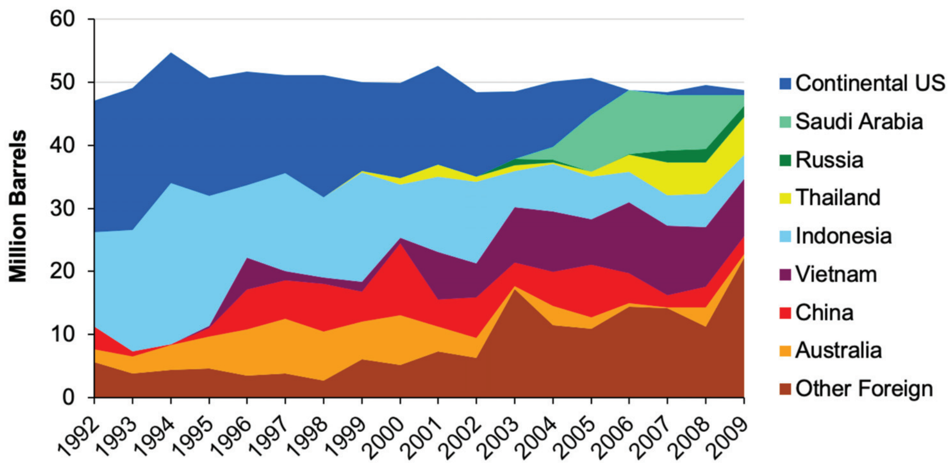

Figure 8. The flows of petrochemical fuels to the Hawaiian Archipelago from the world's major oil-producing regions. Adapted from Cooke and Parsons [58].

If the material flows for the State of Hawaii were studied as a single-level system without examining their connections to the global economy, these supply chain relationships and associated political and economic dynamics would be overlooked. Studying these relationships is vital to understanding how material flows may change in the future, such as could occur with supply chain disruptions due to economic sanctions. These insights are also important for understanding how decisions made at lower-level holons could shape material flows at higher-level holons. This is especially important now that the Hawaiian state legislature has adopted the goal of generating 100% of its electricity from renewable energy resources by 2045 [59,60].

4. Discussion

4.1. Data Challenges and Benefits of Performing an Industrial Ecology Holarchic Analysis

The results of analyses presented in this study illustrate how a holarchic investigation of material flows could benefit researchers in at least two ways. First, characterizing materials flows for multiple holarchic levels could provide frames of reference for understanding a holon's relative contributions to material flows at higher- and lower-level holons. For example, we found that Hilo and Kona together consumed 61% of all fossil fuels consumed on the Big Island, and the Big Island's fossil fuel consumption accounted for 6.5% of all fossil fuels consumed in the State of Hawaii. It follows that Hilo and Kona consumed approximately 4% of all fossil fuels consumed in the state. While appearing to be simple, these comparisons spanning more than two system levels will be difficult to make with conventional MFAs, which conceptualize material flows at a single system level. A holarchic MFA would allow for analysis similar to examining a contribution tree for environmental impacts in life cycle assessment [61]. Extending this analysis to higher-level holons like Hawaii's global supply system for fossil fuels could also illuminate the dependence between holarchic levels and associated political and economic factors, as in the analysis of petroleum imports in Section 3.5 above. The results from holarchic MFAs could also help identify opportunities for recovery of material outputs from a holon by examining flows for higher-level holons and evaluating whether the systems have any displaceable inputs.

The second benefit of a holarchic analysis is that it may be useful to quantify material flows for systems that are difficult to characterize because of data scarcity or complicated system boundaries. Material data often involve some level of aggregation or assumptions. There is also the additional complexity introduced when dealing with system boundaries that span numerous administrative units. These issues may be especially important for systems that are understudied, such as rural economies. As an example of how the holarchy framework could address this issue, our Big Island results illustrated how the material flows for rural areas could be quantified by subtracting the flows for urban areas from those of the higher-level holon. The quantity for biomass extraction in the more rural areas of the Big Island can be derived from material accounts for Hilo, Kona, and the overall Big Island. Data had been derived for the next higher-level holon in our example, and material flows for urban areas were less complicated to quantify than other flows on the Big Island. These forms of analyses could, of course, also be applied to material flows in non-island systems.

Such multi-level analyses of material flows may be difficult to achieve in practice, however. While a holarchic analysis could help fill some data gaps, the gap being evaluated may be too wide to allow for any approximation. In the case of waste accounts in the U.S., most counties and states do not report material recovery and make comprehensive accounting of recycling almost impossible. More potential difficulties in conducting holarchic MFAs arise from the classification categories used to compile material accounts. Even if data are available, the same materials may be aggregated and reported under different material categories based on the classification system used by the entity responsible for accounting. Again, such an issue is highly relevant for waste accounts in the U.S. This may not be a problem for materials for which reporting is required and standardized by regulating institutions, however. One potential issue about material categories, not specific to the context of a holarchic analysis, is that the classification categories may simply be inadequate for certain analyses. In our compiled dataset for Hawaii, more than half of the exported biomass is categorized as "other" or "food products not elsewhere classified" under the Eurostat methodology. Such rough aggregations make granular comparisons of flows difficult. These challenges demonstrated the need for a better, standardized material accounting system.

4.2. The Archipelago Over Time (Temporal Holarchic Analysis)

Our analysis for holon level 5 illustrated how a holarchic analysis could help understand global material flow relationships with appropriate time-series data. In some cases, holons or holachic systems can be studied over a longer time period, enabled by historic data to start and then by continuing data acquisition and analysis. Figure 9 presents historical exports from the Hawaiian Islands (holon level 4) to the rest of the world compiled mainly from annual reports prepared by the firm Peirce and Brewer and the Honolulu Collector General's Office (working paper by Chertow and Paul [26]). The material accounts reflected in the figure indicate the emergence and decline of several industries in the Hawaiian Kingdom.

The material flows for the Hawaiian Islands were mostly self-contained until foreign commercial ships began to arrive after Captain Cook's "discovery" of the islands in 1778. In the following centuries, the islands' socio-economic metabolism went through a series of dramatic transformations, shaped mostly by global economic factors. For example, the whaling trade served as the backbone of Hawaii's economy during the mid-nineteenth century, but gradually declined as the whale populations diminished, the American Civil War reduced the whaling fleet, and whale oil faced competition from kerosene and the growing petroleum industry [62,63]. From the 1850s, investors turned to exporting agricultural products, especially sugar, an activity that was increasingly profitable owing to tariff arrangements and increasing demand from fast-growing populations in the American West [63,64].

Sugar exports were also captured in our MFA for the Hawaiian Islands. The export quantities, however, hardly resemble what was once the Hawaiian Islands' largest industry, as agriculture became cost-ineffective and Hawaii transitioned to a service-based economy. More recently, the last sugar plantation in the State of Hawaii, located on Maui, ceased operations in December 2016. Maui's land use, local economy, and material footprint may since have changed significantly. Analyzing material flows for a single system level certainly has its value. However, it is also important to think about the interconnections with higher- and lower-level holons, and ideally, over time, to understand fully which factors shape material flows at each holarchic level.

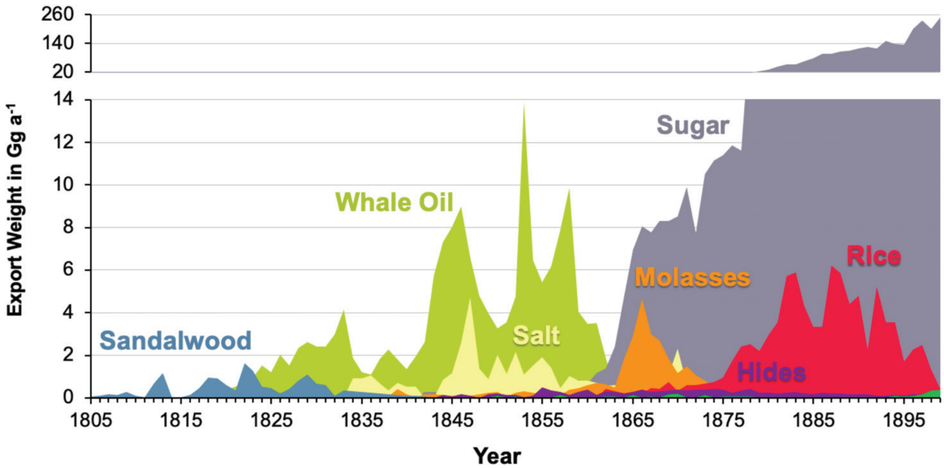

Figure 9. Exports from the Hawaiian Archipelago, 1805–1900. Data from working paper by Chertow and Paul [26].

4.3. Comparing Holons at the Same Holarchic Level

While this study principally focuses on comparing relationships across higher- and lower-level holons, useful information is also available by comparing the metabolism of holons at the same holarchic level (as in the comparison of Hilo and Kona in Section 3.2 above) in the student work compiled and presented by Kanaoka [55] (Figure 10).

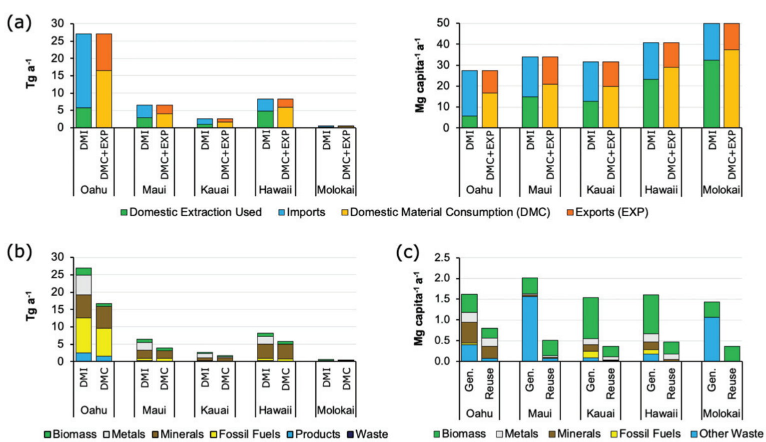

Figure 10. (**a**) Direct material input and downstream material flows for five Hawaiian Islands in 2007. Left: total flows for islands, right: flows per capita de facto. (**b**) Direct material input and domestic material consumption by material type for five Hawaiian Islands in 2007. (**c**) Waste generation and reuse per capita de facto for five Hawaiian islands for various years: Oahu (2005), Maui (2006), Kauai (2005), the Island of Hawaii (2007), and Molokai (2006). Results for Lanai are not shown due to data gaps. Abbreviations: DMI: Direct material input; DMC: Domestic material consumption; EXP: Exports; Gen.: Generation. Adapted from Kanaoka [55].

As with the case of fossil fuel consumption in a previous section, Oahu accounted for the majority of the direct material input for the State of Hawaii in 2007, followed by the Big Island, then Maui (Figure 10a). For most islands, non-metallic minerals represented the largest ratio of domestically consumed materials (Figure 10b), most of which were used in construction. The only exception was Oahu, which imported and refined crude oil for use on all of the islands. Of the non-metallic-mineral inputs to each of the islands, 84–96% by mass was extracted on-island rather than imported.

The comparison of islands also showed that material flows per capita for islands had a strong negative correlation with population density (Figure 10a). This trend was in line with findings from Eurostat's MFA of 28 EU countries, which indicated that countries with higher population densities consumed fewer materials per capita [65]. For this reason, it was observed that the two disparately sized islands, the Big Island and Molokai, had similar material flows per capita that were significantly larger than the remaining islands. These results may illustrate the increasing effect of urbanization on resource efficiency from a materials perspective.

The quantities of waste generation and reuse per capita appeared to be comparable across the islands, but their compositions did not (Figure 10c). We found that the contrast in waste composition was mainly because of differences in the waste accounting methods employed by each county in Hawaii. There is no national standard for waste accounting in the U.S., so counties categorize the same materials under different waste categories, even within a single state. Similarly, some of the waste classification categories used by countries were not compatible with the Eurostat methodology. This issue illustrates some of the practical challenges for conducting a holarchic analysis.

4.4. Related Analyses in Industrial Ecology

The application of the holarchy framework to industrial ecology has been extremely limited, although there appears to be increased interest in recent years. One line of work develops minimization models for the environmental impacts of a product system-of-systems rather than merely individual product systems [66–68]. Another study proposed the holarchy framework for structuring supply chains equipped with smart technologies for improving their environmental sustainability [69]. Additionally, DeLaurentis and Ayyalasomayajula [70] explored how tools from industrial ecology could be integrated with system-of-systems models to better assess the environmental impacts of complex adaptive systems. Other applications of holarchy to material flows have mostly been qualitative, to conceptualize how socio-economic systems relate to the natural system (e.g., [71]) or how socio-economic systems include energy and material systems (e.g., [72]).

4.5. Opportunities for Further Research

The Hawaiian Islands holarchic MFA has provided a glimpse of the enhanced insight into social metabolism and material flows that the approach can potentially offer. To explore industrial ecology holarchy more generally, it will be necessary to recognize that two basic requirements exist for any material-related holon: a clearly defined spatial boundary and some way of monitoring or estimating flows across that boundary. New York City, much of which is connected by toll bridges, might form another example, with sections of Manhattan Island, the Borough of Manhattan, and New York City itself as candidate holons. More generally, some industrial ecology analyses have used multi-holonic data or data gaps to fill in missing information in systems that were not recognized as holarchic. A clear example is the zinc MFA of Meylan and Reck [73], which quantified holons at country, continent, and (though not explicitly computed) planetary levels. From that perspective, it is easy to imagine an extension of holarchic levels, this time downward, for example to Indonesia and its constituent islands, should appropriate data be available. Other examples doubtless can be devised by imaginative researchers, including those of non-island systems. It should be noted, however, that comparisons across holons without common governance structures, as seen in Hawaii, may be more difficult to achieve. Finally, as analyses of country-level imports and exports have provided much useful information on material flow and use, the extension of MFA into a variety of smaller-scale geographical entities is likely to offer new insight as well. We encourage industrial ecologists to explore and profit from applying the holarchic concept to a variety of multi-holonic material stocks and flows around the world.

Supplementary Materials: Supplementary materials can be accessed at http://www.mdpi.com/2071-1050/12/8/3104/s1.

Author Contributions: All authors contributed equally to this work. M.R.C. and T.E.G. contributed to research design and provided supervision. T.E.G. conceptualized the study. M.R.C. organized and managed the project. Data acquisition, analysis, and interpretation were made by K.S.K. and J.P. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded over several years by the US National Science Foundation (Grant No. 0948781), the Hawaii Community Foundation, the Japan Foundation, the field trip fund of the Yale School of Forestry and Environmental Studies, and the Center for Industrial Ecology.

Acknowledgments: We are grateful to the many students cited in the reference section whose research provided the basis for much of this study. Former PhD student Matthew Eckelman played a formative role on the Oahu study, and former research assistant Frederick Reppun collated a great deal of data. We also thank the Kohala Center, especially Matt Hamabata and Betsy Cole for our cultural education, and the Hawaii Community Foundation for the original Oahu funding. We appreciate the support of the Yale School of Forestry and Environmental Studies and offer a great "mahalo" to all of our Hawaiian Island hosts.

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

References

1. Koestler, A. *The Ghost in the Machine*; Hutchinson: London, UK, 1976; ISBN 978-0-09-127130-5.
2. Maier, M.W. Architecting principles for systems-of-systems. *Syst. Eng.* **1998**, *1*, 267–284. [CrossRef]
3. Borangiu, T.; Gilbert, P.; Ivanescu, N.-A.; Rosu, A. An implementing framework for holonic manufacturing control with multiple robot-vision stations. *Eng. Appl. Artif. Intell.* **2009**, *22*, 505–521. [CrossRef]
4. Holonic Manufacturing Systems. *ANEMONA: A Mulit-Agent Methodology for Holonic Manufacturing Systems*; Botti, V., Giret, A., Eds.; Springer Series in Advanced Manufacturing; Springer: London, UK, 2008; pp. 7–20, ISBN 978-1-84800-310-1.
5. Colombo, A.W.; Schoop, R.; Neubert, R. An agent-based intelligent control platform for industrial holonic manufacturing systems. *IEEE Trans. Ind. Electron.* **2006**, *53*, 322–337. [CrossRef]
6. Ounnar, F.; Pujo, P.; Mekaouche, L.; Giambiasi, N. Customer–supplier relationship management in an intelligent supply chain network. *Prod. Plan. Control* **2007**, *18*, 377–387. [CrossRef]
7. Tuzkaya, U.R.; Önüt, S. A holonic approach based integration methodology for transportation and warehousing functions of the supply network. *Comput. Ind. Eng.* **2009**, *56*, 708–723. [CrossRef]
8. Ulieru, M.; Cobzaru, M. Building holonic supply chain management systems: An e-logistics application for the telephone manufacturing industry. *IEEE Trans. Ind. Inform.* **2005**, *1*, 18–30. [CrossRef]
9. Mahmoud, M.S.; Azher Hussain, S.; Abido, M.A. Modeling and control of microgrid: An overview. *J. Frankl. Inst.* **2014**, *351*, 2822–2859. [CrossRef]
10. Garmestani, A.S.; Allen, C.R.; Cabezas, H. Panarchy, Adaptive Management and Governance: Policy Options for Building Resilience Resilience & Environmental Law Reform Symposium. *Neb. Law Rev.* **2008**, *87*, 1036–1054.
11. Gotts, N. Resilience, Panarchy, and World-Systems Analysis. *Ecol. Soc.* **2007**, *12*, 1–24. [CrossRef]
12. Kasai, S.; Li, N.; Fang, D. A system-of-systems approach to understanding urbanization—State of the art and prospect. *Smart Sustain. Built Environ. Bingley* **2015**, *4*, 154–171. [CrossRef]
13. Kay, J.J. On complexity theory, exergy, and industrial ecology. In *Construction Ecology: Nature as a Basis for Green Buildings*; Kibert, C.J., Sendzimir, J., Guy, G.B., Eds.; Spon Press: New York, NY, USA, 2002; pp. 72–108, ISBN 0-415-26092-2.
14. Spiegelman, J. Beyond the Food Web Connections to a Deeper Industrial Ecology. *J. Ind. Ecol.* **2003**, *7*, 17–23. [CrossRef]
15. Deschenes, P.J.; Chertow, M. An island approach to industrial ecology: Towards sustainability in the island context. *J. Environ. Plan. Manag.* **2004**, *47*, 201–217. [CrossRef]
16. Grant, K.T.; Estes, G.B. *Darwin in Galápagos: Footsteps to a New World*, 1st ed.; Princeton University Press: Princeton, NJ, USA, 2009; ISBN 978-0-691-14210-4.

17. Singh, S.J.; Grünbühel, C.M.; Schandl, H.; Schulz, N. Social Metabolism and Labour in a Local Context: Changing Environmental Relations on Trinket Island. *Popul. Environ.* **2001**, *23*, 71–104. [CrossRef]
18. Lenzen, M. Sustainable island businesses: A case study of Norfolk Island. *J. Clean. Prod.* **2008**, *16*, 2018–2035. [CrossRef]
19. Krausmann, F.; Richter, R.; Eisenmenger, N. Resource Use in Small Island States. *J. Ind. Ecol.* **2014**, *18*, 294–305. [CrossRef] [PubMed]
20. Nielsen, S.N.; Jørgensen, S.E. Sustainability analysis of a society based on exergy studies—A case study of the island of Samsø (Denmark). *J. Clean. Prod.* **2015**, *96*, 12–29. [CrossRef]
21. Cecchin, A. Material flow analysis for a sustainable resource management in island ecosystems: A case study in Santa Cruz Island (Galapagos). *J. Environ. Plan. Manag.* **2017**, *60*, 1640–1659. [CrossRef]
22. Allen, C.R.; Angeler, D.G.; Garmestani, A.S.; Gunderson, L.H.; Holling, C.S. Panarchy: Theory and Application. *Ecosystems* **2014**, *17*, 578–589. [CrossRef]
23. Holling, C.S. From complex regions to complex worlds. *Ecol. Soc.* **2004**, *9*, 11. [CrossRef]
24. Busch, J.; Sanz Cortes, R.; Srivastava, C. *Molokai Material Flow Analysis*; Yale School of Forestry & Environmental Studies: New Haven, CT, USA, 2012.
25. Chertow, M.; Miyata, Y. Assessing collective firm behavior: Comparing industrial symbiosis with possible alternatives for individual companies in Oahu, HI. *Bus. Strategy Environ.* **2011**, *20*, 266–280. [CrossRef]
26. Chertow, M.; Paul, A. Material Succession in Hawai'i: Using Industrial Ecology to Illuminate Environmental History. Working Paper. 2013.
27. Chertow, M.R.; Seto, K. Materials flows and land use change in two urban areas of Hawai'i Island. In Proceedings of the Ecological Society of America Annual Convention, Austin, TX, USA, 7–12 August 2011.
28. Davies, M.; Gagne, C.; Hausfather, Z.; Lippert, D. *Analysis and Recommendations for the Hawai'i County Energy Sustainability Plan*; Yale School of Forestry & Environmental Studies: New Haven, CT, USA, 2007. Available online: https://kohalacenter.org/archive/pdf/analysis_and_recommendations.pdf (accessed on 31 August 2017).
29. De Sa, R.; Emmerman, D.; Veysey, D. *Closing the Loop on Molokai: Livestock Production on a Rural Hawaiian Island*; Yale School of Forestry & Environmental Studies: New Haven, CT, USA, 2013. Available online: http://kohalacenter.org/archive/pdf/Research_YaleMolokaiLivestockReport2013.pdf (accessed on 31 August 2017).
30. De Stercke, S.; Seligman, J.; Teng, J.; Zhao, Y.; Cooke, C. *Energy Efficiency in Low-Income Communities on Hawai'i Island*; Yale School of Forestry & Environmental Studies: New Haven, CT, USA, 2011. Available online: http://kohalacenter.org/archive/pdf/EnergyEfficiencyinLowincomeCommunitiesonHawaiiIslandYaleCenterforIndustrialEcologyV3.pdf (accessed on 31 August 2017).
31. Diao, Z.; Dorji, S.; Kavlak, G.; Zingale, A. *Material Flow Analysis for the Island of Kaua'i*; Yale School of Forestry & Environmental Studies: New Haven, CT, USA, 2011.
32. Douglas, F.; Franceschini, L.; Mak, T.; Prasodjo, R.; Xhurxhi, S. *Tire Recycling in Hawai'i*; Yale School of Forestry & Environmental Studies: New Haven, CT, USA, 2013.
33. Eckelman, M.; Chertow, M. *Linking Waste and Material Flows on the Island of Oahu, Hawai'i: The Search for Sustainable Solutions*; Yale F&ES Publication Series; Yale School of Forestry & Environmental Studies: New Haven, CT, USA, 2009. Available online: https://elischolar.library.yale.edu/fes-pubs/40/ (accessed on 16 December 2019).
34. Eckelman, M.J.; Chertow, M.R. Using Material Flow Analysis to Illuminate Long-Term Waste Management Solutions in Oahu, Hawaii. *J. Ind. Ecol.* **2009**, *13*, 758–774. [CrossRef]
35. Eckelman, M.J.; Chertow, M.R. Life cycle energy and environmental benefits of a US industrial symbiosis. *Int. J. Life Cycle Assess.* **2013**, *18*, 1524–1532. [CrossRef]
36. Espinoza, F.; Heinemann, A.; Sima, L. *Material Flow Analysis for the Island of Oahu: Military Sector*; Yale School of Forestry & Environmental Studies: New Haven, CT, USA, 2008.
37. Famely, J.; Gladek, E.; Ziemba, C. *Materials Flows on The Island of Oahu: Imports, Exports and Resource Extraction*; Yale School of Forestry & Environmental Studies: New Haven, CT, USA, 2008.
38. Fugate, E. *Life Cycle Energy Inventory of Hawaii Island Water Systems*; Yale School of Forestry & Environmental Studies: New Haven, CT, USA, 2008.
39. Fugate, E.; Iversen, J. *Water, Food, and Energy on the Big Island of Hawai'i*; Yale School of Forestry & Environmental Studies: New Haven, CT, USA, 2008.

40. Houseknecht, M.; Kim, C.; Whitman, A. *Material Flows on the Island of Hawai'i*; Yale School of Forestry & Environmental Studies: New Haven, CT, USA, 2006. Available online: http://kohalacenter.org/archive/pdf/hi_mfa.pdf (accessed on 31 August 2017).
41. Jenkins, M.; Pierson, N.; Pohnan, E.; Ramirez, J.S.; Wang, S. *Material Flow Analysis for the Island of Maui*; Yale School of Forestry & Environmental Studies: New Haven, CT, USA, 2012. Available online: http://sustainablemaui.org/wp-content/uploads/2012/05/Material-Flow-Analysis-for-the-Island-of-Maui-final.pdf (accessed on 31 August 2017).
42. Johnson, J.; Chertow, M. Climate stabilization wedges in action: A systems approach to energy sustainability for Hawaii Island. *Environ. Sci. Technol.* **2009**, *43*, 2234–2240. [CrossRef] [PubMed]
43. Johnson, J.; Leistra, D.; Opton-Himmel, J.; Smith, M. *Hawaii County Baseline Energy Analysis*; Yale School of Forestry & Environmental Studies: New Haven, CT, USA, 2007. Available online: http://kohalacenter.org/archive/pdf/hawaii_county_baseline_energ.pdf (accessed on 31 August 2017).
44. Lan, A.; Leighton, L.; Wegmueller, S.; Yost, J. *Talking Story in Ka'u: Comparative Examination of Land Uses for Diversified Agriculture and Biofuel Feedstock Production*; Yale School of Forestry & Environmental Studies: New Haven, CT, USA, 2013.
45. Mosher, M.; Pinheiro, T. *Material Flow Analysis of Lana'i, Hawaii*; Yale School of Forestry & Environmental Studies: New Haven, CT, USA, 2012.
46. Oden, M.; Park, J.; Zaidel, K. *Management of Opala on the Island of Oahu*; Yale School of Forestry & Environmental Studies: New Haven, CT, USA, 2008.
47. Parthasarathy, T.; Gilbert, H.; Arabshahi, N. *Material Flows on the Island of Oahu: Private Sector*; Yale School of Forestry & Environmental Studies: New Haven, CT, USA, 2008.
48. European Commission. *Economy-Wide Material Flow Accounts Handbook*; European Commission: Luxembourg, 2018; ISBN 978-92-79-88337-8.
49. U.S. Army Corps of Engineers. Manuscript Cargo and Trips Data Files, Statistics on Foreign and Domestic Waterborne Commerce Move on the United States Waters. Available online: https://usace.contentdm.oclc.org/digital/collection/p16021coll2/id/1796 (accessed on 1 December 2019).
50. U.S. Department of Agriculture National Agricultural Statistics Service. On-line Reports Archive. Available online: https://www.nass.usda.gov/Statistics_by_State/Hawaii/Publications/Archive/index.php (accessed on 3 February 2019).
51. U.S. Geological Survey National Minerals Information Center. The Mineral Industry of Hawaii. Available online: https://www.usgs.gov/centers/nmic/mineral-industry-hawaii (accessed on 3 February 2019).
52. Hawaii Department of Business, Economic Development and Tourism. State of Hawaii Data Book. Available online: https://dbedt.hawaii.gov/economic/databook/ (accessed on 10 September 2017).
53. U.S. Census Bureau. Economic Census. Available online: https://www.census.gov/prod/www/economic_census.html (accessed on 3 February 2019).
54. U.S. Department of Labor Mine Safety and Health Administration. Mine Data Retrieval System. Available online: https://www.msha.gov/mine-data-retrieval-system (accessed on 3 February 2019).
55. Kanaoka, K. *Comparative Material Flow Analysis for the Hawaiian Islands*; Duke University: Durham, NC, USA, 2018.
56. Roos, J.; Borum, N.; Bak, L. *Marine Cargo and Waterborne Commerce in Hawaii's Economy: Trends and Patterns in Hawaii Marine Cargo 2001–2016*; State of Hawaii Department of Business, Economic Development and Tourism: Honolulu, HI, USA, 2019.
57. Finizza, A.J.; Gieskes, T.E.; Hackett, D.J.; Haggquist, G.; Monfiletto, J. *Study of Fuel Prices and Legislative Initiatives for the State of Hawaii*; Stillwater Associates: Irvine, CA, USA, 2003.
58. Cooke, C.P.; Parsons, D.C. *County of Hawai'i Energy Sustainability Program: Five Year Roadmap*; Kohala Center: Kamuela, HI, USA, 2012.
59. Fialka, J. As Hawaii Aims for 100% Renewable Energy, Other States Watching Closely. Available online: https://www.scientificamerican.com/article/as-hawaii-aims-for-100-renewable-energy-other-states-watching-closely/ (accessed on 1 December 2019).
60. Daigneau, E. From Worst to First: Can Hawaii Eliminate Fossil Fuels? Available online: https://www.governing.com/topics/transportation-infrastructure/gov-hawaii-fossil-fuels-renewable-energy.html (accessed on 1 December 2019).

61. Matthews, H.S.; Hendrickson, C.T.; Matthews, D. Life Cycle Assessment: Quantitative Approaches for Decisions that Matter. Available online: https://www.lcatextbook.com/ (accessed on 18 November 2019).
62. Abdelal, R.; Kirshner, J. Strategy, economic relations, and the definition of national interests. *Secur. Stud.* **1999**, *9*, 119–156. [CrossRef]
63. Kuykendall, R.S. *The Hawaiian Kingdom: Twenty Critical Years, 1854–1874*; University of Hawaii Press: Honolulu, HI, USA, 1953; Volume 2, pp. 137–141, ISBN 978-0-87022-432-4.
64. MacLennan, C.A. Hawai'i Turns to Sugar: The Rise of the Plantation Centers, 1860–1880. *Hawaii. J. His.* **1997**, *31*, 97–125.
65. Eurostat. Material Flow Accounts and Resource Productivity. Available online: http://ec.europa.eu/eurostat/statistics-explained/index.php/Material_flow_accounts_and_resource_productivity (accessed on 28 April 2018).
66. Kawakami, K.; Fukushige, S.; Kobayashi, H. A Functional Approach to Life Cycle Simulation for System of Systems. *Procedia CIRP* **2017**, *61*, 110–115. [CrossRef]
67. Kobayashi, H.; Matsumoto, T.; Fukushige, S. A simulation methodology for a system of product life cycle systems. *Adv. Eng. Inform.* **2018**, *36*, 101–111. [CrossRef]
68. Mennenga, M.; Cerdas, F.; Thiede, S.; Herrmann, C. Exploring the Opportunities of System of Systems Engineering to Complement Sustainable Manufacturing and Life Cycle Engineering. *Procedia CIRP* **2019**, *80*, 637–642. [CrossRef]
69. Martín-Gómez, A.; Aguayo-González, F.; Luque, A. A holonic framework for managing the sustainable supply chain in emerging economies with smart connected metabolism. *Resour. Conserv. Recycl.* **2019**, *141*, 219–232. [CrossRef]
70. DeLaurentis, D.A.; Ayyalasomayajula, S. Exploring the Synergy Between Industrial Ecology and System of Systems to Understand Complexity. *J. Ind. Ecol.* **2009**, *13*, 247–263. [CrossRef]
71. Ramaswami, A.; Weible, C.; Main, D.; Heikkila, T.; Siddiki, S.; Duvall, A.; Pattison, A.; Bernard, M. A Social-Ecological-Infrastructural Systems Framework for Interdisciplinary Study of Sustainable City Systems: An Integrative Curriculum Across Seven Major Disciplines. *J. Ind. Ecol.* **2012**, *16*, 801–813. [CrossRef]
72. Gardner, G. *The City: A System of Systems. In Can a City Be Sustainable?* Island Press: Washington, DC, USA, 2016; pp. 27–44, ISBN 978-1-61091-756-8.
73. Meylan, G.; Reck, B.K. The anthropogenic cycle of zinc: Status quo and perspectives. *Resour. Conserv. Recycl.* **2017**, *123*, 1–10. [CrossRef]

© 2020 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (http://creativecommons.org/licenses/by/4.0/).

sustainability

MDPI

Article

The "Metal-Energy-Construction Mineral" Nexus in the Island Metabolism: The Case of the Extractive Economy of New Caledonia

Jean-Baptiste Bahers [1,2,*], Paula Higuera [1,3], Anne Ventura [1,4] and Nicolas Antheaume [1,3]

1 Institut de Recherche des Sciences et Techniques de la Ville (IRSTV), Ecole Centrale de Nantes, 44321 Nantes cedex 3, France; paula.higuera@ifsttar.fr (P.H.); anne.ventura@ifsttar.fr (A.V.); nicolas.antheaume@univ-nantes.fr (N.A.)
2 CNRS, UMR ESO (Spaces and societies), Institute of Geography, University of Nantes, 44321 Nantes cedex 3, France
3 Laboratory of Economics and Management Nantes Atlantique (LEMNA), University of Nantes, 44322 Nantes, France
4 University Gustave Eiffel (IFSTTAR), MAST GPEM, Campus of Nantes, Route de Bouaye, CS5004, FR-44344 Nantes cedex, France
* Correspondence: jeanbaptiste.bahers@univ-nantes.fr

Received: 16 January 2020; Accepted: 5 March 2020; Published: 12 March 2020

Abstract: The concept of island metabolism strives to implement the principles of social ecology at the island scale. It is, therefore, a question of analyzing the flows of materials and energy passing through these territories, as well as the resource base needed to sustain their activities. We propose to develop a nexus approach to the New Caledonian island metabolism to understand the interactions between biophysical structures and societal, as well as economic, activities. Metals, construction minerals, and energy are good symbols of economies based on the extraction of non-renewable resources. This is why, in this article, we sought to investigate how the "metal-energy-construction mineral" nexus can affect the resilience and metabolic sustainability of the extractive island of New Caledonia. We carried out the Material and Energy Flow Analysis (MEFA) of each nexus subsystem for 2016 and of the nodes of interdependence. We also interrogated the role of importing countries because the island's metabolism is dominated by the nickel extraction industry. Indeed, the metabolic profile of this island corresponds to the one of a supply territory for other consumption territories. The latter outsource the impacts of their own consumption to New Caledonia. Finally, based on interviews with economic stakeholders, we studied the potential building blocks for the emergence of an industrial symbiosis in the nexus.

Keywords: island metabolism; MFA; nexus approach; industrial waste; metabolic profile

1. Introduction

1.1. Research on the Metabolism of Islands: What Resilience and Sustainability for These Territories

The concept of island metabolism strives to implement the principles of social ecology [1,2] at the island level. It is, therefore, a question of analyzing the flows of materials and energy, which pass through these territories and the resource base needed to sustain their activities. Methodologies to measure material and energy balances have been developed, in which metabolic indicators are used, derived from material flow analysis (MFA), such as Domestic Material Consumption (DMC), Net Addition to Stock (NAS), or Domestic Process Outputs (DPO), among others. These indicators are often combined with economic indicators to reveal the efficiency of productive systems and consumption patterns. Pioneer work has been carried out on the islands of Iceland, Trinidad, Grenada, or Samothraki in Greece [3–7] that has enabled, in very different contexts, us to understand the metabolic profiles of these islands and to describe the perspectives for local sustainability. Comparing resource consumption and the evolution of the gross domestic product (GDP) over a long period of time is also an expected objective of this research field, such as in the work of Martinico-Perez et al. [8], who conducted a study of the socio-economic metabolism of the Philippine archipelago, in order to understand the evolution of island environmental pressures.

Additionally, other scholars, especially in the field of industrial ecology, have taken an interest in island metabolism. These researchers produced analysis and recommendations towards the implementation of industrial synergies, defined as the exchange of co-products or waste between economic actors [9,10]. Political ecology has, in turn, provided specific studies to link the biophysical properties of islands with their social and geopolitical characteristics. Thus, the collapse of ecological environments related to water or forest resources [11,12] and the environmental consequences of industrial activities, such as tourism [13], mines [14], or extraction of fossil fuels [15], have been studied. Finally, a French school of thought denominating itself as "territorial ecology" [16] proposes the notion of territorial metabolism, in view of establishing methodological links between flow analysis and their modes of spatial governance, as well as the social and environmental consequences of material circulation.

These various approaches of island metabolism make it possible to understand how these territories depend on the exploitation of natural resources exported to world markets. Their economic apparatus is structured around types of exploitation: such as extracting minerals, fossil fuels or water from below ground deposits, or using aboveground vegetation. These activities lead to excessive production of waste in relation to the number of inhabitants, as will be further detailed in the next section. Furthermore, some islands export most of their production and import almost all of their food, energy, or material needs [3]. These economic and power relations between mining territories and importing areas [17] perfectly illustrate the context of the metabolic relationships of islands with the rest of the world and highlight metabolic vulnerabilities.

Issues related to economic and environmental resilience thus appear to be essential to enable small islands, considered as life-size laboratories for methodological and political experimentation, to be more sustainable and more self-sufficient. Reducing these vulnerabilities is a considerable challenge and involves evaluating local energy or bioeconomic policies, as previously analyzed in the Galápagos Islands [18] and the Balearic Islands [19]. The perspective of resource efficiency is therefore an essential alternative in these extractive economies to possibly reduce the metabolic vulnerabilities of these islands [20] and to analyze if a new circulation of materials can reduce existing unbalances and weaknesses in the socioeconomic metabolism.

1.2. The "Metal-Energy-Construction Mineral" Nexus

Social and island metabolism are essentially linked to the nexus of resources, that is to say, the "links between different forms of interdependent uses of resources as well as the institutional settings and broader societal conditions under which they occur" [21]. With a nexus approach, resources that enable the functioning of human societies are not analyzed as silos but, on the contrary, as interactions between biophysical structures and societal organization. It is thus necessary to acknowledge that the use of a resource is dependent on the mobilization of other flows of material and energy in connection with a social structure. In addition, the integration of a "nexus-thinking" analysis shows the importance of combining several methodological approaches, as indicated in the review of Newell et al. [22]. Indeed, a modeling approach, such as MFA, is essential to measure the socio-economic metabolism of territories [2,23] and to understand the evolution of consumption indicators and resource demands. These flows are interdependent and require a complex analysis of their material dynamics. However, we cannot just quantify flows without a socio-political approach integrating these concepts with institutional, economic and social actors. Albrecht et al. [24] demonstrate the need for mixed and transdisciplinary approaches that integrate the socio-economic and political dimensions of resources, as well as involve stakeholders and policy-makers.

Many reviews have been produced on the concept of nexus, as a new scientific buzzword. They mainly concern the water-energy-food (WEF) nexus [24–27]. However, existing research did not study territorial issues, beyond administrative perimeters. The work of Newell et al. [22] partially fills this gap for urban areas. In particular, their article concludes that the multi-scalar, institutional, and governance aspects are little discussed in the WEF nexus literature, unlike quantitative and modeling approaches. Other research has already shown the strong conceptual links between urban metabolism and nexus [28–30]. The results obtained are a basis for questioning resource use from a political and social point of view in urban areas.

In addition, a majority of studies focus on the WEF nexus, whereas many other nexus could have been studied [21,30,31]. To our knowledge, the links between the flows of metals, building construction minerals, and energy have never been addressed, despite being three of the main flows of social metabolism. Metal slags are common wastes of all extraction activities, which have historically led to drastic changes in landscapes in the past century, forming hills, such as the famous ones called "*crassiers*" for iron ore extraction in the East of France or "*terrils*" for hard coal mining in the North of France. In the last years of the 20th century, it was progressively discovered that some of these waste hills contributed to soil and water pollution but also that they were composed of interesting minerals. Today, *crassiers* no longer grow because iron slags are very popular and important added value products for the cement industry. This illustrates how the links between the three "metal-energy-construction mineral" sectors operate. Moreover, they are three categories of resources that are economically critical and are likely to have reached their production peak [32]. Finally, metals, construction minerals, and energy are a good symbol of economies based on the extraction of non-renewable resources [33], as are some islands [34]. This is why, in this article, we seek to investigate how the "metal-energy-construction mineral" nexus can affect the resilience and metabolic sustainability of an extractive island.

2. Case Study: The Island Metabolism of New Caledonia

Our investigation is entirely in line with the case of the New Caledonian archipelago. The extraction and production of nickel forms a large part of the socio-economic metabolism of the island, as this industry is a major part of the economy. In addition, the transformation processes (hydrometallurgy and pyrometallurgy) discharge huge amounts of ferronickel slags, greenhouse gases, and wet residues (for the hydrometallurgical process). Today, nickel slags are sometimes locally used as road embankments, and some projects seek solutions to turn them into building materials (see Section 4.3).

The mining and metallurgical sector accounts for 14% of employment in New Caledonia [35], half of which is direct employment (mining, metallurgy) and the other half subcontracting, construction, transport, or associated services. The nickel sector is responsible for the majority of exports. The economic footprint of nickel extraction does not stop with extractive and metallurgical activities because this sector also has a ripple effect on the rest of the economy through its use of subcontracting and the consumption of its employees. Today, nickel is used for batteries, coins, hygienic packaging (especially food), and especially for making non-corrosive alloys or superalloys in all industrial sectors, such as the automotive industry, aviation, or chemistry.

New Caledonia was the world's sixth-largest producer of nickel in 2014, and its reserves are considerable: 15% of the global total identified to date [35]. The main forms of nickel ores are of two types: sulfide ores and oxidized ores. Nickel in sulfide ores accounts for 65% of global production and is mined underground. Nickel from oxidized ores, found in New Caledonia, accounts for 35% of world production.

The mining area is well distributed over the whole of "*Grande Terre*" and the "Belep Islands" (cf. Figure 1). Mineral extraction is based on mining concessions, either directly operated by the mining branches of metalworkers, or by "minor miners", who own a domain, as well as export licenses. The ore, which is processed locally, is distributed between three metallurgical sites:

- The "Société Le Nickel" (SLN) plant: its capital is 56% owned by Eramet (French industrial company), 34% by STCP (Provinces of New Caledonia), and 10% by Nisshin Steel (stainless steel producer in Japan). It uses a pyrometallurgical process and produces ferronickel. It is the oldest corporation on the island.
- The "Koniambo Nickel SAS" plant processes high-grade saprolites from the Koniambo mountain in the North Province using a pyrometallurgical process. Its capital is 51% owned by the South Pacific Mining Corporation (SMSP) (itself owned by the North Province), and the remaining 49% was recently acquired by Glencore (British-Swiss company), which purchases all the ferronickel that is produced by this plant. The plant went into production in 2013. It is considered as a political "instrument" for the emancipation of native indigenous populations (Kanaks) from France [36].
- In 2010, the "Vale Inco" hydrometallurgical plant started its operations. It is 95% owned by a private international consortium (including the Brazilian company Vale), and the remaining 5% is held by the Southern and Northern Provinces.

Another major player in mining is the Nickel Mining Company SAS, which operates several mining centers to supply the ferronickel production plant in Gwangyang (South Korea). This South Korean pyrometallurgical plant, which began operations in 2008, has an annual production capacity of 30,000 tons of ferronickel.

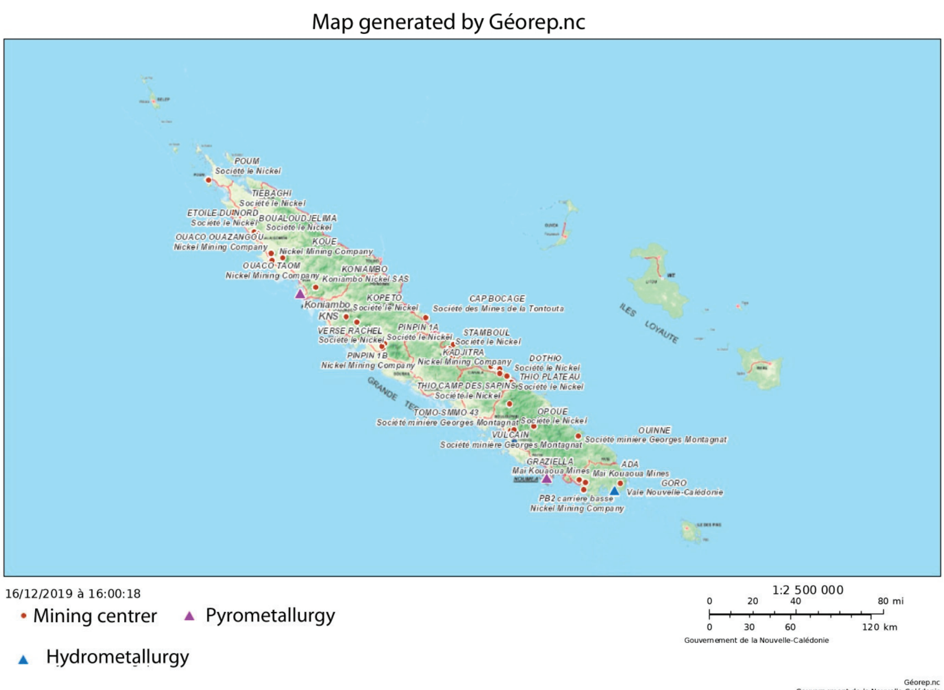

Figure 1. The mining and metallurgical centers of New Caledonia (Data - *Gouvernement de la Nouvelle-Calédonie – creative commons licence*).

Extractive economies do not go without conflicts over the associated social metabolism, [37–39], and the case of nickel extraction in New Caledonia is no exception: it is not without conflict or socio-environmental controversy. If this sector employs many workers, the relationship of islanders with nickel is delicate. For example, it is known that the Kanaks call it "the shit" [40]. Since the 2000s, the "*Rhéébù Nùù*" Committee and the Native Council for the Management of Natural Resources in Kanaky New Caledonia were opposed to the launch of the Vale Inco project (formerly named Goro-Nickel) [41]. This conflict is related to pollution from extraction, such as in Thio [42], and to sulfuric acid spills in rivers in 2009, 2012, and 2014 by Vale Inco [43]. Some organizations were created, such as the "*ŒIL*" (Observatory of the environment in New Caledonia) in 2009, the mission of which is to protect the environment. This mission is shared between different categories of stakeholders [43]. More recently, a socio-economic conflict affected the exploitation of nickel. In 2015, mine truckers, allied to the miners, opposed the local government's ban on exporting nickel ore to China [44]. This ban took place in the context of falling world prices and tough negotiations with existing Australian customers, wishing to revise existing contracts and push their advantage in a drastic way.

3. Method: MFA for the Nexus from International Local Data and Interviews

3.1. At the Level of the Island Flows

Many methods exist for modeling resources nexus in order to analyze the sustainability of territories [31], such as the Biogeophysical model, Life Cycle Assessment or Cost – Benefit analysis. We chose MFA to assess the trajectory of intra and extra-island flows by quantifying them, but also by spatializing them. This method also makes it possible to characterize stocks and material consumption by measuring flows of materials and energy entering the island, which are transformed and disposed of [45–47]. In addition, previous research has demonstrated the value of using MFA to understand resources nexus [21,48].

We first set up a Eurostat MFA [49,50] to gather some data and obtain metabolic indicators comparable with other islands [3,20,51]. Hence, we were able to discuss socioeconomic metabolism in this territorial context in relation to indicators of the DMC such as unused extraction, domestic processing output (DPO) and addition to the stock (NAS). The metabolic profile of the archipelago is therefore very unique and highlights what these extractive economies are. They are a real supply base for other economies, with flows associated to exports.

3.2. At the Nexus Scale

We focused on the three sectors, studied as three subsystems. A large part of the data from the previous step was broken down by each sector, but the system boundaries of the MEFA (Material and Energy Flow Analysis) are very different from the Eurostat MFA, as we define our own system boundaries in Figure 2. Each subsystem can be considered as a MEFA based on the chain of resources [48,52,53], from resource extraction to end of life, including import, distribution, consumption, and export stages. The system boundaries, as defined in Figure 2, highlight what processes occur in New Caledonia. Hence, extraction and waste collection, which includes final disposal in New Caledonia, are considered to be inside the system boundaries. Process consumption is not comparable to the Eurostat DMC because it is a step of the chain and not an indicator. We then translated the concept of interdependencies as links between the sectors (cf. Figure 2), at different stages. Table 1 describes the primary data used for Figure 2 and the indicators discussed in Section 4.2.

A discussion of uncertainties is necessary to understand the material flow analysis. First of all, the majority of the sources come from local databases (Customs Office, Input-Output table, Import-export statistical studies, and environmental energy). They come either from the statistical institute of New Caledonia (ISEE) or from the governmental service for industry, mines, and energy (DIMENC). These data are subject to uncertainties, such as statistical variation and spatio-temporal variability [54]. They also come from questionnaires sent to companies, which certainly have the obligation to complete them but are subject to random checks only. These uncertainties are described as "measurement errors" by Patricio and colleagues [55] because these data are collected by the institutions providing the databases. Finally, they do not take into account *free riders* or informal sectors, which can be important in island metabolism [20]. This type of uncertainty is "aleatory" [54], which means that it results from randomness and that the variability cannot be reduced. As regards data from the interviews, they are dependent on the "subjective judgment" of economic actors [54]. Yet, we cross-checked these data with the principle of mass balance for the MFA, which provides the verification of tendency. This is an "epistemic" uncertainty [54], meaning a lack of knowledge, which is minimized through cross-examination. To improve the accuracy of the results, we carried out a temporal analysis, inspired by dynamic material flow analysis [56], in order to see the evolution of flow data and metabolic indicators (see Section 4.2)."

Table 1. Source and processing of data for the material flow analysis.

PRIMARY DATA for Figure 2	**Source**	**Year of Data**	**Types of Processing**
Metals extraction	USGS ***	2001–2016	None
Unused extraction	Interviews with economic stakeholders	2016	This data is verified with USGS-ISEE ** (difference between extraction and exports)
Metallurgical process	ISEE - Input-Output table of New Caledonia economy	2016	None
Metals Waste collection	Interviews with economic stakeholders	2016	Ratios from interviews and inputs of metals processing
Metals exportation	ISEE ** - Customs Office of New Caledonia	2001–2016	None
Import of fossil fuels	ISEE ** – Energy Environment	2001–2016	None
Energy transformation	DIMENC * Government of New Caledonia : Energy transition diagnostic and planning	2015	Estimate based on ISEE ** data (10% increase of imports)
Energy distribution	ISEE ** – Energy Environment	2016	
Energy consumption	DIMENC * Government of New Caledonia : Energy transition diagnostic and planning	2015	Estimate based on ISEE ** data (10% increase of imports)
Energy losses	DIMENC * Government of New Caledonia : Energy transition diagnostic and planning	2015	Estimate based on ISEE ** data (10% increase of imports)
Atmospheric emissions	DIMENC * Government of New Caledonia : Energy transition diagnostic and planning	2015	Estimate based on ISEE ** data (10% increase of imports)
Imports of minerals	ISEE ** - Customs Office of New Caledonia	2001–2016	None
Minerals extraction	DIMENC * Government of New Caledonia :	2007; 2016	None
Minerals transformation	ISEE ** - Input-Output table of New Caledonia economy	2016	None
Cement consumption	ISEE ** - Input-Output table of New Caledonia economy	2001–2016	
Minerals consumption	ISEE ** - Input-Output table of New Caledonia economy	2016	None
Minerals waste collection	Report from Jouanny, 2016	2016	None
INDICATORS for Section 4.2			
DMI = imports *(biomass, minerals, fossil fuels, manufactured products, metals, chemicals)* + extraction *(biomass, minerals, nickel, cobalt)*	For imports: ISEE ** - Customs Office of New Caledonia For extraction: DIMENC * & USGS ***	2001–2016 (2017) 2016	Data for mineral import in 2016 is exceptionally high (+160% of 2015 and 2017). To avoid the effect of an unrepresentative year, we chose 2017 for this data.
DMC = DMI – exports *(nickel, cobalt, , fisheries)*	For exports: ISEE ** - Customs Office of New Caledonia	2016	
DPO = atmospheric emission + exported waste	DIMENC *, ISEE ** Energy Environment	2015, 2016	Estimate based on ISEE ** data (10% increase of imports)

Notes: * DIMENC = New Caledonian government department for industry, mines, and energy; ** ISEE = New Caledonian Institute of Statitistics and Economic Studies; *** USGS = United States Geological Survey.

Thus, the "metals" subsystem focuses on nickel from its extraction to its export. The spatial trajectory of export is also studied. Hydrometallurgy and pyrometallurgy are both considered. Hydrometallurgy consists of treating the ore by leaching, which is to say by means of a solvent under pressure in order to isolate the nickel. The solution contains dissolved metals but also solid residues, which are then removed by decantation. In the pyrometallurgical process, the ore is successively ground, pre-dried, calcinated, and reduced by fusion in high-power electric furnaces to decant the raw ferronickel. It is sunk and separated by gravity from the slag. The molten slag from the metallurgical process is cooled and fragmented by a curtain of seawater or poured on a slope to form a "flow", which cools in the open air. We decided not to separate these two processes in the MEFA in order to avoid too complex a representation. Thus, the sector is taken as a whole, in connection with the energy sectors and construction minerals. Furthermore, if the "water" sector is not considered in this research, since it is neither highly preponderant nor essential for the functioning of the nickel industry, it nevertheless remains a significant flow in island metabolism.

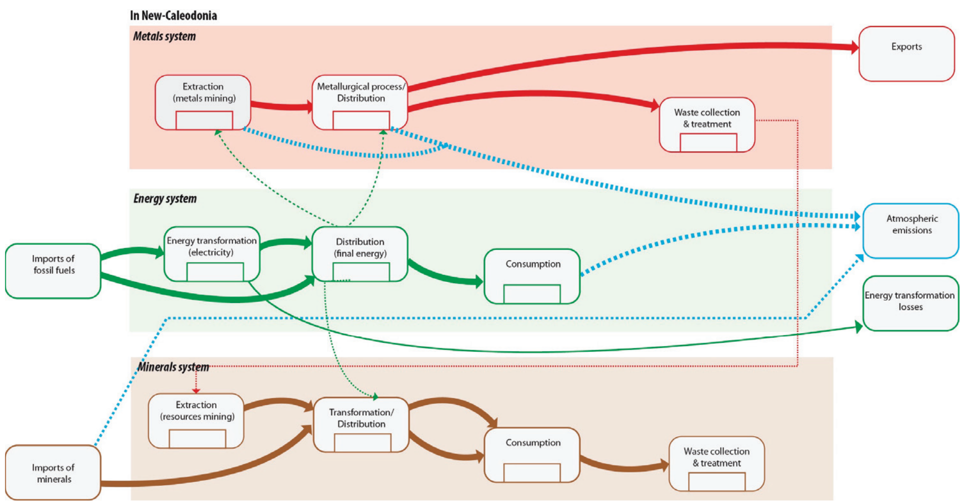

Figure 2. The metal-energy-construction mineral system studied.

Given the high-energy demand of the metal industry processes, the nickel-processing industry "energy" subsystem makes up most of the island's "energy" subsystem. Next to each metallurgical plant is a fossil fuel power plant. Fossil resources are imported from other parts of the world. Consequently, the greenhouse gas emissions of the subsystem are very significant.

The "construction minerals" subsystem sets out to describe the construction and building sector. There is only one cement company on the island, which imports its raw materials. Some other minerals, such as basalt, sand, and stones, are extracted in New Caledonia. Construction minerals are essential to the nickel sector for the construction of metallurgical plants. The strong development of the nickel industry in the 2010s led to a strong growth of construction activities. The analysis of the flows related to the construction minerals sector is a basis for investigating the recovery of nickel slags as a substitute for other materials used in the construction industry. Indeed, there are several technological projects which aim to produce construction mineral products with a market value, from nickel slags, targeting New Caledonian and international markets (mainly in the Asia-Pacific region). Moreover, a small part of the slags is already used for backfilling, especially for roads and sometimes informally, by the inhabitants of the archipelago.

3.3. Field Survey with Island Stakeholders

We carried out a field survey on the archipelago to obtain more detailed data from island stakeholders. Semi-structured interviews [17,57] with key stakeholders were carried out on July 2019. The main themes of the interviews were:

- What are the missions of the stakeholder and his professional network?
- What is the economic structure of the different sectors, and what infrastructure projects are planned?
- How is the supply of materials organized, and what are the main challenges to come?
- How are the environmental, social, and spatial challenges of construction projects taken into account? What are the sticking points and conflicts?

We chose to carry out these interviews with the widest possible range of stakeholders:

- The director of a company in the concrete sector
- An environmental inspector from the environment department of the South Province
- The managing director of a recycling company (which uses plastic waste and slag to make paving stones and curbs)
- The CEO of a professional federation of quarry operators and mining companies
- The managing director of a company in the construction sector
- The representative of the federation of processing industries
- The Head of Technical Studies and Investigation Department of KNS
- The HSEQR (Safety-Environment-Quality) director of SLN

These semi-structured interviews allowed us to reduce the blind spots of local databases, in particular on unused extraction and on the quantities of slag from the nickel industry and their accumulation (see Table 1), on the management of some construction waste and the consumption of construction materials related to major infrastructure projects. There is a gap between the year of the interviews and that of the data collection. However, these interviews allowed us to capture the state of knowledge of stakeholders for a reference year because we warned them that we were working on the 2016 data. This implies asking them for an order of magnitude for this reference year. We also discussed the difficulties and constraints, as well as the levers and opportunities, for the emergence of new synergies in this "metal-energy-construction mineral" nexus. Unfortunately, some essential stakeholders were unable to receive us, such as the cement transformation company. This represents a limitation of our work.

4. Results: The Metabolic Nexus, the Material Footprint of the Island, and Obstacles for the Transition to an Industrial Symbiosis

4.1. The Metabolic Flows of the "Metal-Energy-Construction Mineral" Nexus in New Caledonia

Figure 3 summarizes the results of the MEFA in each nexus subsystem for 2016. The sectors are structured very differently and it should be noted that some operations are absent from the subsystems: there are no imports, and there is no consumption in the "metals" subsystem, and almost no local energy extraction (for convenience of representation, we have not integrated the 0.033 kt petrol equivalent of primary electrical production through biomass, hydraulics, and wind, which represents 2% of consumption).

The "metals" subsystem illustrates the profile of an extractive island with a considerable nickel production but also cobalt and chromium, which are taken into account in the study. However, nickel represents 98% of the extraction of metals. The imported metal flows, which concern 1.4% of imports (0.0054 million t), are considered as not significant in the subsystem. More than 15 million tons of minerals are extracted from New Caledonian soil. This figure has doubled since 2000 [58,59]. This corresponds to exports of 3.1 million tons in 2002 (cf. Table 1) and 5.8 million tons of nickel and ferronickels in 2016 [60]. The remaining mass concerns the solid and liquid waste streams, which are therefore greater than those of exported nickel ores and ferronickels. Thus, according to interviews with industrial stakeholders, 9.5 million tons of unused extraction materials are produced yearly and are stored on the island. This represents an annual addition to the stock of almost 10 million tons.

Actually, the stakeholders interviewed mention a ratio of 1.25 tons of liquid waste per ton of extracted ore in the case of hydrometallurgy, which results in a production of 6671 ktons/year; and a ratio of 14 tons of slag per ton of ore in the case of pyrometallurgy, which is equivalent to 2900 ktons/year. These "wasted" amounts, which one might call “negative returns”, are far from negligible. However, to date, no measurements have been carried out, using a systematic and formal method, which could allow for their monitoring. As for liquid waste from hydrometallurgy, which consists of water, solvents, and inert waste, it is difficult to estimate the stock because part of the water is returned to the sea, not without causing pollution and controversies (see above). As regards slags, mainly composed of silica and magnesium oxides, the industrial stakeholders we interviewed estimate the stock to be in the range of 20 to 25 million m^3, which is an overwhelming order of magnitude for such a small island. This result raises questions, presented in the following sections, about who is responsible for the dynamics of this production and what are the obstacles to the emergence of recovery streams.

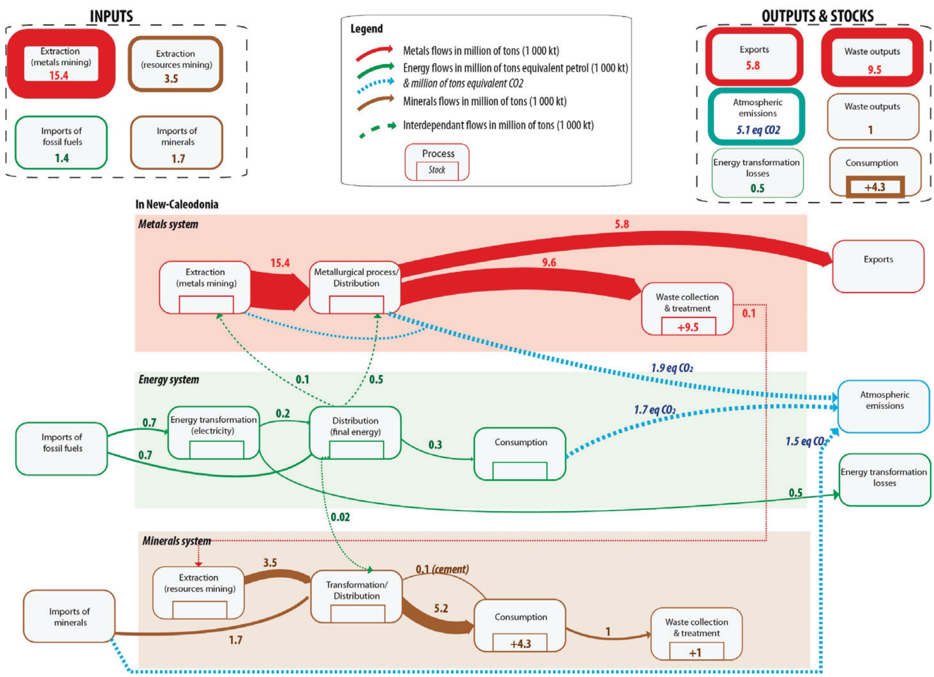

Figure 3. Results of mineral flow analysis (MFA) on the studied nexus.

The “energy” sector is very dependent on imports, growing from 0.65 million tons in 2000 to 1.56 million tons in 2016. This translates into an extremely low energy independence rate of 2.7% in 2016, which has not changed much since 2000 [61]. In addition, fossil fuels are the major source of energy with 63% of petroleum products and 34% of coal. A significant part is transformed into electricity by power plants, which were presented in Figure 3 as a loss of −0.5 million in the transformation process. Transport related to nickel concerns the majority of fossil fuel consumption with 0.2 million tons of petroleum products out of the 0.3 indicated in the consumption stage [62]. Despite investment programs in renewable energies and an increase in their production, it is clear that the energy balance is dependent on imported fossil fuels, which reinforces other economic imbalances.

As regards the construction minerals sector, it is also worth noticing the predominant role of imports—by boat—of these resources, which has increased a lot in recent years (from 0.18 million tons in 2009 to 1.7 in 2017). They account for 33% of material inflows [60], showing an additional dependence on other territories, although a significant fraction of minerals is also extracted locally, in particular basalt and sand, from 10 large quarries on the island [62]. Only one company produces cement, by mixing imported clinker with other components (recycled waste among others). The production of cement has decreased after reaching a consumption peak in 2010 (cf. Figure 4). However, since clinker is imported, and not made locally, this company is not considered as a cement plant. Clinker is imported from other countries, or even from other continents. In addition, there is not a single inert waste treatment facility in New Caledonia, although a constant flow of construction waste is used for damming in the Koutio-Koueta Bay, according to previous studies [63]. There are also unauthorized landfills on the island, making it very difficult to estimate both the flows and the stocks of inert waste.

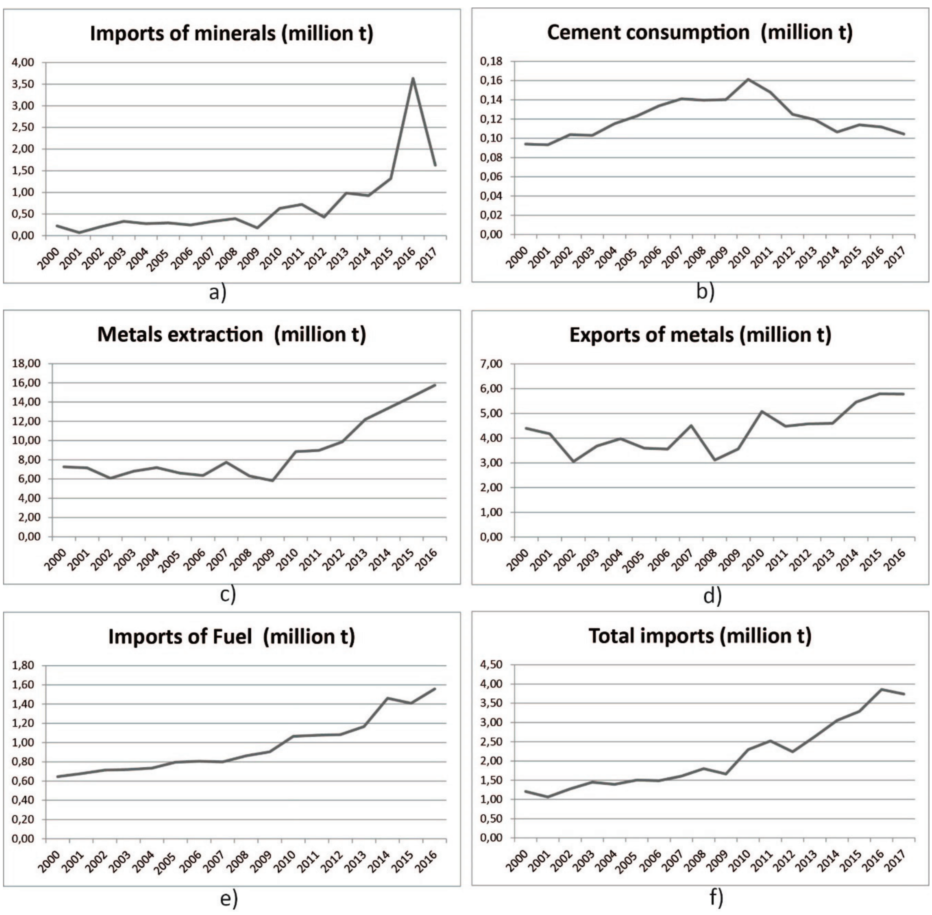

Figure 4. Temporal evolution of indicators (2000–2016). (**a**): Evolution of imports of minerals (million t); (**b**): Evolution of cement consumption (million t); (**c**): Evolution of metals extraction (million t); (**d**): Evolution of exports of metals (million t): (**e**): Evolution of imports of fuel (million t); (**f**): Evolution of total imports (million t)

Dashed arrows indicate the nodes of interdependence. They represent inter-system flows, from the processes of one system to the processes of another system, such as referred in Reference [48]. Thus, these flows do not contribute to the mass balance when they are not of the same color. They correspond to indirect flows in connection between two operations (with different colors). Some energy-related flows correspond to this case. The nodes of interdependence between the three subsystems are of four types. The "metals" subsystem is a very large consumer of energy, imported into the archipelago. This is the first preponderant node of this nexus. The metal sector is very dependent on energy. Indeed, 0.6 million tons of fossil fuels are distributed into the archipelago just for extraction and metallurgy [62]. This corresponds to 66% of total island energy consumption [61]. Thus, energy needs are distributed in a very unequal manner, which gives a very singular island context. The weight of this sector has a strong impact on socioeconomic metabolism. Consequently, the metals subsystem is a very strong producer of greenhouse gases (52% of direct island emissions, of which 47.8% for the metallurgical industry, and 4.2% for extraction in mines [62]). Therefore, the energy sector is closely linked to the metallurgical industry. The second node concerns the energy needs of the "minerals" sector. According to the Observatory of energy [62], the consumption of the construction industry is estimated at 0.02 million tons of mainly petroleum products. This flow is not predominant in the island's metabolism. The third node concerns indirect emissions related to the import of mineral products. The latter represent around 47% of materials imports, an amount which has increased a lot since 2009 [60]. Indirect emissions of minerals imports, which stand at 1.5 million tons of CO_2, come from manufacturing in other countries and from distribution to the archipelago [62]. Even if these emissions do not occur directly in New Caledonia, they are induced by the consumption of mineral products on the island. According to the Observatory of energy [62], they are a major contributor to greenhouse gas emissions and are of the same order of magnitude as the contribution of nickel production, which stands at around 1.9 million tons of CO_2. Even though we do not have precise data on this subject, it is important to note that a very significant part of the minerals consumed is used for the construction of nickel-related infrastructure, such as the metallurgical plants (recently in 2010–2012) and access roads to the mines. Finally, the last node is that of the informal recovery of nickel slag as fill. According to industrial stakeholders, between 5 and 10% of the annual slag production, representing around 150 ktons/year, is reused as a filling material for its draining properties. This is very little compared to the annual production of slag, but it suggests options for a more systematic recovery of slags and a solution to the accumulation of the existing stock.

4.2. Spatialization of Nexus: The Material Footprint of Islands

The study of the "metal-energy-construction mineral" nexus shows volumes of flows which are very high compared to the relatively small population of New Caledonia (around 269,000 inhabitants). If we refer to the MFA indicators from the Eurostat guide [64], as presented in Section 1.1, results are exorbitant. For example, in 2016, according to our calculations (cf. Table 1), the DMI (which corresponds to domestic extractions – without the unused extraction - and imports) and the DMC (which corresponds to DMI from which exports are subtracted) were equal, respectively, to 50.7 and 29.3 tons/capita. By comparison, in France material input and material consumption stand at around 14 and 11 tons/capita/year according to the Eurostat database [65]. That is to say, they are almost three times lower than in New Caledonia. However, the island's metabolism is dominated by "unused extraction", using the terms of the Eurostat method, designating excavated flows without a local economic function [64,66]. These correspond to 35.7 tons/capita. This "unused extraction" mainly comes from the extraction and production of nickel. Likewise, the DPO (which adds up the emissions to nature without controlled landfills) is very high (13.8 tons/capita). This is much more than for France where this figure stands at around 7.2 tons/capita). In the same way, DPO in New Caledonia mainly concerns atmospheric emissions linked to the metallurgical industries (7 tons/capita of CO2 equivalent). Thus, the Nickel sector and its energy and material interdependencies are clearly preponderant in the socio-economic metabolism of New Caledonia.

It is also relevant to compare these indicators with those of the small islands that have already been studied [3,7,8,20]. The DMC in Iceland and in Trinidad are around 23 and 17 tons/capita/year, which is quite similar to New Caledonia (29.3 tons/capita/year). Most of the extraction is used for a production based on local resources which are then exported (aluminum and ferrosilicon in Iceland and petroleum in Trinidad). This results in high rates of energy use and waste from production. The DMI is still much higher in New Caledonia (50.7 tons/capita/year) than in Iceland (29.1 tons/capita/year) but equivalent to Trinidad (43.5 tons/capita/year). On the contrary, the Philippines [8] or Ndzuwani in the Comoros [20] have a very different metabolic profile with a low DMC (6 tons/capita/year in the Philippines and 1.4 tons/capita/year in Ndzuwani), even if the extraction and export of essential oils from Ylang are the main economic sectors of Ndzuwani and the export of metallic ore is important in the Philippines (but this country also has a comparatively larger population, which brings down the per-capita ratio).

When we simulate the DMI and DPO indicators without the nickel supply chain (which remains entirely hypothetical and comes with many methodological limits), we obtain completely different results and much more in line with consumption levels in France. Indeed, without nickel, the DMI and the DPO (which is the atmospheric emissions + exported waste without landfilled waste) would correspond to 46 and 49% of the island indicators, that is to say, 23.6 tons/capita and 6.7 tons/capita, respectively, which is much closer to the French indicators (12 tons/capita for the DMC and 11 tons/capita for the DPO).

However, we can wonder about who is responsible for such high values. Most of the nickel produced is not used for New Caledonian consumption. It is exported to China, South Korea, Japan, Taiwan, the EU, France, and Australia (see Figure 5). These countries are amongst the biggest consumers of nickel in the world. In that perspective, approximately half of New Caledonia's material footprint [67] is imputable to the consumption of these nickel-importing countries, which are therefore responsible at the end of the chain for these environmental impacts. In fact, according to the conceptual terms of socioeconomic metabolism [39,68,69], slags and a large part of energy resource and atmospheric emissions are the raw material equivalents (RME) that "capture consistently the amount of extracted material needed to produce a certain (set of) product(s)" [64]. This metabolic indicator is directly related to the consumption of nickel in China, South Korea, Japan, Taiwan, the EU, and France because it corresponds to flows of energy and building materials necessary throughout the supply chain to produce the goods ultimately consumed in a given area. They are very difficult to identify in studies on socio-economic metabolism because they are generally not accounted for in the importing countries. However, these issues have become very prominent in the scientific literature [25,70]. They provide food for thought on geo-strategic power relationships, as well as on their ensuing impact on the metabolic relationships between territories [17]. In conclusion, the metabolic profile of this island is that of a supply base for other consumption territories, which outsource the impacts of their own consumption to New Caledonia. This result is thus a means of fueling reflections on metabolic outsourcing and therefore on the ultimate responsibility for environmental impacts, notably through the field of political-industrial ecology [71,72].

There are other paradoxical points in New Caledonia: Although it is a supply base for other countries, this island territory is also very dependent on imports. Excluding mining, these imported flows (10.6 tons/capita) are of the same order of magnitude as local extraction and production (13 tons/capita). Imports not related to nickel therefore meet 44% of the material needs of the archipelago, which shows the low autonomy of New Caledonia. In addition, historical trends show a strong increase in these imports, since this indicator was of 5.6 tons/capita in 2000 and of 6.8 tons/capita in 2009, showing a weakening of the material autonomy of New Caledonia.

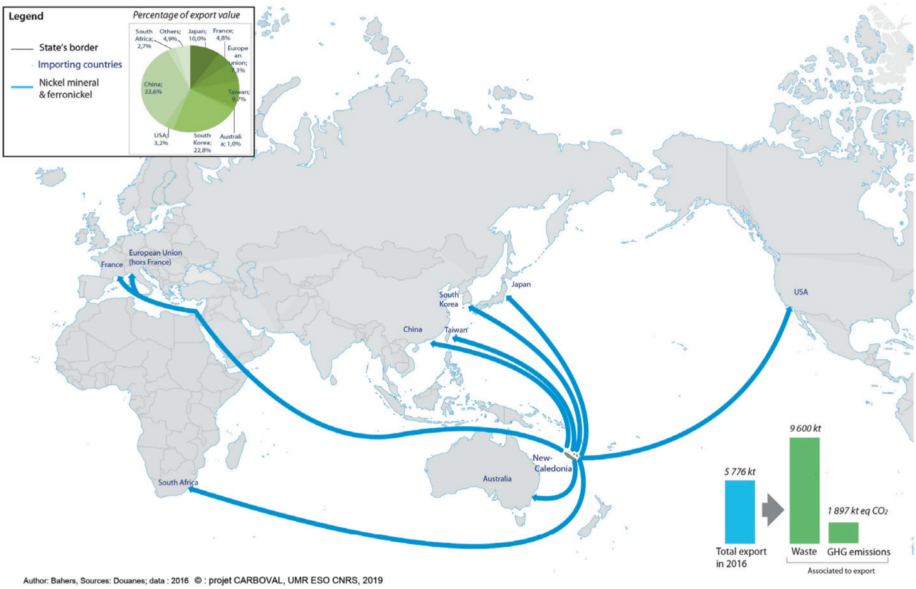

Figure 5. Destinations and amounts in 2016 of nickel exported from New Caledonia (Author: Bahers 2019.

4.3. Potential Building Blocks and Obstacles for the Emergence of an Industrial Symbiosis in the Nexus

According to pyrometallurgical companies in the territory, currently, metallurgical activities produce about 3 million tons of ferronickel slag per year in New Caledonia, out of 9.5 million tons of "unused extracted materials". The chemical and mineralogical characteristics of ferronickel slag show an interesting potential for reuse as building materials, mainly due to the presence of SiO2 and MgO (about 53% and 33%, respectively) [73]. This could lead to the development of an industrial symbiosis [9,74] between the nickel and construction sectors. Ferronickel slag can potentially replace part of the clay used in the manufacture of cement. It can also become a substitute to fine aggregates in the manufacture of concrete or be used as an aggregate for the manufacture of geopolymers and other types of cements [73]. The physiochemical properties of ferronickel slag, combined with the powers devolved to New Caledonia to define new construction standards, different from the French ones, should generate a strong interest for the recovery of this slag and give a second life to the construction sector. This could possibly reduce the import of mineral resources. However, today, this is not the case.

Indeed, when island stakeholders were interviewed we identified several obstacles. According to them, the current economic situation of the construction sector is not favorable. Since 2012, after the end of construction phases of the north and south metallurgic plants, the activity in the construction sector went substantially downwards. Concrete consumption has been decreasing since 2010, and production has been lowered by an average of 30% between 2010 and 2016. Consequently, the number of employees in this industry continues to decline: 1300 jobs could be destroyed in 2019, out of 6700 employees in total. Furthermore, for the economic and market forces of the construction sector, ferronickel slag is a material that may put the activity of the quarries currently in operation in New Caledonia at risk. Some stakeholders from the construction sector also express the idea that, today, there are also many important barriers (without specifying them more in depth) to the entry of new actors in the concrete market.

Other hurdles concern the possible construction materials themselves. Today, for concrete producers, there is no scientific evidence proving that ferronickel slags provide identical or better performance for concrete compared to conventional cements or aggregates. Indeed, the mineralogical characteristics of ferronickel could generate an alkali-silica reaction and impair the strength of the concrete; this parameter is an important limitation in international construction standards, notably in Japan and Australia [73].

Finally, geographic isolation and the small size of the New Caledonian market will play an important role in any slag recovery strategy. According to the stakeholders concerned with local economic development, New Caledonia is a remote and poorly self-supplied territory, which generates high transportation costs. The availability of building materials is higher than the needs of the territory because of a small population. Any recovery option has to bet on foreign markets in order to export recovered ferronickel slag to the closest foreign markets, such as Japan, Australia, New Zealand, and the Pacific Community. In this case, it is important to consider foreign construction standards, their local policies concerning the use of metallurgic slag, and their political strategy as concerns local versus foreign sources of supply. According to a business manager we interviewed, exporting to the Pacific Community is not an obvious option. For example, although the Vanuatu archipelago does not have a geological bed that provides quality aggregates for construction, local and low-quality materials are preferred in order to maintain constructive independence.

These elements point out the difficulties of making the local construction industry evolve, mainly due to the structure of the market and to the island constraints of New Caledonia.

5. Conclusions

New Caledonia is currently facing important interconnected economic, resources, and environmental issues.

As Wiedman et al. mention: "Two fifths of all global raw materials were extracted and used just to enable exports of goods and services to other countries" [67]. As an extractive economy, it provides important nickel resources to the world. But far from ensuring flourishing economic perspectives through a positive trade balance, the situation increases its material dependency by requiring imports of huge amounts of energy resources in order to enable nickel production. Two thirds of local energy consumption, based mainly on imported fossil fuels, and half of CO2 equivalent emissions are caused by the nickel production industry.

As an island, and although responsibilities can be attributed to nickel consuming countries, New Caledonia indirectly contributes to weakening its own position against the rise of sea level provoked by climate change, through its local emissions of greenhouse gases. The situation of the island also emphasizes the issue of land availability and local pollution considering the huge amounts of waste generated by nickel extraction and production. Indeed, we cannot neglect the wider environmental impacts of nickel mining in New Caledonia, which is in addition to being a very high greenhouse gas emitting industry, resulting in very significant land-use changes (from mines but also sedimentation of slags), acidification, and eco-toxicity, according to life cycle assessments studies [75,76]. A future in which the nickel reserves could be exhausted is not currently envisaged in New Caledonia because reserves are important. However, as shown by Mudd [77], the island could experience degrowth, forced by the depletion of fossil fuel resources and environmental cost constraints. This would further increase the economic and metabolic unbalances of the island. Furthermore, this situation will not eliminate local, long-term environmental impacts linked to existing stocks. We must now consider reducing these impacts and, at the same time, repairing environmental damage. This is an ambitious future research objective.

A possible nexus of minerals for the construction sector could be added to the one of metal - energy, by recovery of nickel slags. It could be globally positive if it fulfills several conditions. First, it should reduce the dependency of the island on imports of minerals that are indirectly responsible for one third of greenhouse gas emissions. A deeper analysis of imported minerals, and their use, should be conducted to estimate how recovered nickel slags could become a substitute for them. Second, nickel slag recovery should contribute to reducing the global contribution of the island to both climate change and local pollution. The carbon footprint of various recovery possibilities should be assessed using Life Cycle Assessment, combined with Material Flow Analysis, to ensure the match between products obtained from nickel slag recovery, and local and closest foreign markets. Obviously, increasing transportation by exports of products recovered from nickel slags, possibly balanced by decreasing transportation of mineral imports, should be accounted for at the territorial level to assess the carbon footprint. Furthermore, the economic value of products issued from slag recovery is a crucial factor for the assessment. If there is no market for these products, there can be no hope of addressing imbalances in the island's metabolism. This global assessment is precisely the objective of the carboscories and carboval research projects studying the possibility of nickel slag recovery and using a mineralization process enabling CO2 capture [78]. Third, local actors should be involved and take part in the strategic changes to come, in order to ensure that they can benefit from possible long-term evolution. Indeed, there is a strong risk of consolidating an economy based on the extraction of nonrenewable resources.

Finally, New Caledonia perfectly illustrates the metabolic challenges of small extractive islands. These small extractive islands have political economy issues in common because their metabolism reinforces their social, environmental, and economic vulnerabilities. As Anke Schaffartzik and Melanie Pichler point out [79], the role of extractive economies needs to be better understood by identifying synergies and trade-offs in the use of global resources. This is an issue of coupling approaches in political ecology and social ecology, in order to provide biophysical and socio-political conceptualizations within the interdisciplinary sustainability sciences. The "metal-energy-construction mineral" nexus has made it possible to grasp the complexity of the flow circulation and its environmental consequences. In this respect, this method makes it possible to enrich knowledge on the sustainable metabolic transformations of small extractive islands.

Author Contributions: Conceptualization, formal analysis; J.-B.B., P.H., A.V., N.A. All authors have read and agreed to the published version of the manuscript.

Funding: The authors gratefully acknowledge funding from the "Agence calédonienne de l'énergie" (New Caledonian energy agency) and ADEME (French environmental agency), contract "Carboval" research project.

Acknowledgments: We want to thank the stakeholders that we interviewed and the reviewers for their valuable comments.

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

References

1. Social Ecology. *Society-Nature Relations across Time and Space*; Haberl, H., Fischer-Kowalski, M., Krausmann, F., Winiwarter, V., Eds.; Springer: Berlin/Heidelberg, Germany, 2016.
2. Haberl, H.; Wiedenhofer, D.; Pauliuk, S.; Krausmann, F.; Müller, D.B.; Fischer-Kowalski, M. Contributions of sociometabolic research to sustainability science. *Nat. Sustain.* **2019**, *2*, 173. [CrossRef]
3. Krausmann, F.; Richter, R.; Eisenmenger, N. Resource Use in Small Island States. *J. Ind. Ecol.* **2014**, *18*, 294–305. [CrossRef] [PubMed]
4. Petridis, P.; Fischer-Kowalski, M. Island Sustainability: The Case of Samothraki. In *Social Ecology*; Haberl, H., Fischer-Kowalski, M., Krausmann, F., Winiwarter, V., Eds.; Springer: Berlin/Heidelberg, Germany, 2016.
5. Singh, S.J.; Grünbühel, C.M.; Schandl, H.; Schulz, N. Social Metabolism and Labour in a Local Context: Changing Environmental Relations on Trinket Island. *Popul. Environ.* **2001**, *23*, 71–104. [CrossRef]
6. Fetzel, T.; Petridis, P.; Noll, D.; Singh, S.J.; Fischer-Kowalski, M. Reaching a socio-ecological tipping point: Overgrazing on the Greek island of Samothraki and the role of European agricultural policies. *Land Use Policy* **2018**, *76*, 21–28. [CrossRef]
7. Symmes, R.; Fishman, T.; Telesford, J.N.; Singh, S.J.; Tan, S.-Y.; Kroon, K.D. The weight of islands: Leveraging Grenada's material stocks to adapt to climate change. *J. Ind. Ecol.* **2020**, 1–14, forthcoming. [CrossRef]
8. Martinico-Perez, M.F.G.; Schandl, H.; Fishman, T.; Tanikawa, H. The Socio-Economic Metabolism of an Emerging Economy: Monitoring Progress of Decoupling of Economic Growth and Environmental Pressures in the Philippines. *Ecol. Econ.* **2018**, *147*, 155–166. [CrossRef]

9. Deschenes, P.J.; Chertow, M. An island approach to industrial ecology: Towards sustainability in the island context. *J. Environ. Plan. Manag.* **2004**, *47*, 201–217. [CrossRef]
10. Eckelman, M.J.; Chertow, M.R. Using Material Flow Analysis to Illuminate Long-Term Waste Management Solutions in Oahu, Hawaii. *J. Ind. Ecol.* **2009**, *13*, 758–774. [CrossRef]
11. Cole, S. A political ecology of water equity and tourism: A Case Study from Bali. *Ann. Tour. Res.* **2012**, *39*, 1221–1241. [CrossRef]
12. Thompson, B.S. The political ecology of mangrove forest restoration in Thailand: Institutional arrangements and power dynamics. *Land Use Policy* **2018**, *78*, 503–514. [CrossRef]
13. Gössling, S. *Tourism and Development in Tropical Islands: Political Ecology Perspectives*; Edward Elgar: Cheltenham, UK, 2003.
14. Allen, M.G.; Porter, D.J. Managing the transition from logging to mining in post-conflict Solomon Islands. *Extr. Ind. Soc.* **2016**, *3*, 350–358. [CrossRef]
15. Harrison, C.; Popke, J. Geographies of renewable energy transition in the Caribbean: Reshaping the island energy metabolism. *Energy Res. Soc. Sci.* **2018**, *36*, 165–174. [CrossRef]
16. Barles, S. Society, energy and materials: The contribution of urban metabolism studies to sustainable urban development issues. *J. Environ. Plan. Manag.* **2010**, *53*, 439–455. [CrossRef]
17. Bahers, J.-B.; Tanguy, A.; Pincetl, S. Metabolic relationships between cities and hinterland: A political-industrial ecology of energy metabolism of Saint-Nazaire metropolitan and port area (France). *Ecol. Econ.* **2020**, *167*, 106447. [CrossRef]
18. Cecchin, A. Material flow analysis for a sustainable resource management in island ecosystems. *J. Environ. Plan. Manag.* **2016**, *0*, 1–20. [CrossRef]
19. Ginard-Bosch, F.J.; Ramos-Martín, J. Energy metabolism of the Balearic Islands (1986–2012). *Ecol. Econ.* **2016**, *124*, 25–35. [CrossRef]
20. Bahers, J.-B.; Perez, J.; Durand, M. Vulnérabilité métabolique et potentialités des milieux insulaires. Le cas de l'île de Ndzuwani (Anjouan), archipel des Comores. *Flux* **2019**, *116–117*, 86–104. [CrossRef]
21. Schaffartzik, A.; Wiedenhofer, D. Linking society and nature: Material flows and the resource nexus. In *Routledge Handbook of the Resource Nexus*; Routledge: London, UK, 2017.
22. Newell, J.P.; Goldstein, B.; Foster, A. A 40-year review of food–energy–water nexus literature and its application to the urban scale. *Environ. Res. Lett.* **2019**, *14*, 073003. [CrossRef]
23. Barles, S. Urban metabolism of Paris and its region. *J. Ind. Ecol.* **2009**, *13*, 898–913. [CrossRef]
24. Albrecht, T.R.; Crootof, A.; Scott, C.A. The Water-Energy-Food Nexus: A systematic review of methods for nexus assessment. *Environ. Res. Lett.* **2018**, *13*, 043002. [CrossRef]
25. Dai, J.; Wu, S.; Han, G.; Weinberg, J.; Xie, X.; Wu, X.; Song, X.; Jia, B.; Xue, W.; Yang, Q. Water-energy nexus: A review of methods and tools for macro-assessment. *Appl. Energy* **2018**, *210*, 393–408. [CrossRef]
26. Hamiche, A.M.; Stambouli, A.B.; Flazi, S. A review of the water-energy nexus. *Renew. Sustain. Energy Rev.* **2016**, *65*, 319–331. [CrossRef]
27. Arthur, M.; Liu, G.; Hao, Y.; Zhang, L.; Liang, S.; Asamoah, E.F.; Lombardi, G.V. Urban food-energy-water nexus indicators: A review. *Resour. Conserv. Recycl.* **2019**, *151*, 104481. [CrossRef]
28. Fan, J.-L.; Kong, L.-S.; Wang, H.; Zhang, X. A water-energy nexus review from the perspective of urban metabolism. *Ecol. Model.* **2019**, *392*, 128–136. [CrossRef]
29. Dalla Fontana, M.; Boas, I. The politics of the nexus in the city of Amsterdam. *Cities* **2019**, *95*, 102388. [CrossRef]
30. Singh, S.; Kennedy, C. The Nexus of Carbon, Nitrogen, and Biodiversity Impacts from Urban Metabolism. *J. Ind. Ecol.* **2018**, *22*, 853–867. [CrossRef]
31. Liu, J.; Hull, V.; Godfray, H.C.J.; Tilman, D.; Gleick, P.; Hoff, H.; Pahl-Wostl, C.; Xu, Z.; Chung, M.G.; Sun, J.; et al. Nexus approaches to global sustainable development. *Nat. Sustain.* **2018**, *1*, 466–476. [CrossRef]
32. Sverdrup, H.; Koca, D.; Ragnarsdottir, K.V. Peak Metals, Minerals, Energy, Wealth, Food and Population: Urgent Policy Considerations for a Sustainable Society. *J. Environ. Sci. Eng.* **2013**, *2*, 499–533.
33. Malm, A. *Fossil Capital: The Rise of Steam Power and the Roots of Global Warming*; Verso: New York, NY, USA, 2016.
34. Allen, M.G. Islands, extraction and violence: Mining and the politics of scale in Island Melanesia. *Political Geogr.* **2017**, *57*, 81–90. [CrossRef]

35. Apanon, C.; Fremont, K.D. L'impact du Nickel en Nouvelle-Calédonie: Deux Emplois Privés Sur Dix Liés au Secteur Nickel en 2012. Available online: https://catalogue.nla.gov.au/Record/7089541 (accessed on 9 March 2020).
36. Kowasch, M. Nickel mining in northern New Caledonia—A path to sustainable development? *J. Geochem. Explor.* **2018**, *194*, 280–290. [CrossRef]
37. Martinez-Alier, J. Social Metabolism, Ecological Distribution Conflicts, and Languages of Valuation. *Capital. Nat. Soc.* **2009**, *20*, 58–87. [CrossRef]
38. Conde, M. Resistance to Mining. A Review. *Ecol. Econ.* **2017**, *132*, 80–90. [CrossRef]
39. Schaffartzik, A.; Mayer, A.; Eisenmenger, N.; Krausmann, F. Global patterns of metal extractivism, 1950–2010: Providing the bones for the industrial society's skeleton. *Ecol. Econ.* **2016**, *122*, 101–110. [CrossRef]
40. Trépied, B. Des conduites d'eau pour les tribus. Action municipale, colonisation et citoyenneté en Nouvelle-Calédonie. *Rev. Dhistoire Mod. Contemp.* **2011**, *58*, 93–120. [CrossRef]
41. Horowitz, L.S. Environmental violence and crises of legitimacy in New Caledonia. *Political Geogr.* **2009**, *28*, 248–258. [CrossRef]
42. Meur, P.-Y.L. La terre en Nouvelle-Calédonie: Pollution, appartenance et propriété intellectuelle. *Multitudes* **2010**, *41*, 91–98. [CrossRef]
43. Merlin, J. L'émergence d'une compétence environnementale autochtone? *Terrains Trav.* **2014**, *24*, 85–102. [CrossRef]
44. Demmer, C. L'export du nickel au cœur du débat politique néo-calédonien. *Mouvements* **2017**, *91*, 130–140. [CrossRef]
45. Bahers, J.-B.; Barles, S.; Durand, M. Urban Metabolism of Intermediate Cities: The Material Flow Analysis, Hinterlands and the Logistics-Hub Function of Rennes and Le Mans (France). *J. Ind. Ecol.* **2019**, *23*, 686–698. [CrossRef]
46. Rosado, L.; Kalmykova, Y.; Patrício, J. Urban metabolism profiles. An empirical analysis of the material flow characteristics of three metropolitan areas in Sweden. *J. Clean. Prod.* **2016**, *126*, 206–217. [CrossRef]
47. Athanassiadis, A.; Bouillard, P.; Crawford, R.H.; Khan, A.Z. Towards a Dynamic Approach to Urban Metabolism: Tracing the Temporal Evolution of Brussels' Urban Metabolism from 1970 to 2010. *J. Ind. Ecol.* **2016**, *21*, 307–319. [CrossRef]
48. Liang, S.; Qu, S.; Zhao, Q.; Zhang, X.; Daigger, G.T.; Newell, J.P.; Miller, S.A.; Johnson, J.X.; Love, N.G.; Zhang, L.; et al. Quantifying the Urban Food–Energy–Water Nexus: The Case of the Detroit Metropolitan Area. *Environ. Sci. Technol.* **2019**, *53*, 779–788. [CrossRef] [PubMed]
49. EUROSTAT. Economy-Wide Material Flow Accounts (EW-MFA) Compilation Guide. 2013. Available online: https://ec.europa.eu/eurostat/documents/1798247/6191533/2013-EW-MFA-Guide-10Sep2013.pdf/54087dfb-1fb0-40f2-b1e4-64ed22ae3f4c (accessed on 9 March 2020).
50. Voskamp, I.M.; Stremke, S.; Spiller, M.; Perrotti, D.; van der Hoek, J.P.; Rijnaarts, H.H.M. Enhanced Performance of the Eurostat Method for Comprehensive Assessment of Urban Metabolism: A Material Flow Analysis of Amsterdam. *J. Ind. Ecol.* **2017**, *21*, 887–902. [CrossRef]
51. Singh, S.J.; Haas, W. Complex Disasters on the Nicobar Islands. In *Social Ecology: Society-Nature Relations across Time and Space*; Haberl, H., Fischer-Kowalski, M., Krausmann, F., Winiwarter, V., Eds.; Springer: Berlin/Heidelberg, Germany, 2016.
52. Bahers, J.-B.; Kim, J. Regional approach of waste electrical and electronic equipment (WEEE) management in France. *Resour. Conserv. Recycl.* **2018**, *129*, 45–55. [CrossRef]
53. Baccini, P.H.; Brunner, P. *Metabolism of the Anthroposphere*; Springer: Berlin/Heidelberg, Germany, 1991.
54. Laner, D.; Rechberger, H.; Astrup, T. Systematic Evaluation of Uncertainty in Material Flow Analysis. *J. Ind. Ecol.* **2014**, *18*, 859–870. [CrossRef]
55. Patrício, J.; Kalmykova, Y.; Rosado, L.; Lisovskaja, V. Uncertainty in Material Flow Analysis Indicators at Different Spatial Levels. *J. Ind. Ecol.* **2015**, *19*, 837–852. [CrossRef]
56. Džubur, N.; Buchner, H.; Laner, D. Evaluating the Use of Global Sensitivity Analysis in Dynamic MFA. *J. Ind. Ecol.* **2017**, *21*, 1212–1225. [CrossRef]
57. Deutz, P.; Baxter, H.; Gibbs, D.; Mayes, W.M.; Gomes, H.I. Resource recovery and remediation of highly alkaline residues: A political-industrial ecology approach to building a circular economy. *Geoforum* **2017**, *85*, 336–344. [CrossRef]
58. ISEE. Tableaux de l'Economie Calédonienne. Available online: http://www.isee.nc/publications/tableau-de-l-economie-caledonienne-tec (accessed on 9 March 2020).

59. USGS. 2016 Minerals Yearbook—The Mineral Industry of New Caledonia. Available online: https://www.usgs.gov/media/files/mineral-industry-new-caledonia-2016-pdf (accessed on 9 March 2020).
60. ISEE. Commerce extérieur Customs Office of New Caledonia Données de la Direction Régionale des Douanes. Available online: http://www.isee.nc/economie-entreprises/economie-finances/commerce-exterieur (accessed on 9 March 2020).
61. ISEE. Energie Environnement Données Sur le Bilan Énergétique. Available online: http://www.isee.nc/economie-entreprises/entreprises-secteurs-d-activites/energie-environnement (accessed on 9 March 2020).
62. DIMENC. Gouvernement de Nouvelle-Calédonie Schema Pour la Transition Energetique de la Nouvelle-Caledonie. Available online: https://maitrise-energie.nc/espace-presse/schema-pour-la-transition-energetique-de-la-nouvelle-caledonie (accessed on 9 March 2020).
63. Jouanny, M. Réhabilitation d'un site d'enfouissement de déchets inertes en parc d'activités dynamique et durable. *Mémoire de projet individuel à Polytech Tours* **2016**, *37*.
64. Eurostat. Economy-Wide Material Flow Accounts Handbook. 2018. Available online: https://ec.europa.eu/eurostat/documents/3859598/9117556/KS-GQ-18-006-EN-N.pdf/b621b8ce-2792-47ff-9d10-067d2b8aac4b (accessed on 9 March 2020).
65. Material Flows and Resource Productivity—Eurostat. Available online: https://ec.europa.eu/eurostat/web/environment/material-flows-and-resource-productivity (accessed on 18 February 2020).
66. Yoshida, K.; Fishman, T.; Okuoka, K.; Tanikawa, H. Material stock's overburden: Automatic spatial detection and estimation of domestic extraction and hidden material flows. *Resour. Conserv. Recycl.* **2017**, *123*, 165–175. [CrossRef]
67. Wiedmann, T.O.; Schandl, H.; Lenzen, M.; Moran, D.; Suh, S.; West, J.; Kanemoto, K. The material footprint of nations. *Proc. Natl. Acad. Sci. USA* **2015**, *112*, 6271–6276. [CrossRef] [PubMed]
68. Bringezu, S.; Schütz, H.; Steger, S.; Baudisch, J. International comparison of resource use and its relation to economic growth: The development of total material requirement, direct material inputs and hidden flows and the structure of TMR. *Ecol. Econ.* **2004**, *51*, 97–124. [CrossRef]
69. Schandl, H.; Fischer-Kowalski, M.; West, J.; Giljum, S.; Dittrich, M.; Eisenmenger, N.; Geschke, A.; Lieber, M.; Wieland, H.; Schaffartzik, A.; et al. Global Material Flows and Resource Productivity: Forty Years of Evidence. *J. Ind. Ecol.* **2018**, *22*, 827–838. [CrossRef]
70. Linton, J.; Budds, J. The hydrosocial cycle: Defining and mobilizing a relational-dialectical approach to water. *Geoforum* **2014**, *57*, 170–180. [CrossRef]
71. Baka, J.E. Political-industrial ecologies of energy. In *Handbook on the Geographies of Energy*; Edward Elgar Publishing: Cheltenham, UK, 2017.
72. Cousins, J.J.; Newell, J.P. A political–industrial ecology of water supply infrastructure for Los Angeles. *Geoforum* **2015**, *58*, 38–50. [CrossRef]
73. Higuera, P. *Évaluation Technico-Économique des Débouchés de Valorisation des Scories de Nickel. Territoire: Nouvelle-Calédonie*; IAE Nantes—Économie & Management Université de Nantes: Nantes, France, 2019.
74. Chertow, M.R. "Uncovering" Industrial Symbiosis. *J. Ind. Ecol.* **2007**, *11*, 11–30. [CrossRef]
75. Norgate, T.E.; Jahanshahi, S.; Rankin, W.J. Assessing the environmental impact of metal production processes. *J. Clean. Prod.* **2007**, *15*, 838–848. [CrossRef]
76. Nakajima, K.; Nansai, K.; Matsubae, K.; Tomita, M.; Takayanagi, W.; Nagasaka, T. Global land-use change hidden behind nickel consumption. *Sci. Total Environ.* **2017**, *586*, 730–737. [CrossRef]
77. Mudd, G.M. Global trends and environmental issues in nickel mining: Sulfides versus laterites. *Ore Geol. Rev.* **2010**, *38*, 9–26. [CrossRef]
78. Ventura, A.; Antheaume, N. Environmental assessment of carbon capture and utilization: A new systemic vision—application to valorization of nickel slags. In Proceedings of the International Workshop CO2 Storage in Concrete, Marne-La-Vallée, France, 24–26 June 2019.
79. Schaffartzik, A.; Pichler, M. Extractive Economies in Material and Political Terms: Broadening the Analytical Scope. *Sustainability* **2017**, *9*, 1047. [CrossRef]

© 2020 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (http://creativecommons.org/licenses/by/4.0/).

sustainability

MDPI

Article

Samothraki in Transition: A Report on a Real-World Lab to Promote the Sustainability of a Greek Island

Marina Fischer-Kowalski [1,*], Markus Löw [2], Dominik Noll [1], Panos Petridis [1] and Nikolaos Skoulikidis [3]

1. Department for Social Sciences, University for Natural Resources and Life Sciences, A1070 Vienna, Austria
2. Department of Forest Inventory, Austrian Research Centre for Forests, A1131 Vienna, Austria
3. Institute of Marine Biological Resources & Inland Water, Hellenic Centre for Marine Research, Anavyssos, 19013 Attica, Greece

* Correspondence: marina.fischer-kowalski@boku.ac.at

Received: 12 December 2019; Accepted: 25 February 2020; Published: 3 March 2020

Abstract: This is a case study on a small mountainous island in the Aegean Sea with the policy goal of preparing it to become member of UNESCO's World Network of Biosphere Reserves. While the local community opted for such an identity very early on, there are a number of obstacles to be overcome. The multidisciplinary research is based upon a sociometabolic approach and focuses on two issues: The transformation of agriculture, mainly herding of sheep and goats, and the shift to tourism. The degradation of the landscape caused by extensive roaming of goats and sheep constitute one of the major sustainability challenges of the island. We analyze farmers' opportunities and describe new initiatives to get out of this deadlock. The impacts of the transition to tourism are addressed from an infrastructural perspective: A shift from traditional stone buildings to bricks and concrete, the establishment of new roads and ports, and the challenges to water supply and wastewater removal, also with reference to the quality and amounts of wastes generated that need to be dealt with. The island has so far escaped mass tourism and attracts mainly eco-tourists who value its remoteness and wilderness. We discuss how to serve this clientele best in the future, and increase local job opportunities and income while maintaining environmental quality. Finally, we reflect upon emerging new forms of local collaboration and the impact of our research efforts on a sustainability transition that might be on its way.

Keywords: island sociometabolic regime; transdisciplinary research; real-world learning lab for sustainability transition; livestock herding; subsidies and overgrazing; tourism infrastructure; UNESCO Biosphere Reserves

---

1. Introduction

The small (178km^2) Greek island Samothraki ("Σαμοθράκη") in the Northern Aegean Sea (Figure 1) finds itself in a situation of transition between being dominated by traditional agriculture (mainly herding of small ruminants) and tourism. The island hosts a unique ecological diversity, mainly because of its rich water resources and its heterogeneous landscape. Along the island's stream courses and around the natural crystal-clear waterfalls and pools abound old oriental plane forests, while pristine old growth oak populations still persist at the hills of the central Saos-massif (1611m) [1,2].

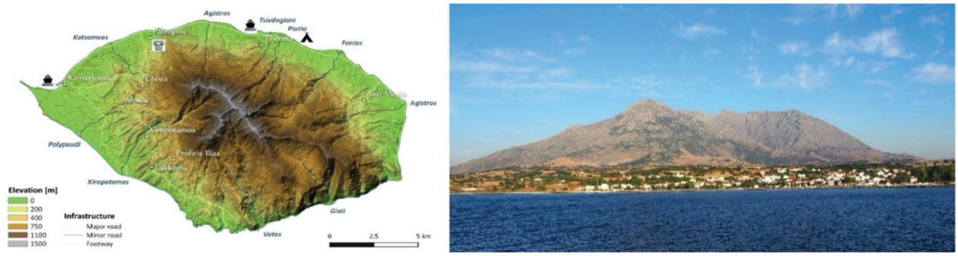

Figure 1. (**a**) Physical map of the island Samothraki [3]; (**b**) view from the NW.

Samothraki has been inhabited since prehistoric times and the fabric of the present society is still shaped by its history (www.sites.google.com/view/samothraki/history, accessed on December 2019). The most celebrated part of this history is represented by the remains of the "Sanctuary of the Great Gods", a site of important Hellenic and Pre-Hellenic religious ceremonies. There, the Samothrakian or "Kavirian" Mysteries [4] took place, enigmatic rites open to both slaves and free people, even children. Herodotus and Pythagoras, for example, have taken part in them. In the fourth century BC, Philip II from Macedonia occupied the island; he is said to have met his wife on the Saos mountain, to later become father of Alexander the Great. During the Roman imperial period, Samothraki became an international religious center where pilgrims flocked in from all over the Roman world. The Bible records that Apostle Paul, in the first century CE, sailed on a missionary journey to Samothraki (www.sites.google.com/view/samothraki/history, accessed on December 2019). After a phase of Byzantine and then Genoan rule, Samothraki was conquered by the Ottoman Empire. An insurrection during the Greek War of Independence (1821–1831) led to a massacre of local population, in response to their refusal to pay taxes. Following the Balkan Wars, the island came under Greek rule in 1913. In the 1950s and 1960s, local poverty drove out a large number of men and families seeking work in the German automobile industry (In the Stuttgart area, there still exists a large and active cultural association of Samothrakians, many of whom are also entitled to vote on the island in local elections [5].) (Figure 2). They brought home money as well as knowledge of the language and the German industrial culture. During the time of military dictatorship in Greece (1967–1974), Samothraki was a place of exile for political dissidents. Thus, the history of this island has been marked by singular cultural and political features, and repeated population shifts.

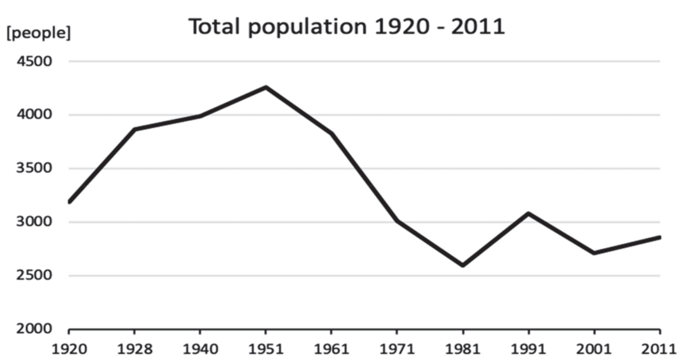

Figure 2. Number of inhabitants on Samothraki 1920–2011 (source: ELSTAT).

In the decades after World War I, the local population had been growing to a peak of 4200 people. It then strongly declined and increased again with beginning tourism in the early 1980s (Figure 2).

Socioeconomically, the resident population gradually shifted from the primary sector towards the tertiary sector (Figure 3). Currently, there is a large group of poorly educated (sometimes illiterate), predominantly elderly farmers and a few fishermen leading a traditional lifestyle with little contact to outsiders. The secondary sector represents only a small and lately decreasing fraction of the island's economic activity. There is one olive press, a dairy, a small winery, a beer brewery, and several bakeries, as well as some construction and mining activity. There also used to be a municipal wheat mill. In contrast, the tertiary sector has grown substantially during the last decades and now employs 60% of the island's workforce. This better educated and more informed part of the population is working mostly in the service sector, tourism, and administration.

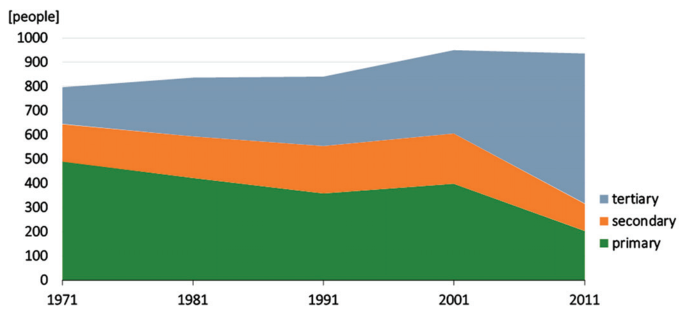

Figure 3. Economically active population by sectors 1971–2011 (source: ELSTAT).

To a visitor in the early 2000s, Samothraki appeared as a place of overwhelming archaic, largely untouched, natural and cultural beauty, but also endangered. Scientists had already been engaged in recording the island's aquatic quality and aquatic/terrestrial biodiversity, and found it highly impressive but under threat, although the majority of stream basins illustrate reference ecological conditions [1,6]. How could further research contribute to secure the unique natural qualities of this island? This would presuppose to create a vision and an identity for the community on this island that would frame the local conditions not as "backwardness", poverty, and lack of modernity to be overcome, but as a worthy heritage and asset to be developed in a targeted way. It could only be successful if the local population would identify and be able to anticipate clear benefits from such a vision, benefits that would outweigh negative trade-offs. The concept that seemed best attuned to pursuing a pathway of both nature conservation and socio-economic benefits through sustainable social use of ecosystems appeared to be UNESCO's Biosphere Reserve concept [7]. (Biosphere Reserves are areas that encompass valuable ecosystems and social communities that wish to combine the conservation of ecosystems with their sustainable use. They are nominated by national governments and remain under sovereign jurisdiction of the states where they are located, but become internationally recognized by UNESCO. Biosphere reserves form a World Network under the protection of UNESCO. Within this network, exchange of information, experience and personnel are facilitated. At present, there are about 700 biosphere reserves in over 120 countries (See: http://www.unesco.org/new/en/natural-sciences/environment/ecological-sciences/biosphere-reserves/)). This idea built upon the fact that over three-quarters of the island's surface had been already designated as a Natura 2000 conservation area. Our team started a first research effort in this direction in 2007 to find answers to the following questions: Does the island of Samothraki provide adequate natural, social, and economic opportunities for a pathway of nature conservation and sustainable development as envisioned in the UNESCO Biosphere Reserve concept? Is the vision of becoming a Biosphere Reserve attractive to local (and regional) stakeholders? Does it offer containment and an identity that is welcome and promising? These questions were dealt with a literature and data review, and a representative survey (N=1511) of residents and tourists [8] leading to positive conclusions: The island's landscape and biodiversity proved to be quite exceptional and highly worthy of protection; second, the local population, and even more so the tourists, gave support to a conservationist rather than a modern industrial developmental course. The outcome was a unanimous decision of the local municipal council in favour of an application to UNESCO. Scientists from the Institute of Social Ecology from Vienna helped to prepare the application form, and it was formally submitted as signed by the Mayor and other responsible Greek authorities in 2013 [9]. Unfortunately, though, it turned out that the Greek state had not yet fulfilled the legal and managerial preconditions associated with Natura 2000; thus, the application was deferred by UNESCO on the grounds of insufficient legal protection of the core conservation areas. This backlash made clear that it would take a longer breath, a more systemic perspective in research, as well as stakeholder mobilization and the building of policy alliances [8]. In other terms, we were heading for a "real world lab" to achieve a sustainable pathway for Samothraki [10,11].

2. Heuristics and Methods

In order to be able to influence development dynamics, it seems appropriate to look upon islands as complex socio-ecological systems. In island studies, this perspective is not so common [12–14]: Rather, there is a focus on particular problems such as food security [15], migration [16], or overgrazing [17]. Guiding local sustainable development means to understand the conditions under which socio-economic activities can support the quality of life and the income of the islanders while sustaining (or even improving) the quality and resilience of the natural environment. Such a comprehensive research question can best be addressed by focusing on the exchange relations between the respective socio-economic sectors and the local environment with the help of a heuristic sociometabolic model [18,19] as outlined in Figure 4, specified for the case at hand.

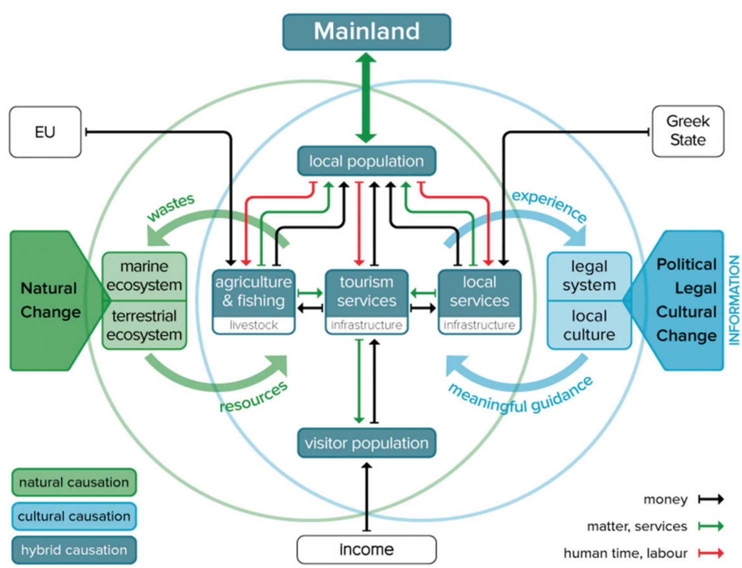

Figure 4. Sociometabolic system model for the relevant stocks and flows within and between the local society and its natural environment. [20] (p.14).

When critical stocks cannot be reproduced, the system might 'collapse' [21,22]. Briefly said, a balanced sustainable development implies not to increase socio-economic stocks excessively, using natural resources carefully and efficiently, creating effective synergies between the sectors of the economy, and using commons with fairness and responsibility [18,23]. Across the years of research, this model served as a mind map for what matters for the sustainability of the island, and guided the selection of variables to be measured, the interrelations to be analyzed, and the attention for critical thresholds. In the core area of the model figures the human population (both residents and visitors) and their involvement in the three socioeconomic sectors: Agriculture and fishing, tourism services, and local public services (administration, schools, medical, care, and technical services). The sectors control certain biophysical infrastructures (animal livestock, built infrastructure, technical infrastructures). They draw on certain natural resources and generate wastes and emissions. They require human labor power and provide economic benefits. All these processes are subject to cultural and legal guidance, which they in turn influence across time.

Beyond this, such an island system is of course strongly linked to the outside world: Economically, to the Greek state, the European Union (Common Agricultural Policy, EU-CAP in brief, subsidies), and to the income the tourists earn somewhere else and spend on the island. Politically, legally, and culturally, it depends on the overall situation in Greece and beyond, and its natural conditions depend on broader environmental change (such as global warming). All these interrelations matter for finding a sustainable course. Across the years, the research team sought to operationalize quantitatively all stocks and flows shown in Figure 4. Beyond this, it documented their environmental impacts, and supported local stakeholders in finding solutions (responses). For a better understanding of this multi-method approach, Table 1 provides an overview structured according to the more conventional DPSIR—drivers, pressures, states, impacts, responses—framework [24].

The research process across more than a decade built upon yearly summer schools, each organized in collaboration between universities, research institutions, local and national authorities, NGOs, and UNESCO branches, with about 150 students altogether, from more than 20 countries and 40 universities [7,20,25–27]. The summer schools were designed in such a way that in each of them—depending on the scientific background and the research interests of the respective institutions and students participating—addressed certain research tasks contributing to the overall research question and helped to achieve maximum synergistic effects between learning, research, and addressing policy goals for local development. At the same time, they showed our continuous presence on the island to numerous locals, members of the municipality, and the regional administration. Part of our research also involved local so-called citizen scientists in ongoing explorations, thus feeding back our findings to stakeholders and the island's public. A small producer visualized this research process across several years in the film "Wings of Samothraki" in English and Greek. (www.sustainable-samothraki.net/activity/wings-of-samothraki/, accessed on December 2019).

This article attempts a synoptic view of the findings accumulated so far. The results presented are structured according to the two core sectors of the island's economy, agriculture and tourism, their development dynamics, and their environmental impacts. In the discussion, we place these findings in a broader perspective on the island's chances of a comprehensive sustainable course, and the role of scientific research in its support.

Table 1. Overview of research questions, indicators and methods used, according to the drivers, pressures, states, impacts, responses (DPSIR) framework [24].

	Agricultural Sector		Tourism Sector	
	Indicator	**Methods Used**	**Indicator**	**Methods Used**
Drivers	system of EU-CAP subsidies, Greek variant	statistical analysis of the "transparency database" for EU-CAP subsidies for the years 2014–2016 [28], supplemented by expert interviews [29,30]	tourists: numbers, their expectations and spending tourism entrepreneur expectations	analysis of port statistics 2002–2017 survey of tourists (random sample of ferry passengers, N=1425) interviews with tourism entrepreneurs [31]
Pressures	excessive number of grazing animals	analysis of data from agricultural statistics and utilization of a bottom-up metabolic model for estimating the feed demand of sheep and goats [32,33]	expansion of tourist infra-structures; use of non-reusable nor degradable materials	construction history from municipal sources; dynamic bottom-up modelling of materials use, maintenance requirements and wastes [34]
States	vegetation cover	estimation of local NPP for different land cover classes [32]; time series analysis of remote sensing data (satellite images) of the land cover of the island (NDVI) 1984–1916 [3] analysis of spatial and age structure of mountain oak forests [2]	freshwater resources, quantity, and quality	drinking water quality of spring water; ecological quality of streams, wetlands, and lagoons; hydrometeorological analysis of the Fonias river basin; estimation of freshwater resources availability and water abstraction [6,35,36]
Impacts	loss of vegetation cover, erosion	remote sensing [3] erosion [37] lack of forest regeneration [2]	increase of water demand and wastewater production	documenting inadequate water supply and wastewater management [36]
Responses	introduction of sown bio-diverse pas-tures (SBP) improving farmers' business practices support for farmers cooperatives	SBP field experiments with farmers (20 fields, for 3–4 years) [27] development of a "Happy Goats App" decision support tool for farmers [38] follow-up interviews with farmers to explore their income & costs [33] olive oil and livestock cooperatives actually formed in 2018/19	better synergies with local agriculture sector support for legal eco-camping	interviews with restaurant owners to explore / support use of local produce [27] survey of campers 2017; development of an eco-camp concept for the municipality [27]

3. Results

The narrative of our results follows the interlinkages as outlined in the sociometabolic model [18,19] in Figure 4. We describe the stocks of the terrestrial ecosystem and their dynamics. We do not quantify these stocks, as by NPP for example, like in [32], but describe them qualitatively as landcover and forest. We build our analysis on data published by members of our team on the quantification of stocks of the core socioeconomic sectors (as livestock [33] and built infrastructures [34]), the natural resources required by these stocks for their reproduction/maintenance, and the impacts of this resource use on natural stocks. For the built infrastructure, we also discuss the (pending) issue of future waste flows, i.e., backflows from society to the ecosystems. We relate these processes to the size (stocks) of the resident and visitor populations, and describe key socioeconomic flows required for their reproduction (such as income), as well as the origin of these flows from EU-CAP subsidies, visitor expenditures, and the Greek state, following Figure 4 (black arrows). With regard to the "cultural flows" (as pictured in blue in Figure 4), the reader is referred to the discussion section that draws on our findings from qualitative social research as described in Table 1 among the drivers and responses according to the DPSIR logic.

3.1. The Terrestrial Ecosystem and the Agricultural Sector (Livestock Herding)

Grazing is the dominant land use on the island. More than half of the total area is unfenced rangeland [29], used for spatially extensive but quantitatively intensive livestock breeding. As a result, Mediterranean macchia, different types of phrygana, bracken, and other vegetation formations (largely caused by grazing) dominate large areas of the island [1] "Natural vegetation on Samothraki occurs only in areas inaccessible to sheep and goats, e.g., sheer rock and steep ravines. In general, the natural plant communities are at various levels of degradation due to heavy grazing" [1] (pp. 46–47).

During the second half of the past century, many Greek islands passed through substantial land use transitions, followed by land cover changes that have often led to various degradation processes (e.g.,) [17,39]. In the Mediterranean Basin, intense grazing is a widespread phenomenon that can trigger severe soil erosion. Today it is clear that Samothraki's grazing system has also decoupled from its natural basis: A much too high number of undernourished and underutilized animals exploit and degrade pastures, thus magnifying natural soil erosion, and endangering the entire social-ecological equilibrium of the island [32]. This was lucidly demonstrated by a major weather event in September 2017 that triggered several landslides, demolished buildings, and covered large parts of the main town with rocks and debris. (https://watchers.news/2017/09/28/samothraki-flood-greece/, accessed on December 2019).

Samothraki is characterized by a diverse land cover (LC), typical for semi-natural Mediterranean landscapes (Figures 5 and 6). Only 6.5% of the total area is used as cropland (and the crops harvested there are mainly used for animal feed). Semi-open grassland (27.8%), with only few trees persisting, is the most common LC-type. It is evenly distributed but mainly present as a transition zone from thick shrubberies to areas covered by open grasses, forming a vegetal belt on medium altitudes. Shrubland (20.1%), primarily dense matorral and garrigue, occurs all over the island. In the southern part, this includes olive plantations and pseudo-macchia. Woodland and macchia (13.6%) dominate on the northern and eastern slopes. Riparian woodland (Platanus orientalis) stretches along perennial streams and intermittent creeks and extends up to the stream mouths, a unique characteristic considering Greek islands. Open landscapes (scattered grass, 13.3%) appear almost exclusively in mountainous areas. Finally, 6% of Samothraki show no land cover (bare soil).

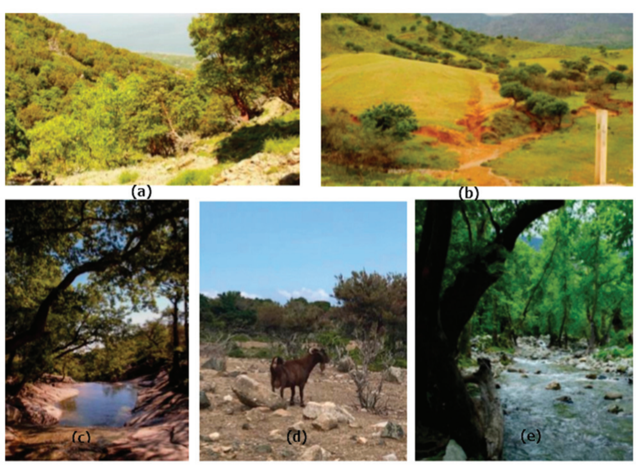

Figure 5. Typical landcover types on the island: (**a**) Dense Macchie (upper left), (**b**) semi-open grassland with severe erosion patterns (upper right), (**c**) up-stream woodlands dominated by oak besides a typical fresh water pool (lower left), (**d**) a browsing goat on a heavy overexploited lowland pasture with weed invasion (bracken fields) in the background (lower middle), (**e**) and a down-stream riparian *Platanus orientalis* woodland (lower right).

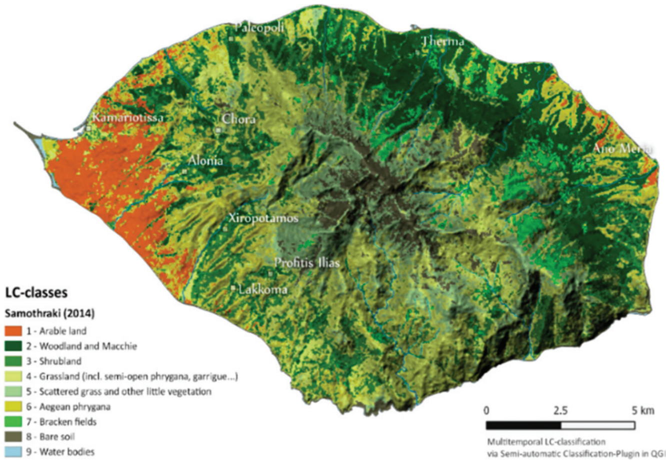

Figure 6. Discrete land cover classes on Samothraki 2014 (verified by ground-truth assessments 2016) [3].

Two LC-types deserve special consideration. Both can be linked to specific former land use patterns: Bush encroachment and weed invasion [17,40]. Bracken fields (Pteridium aquilium) appear only in the island's more humid northeastern half. Most of it occurs in remote areas, around woodland borders, and on high altitudes above the tree line (Figure 7b). Lowland pastures are also infested by closed cover patches of this undesired weed (bracken is undesired because livestock does not feed on it, which is the reason that it becomes so dominant). Sarcopoterium spinosum, which characterizes the typical Aegean phrygana, occurs in low to medium altitudes but not on mountainous rocky terrains. It appears mainly around the lower smooth shaped foothills of the pasture farming-based villages.

(a) (b)

Figure 7. (**a**) Aegean phrygana and (**b**) bracken fields among dispersed mountain oak [3].

In higher altitudes on the northern and eastern slopes of mount Saos, there are pristine woodlands (Quercus petraea) that drew our special attention for two reasons: First, because they allow us to reconstruct a longer term history of land-use practices, and second, because their survival is essential for the stabilization of soil and the containment of erosion [37]. A detailed investigation of two remaining forest areas [2] came to the conclusion that there has been a long history of intensive silvo-pastoral land use, particularly in the 18th and early 19th century. This was apparently interrupted by the massacre by Ottoman troops in 1821 that severely decimated the local population and livestock and thus allowed for several decades of forest regrowth. In the second half of the 19th century, though, massive forest clearing occurred for the production of charcoal (an export product of the island at the time), and silvo-pastoral practices were resumed. According to this analysis, 86% of the forests are currently in a critical state, classified by several criteria as of high regeneration priority; the youngest tree found was of the cambial age of 47 years (with an average cambial age of 151 years across the two areas investigated). The main reason behind the lack of forest regrowth identified by pasture tracks and feces count was animal grazing. This comes as no surprise if one looks at the development of animal numbers on the island (Figure 8).

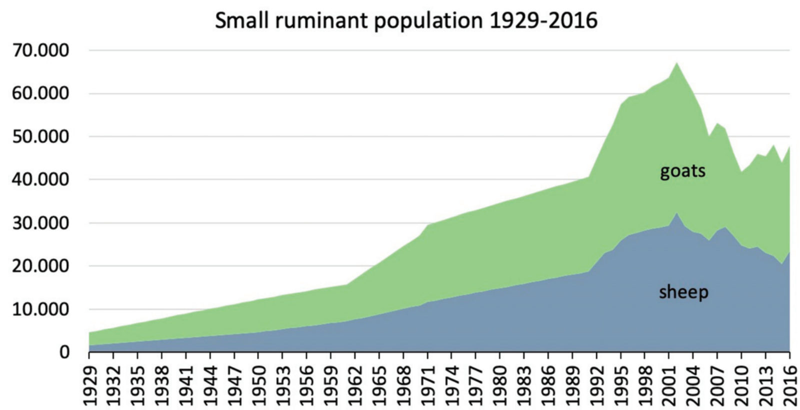

Figure 8. Number of small ruminants on Samothraki (source: ELSTAT, own interpolations).

According to the European compliance standards of 1.4 head/ha, the island could sustain about 23,500 grazing animals [32], but this number had already been surpassed in the late 1960s, and in 2002, the small ruminants reached a peak with almost 70,000 animals. Interestingly, we then observe a sudden decline, particularly of the goat population, to about 45,000 animals, a number that is nevertheless still almost twice as much as the cross-compliance recommendation by the EU. How did this decline come about? Before we report on our search for an explanation, Figure 9 documents how this process reflects itself in land cover change, investigated on the basis of satellite imagery.

Figure 9 shows that a major part of Samothraki's land cover had become up to 40% less "green" by the year 2002, as compared to reference year 1984 (the year of the first available satellite images), and then gradually recovered and stabilized at a level still markedly below the 1984 standard. This timeline corresponds very well to the development of animal numbers shown in Figure 8. In order to adequately interpret the drivers behind the positive LC-development of the recent years, one must scrutinize altered land management practices, or rather a shifted "style" of daily local husbandry. The latter is decisive for the pasture capacity of an area [41,42].

Samothraki's grazing regime was strongly influenced by basic land use transitions at greater scales. In Greece, the last "traditional" subsistence-based forms of peasantry were finally dissolved by around 1945. This was followed by an era that secured fundamental (land use) rights [43] to single farmers—a system still in place in the background of current EU-CAP regulations. Since then, Greece encountered trajectories towards industrial agriculture, but at a much slower pace compared with the rest of Europe, and even less so in marginal mountainous and insular areas [44]. Initially, the local mode of livestock breeding expanded in animal numbers [45], accompanied by a steadily decreasing esteem of the local rangeland state [17]. Samothraki seems to have remained in an "in-between grazing management regime". Key modernization projects remained unfulfilled. This concerns industrial processing and storing, land reclamation, increased access to markets, and the establishment of cooperatives [43]. On the one hand, hardly any traditional management (such as regularly burning weeds) is practiced, and on the other hand, Samothraki did not undergo profound modernization and industrialization processes. Human labor was substituted by energy inputs via improved physical infrastructures (e.g., roads to higher altitudes), fossil energy-based mobility (e.g., pick-ups and tractors), or through the import of external fodder, but hardly by any modern technologies of animal utilization and marketing, let alone efforts at organic farming. Reviewing Samothraki's land use system in a broader historical context reveals that a dwindling income and few future prospects for the older farmers have resulted in the establishment of an effort-minimizing style of farming that harms the pastureland and does neither benefit the animals nor the farmers (Figure 10).

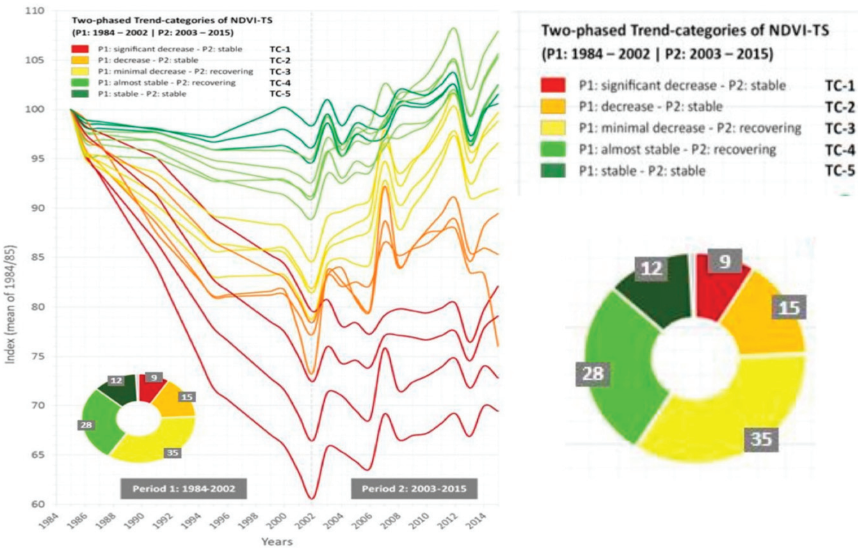

Figure 9. Courses of fractional vegetation cover or "green-ness" (NDVI) of major temporal clusters of land cover on Samothraki since 1984; five trend categories are distinguished (upper right graph). Lower right graph shows their spatial share (cropland excluded) [3].

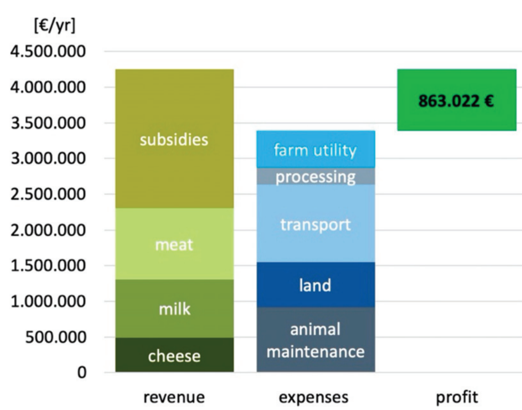

Figure 10. Sources of Samothraki's 171 economically active herders' income and expenditure in 2016. The above shown profit corresponds to 5000€ per herder and year [33].

However, the question remains, why did livestock farmers on Samothraki respond to this situation by steadily increasing the size of their herds beyond feed availability? According to Figure 8, this process started in the early 1960s, accelerated in the 1980s, and virtually exploded in the 1990s. The most suitable explanation we can offer is agricultural subsidies, first from the Greek state and then from the European Union. Those subsidies aimed at compensating farmers for decreasing market prices by providing an extra income based on their production volumes, thus creating a strong incentive to raise animal numbers. As market prices for animal products declined, the share of subsidies in small farmers' income increased, and thus their dependence on them (see Figure 10). The EU-CAP subsidy policy changed in 2003, but there was a significant delay until those changes were implemented by Greek authorities, and even more delay until farmers could really comprehend on what grounds they do receive the subsidies estimate [29,46,47].

Thus, in effect, livestock farmers still live on a very low average income of 5000€ per year, half of it from subsidies; we do not expect the income of the other farmers to be any higher. The total number of farmers has been strongly declining in the past decade (Figure 3)—but death or retirement of farmers does not necessarily diminish their "grazing rights" (as defined by the regional agricultural administration), nor the access to subsidies.

Then why did animal (in particular, goat) numbers drop so suddenly after 2002, by well over a third within a few years? The most suitable answer we came up with on the basis of dozens of farmers' interviews, observation accounts, and modelling efforts, is the following: A reduced amount of available food on pastures (Figure 9) and insufficient additional feed from farmers, in the absence of substantially increased slaughtering rates, caused animals to die prematurely, and to have their reproduction rates severely diminished. What we witness here seems to be a real, natural kickback, resulting in a "tipping point" of animal numbers.

Still, current livestock numbers exceed the grazing capacity of the land [32], and the abandonment of labor-intensive management practices (e.g. [17,48]) determines to a large extent the composition of land cover. Aegean phrygana and bracken could spread on pastureland. Thus, grazing pressure intensifies on rangelands not yet affected by such bush or weed encroachment (Figure 11) This, together with the lack of recovery of heavily degraded areas, suggests that the island is severely *overgrazed*, not just heavily grazed. In this context, "overgrazed" refers to grazing that degrades the standing biomass in a way that weakens the overall productivity basis of rangelands in the long run [3]. Although vegetation increases again (Figure 9), this does not necessarily imply a recovery of vegetation suitable as animal feed and an increase in pasture productivity.

(a) (b)

Figure 11. Pictures of (**a**) overgrazed and (**b**) eroding areas.

At present, the main limiting factors for achieving a sufficient grazing capacity are accelerating bush encroachment and the loss of topsoil. Current land use patterns indicate large missing potentials and Samothraki's livestock production system finds itself in a deadlock [36]. Grazing pressure is still too high to allow for regaining sufficient vegetation productivity. One of the key measures in our project was experimental: To offer farmers a seed mixture developed in Portugal for "sown biodiverse pastures" (SBP), with a high share of legumes, for free. We established a pilot project in collaboration with the University of Lisbon, its spin-off Terraprima (www.terraprima.pt/en, accessed on December 2019), and local farmers, in order to assess the effectiveness of Sown Biodiverse Pastures (SBP) on Samothraki. The SBP system is based on sowing up to 20 species/varieties of legumes and grasses that are self-maintained for at least 10 years, with all used species native to the island. The legumes, being 'natural factories' of nitrogen, minimize the need for synthetic fertilisers, increase the amount of carbon bound in biomass and are more resistant to grazing. After some skepticism, this was well received, and the experimental fields properly tended yielded between 20% and 50% higher productivity than neighboring fields [27]. The soil, therefore, is obviously not the key limiting factor for productivity, but rather poor practices and overgrazing.

Besides overgrazing, another factor limiting soil cover is naturally occurring erosion. This derives from tectonically deformed bedrock, steep slopes, and restricted groundwater aquifers creating flash floods. Recent research results [37] showed that soil loss under the present situation of animal grazing was 15.8 t/ha, with most vulnerable being an area extending from the center of the island to the adjacent steep headwater areas of its streams. The simulation of a non-grazing scenario resulted in a soil loss diminishing by 25%, indicating that overgrazing alone cannot explain the high erosion rates of the island. Possibly, the massive deforestation that took place during the last centuries degraded soil cover already before overgrazing became the overwhelming cause for soil erosion. Thus, soil loss prevention actions should not only target grazing management, but should be the subject of an integrated plan for natural vegetation regeneration, including reforestation to the greatest possible extent, as well as constructive practices, e.g., building of terraces, and the extension of Sown Biodiverse Permanent Pastures [37].

The devastating landslides in 2017 (https://watchers.news/2017/09/28/samothraki-flood-greece/, accessed on December 2019) emphasized the importance of an appropriate ground cover recovery. Samothraki's socio-ecological future as a tourist destination and even more so as a UNESCO Biosphere Reserve will depend on improving this situation.

3.2. Tourism Dynamics and its Impacts on Infrastructure and Income

Samothraki's infrastructural modernization essentially commenced in the 1960s with the establishment of an electricity network fed by local diesel generators (active until 2000, when an under-water cable connected the island to the central Greek grid), and an extension of the main port.

In the 1980s, after the end of the military dictatorship in Greece (1974) and its subsequent accession to the EEC, the road network was extended along the north coast, and a second smaller port was built (see Figure 1a port at Therma). This additional port was nourished by the hope for increased tourism, and attracting more prosperous tourists with their yachts. This hope was not fulfilled: The port construction instead proved to continuously attract tons of sand and gravel to fill the port basin [49], not allowing access for larger ships (Figure 12a).

(a) (b)

Figure 12. (**a**) Basin of the port in Therma and (**b**) a traditional stone house on Samothraki.

In the 1980s, traditional stone buildings still dominated the architecture of houses (Figure 12b). By the early 1960s, a new building technology gradually set in, facilitated by the savings brought home by migrant workers returning from Germany, and by loans taken under the prospect of future profits from tourism: Brick and concrete buildings became the choice of the time. While traditional stone buildings in remote agricultural areas were mostly abandoned, construction of brick and concrete buildings, ports, and roads resulted in a two-fold increase of in-use stocks (Figure 13). Fortunately, authorities were wise enough to protect the scenic central town of the island, Chora, and largely preserve its traditional style of architecture up to now (www.sites.google.com/view/samothraki/history, accessed on December 2019). In the decades following, tourism and income development did not take off as steeply as had been expected and the Greek debt crisis after 2008 brought local construction activities more or less to a standstill [34].

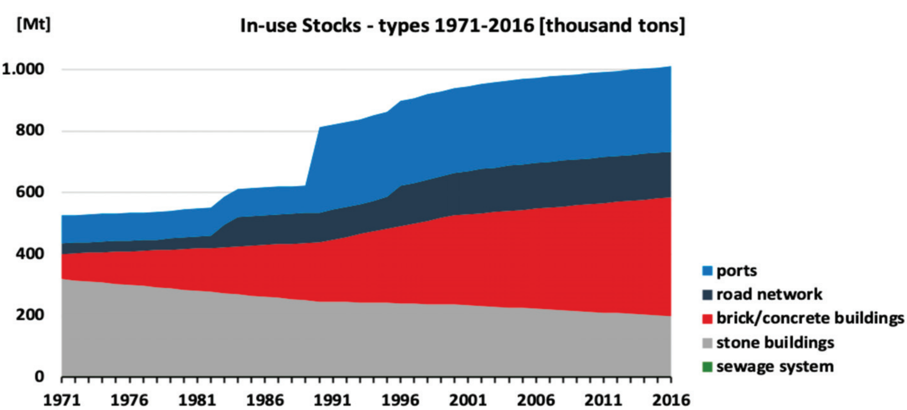

Figure 13. In-use stocks of construction materials on Samothraki 1971–2016 [34].

While stocks-in-use had doubled, essential infrastructural functions are still not taken care of: Settlements are served by septic tanks, and only two (Chora and Lakoma with 653 and 317 inhabitants, respectively) partly afford sewage systems that discharge untreated water to adjacent streams, thus threatening their ecological integrity. According to its Operational Program (2014–2019), the Municipality of Samothraki plans the construction of a sewage system and a wastewater treatment plant for Kamariotissa as well as the replacement of the obsolete sewage system of Chora [50]. Freshwater supply to the settlements and the tourism establishments had not seen any major investments [36], despite the fact that demand in the summer months had soared. Fortunately, Samothraki is an island with significant freshwater resources (particularly in the north) and water quality is excellent [6]. However, as a result of unsustainable water management, some settlements and crops suffer from water scarcity during the summer period, and a number of streams face artificial desiccation with adverse ecological consequences [6]. Also, the island remains vulnerable since flood forecasting and respective abatement measures are missing. Currently, water management is carried out in old-fashioned, ad hoc, and, frequently, individualistic ways that are often inadequate to satisfy the needs, especially during extreme events, like floods and prolonged droughts [36]. Thus, while Samothraki does not suffer from water scarcity, like so many islands do, it is still confronted with several management challenges.

Over the last four decades, the demand for additional floor space for the growing tertiary sector, tourist establishments, supermarkets, storehouses, and other small businesses has led to a shift of the economic center of the island, Chora, to the port city of Kamariotissa. Since the 1960s, Kamariotissa underwent a threefold population increase (from 277 in 1961 to 940 inhabitants in 2001), while most of the other settlements on the island declined; e.g., the population of Chora, the island's capital, dropped from 1555 to 698 during the same period [34].

The expansion of the built environment contributed to the welfare of the island community but left its mark on the landscape. Since local extraction of non-metallic minerals had been banned in 1991, all construction materials must be imported. The prices for these materials have been rising and the growing material stocks require increased maintenance. In the past, construction and demolition wastes were practically non-existent or re-used, but now, their large amounts lack legal deposition opportunities. Given new EU regulations, the shift to new building materials will constitute a major challenge in the future. This also applies to the roads. Due to the island's steep terrain and erosion processes, asphalt roads wear down very quickly, while bridges and exposed stretches are regularly washed away by severe weather events and often require fortification by concrete walls [34]. The need to ship the necessary materials to the island (and wastes off the island) generates additional costs, not viable for the local municipality. A sustainable solution would require reducing the import of environmentally problematic construction materials, and utilizing more locally abundant resources, such as wool or straw for insulation purposes, and possibly even the carved stone material from abandoned houses that is plentifully available.

The island's infrastructure serves the permanent residents, whose number, after peaking around 4200 in 1951, has stabilized since the 1980s at about 2800 (Figure 2). It also serves an increasing number of temporary residents, such as owners of second homes, seasonal workers employed in the tourist sector, and tourists. We estimated the size and composition of these latter groups from surveys among the departing travelers on ferries, which are practically the only way to reach the island (Figure 14). With the help of monthly port statistics, and information on the length of stay and travel frequencies from our surveys, we estimated the size and composition of all groups. This information had so far been missing and will be particularly valuable for the future planning and managing of infrastructures and socio-metabolic requirements (e.g., food, water supply, and waste disposal). Thus, on top of the permanent residents, during the summer season, we estimate an additional 3000 secondary homeowners, and their numbers are rising (Table 2). Moreover, there are family visitors in the order of magnitude of 1800 and about 2000 seasonal workers. On top of this, the island receives about 22,000 tourists per season (Table 2). This means that during the summer months, with a strong peak from mid-July to mid-August, the island has to sustain a daily population of around 7000 people (2800 inhabitants plus 4300 visitors).

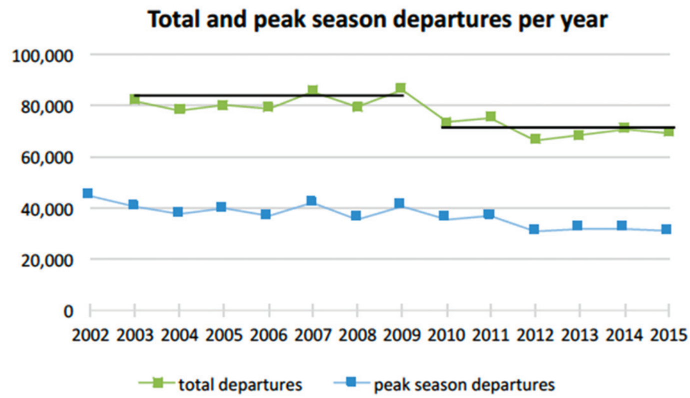

Figure 14. Ferry passenger departures from 2002 to 2015 per year and during the peak season (source: Port authorities of Samothraki and Alexandroupolis). The black lines indicate the average number of passengers for this period [31].

Table 2. Visitors to the island during summer season, their length of stay, and consumption expenditures.

	Persons	Length of Stay	Daily Consumption Estimates		Summer Spending Estimate	
		Av. Days	Low:€/Day	High:€/Day	Low:€/Season	High:€/Season
second homeowners	3000	20	33.7	41.2	2,022,000	2,472,000
seasonal workers	2000	23	16.5	22.2	759,000	1,021,200
family visitors	1800	19	29.8	37.8	1,019,160	1,292,760
tourists (hotel/rented room)	13,000	5	72.4	86.9	4,706,000	5,648,500
tourists (camping)	9000	9	38.1	45.5	3,086,100	3,685,500
all tourists	22,000	7			7,792,100	9,334,000
all visitors	28,800				11,592,260	14,119,960

Source: Own calculations on the basis of visitor surveys 2008 and 2015, and port statistics.

The overnight accommodations offered in hotels and private rooms exceed the demand by more than 40% [31]. The preferred option, chosen by over a third of the tourists, is camping, either at the municipal coastal forest camping grounds, or freely next to the rivers up the mountain. Tourist accommodation is mainly offered in small family-owned businesses. In this, Samothraki clearly differs from typical Mediterranean tourist destinations with big hotel complexes and energy-intensive accommodation infrastructure. It rather falls in the category of "vacation islands". On vacation islands, pressures mainly stem from the impacts of permanent infrastructure for visitors and the environmental resources consumed [51]. There are virtually no organized mass tourism operators, apart from the occasional bus from the Greek mainland. One of the reasons behind this is the unpredictability of the ferry connection to the mainland, where one owner has a monopoly, changing the schedule by the week, not adjusting it to plane or bus timetables at the mainland port city.

When evaluating the sustainability of tourism on Samothraki, camping plays a big role. Campers spend only half as much money per week as tourists staying in hotels and private rooms. Nevertheless, their overall contribution to local income from tourism is about 40%, as campers generally stay for a longer period [Table 2]. Moreover, campers walk and use public transportation more often. While less than 15% of people staying in hotels or private accommodations stated to have walked, biked, or used public transport, 31% of campers on the municipal camping grounds and 53% of all free campers did so. In addition, campers are more likely to return to the island. During the peak season of 2015, about 70% of all campers declared their certainty to come back to Samothraki, while among tourists staying in hotels or private accommodation, just 49% felt sure to come back. Therefore, people camping on Samothraki are more faithful and have lower infrastructural demands, while still contributing substantially to the island's income (data analysis from visitor survey 2015, N=1471, and camper survey 2017, N=870).

Based on our estimates, tourism generates about 13 million€ annually, which account for almost half of the island's income (Table 3). While in terms of economic activity in 2001, the primary sector—consisting of agriculture, livestock herding, and fishery—still dominated, in the following decade a massive social change occurred: Many farmers decided to retire (Figure 3), and the active population in the tertiary sector soared. This happened despite the fact that tourism, during this decade, has been stagnating (Figure 13). Note, however, that it is a common practice for many locals to maintain a diversified household economy, based to some degree on subsistence agriculture and some animals while seasonally utilizing tourism opportunities [52].

Table 3. Annual gross inflows of money to the island from outside (see black arrows in Figure 4). Estimate for the period 2001–2011.

<table>
<tr><th></th><th>In Thousand€</th><th>% of Overall Income</th><th>% of Active Population 2001(1)</th></tr>
<tr><td>inflow from tourism</td><td>13,000 (2)</td><td>49</td><td>21</td></tr>
<tr><td>inflow from CAP subsidies</td><td>3000 (3)</td><td>11</td><td rowspan="2">42</td></tr>
<tr><td>inflow from agricultural sales</td><td>2300 (4)</td><td>9</td></tr>
<tr><td>income from fishing</td><td>4000 (5)</td><td>15</td><td>9</td></tr>
<tr><td>salaries from public sources</td><td>4480 (6)</td><td>17</td><td>28</td></tr>
<tr><td>total</td><td>26,780</td><td>100</td><td>100</td></tr>
</table>

Sources: (1) ELSTAT; no detailed occupational statistics available since 2001; (2) average of low and high estimate in Table 1, rounded; (3) EU transparency database for 2015 www.transpay.opekepe.gr; (4) Source: interviews with herders on their sales on the island and exports. Income from olive oil or honey sales not included, nor the sale of cheese through the dairy; (5) source: Evros Prefecture for the whole region, average of the period 2002-2010. Samothraki's share is estimated at 1/2 of the total; (6) Salaries for public administration and defense, education, health and other community services (224 employees in 2011, not necessarily full-time). Assumed average annual salary 20 000€. Pension payments not included.

In effect, with reference to Figure 4, the tourism sector provides the island with an income needed to sustain the resident population, and it creates a challenge to local waste management; but, if infrastructure were wisely handled, much less of a challenge to the local ecosystem than the agricultural sector and livestock herding.

4. Discussion: On the Chances for a Sustainable Future of the Island, and the Role of Science to Support It

This transdisciplinary sociometabolic research was supposed to serve two distinct goals: One goal was to explore and reconstruct the systemic conditions and dynamics of how this local society interacts with the island's natural environment (Figure 4), and where the risks and chances for sustainable outcomes lie. This was the scientific challenge to respond to with multiple methods. The other goal was to connect to existing motivations for finding a sustainable pathway, to strengthen them, and help local people to organize. This did require regular and effective local communication of scientific insights, but also a deeper understanding of local mindsets and habits. This was the transdisciplinary nature and the practical-political part of the task.

Our scientific findings, as reported in the previous section, demonstrate serious threats to a sustainable future of the island: Most prominently, a progressive loss of vegetation cover and dramatically increased erosion and exposure to extreme events, with impacts beyond the economic capacity of the local system. The ongoing ways of expanding built infrastructure are exposed to these risks and bear some ecological and economic risks of their own in terms of raw material acquisition and disposal.

So, what could a successful transition to sustainability look like? The island needs to escape from the deadlock of the dysfunctional traditional farming system that can hardly secure an income for the farmers but destroys the vegetation cover and the landscape. Yet, it is exactly the landscape that provides the core recreational and economic attractions for tourism. Even more of a challenge derives from a recent plan of an international industrial conglomerate, supported by the Greek national administration to establish an industrial wind park (39 windmills) on the top of Saos mountain, in the centre of the area destined for Natura 2000, to produce electricity for export. Such a wind park would be visible from far and completely disrupt the ecotouristically most attractive virgin mountain area, dry out headwater springs and streams and require, for the transport of infrastructure and hundreds of tons of concrete, a new road in very steep terrain up from the seaside to the mountain tops – thus creating a new source of major erosion [37]. The municipal council has unanimously opposed this plan, the regional authority too, but future is open.

There are some ongoing processes that point in this direction: Farmers are getting older and their overall numbers are diminishing younger farmers see their chances in collaboration and finding new ways. Still, market conditions for agricultural products are not very good, several legal regulations stand in the way of direct economic transactions between farmers and the local tourism industry, and traditional political clientelism stabilizes large livestock numbers. With insight spreading, new European CAP regulations ahead, and the urgency of effective nature conservation becoming ever more apparent to everyone and being publicly declared by an application to UNESCO, chances are that the deadlock can be overcome. Our intensive work with farmers (focus groups, individual interviews, and Sown Biodiverse Pastures experiments) may have contributed.

At the same time, experiences over the past decades have dampened hopes for big business in tourism (such as yachts and cruise ships landing, an airport, large hotels, and exclusive cottages for the rich) and prepared the way for more moderate (and more sustainable) expectations that will still allow for decent job opportunities in the service and secondary sector and cash in on the ecological and cultural treasures of the island. Outside of the peak season, the island offers a perfect infrastructural setting for conferences, summer schools, cultural events, mountaineering courses, and health treatments, and may also serve as an international sight for basic and applied environmental and social research. A key precondition, though, is an increased predictability and reliability of the ferry services, also in the pre- and post-season. Thus, there are good chances for maintaining local income without further increasing material stocks and flows for infrastructure.

For the secondary sector, a transition is maybe most urgent technically and socially. Maintenance and repair of existing infrastructure (water supply, roads, electric, and sanitary appliances in tourism establishments and private houses, installation and grid supervision of the many photovoltaic parks on the island) are dearly in demand of qualified labor. Several hundred secondary homeowners are there to welcome caretaking and off-season maintenance of their houses and gardens, and many of them could easily afford that. There is not even one certified mechanic on the island who would be entitled to do the annually required check-up for the cars of the inhabitants. Unfortunately, the Greek education system does not provide adequate learning opportunities for technical jobs and crafts; and thus, wage labor according to the welfare standards common in Europe (monthly pay, payed holidays, access to free or cheap health treatment, unemployment benefit, old age pension) exists practically only for the employees of the public sector, or of large companies. Thus, most of the economically active population on the island is “self-employed”, usually not formally qualified for the jobs they do, and in the field of crafts frequently figure as dayworkers [7], bearing all economic risks from day to day. Specialists, such as those setting up and maintaining the photovoltaic panels, are all employed by outside companies and brought over from outside.

Qualified wage labor, rather than self-employed family labor or "farm hands", is one of the key features of modern society, spreading from the urban centers. This transition is particularly hard to make on islands. In other peripheral areas, commuting daily or weekly for one's job to an urban center is very common, both in the phase of formally learning the skills required, and later in practice. For most islands, this is hardly possible: Distances are too long and connections too unreliable. Maybe a further transition to more IT work will make some of that easier—but unless differentiated and formalized education processes (taking place outside of islands, usually) secure qualifications for complex technical tasks properly, populations on islands will keep facing these challenges. Still, better education should be a pathway towards improving the living standards of the locals without further raising demands upon material and energy resources—possibly even lowering these demands.

Beyond such specific educational requirements that are not well met currently, a local sustainability transition makes high demands upon the ability of a local population to self-organize, to jointly engage in making changes happen [53]. Ways of mutual support must be established between the island's core economic sectors, instead of mutual neglect, destruction, and contempt.

Traditional collaboration patterns in agrarian societies are strongly family centered and hierarchical, with little functional differentiation. You do something because the father tells you so—and not because you are particularly qualified for it. Extended beyond the core family context, this means that if I have the say, you get the job because you are my cousin's cousin, not because you are particularly good at it—the well-known nepotism. In consequence, mutual trust between families and co-citizens is low, each decision is suspected to be in somebody's particular interest, and not for a fair joint benefit. In effect, private (family) property is protected, while the commons tend to be overused. In such a culture, it is very difficult to have people collaborate for complex common goals; for this, one needs networks of like-minded individuals with various competencies who trust each other to be able to work together in functionally differentiated structures with flat hierarchies.

In this respect, in the course of our efforts to stimulate innovative solutions, we could distinguish two main groups of the resident population—we called it the difference between "locals" and "neo-locals". They differ not only in age and educational background, but also in the type of collaboration they prefer and are able to organize with others (see below). "Locals" basically comply with the culture and collaboration patterns described above as traditional and have not spent much of their lives in other settings but the island. "Neo-locals", even if their family roots are on Samothraki, have learned to function also in other settings, and more easily associate with like-minded others to get something done.

Maybe it is the rising share of "neo-locals" among the island population that facilitated, after several failed efforts in the past, the recent emergence of a number of bottom-up initiatives to organize partners for some joint interest. An olive farmers' cooperative was founded and bought a new olive press that now allows its members to label the oil as "organic" and achieve a better price for it; a newly founded "social cooperative" took over one of the defunct municipality's camping sites to everyone's satisfaction; and maybe most importantly, a farmers' association (after many failures in the more distant past) was formed under female leadership (!) that is supposed to organize joint feed ordering and joint sales of sheep and goat, thus achieving better prices and encouraging younger farmers to choose new strategies. Most closely tied to our research project and proceedings is the also newly founded association "Sustainable Samothraki" with about 50 members, devoted to the purpose of making the island more sustainable. The association established an international scientific advisory board (ISAB) from the members of our research team and recently published the policy recommendations of this board widely in English and Greek [54]. Thus, enhancing this ongoing cultural change is another avenue towards improving lives while lessening resource extraction and improving waste disposal. We believe that membership in and exchange with the community of UNESCO biosphere reserves, whenever the Greek government has created the legal conditions required, will support this cultural change.

5. Conclusions

So, finally, during the many years of research, repeated presence, and outreach on the island, activities in the sense of a "real world lab", what did we actually achieve? One answer is relatively easy: We generated salient descriptions and, in some cases, even solid causal explanations of the social and ecological realities and made them bear on public awareness.

For example, one of the locally popular explanations for the obvious decrease of vegetation had been scapegoating the nuclear accident in Chernobyl (in 1986), and not the goats—quite an absurd theory, but widely believed. With another popular explanation we had more difficulties, and almost believed a wrong attribution ourselves: That the rapid increase in livestock numbers was mainly the fault of EU-CAP subsidies. It took us a while to dismantle this assumption and show that reasons were more complex and strongly linked to Greek national, regional, and local regulations (some of them quite at odds with EU-CAP). Another message we could probably get across was that climate change in the Mediterranean meant a higher incidence of extreme weather events and thus a higher risk of landslides, particularly in steep areas lacking vegetation. Reforestation and appropriate infrastructure would be needed to mitigate these risks. Our research probably also reinforced the lowering of expectations for growing tourist numbers and appreciating the income they achieve from campers.

We are less sure that the core insight from the socio-metabolic paradigm got across: Namely, that all material input into the economic process finally ends up as wastes to be dealt with, and that the benefits achieved with sales and purchases would one day need to be balanced by efforts and costs for waste management and removal. These days have already come—but are still poorly recognized.

The scientific descriptions and explanations may not have fully penetrated the minds of the inhabitants and created a dominant public awareness, but they have at least reached many entrepreneurs and the local intelligentsia, our core communication partners, and the public administration. In 2016, the Municipality of Samothraki decided on a "Strategic Plan" according to the following principles [50]: (1) Environmental protection and improvement of the quality of life, (2) strengthening social policy and education, culture, and sport services, (3) economic growth and employment, and (4) improving the administrative capacity of the municipality. This plan also acknowledges the necessity to attract "high quality, alternative tourism". The guiding policy priorities for the Municipality of Samothraki (2016) include: Improving maritime transport and port infrastructure (extension of Kamariotissa port, creation of a marina at Therma); improving solid waste management, constructing waste water treatment plants; expanding, improving, and maintaining the water supply network; restoring the road network; improving health infrastructure; promoting high-quality agricultural and livestock products; and various other goals. How far these plans are related to our research activities and outreach is hard to say—but they reflect many of our policy intentions. The ambitions of the local government, though, are often not matched by higher levels of the Greek governance system, so the final establishment of the Natura 2000 areas in Greece has again been delayed, blocking the island's pathway towards becoming accepted as a Biosphere Reserve by UNESCO—the initial policy goal of our research, and still a policy goal of the municipality.

Another answer extends beyond what to typically expect from science: Our work, and our regular presence, seem to have brought encouragement. They encouraged a number of people not to resign and settle with what was given, but to trust that something better could be achieved. They gained in ability to organize themselves, to raise funds, and to initiate processes. This refers particularly to the members of bottom-up initiatives, but it also applies to several members of the public administration (four different mayors, for example, to varying degrees), interested partners in the regional governments, and a number of local farmers and tourism entrepreneurs. Such an encouragement, if not followed by successes, can easily generate excessive demand upon the leaders, wear them out, and end up in resignation. Thus, it is important to keep up a certain momentum and secure at least a minimal flow of resources and fresh manpower, be it in the form of enthusiastic students who want to learn about the island every year.

Author Contributions: Conceptualization, M.F.-K., P.P.; methodology, M.F-K., M.L., D.N., N.S.; validation, M.F-K., N.S.; formal analysis, M.F.-K., M.L., D.N.,N.S.; investigation, M.F.-K., M.L., D.N., P.P., N.S.; M.F.-K., N.S.; data curation, D.N.; writing – original draft: M.F.-K., M.L., N.S.; writing – review and editing, M.F.-K., D.N., P.P., N.S.; visualization, M.L., D.N.; supervision, M.F.-K.; project administration, D.N.; funding aquisition, M.F.-K., P.P. All authors have read and agreed to the published version of the manuscript.

Funding: This research received external funding from the Austrian MAB-committee at the Austrian Academy of Sciences, contract UF2013 (SamoMAB) and the Austrian National Science Fund, grants number F15P27951-G27 (SUSAKI) and - F15TCS00022 CiSciSusaki).

Acknowledgments: The Alpen Adria University contributed to this research, within the master's program on Social and Human Ecology, by supporting annual summer schools on the island 2012–2019; other supporters of these summer schools, in providing teaching and advice, have been the Hellenic Centre for Marine Research in Athens, in particular Anastasia Lampou, as well as Simron Singh from Waterloo University, Canada. We thank Tiago Domingos (University of Lissabon) for advising us on Biodiverse Sown Pastures and Terraprima (Marjan Jongen, Antonio Martelo) for performing the experiments. Georg Gratzer and Carina Heiling (University of Natural Resources and Life Sciences, Vienna) designed and performed the dendrological part of our study. Much of the diversity and quality of the research is due to the efforts of many highly engaged students and local "citizen scientists" (see various entries at www://sustainable-samothraki.net). Throughout the process, we have been supported by the consecutive Mayors Petroudas, Chanos, Vitsas and Galatoumos, and members of the local administration. Finally, we need to thank numerous local initiatives for their trust and practical help, in particular the president and vice president of the association Sustainable Samothraki, founded in 2016, Carlota Marañon and Giorgos Maskalidis.

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

References

1. Biel, B.; Tan, K. *Flora of Samothraki*; Goulandris Natural History Museum: Athens, Greece, 2014.
2. Heiling, C. Spuren Historischer Ressourcennutzung anhand Dendrologischer Befunde: Eichenwälder auf der Insel Samothraki. Master's Thesis, University of Natural Resources and Life Sciences Vienna, Vienna, Austria, 2018.
3. Löw, M. Spatial Patterns of Land Cover Dynamics on Samothraki Island: Applying Remote Sensing on Complex Mediterranean Pastures. Master's Thesis, Alpen Adria University, Vienna, Austria, 2017.
4. Bremmer, J.N. Initiation into the Mysteries of the Ancient World. In *Münchner Vorlesungen zu antiken Welten*; De Gruyter: Berlin, Germany, 2014; Volume 1.
5. Kolodny, E. *Samothrace sur Neckar. Des. Migrants grecs dans l'agglomeration de Stuttgard*; Institute de Recherches Mediterraneennes: Aix-en-Provence, France, 1982.
6. Skoulikidis, N.; Lampou, A.; Karaouzas, I.; Gritzalis, K.; Lazaridou, M.; Zogaris, S. Stream ecological assessment on an Aegean island: Insights from an exploratory application on Samothraki (Greece). *Fres. Envrion. Bull.* **2014**, *23*, 1173–1182.
7. Petridis, P.; Hickisch, R.; Klimek, M.; Fischer, R.; Fuchs, N.; Kostakiotis, G.; Wendland, M.; Zipperer, M.; Fischer-Kowalski, M. *Exploring Local Opportunities and Barriers for a Sustainability Transition on a Greek Island*; Social Ecology Working Paper 142; Institute for Social Ecology, Alpen Adria University: Vienna, Austria, 2013; Available online: https://www.aau.at/wp-content/uploads/2016/11/working-paper-142-web.pdf (accessed on 20 January 2020).
8. Fischer-Kowalski, M.; Xenidis, L.; Singh, S.J.; Pallua, I. Transforming the Greek Island of Samothraki into a UNESCO Biosphere Reserve. An Experience in Transdisciplinarity. *Gaia-Ecol. Perspect. Sci. Soc.* **2011**, *20*, 181–190. [CrossRef]
9. Greek National MAB Committee. *Samothraki Biosphere Reserve Nomination Form: Final Official Document*; Unesco MAB Programme: Athens, Greece, 2013.
10. Krütli, P.; Pohl, C.; Stauffacher, M. Sustainability Learning Labs in Small Island Developing States: A Case Study of the Seychelles. *Gaia-Ecol. Perspect. Sci. Soc.* **2018**, *27*, 46–51. [CrossRef]
11. Schäpke, N.; Bergmann, M.; Stelzer, F.; Lang, D.J. Labs in the Real World: Advancing Transdisciplinary Research and Sustainability Transformation. *Gaia-Ecol. Perspect. Sci. Soc.* **2018**, *27*, 8–11.

12. Deschenes, P.J.; Chertow, M. An Island Approach to Industrial Ecology: Towards Sustainability in the Island Context. *Envrion. Plan. Manag.* **2004**, *47*, 201–217. [CrossRef]
13. Singh, S.J.; Grünbühel, C.M.; Schandl, H.; Schulz, N. Social Metabolism and Labour in a Local Context: Changing Environmental Relations on Trinket Island. *Pop. Envrion.* **2001**, *23*, 71–104. [CrossRef]
14. Singh, S.J.; Schandl, H. Socio-Economic Metabolism in the Nicobar Islands. Empirical Research in Society-Nature Interactions. In *Exploitation and Overexploitation in Societies Past and Present. IUAES-Intercongress 2001 Goettingen*; Benzing, B., Herrmann, B., Eds.; LIT Publishing House: Münster, Germany, 2003; pp. 169–184.
15. Okoli, A. Socioeconomic Metabolism of Biomass in Jamaica in the Context of Trade and National Food Security: A Time Series Biophysical Analysis (1961–2013). Ph.D. Thesis, University of Waterloo, Waterloo, ON, Canada, 2016.
16. Thomas-Hope, E. Migration, small farming and food security in the Caribbean: Jamaica and St. Vincent and the Grenadines. *Int. Migr.* **2017**, *55*, 35–47. [CrossRef]
17. Kizos, T.; Plieninger, T.; Schaich, H. 'Instead of 40 Sheep there are 400': Traditional Grazing Practices and Landscape Change in Western Lesvos, Greece. *Landsc. Res.* **2013**, *38*, 476–498. [CrossRef]
18. Haberl, H.; Wiedenhofer, D.; Pauliuk, S.; Krausmann, F.; Müller, D.B.; Fischer-Kowalski, M. Contributions of sociometabolic research to sustainability science. *Nat. Sustain.* **2019**, *2*, 173–184. [CrossRef]
19. Krausmann, F. Social Metabolism. In *The Routledge Handbook of Ecological Economics: Nature and Society*; Spash, C.L., Ed.; Routledge: Abingdon, UK, 2017; pp. 108–118.
20. Fischer-Kowalski, M.; Petridis, P. Can Socioecological Research Help to Create a Realistic Perspective for a Sustainable Samothraki? *Sustain. Med.* **2016**, *73*, 12–16.
21. Diamond, J. Collapse. In *How Societies Choose to Fail or Succeed*; Viking: New York, NY, USA, 2005.
22. Petridis, P.; Fischer-Kowalski, M. Island Sustainability: The Case of Samothraki. In *Social Ecology Society-Nature Relations across Time and Space*; Haberl, H., Fischer-Kowalski, M., Krausmann, F., Winiwarter, V., Eds.; Springer: Cham, Switzerland, 2016; pp. 543–554.
23. Ostrom, E. *Governing the Commons. The Evolution of Institutions for Collective Action*; Cambridge University Press: Cambridge, UK, 1990.
24. Kristensen, P. The DPSIR Framework. UNEP Headquarters Nairobi 2004. Available online: https://wwz.ifremer.fr/dce/content/download/69291/.../DPSIR.pdf (accessed on 1 September 2019).
25. Fischer-Kowalski, M.; Petridis, P. *Fifth Summer School on Aquatic and Social Ecology on Samothraki, Greece*; Social Ecology Working Paper 178; Institute for Social Ecology, Alpen Adria University of Natural Resources and Life Sciences: Vienna, Austria, 2019; Available online: https://www.aau.at/wp-content/uploads/2016/11/working-paper-178-web.pdf (accessed on 20 January 2020).
26. Summer University of Samothraki 2016; UNESCO, Global Water Partnership, Mediterranean Information Office for Environment, Culture and Sustainable Development; Institute of Social Ecology, Hellenic Centre for Marine Research. Integrated Management Approaches for Biosphere Reserves and other Designated Areas, 9–22 July 2016. *Sustain. Mediterr.* **2016**, *73*, 1–84.
27. *6th Summer School on 'Aquatic and Social Ecology' on Samothraki, Greece*; Working Paper Social Ecology; Petridis, P.; Fischer-Kowalski, M. (Eds.) Institute for Social Ecology Vienna, University of Natural Resources and Life Sciences: Vienna, Austria, 2020; In Preparation.
28. Δημοσιοποίηση Ποσών Επιδότησης (ΕΓΤΕ/ΕΓΤΑΑ). Available online: https://transpay.opekepe.gr/ (accessed on 12 January 2018).
29. Baierl, C. Analysis of the EU-Common Agricultural Policy Subsidies on the Greek Island of Samothraki. Master's Thesis, Alpen Adria University, Vienna, Austria, 2019.
30. Fuchs, N.A. *Sozial-ökologische Effekte der EU-Agrarsubventionen*; AV Akademikerverlag: Saarland, Germany, 2015.
31. Schwaiger, N. Exploring Sustainable Tourism on Samothraki: Current State and Perspectives. Master's Thesis, Alpen Adria University, Vienna, Austria, 2017.
32. Fetzel, T.; Petridis, P.; Noll, D.; Singh, S.J.; Fischer-Kowalski, M. Reaching a socio-ecological tipping point: Overgrazing on the Greek island of Samothraki and the role of European agricultural policies. *Land Use Policy* **2018**, *76*, 21–28. [CrossRef]

33. Noll, D.; Lauk, C.; Gaube, V.; Wiedenhofer, D. Caught in a deadlock: Small ruminant farming on the Greek island of Samothrace. The importance of regional contexts for effective EU agricultural policies. *Sustainability* **2020**, *12*, 762. [CrossRef]
34. Noll, D.; Wiedenhofer, D.; Miatto, A.; Singh, S.J. The expansion of the built environment, waste generation and EU recycling targets on Samothraki, Greece: An island's dilemma. *Resour. Conserv. Recycl.* **2019**, *150*, 104405. [CrossRef]
35. Dimitriou, E.; Skoulikidis, N. Hydrometereological and Hydrochemical analysis of the Fonias River Basin. In *Fifth Summer School on Aquatic and Social Ecology on Samothraki, Greece*; Social Ecology Working Paper 178; Fischer-Kowalski, M., Petridis, P., Eds.; Institute for Social Ecology: Alpen Adria University of Natural Resources and Life Sciences: Vienna, Austria, 2019; pp. 22–34.
36. Skoulikidis, N.; Lampou, A.; Katopodis, G. Water Metabolism and Water Management. In *Samothraki as a Biosphere Reserve (SamoMAB)*; Report to the Austrian Academy of Sciences; Dominik, N., Ed.; University of Natural Resources and Life Sciences: Vienna, Austria, 2018; pp. 5–36. ISBN 978.
37. Panagopoulos, Y.; Dimitriou, E.; Skoulikidis, N. Vulnerability of a Northeast Mediterranean Island to Soil Loss. Can Grazing Management Mitigate Erosion? *Water* **2019**, *11*, 1491. [CrossRef]
38. Work less- earn more. Available online: www.happygoats.eu/#/ (accessed on 15 December 2019).
39. Hostert, P.; Röder, A.; Hill, J.; Udelhoven, T.; Tsiourlis, G. Retrospective studies of grazing-induced land degradation: A case study in central Crete, Greece. *Int. J. Remote Sens.* **2002**, *24*, 4019–4034. [CrossRef]
40. Hadjigeorgiou, I. Past, present and future of pastoralism in Greece. *Pastor. Res. Policy Pract.* **2011**, *1*, 1–22. [CrossRef]
41. Perevolotsky, A.; Seligman, N.G. Role of Grazing in Mediterranean Rangeland Ecosystems. *BioScience* **1998**, *48*, 1007–1017. [CrossRef]
42. Vallentine, J.F. *Grazing Management*; Elsevier: San Diego, CA, USA, 2014.
43. Jepsen, M.R.; Kuemmerle, T.; Müller, D.; Erb, K.; Verburg, P.H.; Haberl, H. Transitions in European land-management regimes between 1800 and 2010. *Land Use Policy* **2015**, *49*, 53–64. [CrossRef]
44. Damianakos, S. The Ongoing Quest for a Model of Greek Agriculture. *Sociol. Rural.* **1997**, *37*, 190–208. [CrossRef]
45. Kosmas, C.; Detsis, V.; Karamesouti, M.; Kounalaki, K.; Vassiliou, P.; Salvati, L. Exploring Long-Term Impact of Grazing Management on Land Degradation in the Socio-Ecological System of Asteroussia Mountains, Greece. *Land* **2015**, *4*, 541–559. [CrossRef]
46. European Commission. Overview of CAP Reform 2014–2020—Agricultural Policy Perspectives Brief N° 5*/December 2013. DG Agriculture and Rural Development, Unit for Agricultural Policy Analysis and Perspective. 2013. Available online: https://ec.europa.eu/info/sites/info/files/food-farming-fisheries/farming/documents/agri-policy-perspectives-brief-05_en.pdf (accessed on 9 January 2020).
47. Pispini, M. National Proposals for the new CAP. ARC 2020 (Agricultural & Rural Convention). 2014. Available online: https://arc2020.eu/2014/06/greece-national-proposals-for-the-new-cap/ (accessed on 9 January 2020).
48. Giourga, H.; Margaris, N.S.; Vokou, D. Effects of Grazing Pressure on Succession Process and Productivity of Old Fields on Mediterranean Islands. *Environ. Manag.* **1998**, *22*, 589–596.
49. Hohenwarter, S.; Winkler, A.; Zilleruelo, R.; Anagnostou, C.; Lampou, A. Coastal Morphodynamics with a Focus on Anthropogenic Activities and Sustainable Coastal Areas. In *Fifth Summer School on Aquatic and Social Ecology on Samothraki, Greece*; Social Ecology Working Paper 178; Fischer-Kowalski, M., Petridis, P., Eds.; Institute for Social Ecology, Alpen Adria University of Natural Resources and Life Sciences: Vienna, Austria, 2019; pp. 14–21.
50. Municipality of Samothraki. *Operational Program 2014–2019*; Municipality of Samothraki: Samothraki, Greece, 2016.
51. Spilanis, I.; Kizos, T.; Karampela, S.; Vayanni, H. A tourism typology for the Greek islands. In Proceedings of the Island Tourism (International Conference of Trends, Impacts and Policies on Tourism development), Crete, Greece, 15–18 June 2006.
52. Petridis, P.; Huber, J. A Socio-metabolic Transition of Diets on a Greek Island: Evidence of "Quiet Sustainability". In *Socio-Metabolic Perspectives on the Sustainability of Local Food Systems*; Fraňková, E., Haas, W., Singh, S.J., Eds.; Springer International Publishing: Cham, Switzerland, 2017; pp. 263–289.

53. Petridis, P.; Fischer-Kowalski, M.; Singh, S.J.; Noll, D. The role of science in sustainability transitions: Citizen science, transformative research, and experiences from Samothraki island, Greece. *Isl. Stud. J.* **2017**, *12*, 115–134. [CrossRef]
54. Association Sustainable Samothraki. Recommendations of the International Scientific Advisory Board to the Association Sustainable Samothraki. 2019. Available online: http://sustainable-samothraki.net/local_action/sustainable-samothraki-association/scientific-advisory-board/ (accessed on 9 January 2020).

© 2020 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (http://creativecommons.org/licenses/by/4.0/).

sustainability

MDPI

Article

Caught in a Deadlock: Small Ruminant Farming on the Greek Island of Samothrace. The Importance of Regional Contexts for Effective EU Agricultural Policies

Dominik Noll *, Christian Lauk, Veronika Gaube and Dominik Wiedenhofer

Institute of Social Ecology (SEC), University of Natural Resources and Life Sciences (BOKU), Schottenfeldgasse 29, 1070 Vienna, Austria; christian.lauk@boku.ac.at (C.L.); veronika.gaube@boku.ac.at (V.G.); dominik.wiedenhofer@boku.ac.at (D.W.)

* Correspondence: dominik.noll@boku.ac.at

Received: 13 December 2019; Accepted: 19 January 2020; Published: 21 January 2020

Abstract: Sedentary extensive small ruminant farming systems are highly important for the preservation of High Nature Value (HNV) farmland. Both the abandonment of grazing and overgrazing have led to environmental degradation in many Mediterranean regions. On the Greek island of Samothrace, decades of overgrazing by sheep and goats has caused severe degradation of local ecosystems. The present study highlights the importance of regional contexts for national and EU agricultural policies in regard to sustainable development of sedentary extensive livestock systems. By utilizing the conceptual framework of socio-ecological systems research, we analyze the interdependencies of environmental, economic and social factors on a local island level. Results show that between 1929 and 2016, the livestock and land-use system of Samothrace transformed from a diverse system towards a simplified system, solely used for small ruminant production. Total livestock units increased from 2200 in 1929 to 7850 in 2002, declining to 5100 thereafter. The metabolic analysis conducted for the years 1993–2016 shows that 80–90% of the feed demand of small ruminants was covered by grazing, exceeding available grazing resources for at least a decade. The regional implementation of CAP (Common Agricultural Policy) continues to support excessively high animal numbers, while farmers are highly dependent on subsidies and find themselves in an economic deadlock.

Keywords: overgrazing; soil erosion; rural abandonment; sedentary extensive livestock systems; Common Agricultural Policy (CAP); socio-ecological systems; social metabolism; material flow analysis (MFA); mixed methods approach

1. Introduction

Livestock represents a key element in society-nature interactions and is responsible for more than a third of global land use in a wide range of ecosystems [1]. Extensive, pasture-based ruminant and mixed crop-livestock systems provide 70% of milk and 60% of meat globally, utilizing 80% of all agricultural land [2]. In the Mediterranean, extensive, pasture-based ruminant systems have a long tradition dating back to antiquity. This form of livestock management created characteristic landscapes, dominated by heterogeneous plant communities of forests, bushes, herbaceous undergrowth and grassland. A long co-evolutionary process generated “resilient ecosystems with a high species diversity, productivity and utility to society” [3]. As the specific environmental conditions in these regions limit intensive and specialized farming, extensive, pasture-based ruminant systems continue to shape many rural areas up until today [4]. In Europe, these types of ecosystems are considered High Nature Value (HNV) farmland (HNV farmland describes agriculturally used areas with high levels of biodiversity and is one of 35 EU indicators for the integration of environmental aspects into the Common Agricultural Policy (CAP) [5]), with its highest proportions in Portugal, Spain and Greece [6]. In these regions, rough grazing biomass is transformed into high value products, traditionally by small, but increasingly also by large ruminants. The preservation of extensive, pasture-based small ruminant farming systems (SRFSs) is highly important for the protection of HNV farmland and rural communities throughout the Mediterranean [7]. In Greece, small ruminant farms produce 60% of milk and 65% of red meat for the national market, which is unique in Europe and indicates the sector's social and economic importance [8]. The present study addresses the sustainability of extensive SRFSs with a special focus on the Greek island of Samothrace.

Traditionally, SRFSs in Greece were, in most regions, characterized through transhumant activities. Since the beginning of the 20th century, nomadic lifestyles have been in decline, mainly morphing into semi-nomadic or sedentary extensive SRFSs. This model primarily uses common grazing land, provides supplementary feed and is characterized by low investment and productivity [9]. Today, sedentary extensive SRFSs shape rural Greece, and are currently threatened by a multitude of factors. While some regions suffer from complete abandonment of grazing, others are heavily overgrazed [10]. Both trends lead to ecosystem degradation and demonstrate the current economic and social crisis this type of SRFS is experiencing. If grazing is abandoned, shrub and bush encroachment changes species composition and often leads to increased fire risk, while high grazing pressure mostly results in biodiversity loss and soil erosion [11]. Global agricultural industrialization has led to a decline in feed prices and production costs, even though transport distances are larger [1]. Consequently, prices for agricultural products have declined, while extensive, small-scale farms have an increasing difficulty competing in the market. The demand for wool and skins has become so low that today many farmers prefer to dump them.

The EU Common Agricultural Policy (CAP) plays a special role in the transformation of grazing-based farming systems throughout the EU. In some regions, subsidy schemes supported the abandonment of grazing through the conversion of extensive pastures into forests or crop production; while in other regions, grazing was intensified through direct payments that initiated higher animal stocking rates [12]. Local socio-economic contexts and needs are often insufficiently taken into consideration by EU-wide agricultural policies, resulting in mixed outcomes for farmers [13]. The aim of the present study is to highlight such a local socio-economic context on the Greek island of Samothrace, where the transformation of local agriculture was identified as the major driver for ecosystem degradation and widespread soil erosion [14–16].

The importance and multiple challenges faced by SRFSs in Greece and other Mediterranean regions, calls for a comprehensive research approach, focusing on environmental, social and economic aspects simultaneously [17]. In our case study, we aim to analyze the interdependencies of environmental, economic and social factors regarding the SRFS on Samothrace. We use the conceptual framework of socio-ecological systems research, as it builds a useful link between biophysical and socio-economic processes, by describing the exchange of materials and energy between society and nature [18,19]. The utilized mixed methods approach [20], integrates data on environmental, economic and social aspects of small ruminant farming from various sources and builds upon the long-term research project on the island. The integration of monetary flows expressed in relative prices complements the socio-metabolic approach, as it directly influences biophysical flows through farmers' behavior [21]. This approach allows us to derive sustainability indicators, assess socio-economic drivers, and define possible pathways for a sustainable future for agriculture on Samothrace. The study is guided by the following research questions: What factors contribute to and represent the current sustainability crisis of the SRFS on Samothrace? What are the socio-economic drivers for the regression of sedentary extensive SRFSs in Greece? What role does the EU Common Agricultural Policy (CAP) play, in the context of the current sustainability crisis of small ruminant farming on Samothrace? What could a sustainable future of small ruminant farming in the Mediterranean look like?

In Section 2, we outline the methodological approach by introducing the study site in Section 2.1, the conceptual framework in Section 2.2, the biophysical assessment in Section 2.3, the socio-economic assessment in Section 2.4 and the evaluation of uncertainty of input data in Section 2.5. Results are provided in Section 3. The Discussion in Section 4 contains chapters about the sustainability crisis of the SRFS on Samothrace in Section 4.1, the regression of sedentary extensive SRFSs in the Mediterranean in Section 4.2, the role of EU CAP in the changes affecting the SRFSs of Samothrace in Section 4.3, and the future of small ruminant farming in the Mediterranean in Section 4.4. Conclusions are provided in Section 5.

2. Material and Methods

2.1. The Island Samothrace

Samothrace stretches over 178 km^2 and is one of the very few hotspots of preserved archaic wilderness among the Greek islands. Its remote location in the north-eastern Aegean Sea, the pebbly nature of most beaches and often unclear land ownership, averted economic exploitation and mass tourism on the island. The 1611 m high mountain range *Σάος* gives Samothrace its geomorphological character and shapes the distinct microclimates. While the northern side presents itself in lush green with old forest cover and numerous streams of drinkable water, the southern and western sides are shaped by a rather typical dry summer Mediterranean climate and vegetation. A large proportion of the island's terrestrial area is part of the Natura 2000 network, and since 2012, the island has been a UNESCO MAB ("UNESCO's Man and Biosphere (MAB) Program is an intergovernmental scientific program striving for the improvement of the relationship between people and their environment. The Biosphere Reserve concept started by a Task Force of UNESCO's Man and the Biosphere (MAB) Program in 1974, while the World Network of Biosphere Reserves (WNBR) was launched in 1976. Biosphere Reserves (BR) are terrestrial and/or marine areas that encompass valuable ecosystems and social communities that wish to combine the conservation of ecosystems with their sustainable use. They are established to promote and demonstrate a balanced relationship between humans and the biosphere" (www.sustainable-samothraki.net) candidate [14,22]. The island community of Samothrace is officially registered as 2840 people [23], but is subject to high fluctuations because many people leave the island in winter months or visit the island as tourists, seasonal workers or second homeowners. Of the 1000 economically active residents, 20% work as livestock herders and small-scale farmers. The secondary sector is relatively underrepresented at 10%, while the tertiary sector employs 60% and consists mainly of tourism services.

The development path of recent decades has led to a wide variety of environmental but also social problems which the island community currently must face. One of the major threats to local ecosystems was triggered by the transformation of the local agricultural system. Decades of overgrazing by sheep and goats resulted in biodiversity reduction and widespread soil erosion [15,16]. Since the mid-20th century, farms and farmers are declining, while the small ruminant population increased to unprecedented levels [24]. Increasing feed prices, dependence on subsidies, the lack of marketing opportunities and little cooperation among themselves, have caused local farmers to find themselves in an economic deadlock situation that now threatens the very existence of agriculture on the island.

2.2. The Conceptual Framework

For the present study, we defined the system of investigation as the small ruminant farming system (SRFS) and its most relevant socio-economic and ecological relations, shown in Figure 1. The green circle represents the natural, and the blue circle, the cultural sphere of causation, with the livestock and human population in the overlapping part. The SRFS is defined as the small ruminant population (sheep and goats), its metabolic requirements, its material output in terms of products, the small ruminant farmers and their monetary economy. Terrestrial ecosystems provide the net primary production (NPP) consumed by small ruminants. The SRFS exchanges goods and money with the local population, including visitors. The political, legal and cultural framework is represented by rules and regulations of the Greek state, and the EU and local traditions. The EU provides agricultural subsidies through the Common Agricultural Policy (CAP), and the Greek state pays pensions to retired farmers. The local and visitor population receive money from external markets and through income from external sources (e.g., work or pensions). Wastes are not explicitly assessed in this study, but they are a relevant factor, especially regarding slaughtering residues and emissions.

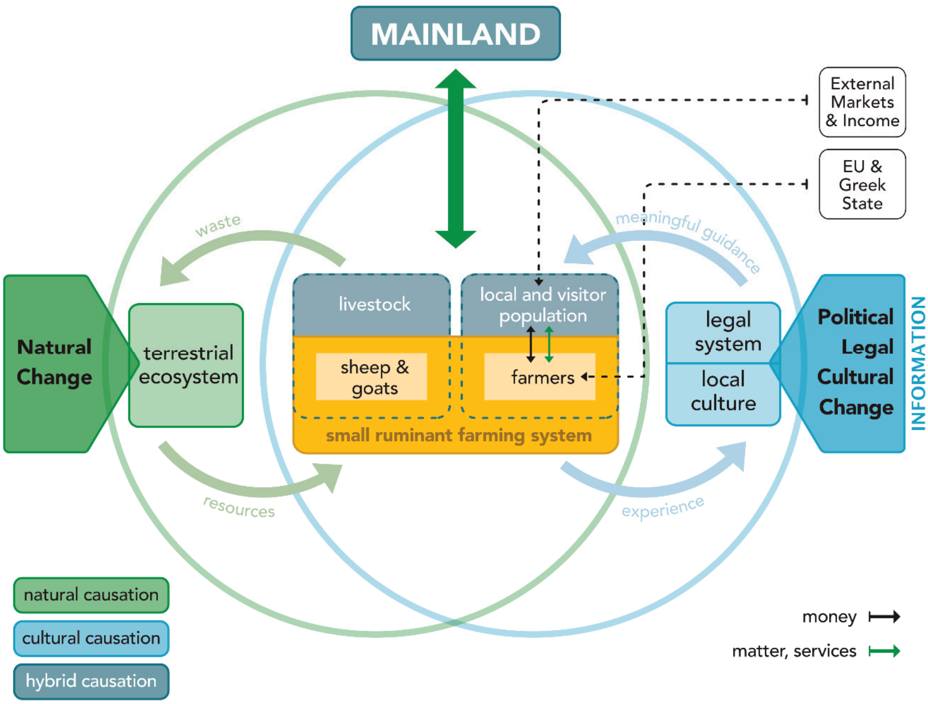

Figure 1. Schematic representation of the studied system and important influential factors. Figure adapted from Petridis et al. and Fischer-Kowalski et al. [25,26].

The present study is part of a long-term research project on Samothrace, beginning in 2008. Thus, we were able to build upon previous research efforts and use data from various sources. The aim of covering environmental, social and economic factors resulted in the need to utilize a mixed methods approach [20]. As indicated by the grey boxes shown in Figure 2, we integrate quantitative and qualitative data from a survey with 23 small ruminant farmers, qualitative data from 12 expert interviews, public statistical data, and data from previous research on land cover dynamics [24,27]. For the assessment of biophysical flows, we utilize a bottom-up or stock-driven approach, to assess the biomass consumption of the SRFS on the island. Detailed documentation can be found in the Supplementary Data (SD) and Information (SI) file.

The Material and Methods section is divided into the biophysical, in Section 2.3, and socio-economic, in Section 2.4, assessment of the SRFS system. The utilization of the metabolic small ruminant model in combination with various data sources requires a systematic assessment of uncertainty of the model and exogenous data [28]. For this reason, we conducted a sensitivity analysis in combination with a qualitative description, and when applicable, an uncertainty range of key input parameters in Section 2.5.

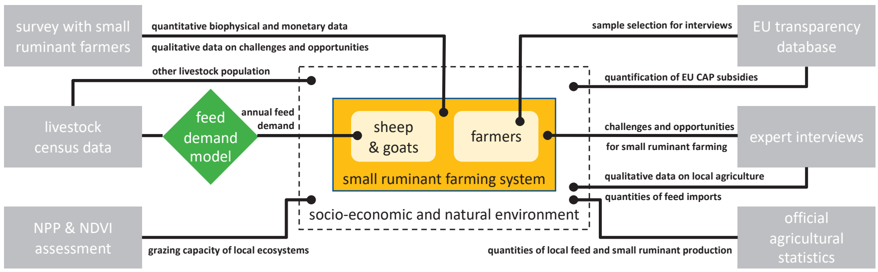

Figure 2. Mixed methods approach as applied to the SRFS (small ruminant farming system) and its socio-economic and natural environment.

2.3. Biophysical Assessment of the Livestock System

The assessment of biophysical conditions is based on the conceptual framework of socio-ecological systems research [18,19], and utilizes the methodological approaches of material and energy flow accounting (MEFA), and principles of human appropriation of net primary production (HANPP) on a local island level. The assessment was conducted in three ways:

1. Livestock units for all livestock species are reconstructed through official livestock census data from 1929 to 2016 [29] and the application of feed requirement factors. Factors for all species, except sheep and goats, were derived from Krausmann et al. [30].
2. For the assessment of feed intake of sheep and goats on Samothrace, we set up the herd and feed rations modules of GLEAM (Global Livestock Environmental Assessment Model) in Excel (For a detailed description of GLEAM, its components and equations, refer to http://www.fao.org/gleam/en/. For a detailed description of equations used for the present study see Supplementary Information: Section 4 and Supplementary Data: Tables S1–S4.) [31]. For the description of this model in Section 2.3.1, we follow the ODD (Overview, Design Concepts, Details) protocol that has been widely used to describe simulation models in multiple disciplines [32,33].
3. For the estimation of the grazing capacity of the island's ecosystems (Section 2.3.2), we used net primary production (NPP) data derived from Fetzel et al. [24], and the Normalized Difference Vegetation Index (NDVI) derived from Löw [27].

2.3.1. Calculation of Metabolic Requirements of Small Ruminants Based on GLEAM

The ODD (Overview, Design Concepts, Details) protocol is structured around *overview*, *design concepts* and *details* sections. Sections *overview* and *design concepts* are provided in Table 1. The *details* section is outlined below and includes the description of the *initial state* of the model and *model input* and *output data*.

Table 1. Overview and design concepts of the utilized modelling approach following the ODD (overview, design concepts and details) protocol.

Overview and Design Concepts of the Utilized Modelling Approach		
Overview	purpose	Assess feed requirements of the local SRFS, based on population dynamics and the potential output of livestock products in regard to the availability of feeding resources on the island
	materials	Grazed biomass and locally produced and imported feed in tons per year
	processes	Population dynamics and energy requirements of sheep and goats, translated into biomass consumption
	spatial and temporal scale	The island of Samothrace from 1993 to 2016
	system overview	Provided in GLEAM model description (see Supplementary Information: Figure S5)
Design Concepts	basic principles	Retrospective, dynamic and bottom-up or stock driven material flow analysis (MFA)
	modelling approaches	Dynamic modelling approach based on the Global Livestock Environment Assessment Model (GLEAM) [31]
	dissipation	Not explicitly modelled
	spatial dimension	A spatially explicit assessment was not conducted
	uncertainty	Systematic uncertainty assessment of all model input parameters based on the framework by Laner et al. [28], as well as systematic sensitivity testing

The **initial state** of the utilized modelling approach is set by the official annual numbers of sheep and goats and their energy requirements, expressed in tons of dry matter and carbon content of biomass. The assessment of the feed intake of sheep and goats on Samothrace is based on GLEAM, which generally follows an LCA approach with the goal of assessing emissions of livestock production systems. GLEAM includes a method to derive feed inputs of small ruminants based on their energy demand, and production output through the utilization of the herd and feed ration modules (Supplementary Information: Figures S6 and S7). These modules were built in Excel by using the equations provided by the FAO in the GLEAM model description.

Model input data was derived from official statistics, survey data, literature and GLEAM model parameters. The herd module requires annual input data for the number of animals, live weights and ratios of cohorts, death, fertility and replacement rates, lambing/kidding intervals and litter size. The feed ration module requires input data for the daily milk production, annual production of fiber, feed rations and their average digestibility and gross energy content. A survey with 23 local livestock farmers was conducted in 2017–2018 to collect data on 176 parameters regarding flock characteristics, production, processing, grazing, feeding, land management, revenue and costs. Modelling of biophysical flows, live weights of animal cohorts, proportion of dairy animals, male to female ratio, lambing or kidding intervals, litter size and daily milk production were derived from survey data (for a detailed description of the selection process and sample see Supplementary Information Section 3). Death and replacement rates, average daily weight gains, average digestibility of feed ration and average gross energy content of feed ration were derived from region specific FAO data provided in the GLEAM model description. Total annual numbers of animals at the end of each year from 1993 to 2016 and their fertility rates were derived from official statistical data. The calculation of feed rations is based on the energy demand of animals in relation to the available amount of feed. Local feed production was derived from official statistical data on annual primary production [29]. Crop residues were calculated based on areas used agriculturally for crop cultivation and factors derived from literature [34]. Data from local traders was used to estimate annual external feed supply through imports. FAO data was used for the share of leaves in the diet. Total available feed was integrated to calculate the feeding ration of small ruminants in which the remaining feeding gap was assumed to be filled by grazing (Supplementary Data: Tables S3 and S4).

Model output data is generated for total feed demand for small ruminants in fresh grass, hay, crop residues, leaves and grains from 1993 to 2016, in tons of dry mass per year (tDM/year) and tons of carbon per year (tC/year). The model further calculates the share of feed demand that was covered by imported feed, locally produced feed and grazed biomass from 1993 to 2016. By multiplying the number of milked animals by the duration of the milking season and the daily production potential, it was possible to estimate the potential annual milk production of all sheep and goats. Standard deviation values for average daily milk production (sheep: ±12%; goats: ±25%) were generated through integration of data from different sources (Supplementary Information: Section 4). The herd module of GLEAM also allows for the calculation of the share of animals that is available for meat production in each cohort. A standard deviation of ±15% was defined. The modelled increase in production of milk and meat would cause a higher feed demand which is not considered in the results.

2.3.2. Estimation of the Grazing Capacity of Local Ecosystems

For the assessment of the potential overutilization of grazing resources through sheep and goats from 1993 to 2016, we provide estimates for local net primary production (NPP), in combination with a trend derived from the assessment of the Normalized Difference Vegetation Index (NDVI). Data on total available biomass for grazing was derived from Fetzel et al. [24], who utilized MODIS Net Primary Production (NPP) data for 9 CORINE land cover classes identified for Samothrace [35]. These land cover classes were grouped into 3 major land-cover types: "arable land", "natural forests", and "principally agricultural land with significant natural vegetation". For each land-cover type, the authors defined maximum biomass off-take levels to ensure that the feed supply estimates from local ecosystems are realistic and would not degrade essential resources. These net primary production (NPP) levels do not represent total aboveground biomass (NPP_{act}) but refer only to the amount that can be grazed without continuous degradation of local ecosystems. For simplification, we refer to this level of net primary production as NPP in this study. The Normalized Difference Vegetation Index (NDVI) trend applied to NPP values is based on previous research. The NDVI for Samothrace was calculated based on LANDSAT-datasets and their spatially discrete land-cover classifications in combination with a time-series analysis of continuous field data on biophysical ecosystem properties [27]. The NDVI trend for the years 1993 to 2016 was applied to the average NPP for the years 2000 to 2004 in order to derive annual NPP values for the covered period. As this approach is prone to relatively high uncertainties, we applied an NPP range of ±27% with regard to an uncertainty assessment for MODIS and NDVI data sources, derived from Jia et al. [36].

2.4. Social and Monetary Assessment of the Local Small Ruminant Farming System

Qualitative and quantitative surveys were conducted in order to integrate information about constraints and opportunities for agriculture on the island and data on the monetary economy of the small ruminant system. 12 qualitative expert interviews with 6 farmers (Expert 1–6), the dairy owner (Expert 7), 2 traders (Expert 8 and 9), 1 municipal employee (Expert 10), 1 local agricultural consultant (Expert 11) and 1 former vice mayor (Expert 12), were conducted between 2012 and 2018. A content analysis in regard to the past, present and future situation of small ruminant farming on the island was also conducted. Qualitative data from the survey with 23 small ruminant farmers was used to describe the sample (Supplementary Information: Section 3). Results of both qualitative analyses have been integrated into the discussion section. For the monetary assessment, retail prices for milk, cheese and meat, meat processing costs and feed costs for hay and grain, were asked for in the survey (Supplementary Information: Table S1 and Figure S1) and multiplied by the actual purchased or sold quantities of products to estimate annual expenses and revenue. Land, transport and farm utility costs were assessed in the survey per farmer, and average values applied to all small ruminant farmers on the island. For 2016, total revenues from milk, dairy products, meat, wool and subsidies are contrasted with total costs for feed, labor, land, transport, farm utility, processing, and the veterinarian. Total income or loss for the entire small ruminant production system and the average farmer was calculated.

2.5. Validation and Uncertainty of the Utilized Model and Data

The sensitivity analysis was applied to biophysical and monetary parameters. 23 input parameters were tested with a freely chosen ±10% factor and their effect on the 6 output variables, total feed demand [tC/year], sustainable grazed biomass [t/year], revenue [€/year], costs [€/year], income [€/year], potential milk production [kg/year], and potential meat production [kg/year] evaluated. Figure 3 shows the deviation of output variables with higher values than ±1.5%. The different colors represent the 6 different output variables in regard to the ±10% deviation of the input variables. The left side represents minus 10%, the right side plus 10% deviation of input variables. Transparent colors indicate a minus deviation, and full color bars represent a plus deviation of output variables. For a detailed description of the uncertainty evaluation of model input parameters see Supplementary Information: Section 6.

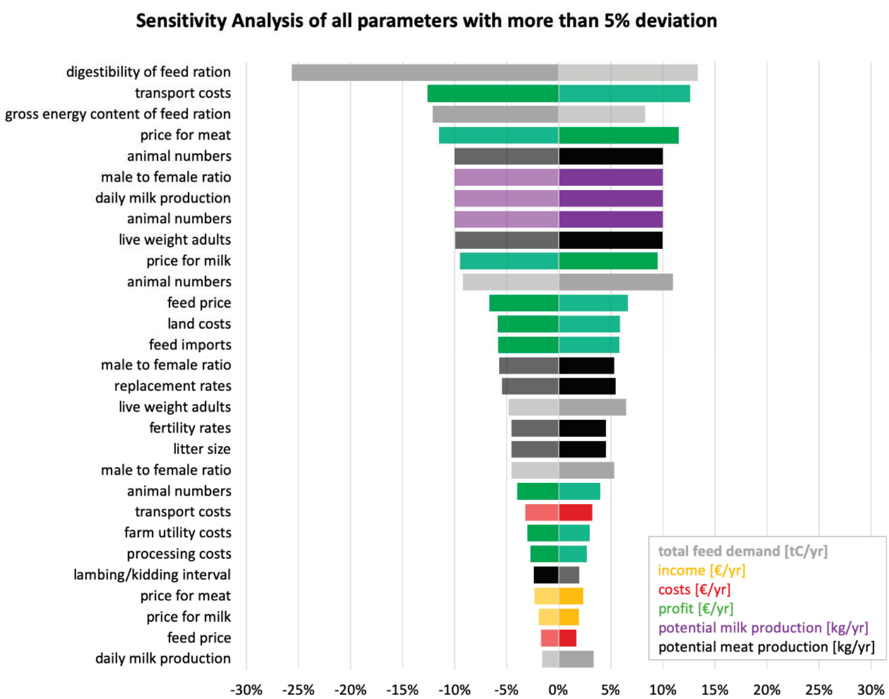

Figure 3. Results from a systematic sensitivity analysis, where each model input parameter was varied by +/−10% and the effects on the main indicator are then plotted.

3. Results

Results contained the development of all livestock units (LSU) from 1929 to 2016 in Section 3.1, th feed demand of the small ruminant population in Section 3.2, the grazing demand in comparison to the grazing capacity from 1993 to 2013 in Section 3.3, an analysis of production potentials in Section 3.4, and the assessment of the monetary economy of the small ruminant farming system (SRFS) in Section 3.5.

3.1. Development of the Total Livestock Units on Samothrace 1929–2016

Figure 4 shows the increasing significance of small ruminants in relation to other livestock species on the island from 1929 to 2016. Total livestock is expressed in livestock units (LSU), which express the nutritional requirements of each species. In 1929, the island had 490 [LSU] cows, 430 [LSU] pigs, 1250 [LSU] Equidae (horses, mules and donkeys), 3026 [LSU] poultry, 1672 [LSU] sheep and 2892 [LSU] goats. Small ruminants represented only 21% of all [LSU] in 1929, compared to cows (22%), pigs (10%), Equidae (45%) and poultry (2%). In 2016, small ruminants represented 93% of all LSU (2276 [LSU] sheep; 2428 [LSU] goats), while cows are reduced to 0%, pigs to 5% (277 [LSU]), Equidae to 1% (56 [LSU]) and poultry remained at 2% (77 [LSU]). Total [LSU] for small ruminants increased from 456 in 1929 to 4478 in 1992 before reaching their peak at 6735 in 2002, declining to values between 4100 and 4800 thereafter. For annual population numbers and [LSU] refer to Supplementary Data: Figure S4.

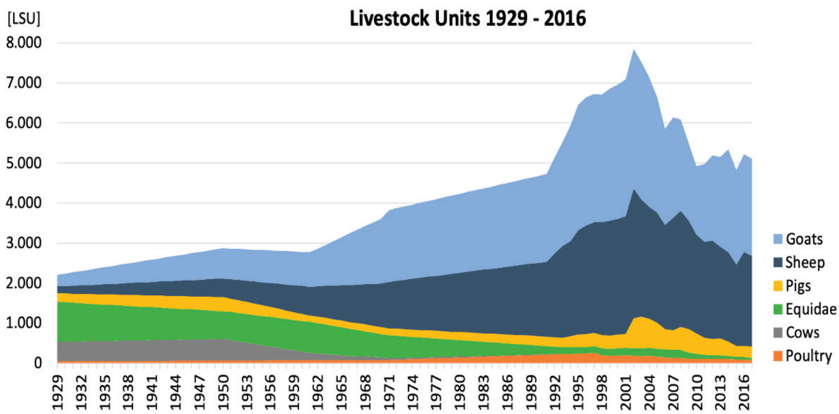

Figure 4. Development of total livestock units [LSU] on Samothrace from 1929 to 2016.

3.2. *The Metabolism of the Small Ruminant Population of Samothrace 1993–2016*

Figure 5 shows the annual feed demand of the small ruminant population in 5 categories: imported feed (orange), locally produced feed (dark yellow), crop residues (yellow), leaves (dark green) and fresh grass (green). Total feed demand was 23,000 tDM/year in 1993, increased to 31,600 tDM/year in 2001, and declined to values between 19,000 and 21,000 tDM/year thereafter. Annual values are provided in Supplementary Data: Figure S5.

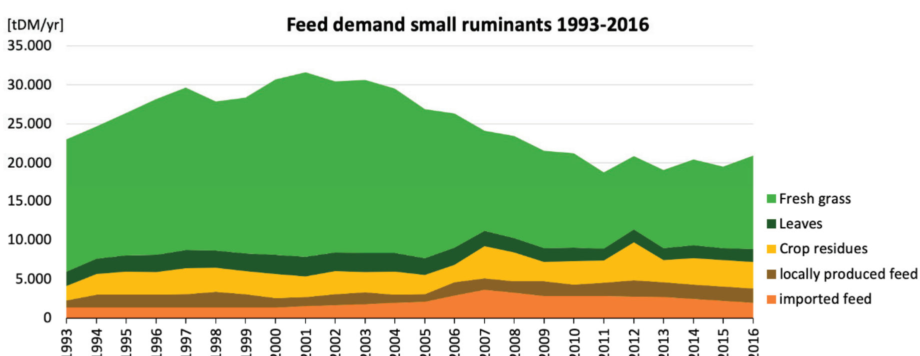

Figure 5. Annual feed demand of the small ruminant population in tons of dry mass (DM) from 1993 to 2016.

3.3. Utilization of Grazing Resources by the Small Ruminant Population

Grazing in local ecosystems accounts for the feed demand categories of fresh grass, leaves and crop residues (Figure 6). In 1993, the grazing demand of the small ruminant population was 9900 tC/year, increasing to 13,700 tC/year in 2001, and declining to values between 7000 and 8000 tC/year thereafter. Herein, we use two boundaries of the net primary production of biomass available for grazing (NPP) to assess the potential overgrazing and therefore, degradation of local ecosystems (see Section 2.3.2). We found that the upper grazing boundary was exceeded for at least 10 years between 1995 and 2005, while the lower boundary was exceeded for almost the entire period.

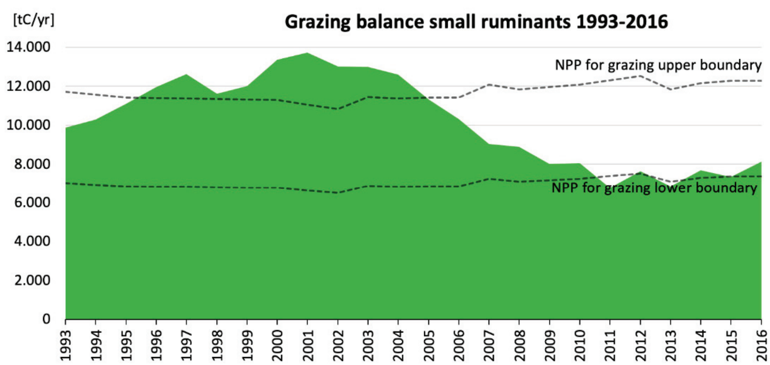

Figure 6. Grazing balance for the small ruminant population in annual tons of carbon (C) from 1993 to 2016. Annual values are provided in Supplementary Data: Figure S5.

3.4. The (Under-)Utilization of Production Potentials

Figure 7 shows the difference between modelled potential and official production numbers between 1993 and 2016, derived from statistical data. Official production of milk (blue solid line) and meat (red solid line) are far below the potential production (dashed lines and standard deviation bars of same color) for the entire period. For the entire period, farmers produced 74% (milk) and 61% (meat) below the modelled production potentials. While potential milk production increases with the population increase from 4800 t/year in 1993 to 6600 t/year in 2002, official production declines from 1330 t/year to 806 t/year. The increase of the official milk production after 2003 can most likely be attributed to the reopening of the local dairy. Annual values are provided in Supplementary Data: Figure S7.

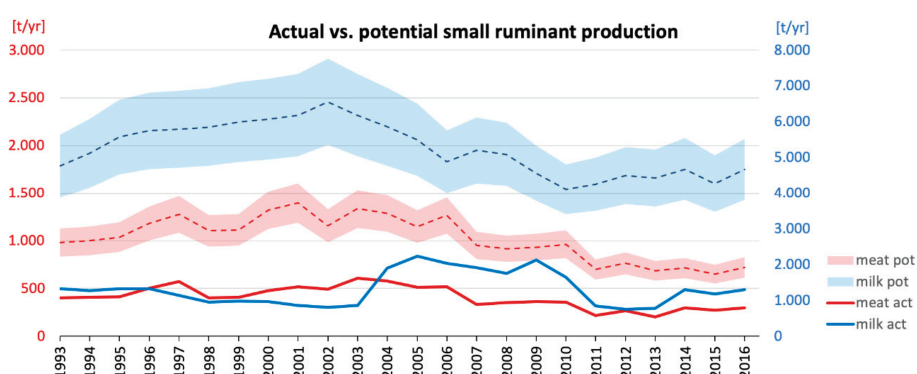

Figure 7. Actual vs. potential production of milk and meat from 1993 to 2016.

3.5. The Monetary Economy of the Small Ruminant Farming System in 2016

Figure 8 plots revenue against cost to estimate the annual income for the entire small ruminant farming system (SRFS) and the average farmer. 171 small ruminant farmers generated a revenue of 4.2 million €/year through milk and milk products, meat and subsidies in 2016. Costs for farm utility, processing, transport, land and animal maintenance were 3.4 million €/year, resulting in a net income of 860,000 €/year. For the single average farmer, this meant a revenue of 25,000 €/year, costs of 20,000 €/year and a net income of 5000 €/year. Values for categories are provided in Supplementary Data: Figure S8.

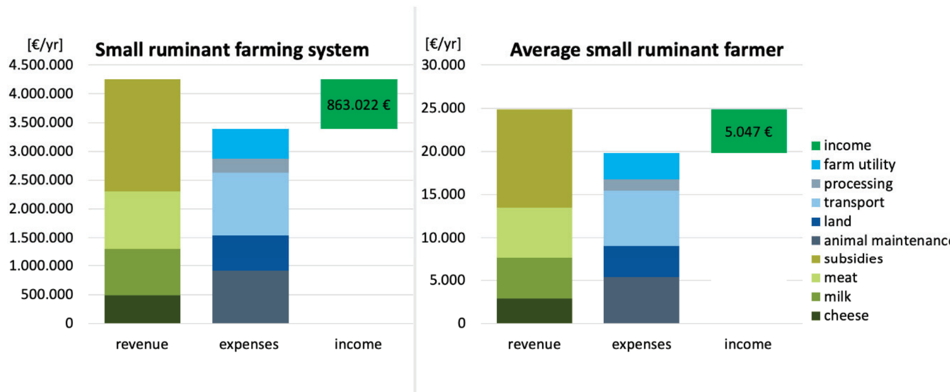

Figure 8. Annual monetary economy of the small ruminant farming system (**left**) and the average small ruminant farmer (**right**) in 2016.

4. Discussion

The integration of biophysical, monetary and qualitative data, in combination with results from previous studies analyzing changes in local ecosystems, enables us to comprehensively describe the current sustainability crisis of the system, its socio-economic drivers and potential ways forward. Consequently, we integrated the quantitative insights gained in the previous sections with qualitative insights from 12 expert interviews and additional literature.

4.1. The Sustainability Crisis of the Small Ruminant Farming System on Samothrace

We found that the small ruminant farming system (SRFS) of Samothrace was highly dependent on local grazing resources throughout the period covered (Figure 5). Thus, a continuous overutilization of local grazing resources undermines the very existence of the system (Figure 6). While both the abandonment and intensification of grazing represent challenges for Mediterranean ecosystems [12], Samothrace is clearly affected by the latter. This, in combination with a social and economic crisis indicated by the low average income of small ruminant farmers (Figure 8) and confirmed in qualitative interviews, threatens the very basis of farming on the island.

Biel and Tan [15] reported, in their extensive survey about the flora of Samothrace, that intense grazing and repeated "slash-and-burn" practices for obtaining pastureland, contributed to fundamental ecosystem changes and threats. A study conducted on the mountainous oak forests in 2017 assessed a sample of 940 trees and found no tree with a younger cambial age than 47 years. The authors concluded that 86% of the island's forests are currently threatened by overgrazing and have *high regeneration priority* [37]. An analysis of the Normalized Difference Vegetation Index (NDVI) based on satellite images from 1984 to 2015 revealed a 40% reduction of large parts of Samothrace's land cover up until 2002, and only a partial recovery in the decade after [26,27]. This development perfectly matches the increase of the small ruminant population prior to 2002 (Figure 4). The reconstruction of the annual herd dynamic and metabolic requirements of all sheep and goats, allows for a reconstruction of the feed demand from 1993 to 2016. From 1993 to 2005, the supplemented feed only represented 10% of the total feed demand, increasing to 20% thereafter (Figure 5). Samothrace, therefore, represents a rather untypical Greek island, as grazing on Greek islands was usually reported to cover below 30% of nutritional needs of small ruminants [8]. Grazing demand surpassed the upper boundary of the estimated NPP between 1995 and 2005, and the lower boundary from the 1980s until today (Figure 6). Thus, the small ruminant population seems to have over-utilized grazing resources for at least a decade, or otherwise, animals were severely undernourished. In reality, it was most likely a combination of both. A reduction of animal numbers is inevitable if local ecosystems are to fully recover. The degradation of pastures is also the most plausible reason for the decline of the small ruminant population after 2002. The reproduction rate of small ruminants was stable at 0.87 from 1993 to 2006 and showed a decline to 0.5 in 2016 (for a more detailed analysis see [24]). Goats were more affected by the population decline between 2002 and 2010 (50%) than sheep (24%). As farmers cannot manage the reproduction of the mostly free roaming goat herds, inadequate feed supply is likely to have played an important role in their declining reproduction rate. This hypothesis is supported by local farmers (Supplementary Information: Section 3) and the fact that farmers started providing more feed only in the years following 2005, when animal numbers were already declining (Figure 5).

The social and economic crisis of the system is reflected in multiple aspects. Of the 23 farmers interviewed for the farm economy survey, 22 have said that they see no future in farming on Samothrace and they advise their children to leave the island. The main reasons given were the increase in prices for feed, high taxes, reduction of subsidies and the declining market prices for products (Supplementary Information: Section 3). For farmers in the north-east of the island, the only local dairy is too far away, so they produce only small quantities of dairy products for their own consumption or, in some cases, their restaurants. Milking is largely done by hand and as prices are so low, it is not profitable for most farmers (Expert Interview 4, 6). The dairy can only process milk between April and July/August and 80% of their production is exported. According to the owner, in recent years they have needed to shut down the production in the middle of July as they cannot sustain their business over the summer (Expert interview 7). In Mediterranean regions, many dairies stop taking milk during summer, as during the later stage of lactation, the coagulating properties of milk deteriorate, which has negative effects on yogurt and cheese production [7]. Many of the farmers interviewed claimed that the low capacity of the dairy is the main reason why they cannot generate any income from milk. Lambs are mainly slaughtered around Easter and kids in the middle of August. Animals are often exported alive as they are purchased by external traders who take care of the transport and the slaughtering. If slaughtered locally, it can legally only be done in the slaughtering house. For many farmers, use of the slaughtering house is inconvenient and too expensive, so they slaughter by themselves and distribute the meat informally or may sell it in their own restaurants. The selling price per kilo is usually lower if the animals are sold alive for export (Expert interview 1, 3, 4, 11). These difficulties are reflected in the current financial situation of local small ruminant farmers (Figure 8). Almost half of their revenue is generated through subsidies, and main expenses are for transport and animal feed. This leaves the average small ruminant farmer with about 5000 € income per year, too little to sustain their business and family.

While the 1990s were, in general, beneficial for small ruminant farming in Greece, as milk prices were high, pastures were lush and farmers received good subsidies, the situation on Samothrace gradually became worse in the last two decades. After 2000, the milk prices started falling and feed prices increased [8]. In the last five years, meat prices on Samothrace have dropped by 40% as traders agreed on a price among themselves before negotiating with individual farmers. Traders benefit from the lack of farming cooperatives on the island that would allow a joint price policy on the part of the farmers (Expert interview 1, 3, 4, 11). The partially coupled subsidy payments, or as stated by local experts, at least the perception that there is a strong correlation, continuously prevent farmers from minimizing their herds (Expert interview 11; Supplementary Information: Section 3). Farmers increased their feed imports slightly after 2005. However, this had more effect on their financial expenses than on the relief of local pastures. The island is disadvantaged in free market competition as transport costs are high, processing facilities are lacking, and the market is flooded with cheap products, mainly from New Zealand and Australia (Expert interview 7, 12). As stated by most interviewed farmers and local experts, without additional income it is not possible to live from small ruminant production on Samothrace today (Expert interview 1, 2, 3, 4, 6, 11).

4.2. The Regression of Sedentary Extensive Small Ruminant Farming Systems

Sedentary extensive small ruminant farming systems (SRFSs) have been regressing at a fast pace over the last decades throughout the Mediterranean [9]. The present case study describes this process on a local island level, contributing to a better understanding of the effects of industrialization on agriculturally-shaped, remote regions within the EU.

Samothrace's socio-metabolic profile was, up until the 1960s, in most aspects, pre-industrial. The first diesel engines for electricity production were installed around 1960, as were the first paved roads, and a port that allowed for larger ships to dock [38]. Samothrace lost 40% of its population between 1951 and 1981 [23], due to a combination of push and pull factors regarding employment opportunities abroad and the fundamental changes affecting the agricultural system of the island. The transformation of local agriculture becomes evident in the changing composition of livestock species shown in ure 4. In 1929, the livestock system had only 2000 livestock units [LSU], was relatively diverse and dominated by Equidae (horses, mules and donkeys). The growth to almost 8000 [LSU] in 2002 occurred almost exclusively in the small ruminant population. While the number of animals has been reduced since then to approximately 5000 [LSU], the livestock system today is still dominated by sheep and goats. The reduction of Equidae and cows documents clearly the loss of one of the central features of livestock in pre-industrial land-use systems, their use as draft animals [39]. Expert interviews confirm the shift in the local livestock system. Up until the 1960s, sheep and goat herders had a special position on the island. People who produced meat and had meat in abundance were considered rich by the community. Back then, nobody possessed more than 100 animals and everything from the animals like meat, milk, wool and skins, was processed and used. Herds of goats grazed in the mountains in the summer and were chased down to the lowlands in winter and for slaughtering (Expert interview 3, 4, 10). With the provision of supplementary feed starting in the 1960s, initially only locally produced, later also imported, the relationship between the herders and the animals changed. While in former times herders chased their animals, following them on foot even over mountainous terrain, animals today come close to the numerous newly built mountain roads when they hear the sound of the farmer's car (Expert interview 4, 10). This reduces the labor efforts of herders but increases their transport costs substantially (Figure 8; Expert interview 6). In the past, animal numbers were kept below the carrying capacity of the island's ecosystems, as there were no feed imports. The introduction of cars, fossil fuels and supplementary feed lowered the labor input but increased monetary costs, and in combination with agricultural subsidies, enabled an increase in animal numbers. Apart from these aspects, the SRFS on Samothrace today is still determined by fairly high labor input, low access to markets, lack of cooperatives and a low level of technological advances. Technological innovation played, therefore, only a minor role in the onset of the transformation of the local livestock system, leaving structural changes in land management and regional markets as more important factors [40].

Despite the lack of statistical data on land use before 1993, the results of the present study clearly indicate that the land use system of Samothrace must have experienced a similar shift, as described by Kizos et al., for the island of Lesvos. In their case study, the authors showed how since the 1960s "complex and multifunctional agrosilvopastoral land use systems were simplified to a pure livestock raising system" [3]. As evident from statistical data and confirmed by local experts, Samothrace's crop production is almost exclusively used for livestock feed today, while this was not the case prior to 1960. The Treaty of Lausanne in 1923 set the beginning of structural land use changes which shaped Greece in the 20th century. Due to population increase and compulsory expropriations, grazing areas were transformed into cultivated land and animals were increasingly kept in enclosures and supplemented with harvested feed [10]. This marked the end of traditional nomadic small ruminant herding in many regions in Greece. At the beginning of the 1930s, agriculture on Samothrace was characterized by small intensive farm holdings in combination with transhumant practices in small ruminant farming. In the decades following 1945, most traditional transhumant or small intensive systems in Greece were then transformed into sedentary extensive systems, in which farmers have only a few ha of land, use communal grazing lands and need to buy supplementary feed [9]. This transition is a good example for the whole of Mediterranean Europe [41], and marked the end of subsistence-based forms of peasantry, also on Samothrace. These changes are reflected in the decline of people employed in the primary sector and the disintegration of half of the island's traditional farm houses between 1971 and 2016 [38]. The allocation of fundamental land use rights to single farmers and the transfer of grazing rights for communal land to the municipal level, changed the situation in the country fundamentally and are of high relevance with regard to current EU CAP (Common Agricultural Policy) regulations.

4.3. The European Common Agricultural Policy (CAP) as a Socio-Economic Driver for Changes Affecting the Small Ruminant Farming System on Samothrace

Subsidy payments, initially by the Greek state and later by EU CAP, represent an important socio-economic driver for changes in local agriculture. This is reflected in the high contribution (50%) of subsidies to local livestock farmers' income (Figure 8). This does not reflect the general situation in Greece, where subsidies usually comprise only a small fraction of farmers' income [42]. Local farmers and agricultural administrators benefitted from sheep and goat farming through specifically-targeted subsidy schemes. More recently, the implementation of the "headage payment" in the early 1990s enabled farmers to increase the size of their herds substantially (Figure 4). One effect of the subsidy payments was that farmers neglected the need for a functioning farming business model. The regular payments simply covered their losses and created a situation in which subsidies became a substantial source of income. Farmers were never educated on how to use these payments in order to create a sustainable business strategy (Expert interview 10, 11). The main achievement of the 2003 reform was the implementation of decoupling of direct payments to farmers from their production numbers in order to reduce farmers' dependence on subsidies and produce according to market demand [43]. This is a process that is still ongoing. This policy was, however, much more directed towards stopping abandonment, as farmers were encouraged to maintain their grazing levels with a cross-compliance maximum of 1.4 heads/ha for degraded semi-mountainous or mountainous pastures, or continue to breed at least 50% of their herds if they graze on communal land [10].

During this reform, it was also made clear by some EU member states that full decoupling could lead to "several risks such as the abandonment of production, the lack of raw material supply for processing industries, or to social and environmental problems in areas with few economic alternatives" [44]. As the sheep and goat sector was considered as one of the sensitive sectors within the EU, member states could continue to couple 50% of payments in this sector [45]. Greece decided to implement this policy in the course of the "health check" of the 2003 reform [46]. The 2013 reform was used to partially reverse the decoupling process that started in 2003, by giving member states the opportunity to "provide coupled support to a wide range of sectors, covering virtually all agricultural production" [47]. Greece further implemented a scheme after the 2013 reform that was created to enable member states to "split the country into several regions in which the reform implementation can differ" [48]. As reported by the interviewed experts, the cross-compliance maximum was circumvented. This was done firstly by farmers declaring communal grazing land multiple times, and later, when this was discovered in 2015, by the regional agricultural administration by simply allocating grazing land on the mainland to local farmers (Expert interview 5, 10, 11). For a region like Samothrace, it is indispensable that the coupling of animal numbers and subsidies can only continue if environmental standards are implemented and enforced. Political clientelism, and stabilizing large livestock numbers, must be overcome. The perception that subsidies directly depend on animal numbers is shared among many farmers and must change. Indeed, farmers who apply environmentally friendly management practices should receive much stronger economic support. The new European CAP regulations, currently under negotiations, should respond to these environmentally and socially threatening discrepancies between European regulations and their local interpretations and implementations.

4.4. The Future of Small Ruminant Farming in the Mediterranean

Sedentary extensive small ruminant farming systems (SRFSs) in the Mediterranean could represent an environmentally sustainable form of livestock production. Due to their resistance to climate extremes, they could also play an important role in the future regarding climate change adaptation [7]. The precondition for this is that the animals feed mainly on biomass not suitable for human consumption, and that the population density is kept so low that ecosystems are not degraded. This, however, would imply that these systems become largely independent from external feed supply, as industrialized feed production connects them with the industrial grain-oilseed-livestock complex [49]. Under these conditions, sedentary extensive SRFSs would contribute to biodiversity and landscape level conservation, minimize environmental hazards, increase the resilience of mixed farming systems, sustain high genetic diversity of small ruminants, and produce high quality products with relatively low monetary and biophysical inputs [50]. Thus, strategies for sustainable development must focus more on the provision of social and economic long-term perspectives for sedentary extensive SRFSs in remote regions.

Currently, there are 23,000 sheep and 24,000 goats on Samothrace, translating into 4700 livestock units (Figure 4). Fetzel et al. [24] defined three major land-cover types suitable for grazing: arable land (32.2 km^2), natural forests (7.9 km^2) and principally agricultural land with significant natural vegetation, natural grasslands and shrublands (134.6 km^2). The cross-compliance maximum of 1.4 heads/ha, implemented by the EU CAP in 2003, would therefore translate into 23,500 animals or a 50% reduction of current animal numbers, if grazing would be abandoned from forests. Defining sustainable numbers of grazing animals for different land-cover classes poses a scientific challenge that cannot be easily overcome. Our data does not allow for a precise definition of a sustainable number of livestock. Spatial and temporal flock distribution, additional feeding, other management practices and natural factors are also highly relevant for sustainable development of grazing-based farming systems. A successful strategy must, therefore, focus on the improvement of sustainable economic, land and livestock management practices in order to relieve pastures and enable farmers to gain sufficient income. Continuous under-utilization of animals (Figure 7) would allow for some increase in production output per animal, without aiming for an intensification equivalent to industrialized systems. At the same time, if the demographic trend continues, the number of people employed in the primary sector will further decline over the next decades. In this context, it is of great importance that retired farmers eventually also lose their grazing rights and give up their herds. These factors could result in a decline of the total number of animals, while young farmers could keep their animals and moderately increase their production output per animal. Although, they will still face problems due to difficult market conditions for agricultural products regarding prices and legal regulation for on-farm sales. These difficulties can only be overcome with a higher level of cooperation. The current lack of cooperation is routed in the historical background of farmers' cooperatives in Greece. In the 1980s and 1990s, cooperatives often became political battlegrounds as they were managed by political representatives or people closely affiliated with political parties who often used these cooperatives for their personal benefit [51]. The experience of most local farmers with these forms of cooperatives was so bad that it shapes cooperation among farmers and their trust of people in general until today (Expert interview 1). It will be a long-term and maybe tiring process but there is no alternative to overcoming doubts and mistrust and finding new ways for a closer collaboration among local farmers. This could eventually lead to a local farmers' cooperative engaging in designing a local brand that stands for high quality and maybe even organic production, which, in turn, can have great advantages for less favored regions in the Mediterranean [52]. In this way, much better prices for their products on regional markets and beyond could be achieved. A cooperative would enable local farmers to, for instance, invest in a mobile alternative to the slaughtering house and in a mobile milking unit, and install cooling facilities for milk collection and storage in regions too far away from a dairy. Currently, first attempts at a new form of cooperation are in progress and it seems like a new momentum for change has been created.

5. Conclusions

This study shows vividly that the effects of industrialization and national or EU agricultural policies on remote regions require special attention. The socio-ecological transformation of recent decades pushed the island community into a dilemma between economic development and preservation needs. Agriculture plays a key role in this process, as the increase of the small ruminant population triggered environmental and social problems which pose threats to the entire island community. The reasons for this development are manifold but are strongly associated with structural land use changes, global industrialization of agriculture and the agricultural market and finally, the regional implementation of the EU Common Agricultural Policy (CAP). To enable a recovery of the local ecosystems, animal numbers must decline substantially. Local socio-economic contexts must be much better taken into account for a new CAP legislation after 2020. Direct payments should reach those who implement measures for sustainable livestock production. The flexibility on a national or regional level should be adapted in a way that a situation, such as that reported in the present study, can be prevented.

Herrero et al. point out that many ideas look great on paper but are only implemented by 10–20% of farmers, for a wide range of reasons. The authors further state that the understanding of environmental implications of livestock systems and factors that need to change has progressed substantially, while little is known of how to practically implement these changes [2]. Transdisciplinary science can play a crucial role in facilitating this process on a local level, by engaging farmers in the scientific process and fostering collaboration among and between farmers and experts from various fields. The long-term research project to which this study contributes, combines analytical and management approaches towards sustainability transitions [53]. Since 2008, researchers have been engaged in a process that tries to achieve scientific progress with a practical outcome. It started with focus group interviews with farmers, which led to a study about the local farming system [54]. Results were used to develop a decision support app (www.happygoats.eu) that was further used to approach local small ruminant farmers. In collaboration with *Terraprima* (www.terraprima.pt), sown biodiverse pastures (SBPs) were applied on 13 plots (SBPs were developed by the Portuguese university spin off *Terraprima* and are based on sowing up to 20 species/varieties of legumes and grasses that are self-maintained for at least 10 years. The legumes, being 'natural factories' of nitrogen, minimize the need for synthetic fertilizers. SBP result in, on average 30%, higher biomass production and higher grazing resistance). A growing number of farmers have become interested in the research project, which will hopefully yield stronger collaboration among farmers and between farmers and researchers in the near future. The response of socio-ecological systems to science interventions only becomes visible after long time intervals. Thus, a systematic evaluation of the impact on the local small ruminant farming system is only possible after a certain period and marks an important next step in this project.

Supplementary Materials: The following are available online at http://www.mdpi.com/2071-1050/12/3/762/s1: Supplementary Information (SI) and Supplementary Data (SD).

Author Contributions: Conceptualization, D.N., C.L., V.G. and D.W.; methodology, D.N. and C.L.; validation, D.N. and C.L.; formal analysis, D.N. and C.L.; investigation, D.N.; resources, D.N.; data curation, D.N.; writing—original draft preparation, D.N.; writing—review and editing, D.N., C.L., V.G. and D.W.; visualization, D.N.; supervision, D.W.; project administration, D.N. and D.W.; funding acquisition, D.N. and D.W. All authors have read and agreed to the published version of the manuscript.

Funding: The authors gratefully acknowledge funding from the Austrian National Science Fund FWF projects SUSAKI (P 27951-G27), CiSciSusaki (TCS 22) and MISO (P27590) and from the Austrian National Committee for UNESCO's "Man and the Biosphere Programme" at the Austrian Academy of Sciences (OEAW). This project has further received funding from the European Research Council (ERC) under the European Union's Horizon 2020 research and innovation programme (grant agreement No. 741950).

Acknowledgments: We wish to thank Giorgos Maskalidis, Carlota Marañon, Jacqueline Kirby, Panos Petridis, Evgenia Tsianou and all participants of the summer schools 2012, 2014, 2016, 2017 and 2019 for their assistance during data collection and many fruitful discussions. We thank the Hellenic Statistical Authority (ELSTAT) for the provision of data and continuous assistance. Further, we want to thank Prof. Marina Fischer-Kowalski for her advice and provision of required resources for conducting this study. Finally, we want to thank the farmers of Samothrace for their collaboration and support.

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

References

1. Steinfeld, H.; Gerber, P.; Wassenaar, T.D.; Castel, V.; Rosales, M.; Rosales, M.; de Haan, C. *Livestock's Long Shadow: Environmental Issues and Options*; Food & Agriculture Org.: Roma, Italy, 2006; ISBN 978-92-5-105571-7.
2. Herrero, M.; Wirsenius, S.; Henderson, B.; Rigolot, C.; Thornton, P.; Havlík, P.; de Boer, I.; Gerber, P.J. Livestock and the Environment: What Have We Learned in the Past Decade? *Annu. Rev. Environ. Resour.* **2015**, *40*, 177–202. [CrossRef]
3. Kizos, T.; Plieninger, T.; Schaich, H. "Instead of 40 Sheep there are 400": Traditional Grazing Practices and Landscape Change in Western Lesvos, Greece. *Landsc. Res.* **2013**, *38*, 476–498. [CrossRef]
4. Rigueiro-Rodríguez, A.; Fernández-Núñez, E.; González-Hernández, P.; McAdam, J.H.; Mosquera-Losada, M.R. Agroforestry Systems in Europe: Productive, Ecological and Social Perspectives. In *Agroforestry in Europe: Current Status and Future Prospects*; Rigueiro-Rodróguez, A., McAdam, J., Mosquera-Losada, M.R., Eds.; Advances in Agroforestry; Springer: Dordrecht, The Netherlands, 2009; pp. 43–65. ISBN 978-1-4020-8272-6.
5. EEA. High Nature Value (HNV) Farmland. Available online: https://www.eea.europa.eu/data-and-maps/data/high-nature-value-farmland (accessed on 13 December 2019).
6. Bernués, A.; Ruiz, R.; Olaizola, A.; Villalba, D.; Casasús, I. Sustainability of pasture-based livestock farming systems in the European Mediterranean context: Synergies and trade-offs. *Livest. Sci.* **2011**, *139*, 44–57. [CrossRef]
7. Caroprese, M. Sustainability of Sheep and Goat Production Systems. In *The Sustainability of Agro-Food and Natural Resource*; Springer: Berlin, Germany, 2015.
8. Hadjigeorgiou, I. Sheep and goat farming and rural development in Greece. In Proceedings of the International Conference Celebrating Pastoral Life Heritage and Economic Development, Athens, Greece, 11–12 September 2014.
9. De Rancourt, M.; Fois, N.; Lavín, M.P.; Tchakérian, E.; Vallerand, F. Mediterranean sheep and goats production: An uncertain future. *Small Rumin. Res.* **2006**, *62*, 167–179. [CrossRef]
10. Hadjigeorgiou, I. Past, present and future of pastoralism in Greece. *Pastor. Res. Policy Pract.* **2011**, *1*, 24. [CrossRef]
11. Álvarez-Martínez, J.; Gómez-Villar, A.; Lasanta, T. The Use of Goats Grazing to Restore Pastures Invaded by Shrubs and Avoid Desertification: A Preliminary Case Study in the Spanish Cantabrian Mountains. *Land Degrad. Dev.* **2016**, *27*, 3–13. [CrossRef]
12. Pinto-Correia, T.; Guiomar, N.; Ferraz-de-Oliveira, M.I.; Sales-Baptista, E.; Rabaça, J.; Godinho, C.; Ribeiro, N.; Sá Sousa, P.; Santos, P.; Santos-Silva, C.; et al. Progress in Identifying High Nature Value Montados: Impacts of Grazing on Hardwood Rangeland Biodiversity. *Rangel. Ecol. Manag.* **2018**, *71*, 612–625. [CrossRef]
13. Pe'er, G.; Bonn, A.; Bruelheide, H.; Dieker, P.; Eisenhauer, N.; Feindt, P.H.; Hagedorn8, G.; Hansjürgens, B.; Herzon, I.; Lomba, A.; et al. Action Needed for the EU Common Agricultural Policy to Address Sustainability Challenges. 2019. Available online: https://www.idiv.de/fileadmin/content/Files_CAP_Fitness_Check/Peer_et_al__CAP_scientists_statement_online_01.pdf (accessed on 20 January 2020).
14. Fischer-Kowalski, M.; Xenidis, L.; Singh, S.J.; Pallua, I. Transforming the Greek Island of Samothraki into a UNESCO Biosphere Reserve. An Experience in Transdisciplinarity. *GAIA-Ecol. Perspect. Sci. Soc.* **2011**, *20*, 181–190. [CrossRef]
15. Biel, B.; Tan, K. *Flora of Samothraki*; Goulandris Natural History Museum: Athens, Greece, 2014; ISBN 978-960-464-585-5.

16. Panagopoulos, Y.; Dimitriou, E.; Skoulikidis, N. Vulnerability of a Northeast Mediterranean Island to Soil Loss. Can Grazing Management Mitigate Erosion? *Water* **2019**, *11*, 1491. [CrossRef]
17. Psyllos, G.; Kizos, T.; Hadjigeorgiou, I.; Dimitrakopoulos, P.G. Grazing land management and sheep farm viability in semi—Arid areas: Evidence from Western Lesvos, Greece. In *Options Méditerranéennes. Series A: Mediterranean Seminars*; CIHEAM-IAMZ: Zaragoza, Spain; Democritus University of Thrace: Xanthi, Greece; Arisstotle University of Thessalniki: Thessalniki, Greece; Hellenic Range and Pasture Society: Thessaloniki, Greece, 2016.
18. Haberl, H.; Fischer-Kowalski, M.; Krausmann, F.; Weisz, H.; Winiwarter, V. Progress towards sustainability? What the conceptual framework of material and energy flow accounting (MEFA) can offer. *Land Use Policy* **2004**, *21*, 199–213. [CrossRef]
19. Haberl, H.; Wiedenhofer, D.; Pauliuk, S.; Krausmann, F.; Müller, D.B.; Fischer-Kowalski, M. Contributions of sociometabolic research to sustainability science. *Nat. Sustain.* **2019**, *2*, 173. [CrossRef]
20. Kelle, U. Die Integration qualitativer und quantitativer Forschung—Theoretische Grundlagen von, "Mixed Methods". *KZfSS Köln. Z. FürSoziol. Soz.* **2017**, *69*, 39–61. [CrossRef]
21. De Molina, M.G.; Fernández, D.S.; Casado, G.G.; Infante-Amate, J.; Fernández, E.A.; Traver, J.V.; Ruiz, R.G. *The Social Metabolism of Spanish Agriculture, 1900–2008*; The Mediterranean Way Towards Industrialization; Environmental History; Springer International Publishing: Cham, Germany, 2020; ISBN 978-3-030-20899-8.
22. Petridis, P. Perceptions, attitudes and involvement of local residents in the establishment of a Samothraki Biosphere Reserve, Greece. *J. Prot. Mt. Areas Res. Manag.* **2012**, *4*, 59–63. [CrossRef]
23. ELSTAT Population Census. Available online: https://www.statistics.gr/en/home/ (accessed on 13 December 2019).
24. Fetzel, T.; Petridis, P.; Noll, D.; Singh, S.J.; Fischer-Kowalski, M. Reaching a socio-ecological tipping point: Overgrazing on the Greek island of Samothraki and the role of European agricultural policies. *Land Use Policy* **2018**, *76*, 21–28. [CrossRef]
25. Petridis, P.; Singh, S.J.; Fischer-Kowalski, M.; Noll, D. The role of science in sustainability transitions: Citizen science, transformative research, and experiences from Samothraki island, Greece. *Isl. Stud. J.* **2017**, 115–134. [CrossRef]
26. Fischer-Kowalski, M.; Löw, M.; Noll, D.; Petridis, P.; Skoulikidis, N. Samothraki in Transition: A Report on a Real World Lab to Promote the Sustainability of a Greek Island. *Sustainability*. Under Review.
27. Löw, M. Spatial Patterns of Land Cover Dynamics on Samothraki Island. Master's Thesis, Alpen Adria University, Vienna, Austria, 2016.
28. Laner, D.; Rechberger, H.; Astrup, T. Systematic Evaluation of Uncertainty in Material Flow Analysis. *J. Ind. Ecol.* **2014**, *18*, 859–870. [CrossRef]
29. ELSTAT Annual Agricultural Statistical Survey. Available online: https://www.statistics.gr/en/home/ (accessed on 13 December 2019).
30. Krausmann, F.; Erb, K.-H.; Gingrich, S.; Lauk, C.; Haberl, H. Global patterns of socioeconomic biomass flows in the year 2000: A comprehensive assessment of supply, consumption and constraints. *Ecol. Econ.* **2008**, *65*, 471–487. [CrossRef]
31. FAO Global Livestock Environmental Assessment Model (GLEAM). Food and Agriculture Organization of the United Nations. Available online: http://www.fao.org/gleam/en/ (accessed on 13 December 2019).
32. Grimm, V.; Berger, U.; Bastiansen, F.; Eliassen, S.; Ginot, V.; Giske, J.; Goss-Custard, J.; Grand, T.; Heinz, S.K.; Huse, G.; et al. A standard protocol for describing individual-based and agent-based models. *Ecol. Model.* **2006**, *198*, 115–126. [CrossRef]
33. Müller, E.; Hilty, L.M.; Widmer, R.; Schluep, M.; Faulstich, M. Modeling Metal Stocks and Flows: A Review of Dynamic Material Flow Analysis Methods. *Environ. Sci. Technol.* **2014**, *48*, 2102–2113. [CrossRef]
34. Krausmann, F. From Energy Source to Sink: Transformations of Austrian Agriculture. In *Social Ecology: Society-Nature Relations across Time and Space*; Haberl, H., Fischer-Kowalski, M., Krausmann, F., Winiwarter, V., Eds.; Human-Environment Interactions; Springer International Publishing: Cham, Germany, 2016; pp. 433–445. ISBN 978-3-319-33326-7.
35. NTSG MODIS GPP/NPP Project (MOD17). Numerical Terradynamic Simulation Group. Available online: http://www.ntsg.umt.edu/project/default.php (accessed on 13 December 2019).
36. Jia, W.; Liu, M.; Yang, Y.; He, H.; Zhu, X.; Yang, F.; Yin, C.; Xiang, W. Estimation and uncertainty analyses of grassland biomass in Northern China: Comparison of multiple remote sensing data sources and modeling approaches. *Ecol. Indic.* **2016**, *60*, 1031–1040. [CrossRef]

37. Heiling, C. *On the State of Oak Forests in Samothraki: Tree Regeneration, Restoration Priorities and Forest Structure as a Mirror of Past Land Use on a Greek Island*; University of Natural Resources and Life Sciences (BOKU): Vienna, Austria, 2018.
38. Noll, D.; Wiedenhofer, D.; Miatto, A.; Singh, S.J. The expansion of the built environment, waste generation and EU recycling targets on Samothraki, Greece: An island's dilemma. *Resour. Conserv. Recycl.* **2019**, *150*, 104405. [CrossRef]
39. Krausmann, F. Milk, Manure, and Muscle Power. Livestock and the Transformation of Preindustrial Agriculture in Central Europe. *Hum. Ecol.* **2004**, *32*, 735–772. [CrossRef]
40. Jepsen, M.R.; Kuemmerle, T.; Müller, D.; Erb, K.; Verburg, P.H.; Haberl, H.; Vesterager, J.P.; Andrič, M.; Antrop, M.; Austrheim, G.; et al. Transitions in European land-management regimes between 1800 and 2010. *Land Use Policy* **2015**, *49*, 53–64. [CrossRef]
41. Rescia, A.J.; Willaarts, B.A.; Schmitz, M.F.; Aguilera, P.A. Changes in land uses and management in two Nature Reserves in Spain: Evaluating the social-ecological resilience of cultural landscapes. *Landsc. Urban Plan.* **2010**, *98*, 26–35. [CrossRef]
42. Galanopoulos, K.; Abas, Z.; Laga, V.; Hatziminaoglou, I.; Boyazoglu, J. The technical efficiency of transhumance sheep and goat farms and the effect of EU subsidies: Do small farms benefit more than large farms? *Small Rumin. Res.* **2011**, *100*, 1–7. [CrossRef]
43. European Commission. The Common Agricultural Policy at a Glance. Available online: https://ec.europa.eu/info/food-farming-fisheries/key-policies/common-agricultural-policy/cap-glance_en (accessed on 13 December 2019).
44. Renwick, A.; Jansson, T.; Verburg, P.H.; Revoredo-Giha, C.; Britz, W.; Gocht, A.; McCracken, D. Policy reform and agricultural land abandonment in the EU. *Land Use Policy* **2013**, *30*, 446–457. [CrossRef]
45. Matthews, A. Two Steps Forward, one Step Back: Coupled Payments in the CAP—CAP Reform 2015. Available online: http://capreform.eu/two-steps-forward-one-step-back-coupled-payments-in-the-cap/ (accessed on 8 January 2020).
46. Canali, G. Common agricultural policy reform and its effects on sheep and goat market and rare breeds conservation. *Small Rumin. Res.* **2006**, *62*, 207–213. [CrossRef]
47. Matthews, A. Brakes Removed from Voluntary Coupled Support—CAP Reform 2018. Available online: http://capreform.eu/brakes-removed-from-voluntary-coupled-support/ (accessed on 8 January 2020).
48. Ciaian, P.; Kancs, D.A.; Espinosa, M. The Impact of the 2013 CAP Reform on the Decoupled Payments' Capitalisation into Land Values. *J. Agric. Econ.* **2018**, *69*, 306–337. [CrossRef]
49. Weis, T. *The Ecological Hoofprint: The Global Burden of Industrial Livestock*; Zed Books: New York, NY, USA, 2013.
50. European Parliament Report on the Current Situation and Future Prospects for the Sheep and Goat Sectors in the EU. Available online: http://www.europarl.europa.eu/doceo/document/A-8-2018-0064_EN.html (accessed on 13 December 2019).
51. Iliopoulos, C.; Valentinov, V. Opportunism in Agricultural Cooperatives in Greece. *Outlook Agric.* **2012**, *41*, 15–19. [CrossRef]
52. Ronchi, B.; Nardone, A. Contribution of organic farming to increase sustainability of Mediterranean small ruminant livestock systems. *Livestig. Prod. Sci.* **2003**, *80*, 17–31. [CrossRef]
53. Fischer-Kowalski, M.; Rotmans, J. Conceptualizing, Observing, and Influencing Social-Ecological Transitions. *Ecol. Soc.* **2009**, *14*, 1–18. [CrossRef]
54. Fuchs, N.A. *Sozial-ökologische Effekte der EU-Agrarsubventionen: Fallstudie zur Ökologischen und Ökonomischen Nachhaltigkeit der Schaf- und Ziegenzucht in Griechenland*; AV Akademikerverlag: Saarbrücken, Germany, 2015; ISBN 978-3-639-78946-1.

© 2020 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (http://creativecommons.org/licenses/by/4.0/).

sustainability

MDPI

Article

Plastics Waste Metabolism in a Petro-Island State: Towards Solving a "Wicked Problem" in Trinidad and Tobago

Kalim U. Shah [1,*], Keron Niles [2], Saleem H. Ali [3], Dinesh Surroop [4] and Doorgeshwaree Jaggeshar [4]

1 Biden School of Public Policy & Administration, University of Delaware, Newark, NJ 19716 DE, USA
2 Institute for International Relations, The University of the West Indies, St. Augustine, Trinidad & Tobago, Newark, NJ 19716 DE, USA; keron.niles@gmail.com
3 Department of Geography, University of Delaware, Newark, NJ 19716 DE, USA; saleem@udel.edu
4 Faculty of Engineering, University of Mauritius, Reduit 80837, Mauritius; d.surroop@uom.ac.mu (D.S.); neha.jaggeshar@uom.ac.mu (D.J.)
* Correspondence: kalshah@udel.edu

Received: 28 August 2019; Accepted: 18 November 2019; Published: 21 November 2019

Abstract: Island systems have limited geographical, ecological, and social capacity to metabolize waste materials produced by the economic activities of their growing populations. Conceptualized as a 'wicked problem', the faults and weaknesses in waste management systems on islands continue to cause acute and cumulative ecological and human health impacts. Trinidad and Tobago is one such island jurisdiction grappling with this situation, particularly being a petroleum-dependent economy. Through the lens of neo-institutional theory, this case study of waste management in Trinidad and Tobago unpacks the efforts, reactions, drivers and circumstances that have led to various successes and failures but no definitive solutions over time, especially regarding plastics and packaging materials. We identify three temporal phases of policy evolution that have altered the waste metabolism trajectory to date: (1) government led patriarchal approach of traditional landfilling combined with behavioral change campaigns to reduce, reuse, and recycle, (2) to a more democratic, shared burden, public-private partnership approach combined with attempts at incentive-based regulations, (3) to the present, more private sector-led voluntary bans on production and use of plastics. This study contributes to our understanding of the institutional factors that shape the search for solutions to the wicked problem of island waste metabolism.

Keywords: plastics; Trinidad and Tobago; institutional; metabolism; waste management; islands; public-private partnerships

---

1. Introduction to Waste Management on Islands

Waste generation is increasingly regarded as one of the most urgent environmental issues of our contemporary era, one demanding global attention. Relative to 2.01 billion tonnes in 2016, the yearly waste generation around the globe is predicted to reach 3.4 billion tonnes in the coming 30 years, representing an increase of 70% in global waste by 2050 [1]. The plight in Small Island Developing States (SIDS) bears no exclusion. With the continuous improvement in their lifestyle and economies, consumption and waste disposal patterns have changed radically. Unlike the agrarian period, the emergence of non-bio-degradable materials in today's time is posing a challenge on island territories [2]. The average waste generation of SIDS inhabitants on a daily basis is 2.30 kg per person compared to the global average of 1.55 kg [3].

The ongoing growth of solid waste and the delayed rate of degradation of most components have been reported as the fundamental factors causing a constant rise in marine litter, notably in the form of long-lasting plastic waste, found at seas and coastal regions [4]. Statistics depict that global plastic production has grown from 1.5 million tonnes in 1950 to 348 million tonnes in 2017 [5]. Owing to its characteristics of being lightweight and non-biodegradable, plastic is hugely favored by manufacturers and consumers. However, these properties are the reasons plastic is troublesome to the marine environment, while the former ascertains its diffusion in the seas, the latter ensures its everlasting existence [6].

With waterways being the dumping ground for plastic waste and encompassing its impacts on the environment, human health, economic and aesthetic value, plastic management is a growing multi-dimensional issue [3,7]. The geographical feature of islands elevates their vulnerability to plastic debris given that dumping areas are located next to the seas or along river streams. Estimates suggest that 80% of marine waste arises from land-based activities and around 2% of the yearly plastic production find their way into the seas. Plastics have been acknowledged as a "silent killer" residing in the marine ecosystem [6].

Several studies have been well documented, bringing forward that islands are becoming the source, temporary reservoir, and final sinks of plastic waste. Back in 2010, the Indian Ocean was discovered to contain a garbage patch, the third major plastic collection spot following the North Pacific Ocean and Pacific Atlantic Gyre. With around 90% of mostly plastic wastes being dumped into the Indian Ocean, over 40 countries, both littoral and African coastal areas, are severely polluted [8]. The remoteness of islands no longer guarantees their protection against plastic debris. For example, Henderson Island in Eastern South Pacific, has been identified to possess the highest record of plastic pollution, notably, 99.8% of the total waste collected on the beach during their study [9]. A second study by [10] highlighted the substantial plastic accumulation on Cocos Island, located on the northern coast of Australia. An estimate of 238 tonnes of anthropogenic waste was reported, out of which 25% were categorized as disposable plastics.

An effective waste management system is viewed as a vital factor to promote sustainable and healthy communities, however, this notion is frequently neglected in low-income countries [1]. From the study of [11] on Seychelles Island, inadequate waste management has been identified as a fundamental driver in making uncontrolled waste disposal an environmental threat. On the other hand, others reported that many countries are finding themselves in a dilemma whereby they can no longer control the amount of waste being generated through their waste management systems. Consequently, large plastics and microplastics eventually land into rivers and seas [12].

Considering the Waste Framework directive under the aegis of the European Standard, islands are required to have proper waste management systems meeting the main objectives of (i) reducing waste generation, (ii) landfill disposal, (iii) reusing and recycling, and (iv) valorization of energy. Nonetheless, island systems around the globe, ranging from Hawaii and the Caribbean area to the Canary Islands, Cyprus, and the Azores, waste management is a problematic sector [13]. Waste generation coupled with tourism association in islands is emerging as an acute environmental burden. Inundated by the sheer capacity of tourism waste generation, waste management in islands is further exacerbated. Several researchers summarised the adverse impacts of the tourism industry in island settings. Waste from tourism has nearly doubled the regional generation rate. Moreover, exposing the community to new cultures and lifestyles, an influence on the consumption and disposal paradigm is being observed [14–16].

A multitude of studies has highlighted the different constraints leading to the mismanagement of wastes in islands around the world. These include frequent problems like inadequate governmental support, lack of long-term planning and insufficiency in skilled personnel, amongst others [17]. Others reported that despite initiatives to reduce waste production, recycling was still at an embryonic stage in several island communities [18]. The lack of markets or markets of sufficient size for recycled materials is also a barrier [19]. Recent studies have identified similar contributing elements to the difficulty of managing wastes: New studies indicated issues of weak governance, shortcomings in formal procedures, land-use competition, and absence of efficient technologies [20]. The cost of operating waste disposal facilities and waste transportation is often challenging for highly indebted island governments [21]. Lack of waste disposal sites and improper landfill planning and construction, owing to the small size and isolated characteristics of islands were mentioned in [22].

2. Island Waste Metabolism Is a *'Wicked Problem'* for Policy-Makers

The demarcation line between "tame" and "wicked" problems was first introduced by Rittel in 1973 [23], where the term "wicked" was used to characterize challenges that were misleading or difficult to detect. They are often affected by the presence of knotty political and social aspects, with such aspects often evolving over time. Wicked problems affect whole systems, which therefore brings forth another problem of framing since the problem can be defined from the different viewpoints of various stakeholders [23,24]. Rittel proposed that the key characteristics of wicked problems include (i) the identification of wicked problems relies on the diversity of opinions of stakeholders, (ii) wicked problems entail no right or wrong, true or false solutions, (iii) since wicked problems have multiple inputs, there are hence a myriad of solutions, (iv) given that each problem is distinct, solutions are also unique and previously identified solutions cannot be applied to new problems, (v) every identified wicked problem leads to another wicked problem [25,26].

Island waste management challenges remain common and the impacts are heightened due to their locations and environmental sensitivity making the situation complicated [3]. Variations in socio-economic and geophysical characteristics across different islands constrain the ability to deploy standardized or scaled solutions to waste streams [27]. In Caribbean countries, variations in the volume of waste, socio-economic standing of communities and traditional waste handling practices all contribute to different national waste management strategies [28].

Given the complex and multifaceted challenge of island waste management, we postulate that it can be framed as a 'wicked problem'. Many of the premises of what characterizes a 'wicked problem' in the field of public policy [29] are notable in the island waste management discourse. These characteristics include (1) wicked problems actually being comprised of a number of overlapping problems where solution sets for one overlap often intensify the magnitude of other overlaps, and (2) wicked problems entangling numerous diverse stakeholders making communication, process coherence toward solutions and negotiations very difficult.

2.1. Tackling Such a Wicked Problem

The literature has decidedly veered towards the premise of 'coping' with or mitigating wicked problems and less so towards ultimate solutions. Three veins of studies look at tackling wicked problems. First is one that is now widely elaborated, deriving from [30] in the design thinking and systems approaches to social planning. This suggests understanding the components and relationships within problem contexts so as to work towards better outcomes. Evolving from this approach has been, for example, the 'integrated systems design' such as Elia and Margherita (2018) which emphasize collective approaches to problem resolution and curating relevant tools and analytical guidelines towards such. This vein of studies tends towards reductionist and mechanistic searches for more favorable problem outcomes. Second, are those studies that promote interdisciplinarity and innovation through collaborative frameworks as the way forward. Here, the value of the eventual coping approach to the 'wicked' problem under investigation becomes less deterministic and more probabilistic. Third, are a growing cohort of studies that are concerned with the underlying motives and determinants of the decisions of actors that are consequential to the problem at hand and its future evolution. Encountered are studies interested in 'management' of problems by leveraging underlying 'carrots and sticks'. [31] for example examines power differentials among actors as the premise for problem-solving, suggesting either authoritative, collaborative or competitive coping strategies. Several others apply psychological frameworks to shed light on actors' motives [32].

2.2. Analysis Through the Neo-Institutional Lens

It is primarily in this third vein of approaches that we introduce neo-institutional theory as an appropriate framework for unpacking and understanding the underlying nature, motivators, and determinants of 'wicked' problems such as island waste metabolism. According to [33],

> "Institutions are social structures that have attained a high degree of resilience. [They] are composed of cultural-cognitive, normative, and regulative elements that, together with associated activities and resources, provide stability and meaning to social life. Institutions are transmitted by various types of carriers, including symbolic systems, relational systems, routines, and artifacts. Institutions operate at different levels of jurisdiction, from the world system to localized interpersonal relationships. Institutions by definition connote stability but are subject to change processes, both incremental and discontinuous."

Institutional theory, therefore, provides a workable framework to analyze the dynamics of actors, stakeholders, and situations in the operating environment. Past studies such as [34] suggest the main institutional complexities related to waste management include weakened regulations and policies, lack of public awareness and uncontrolled waste disposal techniques, but relevance to island context is to date unverified. The application of neo-institutional theory, therefore, describes waste management in terms of policy decisions and actions over time, driven by three fundamental institution forces.

First are the coercive or regulatory forces that empower institutions with the authority to sanction and to set pertinent rules, laws, and regulations, as well as the roles and responsibilities of the involved agencies. Although waste management regulations are enacted in numerous island nations, even basic challenges in enforcement mean that illegal dumping and waste burning, for example, are everyday practices [21,35]. Coupled coercive forces is the influence of the political agenda and commitment to various politically favored solutions. [36] points out that island waste legislation remains archaic and largely unconsolidated, lacking in defined roles and responsibilities, predominantly concentrated on "end of life responses" [2].

Second are normative drivers that involve pressures to take actions that are widely derived from shared beliefs of appropriate behavior, often promulgated by well-coordinated and established actors in society. At the forefront of these are typically community and environmental activist groups, as well as professional associations and business alliances [37]. The increasing professionalization of the waste management sector has been a pivotal factor in raising the profile and importance of waste metabolism on the political and social agenda. Also, importance has been the increasing expertise and capabilities of non-governmental organizations [37].

Third are cultural or cognitive drivers that focus on persistent changes in conceptual beliefs, mental models, and interpretations of shared meanings that societies go through and lead to significant policy changes. This perspective also stresses the importance of achieving change that is internalized by society and culturally supported in order for it to be satisfying and sustainable in the long run. Central to how prevailing societal culture influences waste management is changing norms, attitudes, beliefs, and perspectives across key stakeholders. Recent surveys in island contexts suggest growing awareness and concern about waste issues including reducing volumes and proper disposal [35,36].

Waste management actors both shape and navigate the institutional drivers in the operating environment including norms, rules, and expectations that define what constitutes legitimate behavior. These actors are, therefore, considered to be legitimacy seeking and susceptible to the institutional drivers identified. The legitimacy building actions that actors take can be in different forms, just as these actors are motivated differently by the prevailing institutional drivers. These can include actions geared towards accruing moral, cognitive and/or strategic legitimacy.

The institutional environment and the strategic maneuvers of actors including government, the business sector, and civil society, all shape the evolution of island waste metabolism. The institutional context and the maneuverability of actors are also shaped by the unique limited and constrained context of island geography, resources, and development trajectories [37]. Figure 1 is an illustrative summary of the conceptual framework through which we analyze the case study of Trinidad and Tobago in order to better understand the roles of institutional drivers and actors in waste, particularly plastics, metabolism to date, therefore providing insights pertinent to further disentangling of this wicked problem.

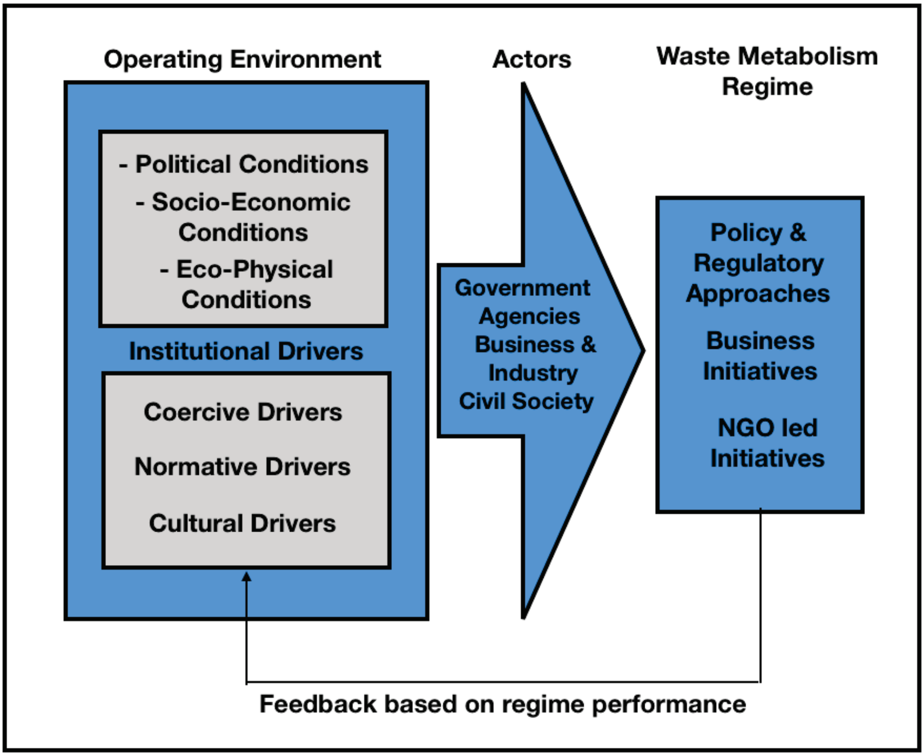

Figure 1. The Institutional Framework in which island waste metabolism exists.

3. Methods

The study is designed as a single explanatory case study research design [38,39] focused on Trinidad and Tobago given the nature of the research objective which is to understand the institutional drivers for waste management policy decisions and management actions over the last decades [39].

Multiple data collection tools and materials will be applied to triangulate and validate primary and secondary data collected from different sources. These include archival data collection and qualitative interviews. Secondary information was collected from public sources including internet and websites (organization websites, newspapers) as well as requests from government and corporate entities for annual reports, publications and communications materials such as quarterly newsletters. Official government archives were also consulted rendering items including Annual National Budgets and breakdowns for public agencies, Public Service Investment Portfolios with allocations to new government projects and national statistical data. Secondary information was important to compliment interviews during the research process but also for content analysis to identify general themes to further explore in interviews [38].

In order to identify interviewees, an initial listing of the key organizations involved with waste metabolism in Trinidad and Tobago was established. The list was constructed through reviews of the secondary information acquired, government reports and newspaper reports (The study approach including identifying key organizations involved in waste management and key informants was facilitated by two study researchers who worked in the Trinidad and Tobago environmental sector.). At least two representatives of each organization were identified as potential informants and requests for interviews were made. For each organization, the target informants were (i) the chief executive or highest-ranked officer involved in waste regulations and (ii) the organizations' technical or operations lead with direct responsibility for waste-related regulatory or operational activities. During this initial round of interviews, where informants identified additional potential informants, these recommendations were evaluated by the research team and a second round of informants from this snowball approach were interviewed [40].

A semi-structured interview approach was adopted for this study [38], whereby a specific interview guide with similar questions was applied to each purposeful informant. The actual wording of the questions was adjusted to suit specific informants, however, the same general lines of inquiry were pursued for all informants [41]. This enabled comparability within and between different informants across the waste metabolism value chain. In face-to-face or online conference call format, interviews lasted approximately thirty minutes.

The proposed data analysis process draws heavily from the constant comparative method which enabled the ongoing analysis and interpretation during the process of data collection itself, between primary and secondary information. The inductive analytical approach of pattern matching and taxonomy coding allowed substantive concepts and themes to emerge primarily from the narratives after which we ascertained which, if any, were associated with the institutional drivers, actors, and actions, operating environment and regulatory or non-governmental waste management decisions and directions [42].

While interview methods are noted for their relative strengths including the ability to focus directly on case study topics, they may also be compromised due to researcher bias, response bias, and inaccurate accounts from informants due to poor recall [42]. To address these weaknesses, we triangulated information from interviews with secondary information. Threats to reliability were reduced in the study design by using semi-structured questionnaires. This approach allowed enough flexibility to capture the story but enough structure to build consistency and ensure quality. Reliability was also reinforced by interviews undertaken by the researchers themselves. Internal validity can be challenged in single case studies. Here it was minimized by triangulation of data sources and the use of multiple respondents at multiple organizational levels.

4. Results and Analysis

4.1. Case Study of Island Waste Metabolism in Trinidad and Tobago

4.1.1. The Current Situation

The magnitude of the waste challenge is illustrated by the most recent waste characterization conducted in 2010 [43]. It identified the different types of waste as follows:

On a national level, with the exception of organic material, plastics dominate the waste-landscape, as a percentage of total waste, particularly in Trinidad (see Figure 2). Notwithstanding this, plastic waste constitutes at least a fifth of total waste on both islands. As it relates to volume, the waste characterization study in 2010 indicated that 700,000 tonnes had been delivered to landfills in Trinidad for the year of the study, while approximately 17,228 had been delivered to the landfill site in Tobago [44]. More recent data pertaining to the character of waste is not available. Figures 3 and 4 illustrate the waste characterization for Trinidad and Tobago respectively, for the year 2010.

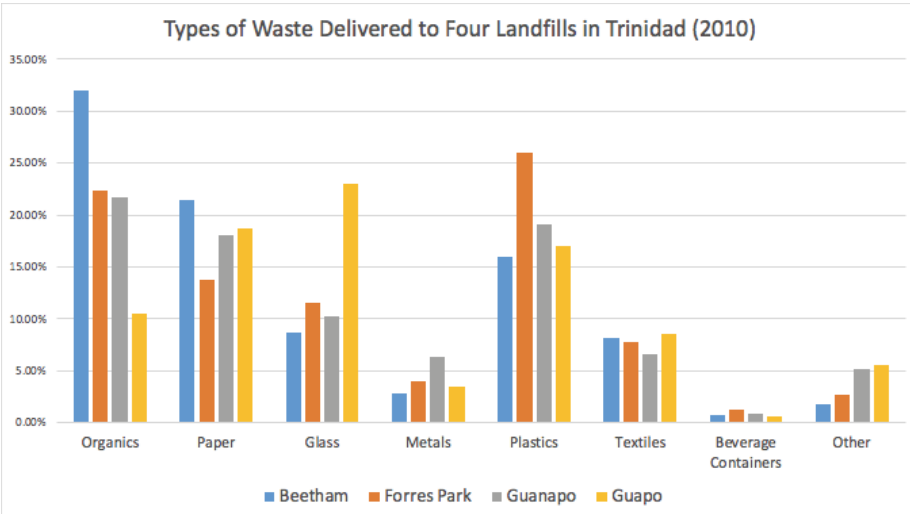

Figure 2. Waste characterization in Trinidad and Tobago for the year 2010. Source: National Waste Recycling Policy, Government of the Republic of Trinidad and Tobago [43].

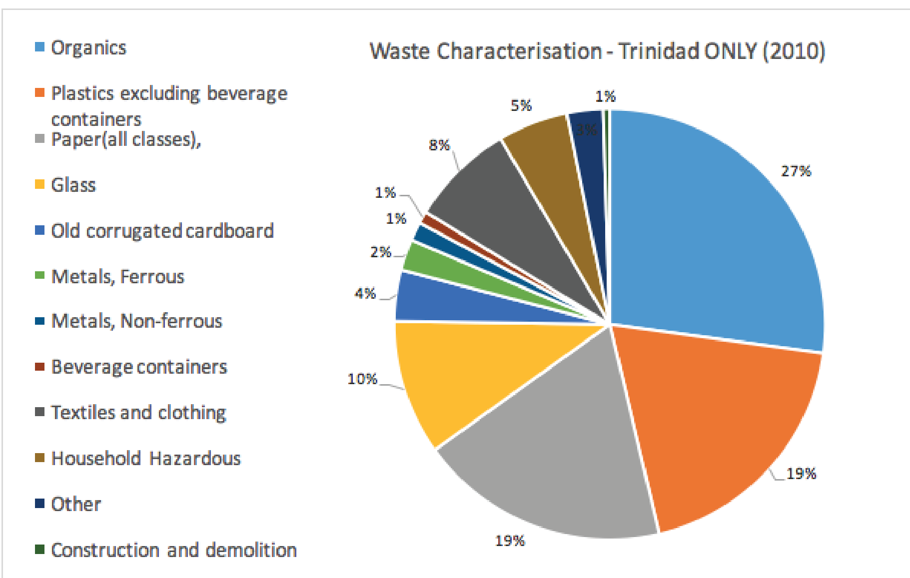

Figure 3. Waste Characterization for the island of Trinidad only, in 2010.

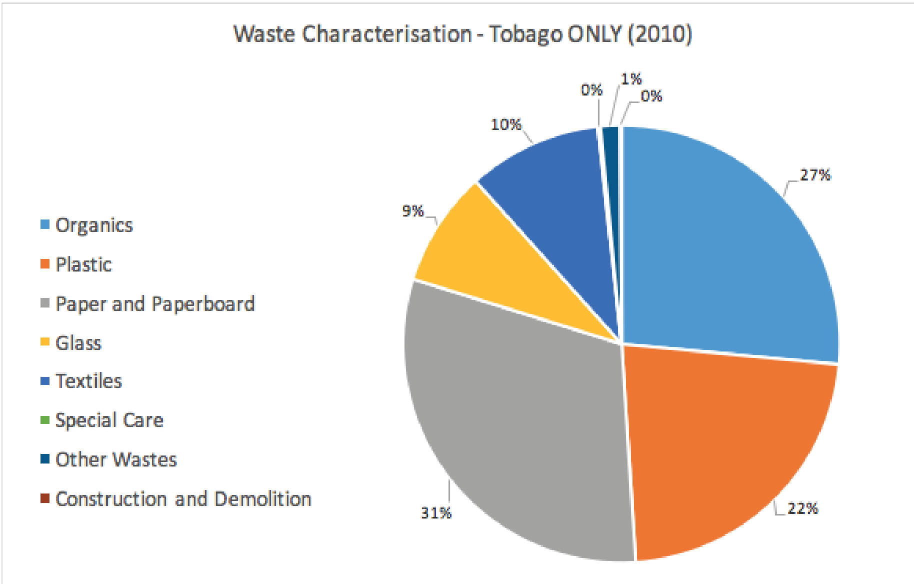

Figure 4. Waste characterization for the island of Tobago only, in 2010.

In terms of expenditure on solid waste management in Trinidad and Tobago, over the course of the last 10 years, Government of Trinidad & Tobago (GORTT) allocations have fluctuated but have decreased overall, from a high of Trinidad & Tobago dollars (TTD) $8.7 million in 2010 to TTD $6.67 million in 2020 (See Figure 5). No expenditure was reported as being allocated to solid waste management for 2015. That aside, in light of recent attempts to improve recycling locally, particularly through the establishment of a Waste Recycling Management Authority (which will initially be housed under the Solid Waste Management Company of Trinidad and Tobago (SWMCOL)), funding allocations have increased in recent times. In fact, in 2019 TTD $1 million was allocated to a "Public Sector Recycling Programme". Similarly, in the 2020 allocation, TTD $5 million was set aside for the upgrade of recovery and recycling facilities, plant and equipment" [45].

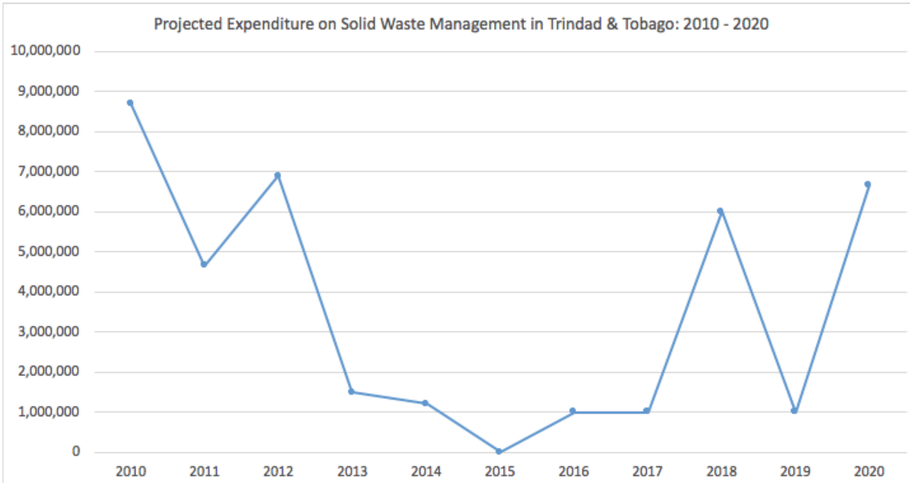

Figure 5. Projected expenditure on solid waste management 2010–2020 (compiled by authors).

4.1.2. The Policy Environment

In modern times, the country's waste management policy landscape has been characterized by an Integrated Solid Waste and Resource Management Policy, National Waste Recycling Policy, and a National Environment Policy. Notably, the National Environment Policy "recognizes major drivers of solid waste generation to be unsustainable consumption patterns and the inefficient use of resources in the production of goods and services" [46]. The need for behavioral change in order to transform the manner in which goods and services are produced and consumed is therefore underscored. However, the theory or model of change employed often involves educational campaigns that follow an approval process very similar to the one mentioned earlier with respect to policy. Some twenty years ago, a National Beverage Container Bill was drafted but to date, has not been approved and passed by Parliament, even as it has cropped up for debate from time to time. The Bill would, among other things, set up bottle (plastic and glass) deposit-return mechanisms and promote producer responsibility among manufacturers. As recently as 2019, the Minister responsible for the Environment identified the passage of this bill as a prime concern.

All these policy instruments find relevance and place in the overarching context of the National Development Strategy of Trinidad and Tobago 2016–2030 (Vision 2030) which promises to strengthen national environmental governance through the: "development of a comprehensive and well-coordinated system to address the many interconnected environmental issues, including: natural resource management (terrestrial ecosystems and forests, biodiversity, water resources and marine ecosystems and resources), waste management (waste disposal, solid waste, electronic waste and hazardous waste), pollution and chemicals management (air pollution, ozone depletion, water pollution, land pollution, marine pollution), built environment management and climate change" [47].

In light of the need for more up to date data to support decision making, in 2019, the SWMCOL issued a public request for proposals for the following:

i. A comprehensive solid waste quantification and characterization study at three (3) landfills
ii. A comprehensive waste centroid study for Trinidad
iii. An assessment of all current public and private waste separation at source and recovery and recycling programs existing throughout Trinidad and Tobago [48].

While steps are being taken to address the lack of data about waste, a further significant challenge with respect to enhancing waste management is related to governance. The introduction of systems to facilitate the recycling of plastics and other materials is in large part dependent upon the reform and strengthening of the institutional framework, established to manage and regulate waste collection and disposal.

4.2. Key Actors

Policy implementation is distributed (or fragmented) across several institutions as shown in Figure 6. SWMCOL is responsible for the "management and control of all wastes severally or jointly with any other company, statutory authority or persons in Trinidad and Tobago" [49]. In 1983, the organization's remit surrounded the operation and management of three landfills. However, in 2003, SWMCOL's mandate was expanded "to include the preservation and upgrade of the environment" which extended to the provision of services such as General and Special Waste Collection, Fecal Waste Disposal, Portable Sanitation Product Rentals and Recycling [49]. Though initially a department of SWMCOL, the Community-Based Environmental Protection and Enhancement Programme (CEPEP), which currently operates as a separate publicly owned company that provides unemployment relief for unskilled labor through the provision of services, focused on "environmental protection, enhancement, and beautification" [50]. However, CEPEP (among other services) also offers waste and dead animal removal services. Additionally, in conjunction with the Office for Disaster Preparedness and Management (ODPM), CEPEP offers clean up services after natural disasters [51].

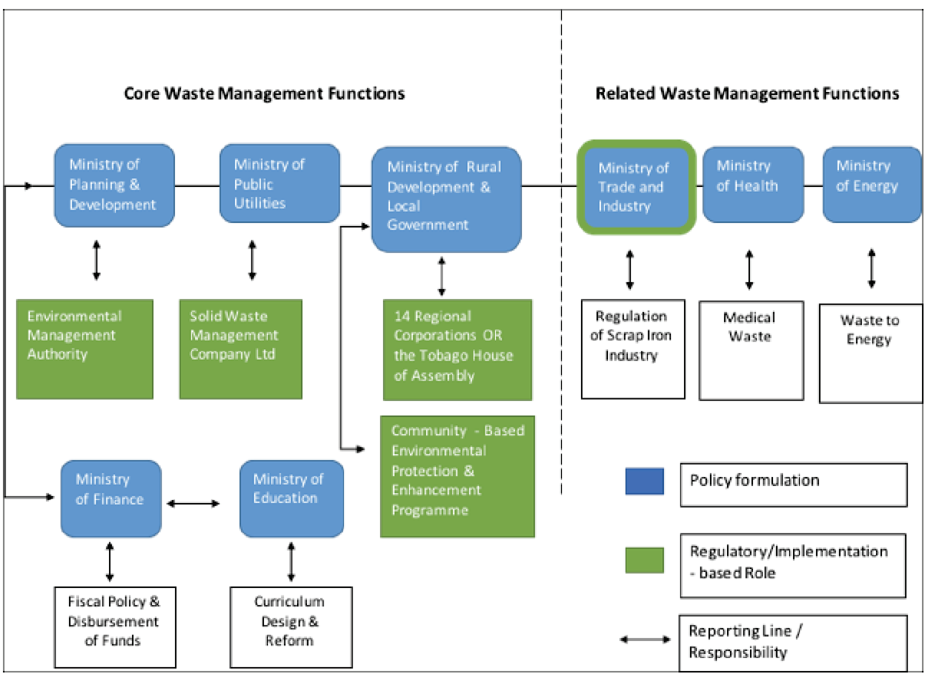

Figure 6. The key institutional actors and relationships.

It should, therefore, be noted that SWMCOL is not responsible for all matters related to waste. The Ministry of Health is responsible for medical waste while the Ministry of Trade and Industry is responsible for the regulation of the scrap metal industry. Additionally, local government authorities are responsible for waste collection and delivery to landfill sites. The Environmental Management Authority (EMA) is tasked, inter alia, with the development and implementation of policies (including the National Environment Policy) and programs for the effective management and wise use of the environment, with the promotion of public awareness and the development of national standards related to the environment [52]. The Act also mandates the organization to "make recommendations for the rationalization of all governmental entities performing environmental functions" [52]. While the EMA has been central to drafting most of the waste management policies currently enacted, it is not directly responsible for implementation.

4.3. Interactions and Outcomes Regarding Plastic Wastes

While these institutional arrangements reasonably serviced municipal, commercial, and industrial waste management including hazardous waste management, no significant efforts were made around waste recycling, particularly for plastics. The only long-standing waste recycling effort in the country was glass bottles whereby the major bottlers voluntarily provided a few cents per returned beer bottle, and this has been the norm since the 1970s. By the early 2000's with the insertion of the newly established EMA in the policy mix, and growing concerns around major flooding events in urban and suburban areas that disrupted business, commerce, and quality of life, fresh interest in waste management grew as the public and authorities began noting the vast volumes of plastic bottles and debris clogging waterways, drains, pipes, and culverts, and also washed out to the nearshore beaches. Interest in reducing and recycling plastics surged.

It should be noted that several attempts have been made by local government authorities to partner with other institutions, including the EMA, in order to boost efforts at recycling at the municipal level within Trinidad and Tobago. For example, the Port of City Corporation partnered with the EMA's recycling initiative known as the 'iCare' initiative in order to launch a 'curbside' recycling program within the nation's capital city [53]. Additionally, in several regional corporations, there have been a number of discrete in-house projects aimed at recycling and reusing tyres, inclusive of a collaborative project with the University of the West Indies focused on researching ways in which recycled rubber produced from automotive and truck scrap tyres (also known as crumb rubber) could be used for road works [49].

Still, however, there were hiccups, especially with the Beverage Container Bill which remained unsupported by major political interests within the manufacturing sector. It is notable that, for example, during this period of concerns with plastics recycling, the manufacture of plastic bottles for water and beverages surged. Manufacturers of plastic products assumed leadership positions in the local Manufacturers Association and Chambers of Commerce, even winning prestigious national awards including the Prime Minister's Exporter of the Year Award and Manufacturer of the Year Award. One particularly problematic optic was the awarding of the Green Business Award to the 'largest, most modern and eco-efficient' commercial bottled water interest in the country. Legislation to enforce recycling was stymied by political and business interests but blamed on the 'complexity and lack of clarity of the policy'. In this environment, with urgency to act, the government and the non-governmental sectors sought to collaborate on solutions.

One of the most ambitious initiatives taken up by the non-governmental sector in partnership with SWMCOL was the Plastikeep Initiative, launched around 2010 by the Greenlight Network. This was a plastic waste recovery project geared toward increasing "public awareness of the proper management of plastic waste, encouraging community participation and building recycling capacity in Trinidad". The project emphasized specifically on community education and the recovery of unwanted or discarded plastics from households. Via this project, Type 1 plastics, also known as Polyethylene Terephthalate (PET) were collected and sent to a SWMCOL Beverage Container Processing Facility, processed into flakes and exported. According to the Greenlight Network (GLN), "other types of plastic not directly processed by SWMCOL were sorted by type and color and baled for export" [54].

Notwithstanding the above, diseconomies of scale restrict the ability of NGOs like GLN, along with other small businesses from making investments in machinery that would allow them to engage in these activities on a commercial scale. In addition to this, the material collected was often co-mingled and contaminated, resulting in a labor-intensive sorting of materials for recycling. Moreover, there was, and still does not exist a legislative or regulatory framework that incentivizes the return or sorting of plastics at the level of the end-user. The GLN was therefore dependent upon on multiple iterations of government financing through the Green Fund (which is the national accumulation of a Green Fund Levy of 0.3% on gross income paid quarterly by companies and business partnerships) to sustain its operations. Indeed, in spite of receiving some support from the private sector, when public funding ceased in 2016 the organization found itself in debt and largely unable to continue.

After almost a decade of effort, Plastikeep was officially closed in 2019 and its collection bins were handed over to the EMA as a component of their Recyclable Solid Waste Collection Project, also referred to as the "iCare" project. iCare, which stands for "Community, Awareness, Recycle, Everyday" is also funded via the aforementioned Green Fund and aims to "create heightened public awareness on the benefits of recycling and the adverse effects of poor waste management." [55]. While it is a positive development that some of the services that were being offered in the past by GLN via Plastikeep are now being offered by the EMA through its iCare program, it should be noted that the eventual demise of a "bottom-up", community-based approach to plastics recovery and recycling has been replaced by a more "top-down", government-operated and funded alternative.

The waste management landscape appears to now be at another inflection point in its progress. Until recently, the business and manufacturing sectors have been very cautious in outwardly supporting some aspects of waste management legislation including the Beverage Container Bill which could essentially place producer responsibility (and cost) back on them. While there has been some evidence of corporate proactivity on waste management initiatives, often as part of the corporate social responsibility portfolio or on direct request of the EMA, this pales in comparison to the political lobbying, pressure, and negotiations to hold back such legislation as the Beverage Container Bill. However, public mood and market perceptions are evolving to become more conscious of these issues and strategically, there may be pressure on business and manufacturing interests to exhibit proactive voluntary efforts, so as to head off the recent government declarations of plastics and Styrofoam bans and finally the passing of the Beverage Container Act. For example, in 2018 the Massy Group, the largest Caribbean regional conglomerate, headquartered in Trinidad and Tobago, adopted a voluntary ban on single-use plastic bags within all of its supermarket and retail store chains [56,57]. The CEO noted,

> "As a responsible, leading retailer we are determined to play a role in the reduction of waste. Along with citizens of every Caribbean country in which we operate, we are collectively accountable for actions which impact the future of the Caribbean. We started this journey by procuring bags made of biodegradable plastic, but it is imperative that we take a stand to reduce our overall consumption of plastic, which is why we introduced a campaign to help end 'double bagging'. Our focus is now on encouraging customers to bring their reusable bags, with the intention to phase out the demand for plastic bags."

5. Discussion

5.1. An Emergent Evolutionary Model of Island Waste Metabolism

Trinidad and Tobago's current approach to waste management can be described as a "top-down" or state-centric model that makes use of traditional land-filling. Reducing and recycling waste has always been a central message but has not received as much focus as disposal and treatment. If the twin-island nation is to transition to an approach that is more democratic in nature and utilizes public-private partnerships along with incentive-based regulations that seek to allow non-government agencies to participate in plastics recovery and recycling, simplification of the current approach to governance as it relates to waste management may be necessary. At present, there is a lack of appropriate or adequate incentives for the private sector or even citizens to participate in the recovery of plastics. In addition, while avenues for public-private partnership exists, a simplified policy landscape would make such ventures easier to pursue. Figure 7 summarizes the institutional evolution of waste in Trinidad and Tobago.

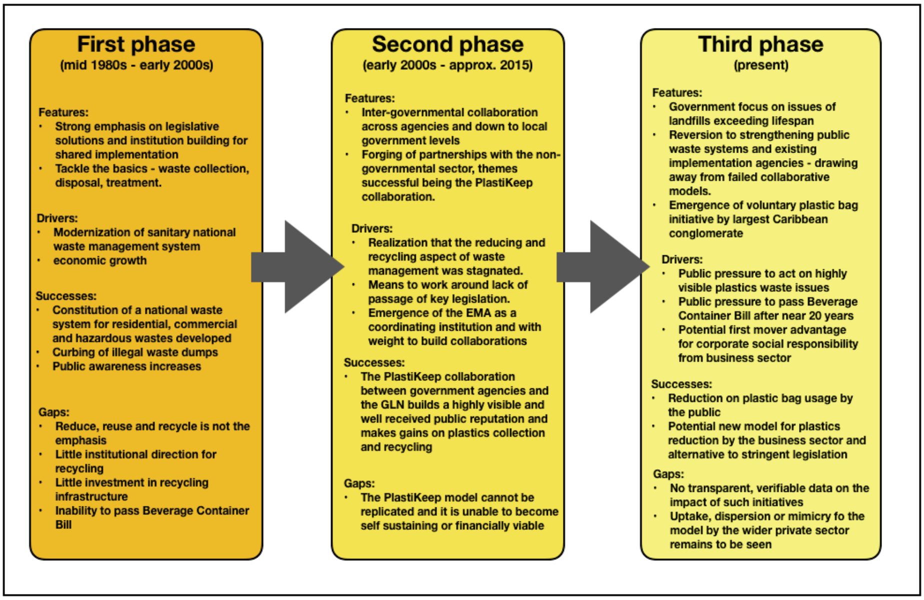

Figure 7. Summary of the institutional evolution of waste, particularly plastics, metabolism in Trinidad & Tobago.

We identified three temporal phases of policy evolution that have altered the waste metabolism trajectory to date: (1) government led patriarchal approach of traditional landfilling combined with behavioral change campaigns to reduce, reuse and recycle, (2) to a more democratic, shared burden, public-private partnership approach combined with attempts at incentive-based regulations, (3) to the present, more private sector-led voluntary bans on production and use of plastics. The latter initiatives now have a positive feedback effect on the government to promote such interventions. The figure below illustrates the three phases proposed.

In the first phase, which is approximated to the late 1980s to the late 1990s, almost sole emphasis was placed on legislative declarations, regulations, and the building of institutions to implement the legislated intents. Coercive pressure was derived from the central government and targeted not only the general public but perhaps more decisively, local and municipal governments. Implementation was shared through mandates in accordance with the respective legislation. One prime piece of legislation that was designed to promote recycling, especially of beverage containers (plastics and glass) has been a 'political football' for near twenty years, with background opposition by major business and manufacturing interests. In public forums, however, both the business sector and government have voiced support for getting the Bill passed but bemoan its 'considerable complexity' and the need to simplify in order to properly implement. The business sector coalesced around an unsaid position of resistance to the Bill, exerting normative group pressure on government through political means, essentially diluting coercive pressures on the business sector and redirecting attention to the inefficiencies in the local government waste management system.

By the early to the mid-2000s, the institutional landscape, public views, and cultural norms were changing. The EMA was now fully functional and overseeing broad policy direction including waste management that was being implemented by SWMCOL and others. There was increasing environmental education and awareness of the public strengthening cognitive pressure on polluters generally. This, coupled with increasing flood events at least partially attributed to refuse clogged drains as well as reports of government attention related to the saturation of existing managed landfills on the island. The context of these conditions and pressures gave rise to a more informed and energized environmental advocacy sector interested in moving beyond the slow-moving government bureaucracy. This ushered in a second phase of sharing the administrative burden of waste management with non-governmental partners through collaborative partnerships. [58] suggests that this is often a natural progression of 'problem-solving', as evidence that the problem faced is indeed a wicked one. It is also pointed out that this route of dealing with the problem through stakeholder collaboration with stakeholders with whom power is dispersed is particularly relevant when at least part of the challenge is the behavioral change among stakeholders or the public. Partnerships, joint ventures, whole of (or joined up) government, international treaties and information campaigns to influence lifestyle choices are all variations on this strategy. More collaborations and larger ones revolved around making progress on reducing and recycling waste. The Plastikeep collaboration between the government and the non-governmental sector was the largest and for nearly a decade, the most successful effort. However, the model was never profitable, as was intended, nor was it even self-sustaining as a business model. It could not attain financial viability without 'crutches' of government aid and financial assistance. That was not the intent and by 2018 it was shuttered by government despite the gains made in collecting and recycling plastics, setting up a national bin system and putting a dent in public behavior with respect to plastics collection for recycling by the public.

The public and the business sector watched on with interest at the increasingly visible successes of the Plastikeep partnership in collecting and recycling plastics. As the finances behind the success were not as visible, it was shocking to most when the government effectively pulled out. By this time, however, the public thought they were seeing a solution in motion and would start being more conscious of their own plastics usage as well as the waste management practices and reputation of the business and manufacturing sectors. The latter would pick up on the increasing coercive pressures from those that mattered to their bottom lines—the consumer public. Growing public comments and the increasingly negative press after flooding events that revealed photos of massive heaps of plastics clogging waterways questioned the legitimacy of business stalwarts as responsible societal actors. The increasing media reports of marine fauna with plastics in and on their bodies reinforced motivation by the business sector including business associations, to change the narrative, if not also their practices and waste management performance. The abundant goodwill that the public seemed to have with the Plastikeep partnership was also an incentive for businesses to take action. This is where we propose that Trinidad and Tobago are entering the third phase in the waste management evolution—voluntary corporate responsibility. The initiatives of Massy Group described above, provide the early prototype of such an evolution in corporate strategy, even as it starts with addressing only plastic bag usage.

The initiative is arguably driven by several factors, not the least of gauging the swirling institutional forces. Factors include the failure of the Plastikeep partnership placing the government in a position again to have to pursue the Beverage Container Bill among other regulatory approaches for waste management. A voluntary effort by such a large conglomerate could dissuade the government that pushing the legislation, which is already an uphill battle with the business sector, may not be a necessary fight. It can also be a new prong in the effort of corporate social and environmental responsibility that can potentially increase brand and corporate reputation value while contributing to a front-burner environmental problem that is in the public eye.

5.2. Learning from the Institutional Evolution Model Observed

If private sector firms and community-based groups are to become more involved in plastics recovery and recycling, the current policy landscape requires clarity and simplification. Not only is there no singular guiding policy that seeks to incentivize the collection and recycling of plastics, but at present, a number of ministries and state agencies have related responsibilities which could make collaboration unnecessarily complex. Stakeholders wishing to engage in collaborative projects with the government first need to engage in research to ascertain the appropriate agencies to be approached in order secure the required permissions and agree upon the terms of cooperation (possibly via a Memorandum of Understanding) before project execution can commence.

In practice, therefore, state agencies must consider how to incentivize the private sector and civil society to participate or even initiate policy dialogues on matters related to waste management governance. Funding has proven to be a limiting factor to NGOs to invest in infrastructure and/or in educational material and campaigns related to improving waste management. It should be noted that while the attempt to provide such a facility via the Green Fund in Trinidad and Tobago is laudable, funding mechanisms of this nature should ultimately encourage financial self-sustainability of NGOs and facilitate the participation of the private sector (particularly as beneficiaries of financial and technical resources). In addition, funding mechanisms should also support long-term partnerships between the public sector and non-governmental organizations (including private firms) on programs that aim to enhance waste management governance. Certainly, if plastics metabolism and wider waste management are to be strengthened within island environments, policy and funding mechanisms that support long term partnerships across different sectors will be required to facilitate joint policy planning and implementation as well as large-scale execution of recycling and waste management initiatives.

While there are a number of policies that relate to waste management governance in Trinidad and Tobago, there is an inadequate comprehensive framework that effectively provides guidance for public, private, or civil society stakeholders willing to enhance the efficient waste collection, disposal, and treatment on the island. Certainly, the absence of a clear framework also makes the formation of strong partnerships between the public and private sectors more difficult. This is noteworthy, as partnerships between private, public, and civil society stakeholders are critical to reforming the current top-down approach to policy formulation within the twin-island republic. To add to this, an enabling policy environment is necessary to promote the participation of the private sector and civil society in the development of programs that actively engage and encourage members of the public to decrease their ecological footprints, especially as it relates to waste.

Programs aiming to introduce practical measures or infrastructure that improves the ability of the population to enhance the efficacy of waste collection and treatment (inclusive of recycling) are likely to be equally as difficult in the absence of clear policy support and guidance. Indeed, the ultimate collapse of the Plastikeep program that was piloted by GLN following the cessation of funding from the State, may be symptomatic of a larger problem related to waste management governance. In the case of the Plastikeep, not only was the project almost entirely dependent on continuous support from the GORTT but perhaps, more importantly, there were no legislative or policy regulations that would have allowed the organization to continue the initiative or introduce a similar project in a commercially viable manner. The absence of policies to support such activities makes bottom-up approaches to waste-management, on the part of individuals, the private sector or civil society, largely untenable.

6. Conclusions

In 2015, the Caribbean group of countries, including many SIDS met in Trinidad and Tobago to chart out a prioritization program for the 17 Sustainable Development Goals (SDGs) promulgated by the United Nations for attainment by 2030. Notably, SDG 12, which focuses on "responsible consumption and production" was absent from the prioritization. Furthermore, the 10 Year Framework Plan (10YFP) for implementing SDG 12 for SIDS and in accordance with the SAMOA Pathway has thus far not provided any tangible policy drivers. The lack of progress at the macro-level of the SDG

Agenda may also be traced to some of the policy inertia due to structural issues identified through this case study.

Notwithstanding the above, while we are unable to answer the question that follows fully within this paper, the evidence presented does raise a larger question of whether or not waste management represents a wicked problem or whether it is simply a symptom of a wicked system of unsustainable production and consumption. Moreover, the paper reviews the unique case of Trinidad and Tobago, which is home to modest but emerging industries that produce consumer goods for local and export markets, and also have the impact of making waste minimization more complex. The additional challenge of effectively processing and minimizing waste from imported and heavily packaged consumer goods make the top-down approach reviewed within the case study more problematic. Indeed, the top-down and fragmented approach to waste management governance within the twin-island surely lends some justification for our characterization of this policy challenge as a 'wicked problem.

The results of our study show that even in small island states, devolution of waste management has the potential to deliver more effective development dividends. Waste management and particularly plastics waste management requires community-level behavioral change and no matter what level of centralized control is exerted, there can be "leakage" in the system given the scale of the challenge. Public-private partnerships may provide a useful opportunity for change but there remains an ongoing concern about linking waste management to the broader development agenda for SIDS.

Author Contributions: Conceptualization, K.U.S. and S.H.A.; methodology, K.U.S.; formal analysis, K.U.S. and K.N.; investigation, K.N.; writing—original draft preparation, K.U.S., K.N. and D.S.; writing—review and editing, D.S., D.J., S.H.A.; visualization, K.N. and K.U.S.

Funding: This research received no external funding.

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

References

1. World Bank. Global Waste to Grow by 70 Percent by 2050 Unless Urgent Action Is Taken: World Bank Report. Available online: https://www.worldbank.org/en/news/press-release/2018/09/20/global-waste-to-grow-by-70-percent-by-2050-unless-urgent-action-is-taken-world-bank-report (accessed on 20 June 2019).
2. UNEP. Emerging Issues for Small Island Developing States. Results of the UNEP Foresight Process. Available online: https://sustainabledevelopment.un.org/index.php?page=view&type=400&nr=2173&menu=1515 (accessed on 20 June 2019).
3. UNEP. Small Island Developing States Waste Management Outlook. Available online: http://wedocs.unep.org/bitstream/handle/20.500.11822/27683/SIDS_WMO.pdf?sequence=1&isAllowed=y (accessed on 19 June 2019).
4. UNEP. Marine Litter. Available online: https://www.unenvironment.org/explore-topics/oceans-seas/what-we-do/working-regional-seas/marine-litter (accessed on 28 October 2019).
5. Global Plastic Production Statista. Available online: https://www.statista.com/statistics/282732/global-production-of-plastics-since-1950/ (accessed on 19 June 2019).
6. Fauziah, S.; Liyana, I.; Agamuthu, P. Plastic Debris in the Coastal Environment: The Invincible Threat? Abundance of Buried Plastic Debris on Malaysian Beaches. *Waste Manag. Res.* **2015**, *33*, 812–821. [CrossRef] [PubMed]
7. Barnes, D.K.A.; Galgani, F.; Thompson, R.C.; Barlaz, M. Accumulation and Fragmentation of Plastic Debris in Global Environments. *Philos. Trans. R. Soc. B Biol. Sci.* **2009**, *364*, 1985–1998. [CrossRef] [PubMed]
8. Africa Must Act Against the Ballooning Indian Ocean Plastic Patch—ISS Africa. Available online: https://issafrica.org/iss-today/africa-must-act-against-the-ballooning-indian-ocean-plastic-patch (accessed on 19 June 2019).
9. Lavers, J.L.; Bond, A.L. Exceptional and Rapid Accumulation of Anthropogenic Debris on One of the World's Most Remote and Pristine Islands. *Proc. Natl. Acad. Sci. USA* **2017**, *114*, 6052–6055. [CrossRef] [PubMed]

10. Lavers, J.L.; Dicks, L.; Dicks, M.R.; Finger, A. Significant Plastic Accumulation on the Cocos (Keeling) Islands, Australia. *Sci. Rep.* **2019**, *9*, 7102. [CrossRef] [PubMed]
11. Duhec, A.V.; Jeanne, R.F.; Maximenko, N.; Hafner, J. Composition and Potential Origin of Marine Debris Stranded in the Western Indian Ocean on Remote Alphonse Island, Seychelles. *Mar. Pollut. Bull.* **2015**, *96*, 76–86. [CrossRef] [PubMed]
12. The Economic Intelligence Unit Limited. Plastic Pollution. Charting the Course for Ocean Sustainability in the Indian Ocean Rim. Available online: https://www.woi.economist.com/content/uploads/2019/02/Charting-the-course-for-ocean-sustainability-in-the-Indian-Ocean-Rim_Full-report.pdf (accessed on 18 June 2019).
13. Santamarta, J.C.; Rodríguez-Martín, J.; Arraiza, M.P.; López, J.V. Waste Problem and Management in Insular and Isolated Systems. Case Study in the Canary Islands (Spain). *IERI Procedia* **2014**, *9*, 162–167. [CrossRef]
14. Kapmeier, F.; Gonçalves, P. Wasted Paradise? Policies for Small Island States to Manage Tourism-Driven Growth While Controlling Waste Generation: The Case of the Maldives. *Syst. Dyn. Rev.* **2018**, *34*, 172–221. [CrossRef]
15. Shamshiry, E.; Nadi, B.; Mokhtar, M.B.; Komoo, I.; Hashim, H.S.; Yahaya, N. Integrated Models for Solid Waste Management in Tourism Regions: Langkawi Island, Malaysia. *J. Environ. Public Health* **2011**, *2011*, 709549. [CrossRef] [PubMed]
16. Willmott, L.; Graci, R.S. *Téoros Revue de Recherche En Tourisme*; Université du Québec: Quebec, QC, Canada, 2012.
17. Morrison, R.J.; Munro, A.J. Waste Management in the Small Island Developing States of the South Pacific: An Overview. *Australas. J. Environ. Manag.* **1999**, *6*, 232–246. [CrossRef]
18. UNEP. CSD7: Waste Management in SIDS. Available online: http://islands.unep.ch/d99-6a2.htm (accessed on 18 June 2019).
19. Owens, E.L.; Zhang, Q.; Mihelcic, J.R. Material Flow Analysis Applied to Household Solid Waste and Marine Litter on a Small Island Developing State. *J. Environ. Eng.* **2011**, *137*, 937–944. [CrossRef]
20. Phillips, W.; Thorne, E. Municipal Solid Waste Management in the Caribbean: A Benefit-Cost Analysis. Available online: https://repositorio.cepal.org/handle/11362/5053 (accessed on 20 June 2019).
21. Mohee, R.; Mauthoor, S.; Bundhoo, Z.M.A.; Somaroo, G.; Soobhany, N.; Gunasee, S. Current Status of Solid Waste Management in Small Island Developing States: A Review. *Waste Manag.* **2015**, *43*, 539–549. [CrossRef] [PubMed]
22. Dissemination of Regional Waste Management Strategy and Action Plan for Zone 6&7 and Launching of Pilot Project|CCET. Available online: https://www.ccet.jp/events/maldives_dissemination_WS_regional_strategy (accessed on 19 June 2019).
23. Kreuter, M.W.; De Rosa, C.; Howze, E.H.; Baldwin, G.T. Understanding Wicked Problems: A Key to Advancing Environmental Health Promotion. *Health Educ. Behav.* **2004**, *31*, 441–454. [CrossRef] [PubMed]
24. Commonwealth Innovations Review. Tackling Wicked Problems in the Public Service. Available online: https://www.capam.org/files/CIRdecember2017january2018.pdf (accessed on 15 June 2019).
25. Sun, J.; Yang, K.; Sun, J.; Yang, K. The Wicked Problem of Climate Change: A New Approach Based on Social Mess and Fragmentation. *Sustainability* **2016**, *8*, 1312. [CrossRef]
26. Parrott, L. The Modelling Spiral for Solving 'Wicked' Environmental Problems: Guidance for Stakeholder Involvement and Collaborative Model Development. *Methods Ecol. Evol.* **2017**, *8*, 1005–1011. [CrossRef]
27. Eckelman, M.J.; Ashton, W.; Arakaki, Y.; Hanaki, K.; Nagashima, S.; Malone-Lee, L.C. Island Waste Management Systems. *J. Ind. Ecol.* **2014**, *18*, 306–317. [CrossRef]
28. Hettiarachchi, H.; Ryu, S.; Caucci, S.; Silva, R. Municipal Solid Waste Management in Latin America and the Caribbean: Issues and Potential Solutions from the Governance Perspective. *Recycling* **2018**, *3*, 19. [CrossRef]
29. Mihajlov, A.N.; Čarapina, H.S.; Drakulić, N.Ž. Waste Technology Transfer from Developed to Developing Countries: Challenge. In Proceedings of the Eurasia 2014 Waste Management Symposium, Istanbul, Turkey, 28–30 April 2014; pp. 1–8.
30. Buchanan, R. Wicked Problems in Design Thinking. *Des. Issues* **1992**, *8*, 5. [CrossRef]
31. Roberts, N. *The International Public Management Review IPMR: The e-Journal of the IPMN*; International Public Management Network: Washington, DC, USA, 2000; Volume 1.
32. Von Thienen, J.; Meinel, C.; Nicolai, C. How Design Thinking Tools Help to Solve Wicked Problems. In *Design Thinking Research*; Springer: Cham, Switzerland, 2014; pp. 97–102. [CrossRef]

33. Scott, W.R. *Institutions and Organizations*; SAGE Publications: Los Angeles, CA, USA, 1995.
34. Squires, C. Public Participation in Solid Waste Management in Small Island Developing States. Available online: http://www.nswai.com/docs/PUBLIC%20PARTICIPATION%20IN%20SOLID%20WASTE%20MANAGEMENT%20IN%20SMALL%20ISLAND%20DEVELOPING%20STATES.pdf (accessed on 20 June 2019).
35. Agamuthu, P.; Herat, S. Sustainable Waste Management in Small Island Developing States (SIDS). *Waste Manag. Res.* **2014**, *32*, 681–682. [CrossRef] [PubMed]
36. SPREP. Pacific Regional Solid Waste Management Strategy 2010–2015. Available online: https://www.sprep.org/attachments/Pacific_RSWMS_2010-2015.pdf (accessed on 18 June 2019).
37. Shah, K.U.; Niles, K. Energy Policy in the Caribbean Green Economy Context and the Institutional Analysis and Design (IAD) Framework as a Proposed Tool for Its Development. *Energy Policy* **2016**, *98*, 768–777. [CrossRef]
38. Berg, B.L.; Lune, H. *Qualitative Research Methods for the Social Sciences*, 8th ed.; Pearson Education Inc.: Boston, MA, USA, 2012.
39. Yin, R. *Case Study Research and Applications—Design and Methods*, 3rd ed.; SAGE Publications: Thousand Oaks, CA, USA, 2003.
40. Merriam, B.S.; Tisdell, E.J. *Qualitative Research: A Guide to Design and Implementation*, 4th ed.; John Wiley and Sons Inc.: San Francisco, CA, USA, 2016.
41. Patton, M.Q. *Qualitative Research & Evaluation Methods: Integrating Theory and Practice*; Sage Publications Inc: Thousand Oaks, CA, USA, 2002.
42. Yin, R. *Case Study Research and Applications—Design and Methods*, 6th ed.; SAGE Publications: Thousand Oaks, CA, USA, 2018.
43. GORTT. *National Waste Recycling Policy*; Government of the Republic of Trinidad & Tobago: Port-Of-Spain, Trinidad, 2010.
44. GORTT. *Integrated Solid Waste and Resource Management Policy*; Government of the Republic of Trinidad & Tobago: Port-Of-Spain, Trinidad, 2010.
45. GORTT. *Development Programme 2019*; Government of the Republic of Trinidad & Tobago: Port-Of-Spain, Trinidad, 2019.
46. Government of the Republic of Trinidad and Tobago. *National Environmental Policy*; Environmental Management Authority: Port of Spain, Trinidad and Tobago, 2018.
47. GORTT. *Vision 2030: Trinidad and Tobago National Development Strategy 2016–2030*; Government of the Republic of Trinidad and Tobago: Port of Spain, Trinidad and Tobago, 2016.
48. GORTT. *Fifth Report of the Joint Select Committee on Finance and Legal Affairs on a Critical Assessment of the Waste Management Policies and Initiatives of the State (with Specific Focus on Solid Waste)*; Ministry of Public Utilities, Government of the Republic of Trinidad & Tobago: Port-Of-Spain, Trinidad, 2019.
49. Parliament of Trinidad and Tobago. *Examination of the Audited Accounts, Balance Sheet and other Financial Statements of the Trinidad & Tobago Solid Waste Management Company Limited (SWMCOL) for the Financial Years 2008–2013*; Sixth Report of the Public Accounts Enterprises Committee: Second Session of the 11th Parliament; Government of Trinidad & Tobago: Port of Spain, Trinidad and Tobago, 2015.
50. CEPEP. About Us. Port of Spain. Available online: https://www.cepep.gov.tt/about-us/about-us/ (accessed on 26 June 2019).
51. CEPEP. What We Do. Port of Spain. Available online: https://www.cepep.gov.tt/about-us/what-we-do/ (accessed on 25 June 2019).
52. Government of the Republic of Trinidad and Tobago. *Environmental Management Act Trinidad & Tobago*; Government of Trinidad & Tobago: Port-Of-Spain, Trinidad, 2000.
53. Matroo, C. TT Produces too much garbage. *Newsday*, 3 June 2019; 17.
54. Greenlight Network. *Frequently Asked Questions on Plastikeep*; Government of Trinidad & Tobago: Port of Spain, Trinidad, 2016.
55. Environmental Management Authority. Recyclable Solid Waste Collection Project (iCare). Port of Spain. Available online: https://spark.adobe.com/page/IDqouUyagvqwa/ (accessed on 26 June 2019).
56. Bridglal, C. Massy Eliminates 18 m Single Use Plastic Bags from Circulation. Trinidad and Tobago Newsday. Available online: https://res.mdpi.com/data/mdpi_references_guide_v5.pdf (accessed on 26 June 2019).

57. Massy Group. Massy Stores Pledges to Reduce Plastic Waste. Massy Group of Companies. Available online: http://www.massygroup.com/News/MASSY_STORES_PLEDGES_TO_REDUCE_PLASTIC_WASTE.aspx (accessed on 26 June 2019).
58. Roberts, N.C. Public Entrepreneurship and Innovation. *Rev. Policy Res.* **1992**, *11*, 55–74. [CrossRef]

© 2019 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (http://creativecommons.org/licenses/by/4.0/).

sustainability

MDPI

Article

The Impact of Hurricane Irma on the Metabolism of St. Martin's Island

Roxana Popescu [1,2,3,*], Hélène Beraud [3] and Bruno Barroca [3]

1 Faculty of Architecture and Urbanism, University of Mons, 7000 Mons, Belgium
2 UMR 241 EIO, University of French Polynesia, 98702 Faa'a, Tahiti, French Polynesia
3 Lab'Urba Laboratory, Gustave Eiffel University, 77454 Champs-sur-Marne, France; helene.beraud@u-pem.fr (H.B.); bruno.barroca@u-pem.fr (B.B.)
* Correspondence: roxana-mihaela.popescu@u-pem.fr; Tel.: +33-07-6708-1259

Received: 7 July 2020; Accepted: 17 August 2020; Published: 19 August 2020

Abstract: Due to their sometimes devastating and, at the same time, transformative effects, the impacts of major hurricanes on small islands leave their mark both on the way territories operate and on their future development. This was the case during the passage of hurricane Irma over the island of Saint Martin in 2017. By analyzing the stocks and circulation of hurricane waste flows, our aim was to see whether the inherent evolution of Saint Martin's metabolism as a result of the island's total destruction tended toward a lasting transformation of its waste management system and, therefore, toward the territory's sustainability. This evolution was analyzed in a diachronic approach and over a short time frame. It was based on three structuring territorial metabolism dimensions: the intensity of waste flows, the spatial structure of the metabolism and the actors and techniques that explain it. Results show that while the intensity of the waste flows changed durably after Irma, the lasting transformation of the spatial structure and the actor system was less obvious and depended on the waste stream. Results also reveal the importance of reflecting on the development of recycling and reuse methods as a solution for improving post-hurricane waste planning on islands.

Keywords: hurricane Irma; territorial metabolism; island waste management; post-disaster stock and flow evolution

1. Introduction

This article focuses on post-hurricane waste management in island areas and, more particularly, revisits the hurricane Irma experience on the French part of the island of Saint Martin (in the West Indies) in September 2017. Twelve years after Hurricane Katrina, which devastated New Orleans in 2005, 2017 was an intense year, with ten consecutive hurricanes in the North Atlantic: Franklin, Gert, Harvey, Irma, José, Katia, Lee, Maria, Nate, and Ophelia. A few days before Irma, hurricane Harvey caused considerable damage in Texas and Houston, mainly due to very heavy rain. Following Harvey, Irma hit the West Indies, particularly affecting the islands of Saint Martin and Saint-Barthelemy (followed by Cuba and Florida). Irma stood out for the truly exceptional speed of its high winds, that lasted for over 24 h and which were estimated by the National Hurricane Center (NHC) at 155 kt (287 km/h) at the time of its passage over Saint-Barthelemy and Saint Martin. There were even short gusts estimated at speeds above 350 km/h [1]. As for the rain, which was not as heavy as for Hurricane Harvey in Texas, it "exceeded 150 mm in 6 h, while an excessively surge of 2.04 m was recorded in Marigot" [2]. At the end of September, Maria, also a category 5 hurricane, passed close to Guadeloupe and Martinique but it mainly affected Dominica and Puerto Rico [3]. Although Maria did not directly touch the islands hit by Irma, the swell generated at sea and the measures linked to the alert strongly disrupted the rescue operations, the solidarity between islands and emergency repairs on buildings (tarpaulins for damaged roofs) and infrastructures. According to the Swiss Re reinsurance company, these three hurricanes—Harvey, Irma, and Maria—caused damages amounting to almost 93 billion dollars on insured property, and the total costs including uninsured property remained significantly higher. An estimate of Harvey's cost just for the Houston region was calculated at almost 200 billion dollars [4]. As far as Irma was concerned, according to the Central Reinsurance Fund, the damage insured under the natural disaster regime exceeded 2 billion euros on the French islands.

More than a third of the cost of recovery [5] relates to disaster waste management. Feedback shows that storms and hurricanes are hazards that generate particularly large amounts of waste [5–7]. Poor management disrupts the progress of emergency services and the restoration of technical networks (water, energy, etc.) and may even cause environmental damage (pollution), health risks (mosquitoes and pests, and open waste-burning), social damage (the pace and choice of areas to be cleared), economic damage (relaunching activities) as well as a deterioration in the image of tourist areas [8–11]. Feedback and the literature show all the difficulties of disaster waste management combining territories and hazards. These difficulties seem to be linked to several phenomena: insufficient waste facility, the need to avoid saturating the capacities of existing waste management systems, the impossibility of projecting one's self in terms of quantity and quality into the nature of the volume of waste. Beraud et al. [9] exposed the specificities of island environments in terms of waste management (availability of land, difficult access to other territories, low diversity of processing and upgrading systems), which make hurricane waste management particularly difficult.

This insular context, as well as the succession of hurricanes that hit structures that were already fragile and disrupted trade between islands, revealed all the difficulties in Saint Martin's waste management system. Setting up, in the middle of the emergency waste storage areas, illegal dumping practices and open-air waste-burning, and the difficulty in treating waste by conventional streams illustrated, on the one hand, the difficulty in managing the exceptional waste flows caused by the hurricane and also revealed, on the other hand, pre-existing weaknesses in the technical system. Beyond resistance and adaptation, the notion of resilience allows us to approach the "crisis" as a time that shows the weaknesses and the strengths of territorial systems in the face of hazard. The post-crisis period is, therefore, a suitable moment for making these systems evolve positively in light of the experience obtained from the crisis [12]. In Saint Martin, the weaknesses of the technical waste management system that appeared during the 2017 hurricane season go beyond the context of hurricane waste and reveal the dysfunctions that had already appeared in waste management during normal times.

In this article, we are concentrating on the transformations which were initiated during the post-disaster time, and which affect waste management. Our hypothesis is as follows: the experience of the 2017 hurricane season, and in particular of Irma, has had a lasting impact on the stocks and circulation of waste flows in Saint Martin.

In order to study this hypothesis, the first part of the article presents the specifics of waste management in Saint Martin from the point of view of its political organization (Section 2.1), waste production (Section 2.2) and the organization of the technical waste management system (Section 2.3). The second part focuses on the methodological framework proposed for studying the validity of the hypothesis specified above. If the mobilization of methods resulting from the territorial metabolism makes it possible to partially meet expectations (Section 3.1), the specificities of post-hurricane waste management as well as the specificities of the island territory force us to improve the standard methods (Section 3.2). Finally, the fourth part characterizes the transformation of the waste-management metabolism by showing up temporal and spatial variables.

2. The Specifics of Saint Martin's Waste Management Organization during Normal Periods

2.1. The Complexity of the Political Organization

Saint Martin is an island located to the north of the West Indies arc, which has been shared between France and the Netherlands since 1648 (the Mount Concorde Treaty). The French part of the island, covering an area of 93 km^2, was administratively attached to the "department" of Guadeloupe from

1947 to 2007. Since 2007, it has had the status of an overseas territory governed by Article 74 of the French Constitution, that is to say, an Outermost Region of the European Union. The Dutch part, Sint Maarten, covers an area of 34 km^2, and is located to the south of the island. It has been an autonomous state dependent on the Netherlands since 2010 and possesses the status of an Overseas Country and Territory of the European Union. Sint Maarten is therefore located outside the EU. The different political affiliation of these two territories has given rise to two separate waste management systems, each with its own administrative constraints. While the French part is subject to European regulations, they do not apply to the Dutch part, which is not part of the European Union. Despite these differences in status, there is no border control between the two parts of the island, which facilitates the free movement of goods but also of waste [13]. The rest of the article is only concerned with the waste management system on the French part of the island. Relations with the Dutch side most certainly influence how the system works but they are unofficial and will not be taken into account in this analysis.

The specific nature of the development and evolution of Saint Martin's waste management system is therefore intrinsically linked to this political organization. Saint Martin is characterized by a dual insularity, both in relation to metropolitan France and to its status as a municipality belonging to Guadeloupe. This geographic distance was reflected by a certain slowness in developing the technical infrastructures required for efficiently collecting and treating the volume of waste at the same speed as that at which the territory has been developing. Until 2007, the municipality of Saint Martin was financially dependent on Guadeloupe, which also had difficulties in acquiring waste treatment infrastructures of a sufficiently high standard and in structuring waste valorization supply chains [14]. Despite certain efforts, informality was very much present there. The landfill operated by the municipality since 1991 was not up to standard and was only equipped with a small composting unit. The recycling unit inaugurated in 2006 did not yet have its administrative permits. The selective collection of packaging waste was already in place, and a private recycling center treated a small part of the recyclable materials, the rest being shipped to Guadeloupe or metropolitan France. The community was also faced with a problem of illegal dumping.

The municipality's change of status to an overseas collectivity, due to the organic law of 21 February 2007, gave Saint Martin more autonomy to exercise all the powers devolved to the municipality, the "department" and the region, as well as those transferred to it by the Government. This means that the environmental code, which regulates waste management in French territories, will continue to be applied, but the collectivity has the possibility to adapt it to the specificities of its territory, after the government's approval. Despite its remoteness from the continent, some eco-organizations also have the obligation to pick up recyclable waste through public procurement contracts put in place by local authorities. Since its autonomy, the collectivity has been responsible for collecting and treating non-hazardous waste. It now develops its own strategy and decides independently on the investments required. Environmental jurisdiction, including the management of hazardous waste, remains, however, the State's prerogative and is handled by the Department of the Environment, Planning and Housing based in Guadeloupe.

This change in the collectivity's status has enabled it to master all the competences concerning waste (from management to strategic planning). Since 2007, the island has experienced an increase in the structure of its collection streams, made possible by the development of collection and processing infrastructures. Concerning collection, voluntary drop-off points for recyclable waste (two 180-L bins, three 770-L bins and, for plastic waste, 43 voluntary drop-off points, forty-one 180-L bins and twenty-two 770-L bins) and the Galisbay Bienvenue collection site have been created [15]. For treatment, a waste-sorting and recycling site called the Grandes Cayes Ecosite has been created, and the landfill for burying household and similar refuse operated by the municipality has been brought up to standard. In compliance with French regulations, the site was classified as a Non-Hazardous Waste Landfill (for household refuse and similar). Waste collection was delegated to local private operators in the context of public procurement procedures. The ecosite operation and the landfill were delegated to the company Verde SXM in 2011.

2.2. Weight of the Tourism Sector Influencing Waste Production and Management

Waste production and management on the island of Saint Martin is closely related to changes in the island's demographic and socio-economic characteristics.

Based in the past on exploiting the salt marshes and cultivating tobacco and then cotton and sugar cane, Saint Martin's current economy is largely tertiary and dependent on tourism, which has grown significantly since the 1980s, driven by the dynamics of the Dutch side and by the opportunities generated by tax exemption systems in 1986. The tourist boom of the 1980s has largely influenced the population's demographic evolution. As a result, the 1980–1990 period was marked by a significant increase in the population, going up from 8000 inhabitants to 28,500 inhabitants. This increase was mainly due to the migratory balance. Migration, which originated largely in Haiti and the Dominican Republic, can be explained by the need for labor in construction and tourism activities. In 2015, Saint Martin had a population of 35,684 inhabitants [16].

Today, the island's activities are concentrated on non-market services and other commercial interests, which respectively account for 6.4% and 33.9% of the total employment. Accommodation and catering and the construction business also benefit from Saint Martin's tourist attractiveness and respectively account for 26.1% and 6.6% of total employment [16].

The tourism sector is, therefore, an important source of waste production, due to related activities, which generate waste themselves (catering, accommodation, and construction), but also to the waste generated directly by tourists. In the context of Saint Martin, it is difficult to separate the different sources. According to data recorded by the Verde SXM company at the entrance to the landfill, the variation in the production of residual household waste over a year is influenced by the drop in the tourist season during the June–September period [17]. In addition, due to its free-port status, which does not oblige port authorities to monitor imports, it is difficult to quantify the volume of waste on the territory.

Although tourism is the pillar of Saint Martin's economy, the French side does not have port and airport infrastructures suitable for handling the mass tourism that benefits the Dutch side, which captures almost all the cruise business. The number of cruise passengers arriving in Marigot, in the French sector, remains extremely low. They do not contribute much to the waste produced directly by tourists. It is more small-scale tourism, where visitors remain longer, which contributes to waste production and calls on local waste collection infrastructures. In this respect, the highest level of tourist frequentation on the French side was reached in 2014, with nearly 594,000 tourists welcomed to Saint Martin and 2,106,000 cruise passengers arriving in transit from the Dutch side. It should be mentioned that tourists coming on a cruise only stay a very short time on the island (one day on average) and are therefore not likely to contribute significantly to waste production. In 2016, 109,979 passengers arrived at Grande Case airport and over 333,000 nights' accommodation were sold. Leisure sailing is also part of the tourist landscape of the island of Saint Martin, which is a popular port of call for navigators with a capacity of around 750 places [16].

The main source of waste generation continues to be the residential population. All finished products on the Saint Martin market are imported, which also generates additional waste due to the packaging required for transporting these products by sea or air. For the year 2015, the Verde SXM company declared that it had buried 18,463 tons of waste generated by the population and 1855 tons of waste generated by professionals, therefore a total of 20,318 tons [17].

A sorting culture is also struggling to find its place on the island. Multiculturalism, which is a specificity of Saint Martin in the Caribbean, was often invoked during the field research by public authorities, associations and residents as being a reason for the difficulties in setting up a sorting system: different socio-economic levels between the communities present on the island, communications in French when not all members of the different communities speak French, different waste management cultures, not enough awareness and educational campaigns adapted to the local specificities, etc.

Selective collection is relatively ineffective. Only an extremely low proportion is sorted and sent to recycling streams. Following a study on the characteristics of the waste present in an underground storage compartment at the Grandes Cayes landfill, carried out in 2018, on a volume of recyclable waste that had undergone selective collection, and estimated at 5370 tons, 5100 tons ended up by being buried. Only 4% of non-glass packaging and 9% of glass packaging [18] was sorted.

2.3. Organization of the Waste Management Service: Streams and Facilities

Waste collection in Saint Martin is organized in four streams: household waste, bulky waste, green waste and selective sorting at voluntary drop-off points. There are several operators for collecting each stream who carry out the same type of collection but on eight different sectors of the island, decided by the local authorities More precisely, there are 12 operators divided into eight collection sectors for household waste and seven collection sectors for bulky waste (which also includes green waste): five operators for collecting household waste, four operators for collecting bulky items, two operators for collecting green waste and one contractor for collecting sorted waste. As can be observed in Figure 1 (below), the organization of the waste collection in 15 areas that overlap and performed by 12 private operators is a local specificity. Moreover, as can be noticed, there are areas where there is no collection of bulky waste, the inhabitants having to transport the waste themselves to the voluntary drop-off points. These voluntary drop-off points are not represented in Figure 1. The collection takes place from 6 p.m. to 6 a.m. Transporters need to make three or four return trips to the landfill to deliver all the waste.

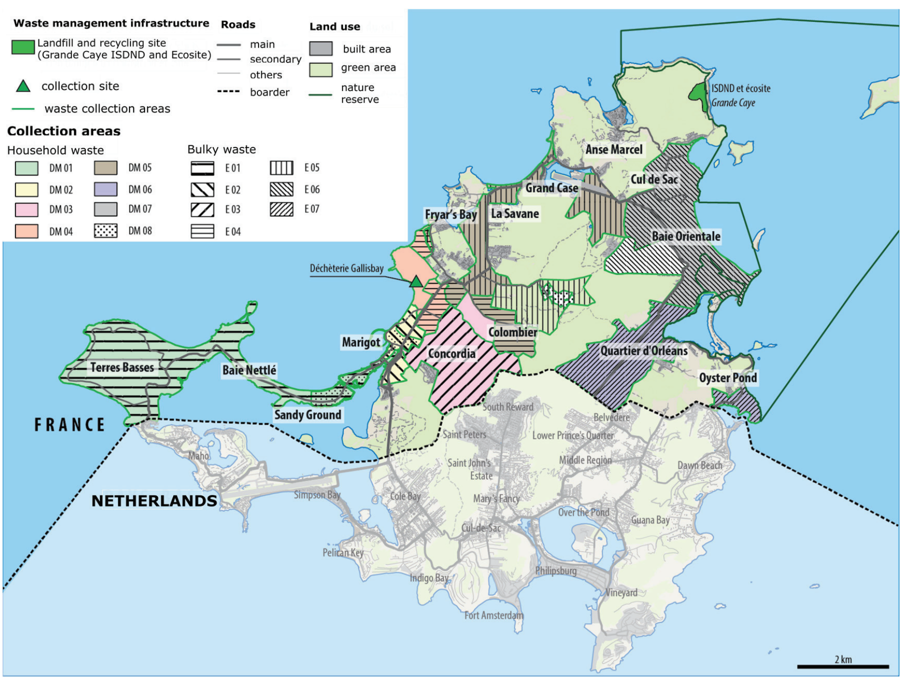

Figure 1. Waste management infrastructure and waste collection areas in Saint Martin (Source: Collectivity of Saint Martin, produced by DéPOs project 2020).

An ELV (End-of-Life Vehicle) treatment center was opened in Grandes Cayes in 2015. It enables vehicle carcasses from the French part of Saint Martin to be decontaminated with the help of a hydrocarbon separator. Since 2013 a treatment unit has also existed for processing infectious risk healthcare waste (DASRI). It is managed by a private company that offers treatment, disinfestation, and shredding. A special vehicle is used for collecting waste from producers: clinics, hospitals, the collectivity of Saint Martin, laboratories, doctors, nurses, midwives, dentists, veterinarians, undertakers and self-treatment patients.

Waste streams (apart from the DASRI) are centralized at the Grande Cayes site, which has become the only facility for waste: household waste collected by private operators (household waste, organic waste, bulky waste, WEEE), waste arriving from the collection and separation site (Galisbay), waste from voluntary drop-off points for collecting household packaging waste, waste from economic operators and waste from general island cleaning campaigns organized by the collectivity at least once a year, plus the ELVs which are systematically collected. On the Grandes Cayes site, waste from the island is either buried, processed and sold locally, redirected to valorization supply chains with eco-organizations or sold on the waste market. In 2013, initial first contracts with eco-organizations were also signed for Waste Electrical and Electronic Equipment (OCA3E eco-organization,) and household packaging (Eco-Emballages). Table 1 shows the different types of waste and their treatment for the year 2015.

Table 1. Waste streams and treatment methods (Source: Verde SXM, Produced by DéPOs Project 2019).

Waste Streams	On-Site Treatment	Destination	Eco-Organization
Green waste	Crushed and mixed with sludge from the collectivity's treatment plant on the composting platform	Sale of compost to NF-U 44-095 standards (from 2014)	NA
Glass	Crushed	Sand and glass gravel are marketed on the island under the name "SWALIGLASS" Marketed to companies on the island for filling electricity supply trenches Used internally on the site for making concrete structures or for route cleanliness	NA
WEEE	Massification Grinding	AER in Guadeloupe International scrap markets	Ecologic
Furniture	Massification		VALDELIA
Ferrous and non-ferrous metal waste	Massification, sorting and compacting	Shipped to international markets after processing in specialized scrap installations in Europe	NA
Cardboard boxes resulting from business activities	Sorted, compacted, and dispatched for upgrading		NA
Packaging waste	Massification	Sorted and upgraded at ECODEC in Guadeloupe	ECODEC EcoEmballages
Batteries and accumulators	Massification		SCRELEC
Bulbs	Massification		Recylum
Used engine oil	Recovered from garages free-of-charge by a service-provider	Upgraded at OSILUB (Rouen) under the terms of an ADEME contract	NA
Cable	Massification	Dispatched to Recyclables for upgrading copper and aluminum	NA
ELV	Storage, decontamination, and dismantling		NA
Rubble	Crushing, sorting	Reuse on site for site design and landfilling	NA

The start-up of these systems as early as 2013 has transformed the circulation of waste flows and increased the volumes of waste leaving the territory. The Verde SXM company noted that there is a need to improve sorting performance by optimizing the sorting platform and by raising awareness among the population and professionals on sorting practices. In 2015, the buried part of waste delivered to the site represented 85% and the recycled part, down on 2014, amounted to 15% [17].

This operation reflects weaknesses which were already summarized by the Saint Martin public authorities in 2014: regulatory difficulties (the obligation to treat waste locally or to export it to Guadeloupe and then to Europe), a market that was not sufficiently developed, a small geographical area available, an overloaded landfill, the absence or the low number of collection and treatment systems for hazardous waste, the low level of recycling, the persistence of illegal dumping. It appears difficult to install effective treatment systems because of the limits induced by the size of the territory and the lack of land [19,20].

Therefore, it is clear that the technical waste management system had already encountered a number of difficulties before hurricane Irma hit, largely due to its insularity, its economics and its political organization. As disasters tend to exacerbate the difficulties felt in normal periods, we wanted to study the impact of this type of phenomenon on the technical waste management system. By relying on the conceptual framework of territorial metabolism, we shall analyze the transformations desired or undergone by the technical waste management system by looking into the waste stocks and waste flow circulation after the passage of hurricane Irma.

3. The Method

3.1. General Methodological Framework

For the past twenty years, work on the island's metabolism has been carried out in the perimeter of socio-ecological studies promoted by the Institute of Social Ecology of Vienna or by industrial ecology [21]. These two fields of research consider the territory as being an interface between society and the biosphere. Territorial metabolism accounts for this interface by representing the territory as a set of stocks and flows of materials and energies circulating within it. In addition to the accounting dimension of flows and stocks, it also covers the description and understanding of the natural and social processes which are at the origin of the circulation of these streams and their evolution, and this in order to modify or transform the territorial metabolism [22,23]. The goals of social ecology and industrial ecology differ somewhat. In simplified terms, where social ecology approaches attempt to include and understand the trajectories of territorial systems and to study and contribute to their socio-ecological transition [24–26], industrial ecology directs its reflexions more toward the knowledge of the streams of current materials for dematerializing or decoupling economic growth and the consumption of materials through symbiosis approaches and work on analyzing life cycles, for example [27]. However, both approaches reflect on the means of improving a territory's sustainability.

Insular territories, in particular, lend themselves to this type of work because the question of their sustainability is paramount. In general, their isolation, their frequently limited size and, consequently, the pressure and conflicts on the subject of land resources, the availability of natural or water resources and their economy, which is often dependent on external factors (tourist activities, agriculture, mineral extraction, etc.), make island territories particularly vulnerable to local and global economic, environmental and social changes [28,29]. Furthermore, such territories have the particularity of having geographic borders that often coincide with administrative borders, which, as such, makes it easier to work on the interactions between societies and the natural environment [21].

In their article, Petridis et al. show the diversity of the work undertaken in the field of industrial ecology and social ecology [21]. It would appear that these works model the flows of materials and energies in order to propose recommendations for a more sustainable management of insular resources, and that others propose to explore the dynamics of socio-ecological transition to measure their consequences on the viability of the territories under study. More specifically, on the subject of waste, the article of Eckelman et al. [29] shows that, if analysis methods of territorial metabolisms are mobilized for defining the volume of waste produced on insular territories together with the circulation of these waste flows, the finality is often an improvement in waste management by reflecting on the development of re-cycling or re-use supply chains or by the use of territorial planning works.

Our work moves along these lines by using territorial metabolism as a conceptual basis. As such, it relates to an insular territory and its waste stocks and flows. Nevertheless, it has the particularity of studying the island in question after the passage of hurricane Irma, after which the island was significantly affected by the production of hurricane waste.

3.2. Specific Methodological Framework

Studies concerning the experience of territories hit by large-scale disasters show that the quantity of waste produced following the damages to buildings, infrastructures and the natural environment can be very significant and diverse [11]. Therefore, looking at the possible evolution of metabolism following hurricane Irma in Saint Martin requires a quantitative approach to waste stocks and flows. In this respect, the analysis can be similar to those already carried out under normal circumstances. Nevertheless, our knowledge of managing this type of phenomenon indicates (1) that these quantities of new waste potentially modify the circulation of waste flows in both time and space over relatively different time periods, and (2) that any such modification is likely to be different depending on the type of waste and on the period during which waste pre-collection occurs (during the immediate post-crisis period, a few months later, or even a few years later).

Works on the evolution of a territory's metabolism have been carried out over more or less long periods in order to study the conditions for implementing a socio-ecological trajectory in continental territories [30–33] or in island territories [34,35], for example. However, these publications do not include studies on the circulation of material flows in shorter time scales. Only three research works have been identified as studying the relationship between a disaster and the development of metabolism: Symmes et al. [36] study the consequences of a natural disaster (a cyclone and a rise in sea level) on building materials present on the Island of Grenada; Quinn [37] analyzes the impact of post-Katrina reconstruction on the New Orleans' metabolism; and Wildenberg and Singh [38] study the consequences of the 2005 tsunami and reconstruction on the socio-ecological system of the island of Kamorta, in the Nicobar archipelago. However, these works do not specifically concern disaster waste management. In this respect, the present article makes a more detailed contribution to the field of island metabolism by working on a disruptive episode over particularly short lapses of time.

To identify the characteristics of the metabolism that we are studying, we will be relying on the three structuring dimensions of territorial metabolism as they were defined by Kampelmann and De Muynck [39]. Therefore, our analysis will focus on the intensity of the metabolism, i.e., the quantities of waste produced and put into circulation. This intensity will be studied in terms of waste flows in order to reveal the effects of the existence (or absence) of waste management streams; the spatial structure of the metabolism, i.e., the spatial organization of waste flows circulation and the part of the metabolism that is internalized or externalized in the system, as well as the actors and techniques that organize waste flow circulation. In this last case, we highlight the roles played by the different actors and all the technical conditions that explain and condition the metabolism. In addition, as previously mentioned, these three driving forces are analyzed in a diachronic approach, so as to take into account the temporal evolutions inherent in post-disaster waste management.

3.3. Data-Collection Method

Data concerning the development of waste-flows circulation on the territory of Saint Martin after the passage of hurricane Irma, in 2017, were collected at the time of two missions carried out in May 2018 [40] and May–June 2019 [41]. Sixty semi-structured interviews were carried out with public stakeholders in waste management, crisis management and regional planning, with building and public works contractors who worked on post-Irma waste management and with private actors in waste management, public services and associations for the protection of the environment (14 interviews in 2018 and 46 interviews in 2019). These interviews were supplemented by discussions with the population in the context of formalized questionnaires (63 inhabitants questioned in 2019) or of semi-structured interviews (16 inhabitants questioned in 2018). These interviews were complemented by a field observation work in order to locate any illegal post-Irma waste-dumping sites and any potential stocks of reconstruction waste that had not yet been collected (abandoned houses damaged by the cyclone).

These discussions and observations enabled quantitative information to be collected on the production of post-Irma waste by assessing the waste arriving at the Grandes Cayes ecosite (the main waste facility for normal waste at Saint Martin). This quantitative data is incomplete and vague, imperfections inherent to disaster waste. This can be explained in several ways: the collection of information on disaster waste is not standardized in post-disaster return on experience, new actors intervene who are not identified as being concerned by waste problems, informal management methods exist, waste is disseminated over time and space, and waste management has been carried out in an emergency situation, which means that part of the volume is not captured by conventional waste management streams, and is therefore not monitored.

In order to reduce these inaccuracies, this quantitative information was supplemented by extra details concerning the organization of waste flow management in the weeks and months following hurricane Irma. These interviews enabled us to increase our knowledge of the volume of waste produced both from quantitative and qualitative points of view, our understanding of the different changes in the organization of waste flow circulation over the territory depending on the post-disaster period and our understanding of post-Irma waste transfer operations deferred over time, as they depended on the date of return of residents who only stay part-time on the island. This phenomenon was also observed in France after storm Xynthia's passage over the Vendée coast in 2010 [42].

4. The Study of the Evolution of Saint Martin's Insular Metabolism after the Passage of Hurricane Irma Applied to Waste Management

The passage of a hurricane generates large quantities of waste. Vegetation, goods, equipment, constructions, cars, etc., are blown away, damaged by the wind or soaked by rain, and, as a result, become waste or debris. However, the moment when this waste is brought to public storage areas varies depending on the time taken for restarting the territory, the urgency with which certain strategic roads and residential areas are cleared (putrescible waste, furniture waste, WEEE and construction waste, for example), the type of damage to businesses or buildings, compensation for disaster victims, etc. The variable production of waste over time is described in the literature as having three phases [8,10,43]. A first, urgent phase, during which roads are cleared in order to provide first aid and to enable vital technical networks to be repaired. During the second, cleaning phase, most waste is collected and treated, and demolition work begins. The largest volume of waste is collected during this period. A third, much longer phase then follows. This is the deconstruction/reconstruction phase (giving rise to construction waste) and the repair phase of infrastructure used for handling post-disaster waste. As shown is Figure 2, the post-hurricane waste flows in Saint Martin also followed these phases, from the moment when the hurricane impacted the island until the territory returned to its normal functioning. The delimitation in time of these phases, as presented in the figure below, is established by the local public authorities. However, the intensity of the waste flows, as will be explained in the following section, shows a different temporal dynamic, that questions whether the waste management public policies are adapted to the needs.

It can be seen that, in these different phases, Saint Martin's territorial metabolism changed in terms of intensity, the spatial organization of its waste flow circulation and the actors who were mobilized.

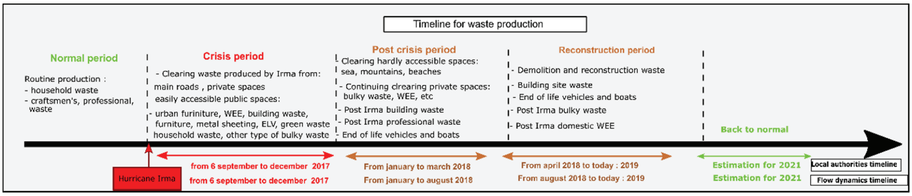

Figure 2. Timeline for the production of waste in Saint Martin following the passage of hurricane Irma (Produced by: DéPOs Project 2019).

4.1. The Intensity of Waste Flows Was Modified in the Long Term after Irma

As has been seen on many other territories [4,8,11], the volumes of waste produced by hurricanes are enormous. On the basis of the discussions held in the field 6 and 18 months after Irma, we were able to highlight this type of increase in waste production [40,41]. Thus, between 7 September 2017 and 30 June 2018, the Grandes Cayes ecosite received 55,889 tons of post-Irma waste. In fact, this waste only represented part of all the waste generated by Irma. According to the director of the Grandes Cayes ecosite, Irma generated the equivalent of two and a half years' production of normal waste, and the equivalent of five years' production of end-of-life vehicles [44]. During the phase of transporting waste from temporary storage sites to the landfill at Grandes Cayes, nearly 300 to 400 trucks entered the ecosite every day, instead of the usual 70 trucks per day. Two years later, the flow of lorries was still higher than normal: approximately 170 trucks per day [44]. The stream of bulky items arriving at the landfill is still three times higher than in normal periods, and reconstruction waste continues to arrive in very large quantities [41].

This significant increase can be seen through the evolution in the quantities of waste treated at the Grandes Cayes site since 2015. Table 2 shows that the volume of waste treated on the site has doubled between 2017 and 2018.

Table 2. Evolution in waste treated by the Grandes Cayes Ecosite (Source: Verde SXM and IREP [45]; Produced by DéPOs—2019).

Year	2015	2016	2017	2018
Quantity of waste treated at Grande Caye Ecosite	34,155 tonnes (Source: Verde) 33,307 tonnes (Source: IREP)	42,311 tonnes (Source: IREP)	83,760 tonnes (Source: IREP)	67,184 tonnes (Source: Verde)

Figure 3, on the other hand, shows the evolution of four specific waste flows from 2017, following the year of hurricane Irma, up to 2019.

The bulky waste is the flow with the most significant increase in variation, encompassing WEEE, furniture and all kinds of goods damaged by the hurricane. As a very limited separation of waste was done during the collection, temporary storage and transportation to the landfill, all these types of waste were included in this category by the Verde SXM company workers when registered at the entry of the landfill. The first peak corresponds to the intense clean-up process during the crisis period (September to December 2017), followed by a drop when the operations were officially over. The second peak shows that, in reality, not all the post-hurricane waste was collected during the crisis period and that waste continued to be produced. This phenomenon can be explained by different local factors, as clean-up actions done by the evacuated inhabitants that started to come back to the island and clean-up campaigns to collect the remaining waste from areas with difficult access. Two years after the hurricane, although stabilized, this flow is still higher than in the pre-Irma period.

Another type of waste flow whose production is still significant in the long term is the construction waste mainly related to current reconstruction operations. Hurricane Irma damaged 95% of the buildings on the island, 27% of which required rebuilding [46]. The production of this type of waste generally takes place at a different time to that of other types of disaster waste. During the crisis, its collection rate dropped comparing to normal times. Indeed, except for metal sheets that were collected during the first months after the hurricane and that were classified as bulky waste, the rubble from buildings whose walls were destroyed, windows or doors, were collected later after the end of the clean-up operations. Once the demolition/reconstruction process begins, other construction waste is produced. To some extent, this depends on the compensation for damage provided to inhabitants by insurance companies, for activities which are insured, on disaster victims' financial resources and the availability of building firms and building materials, for example. Only 49% of the buildings had been rebuilt by August 2019 [47].

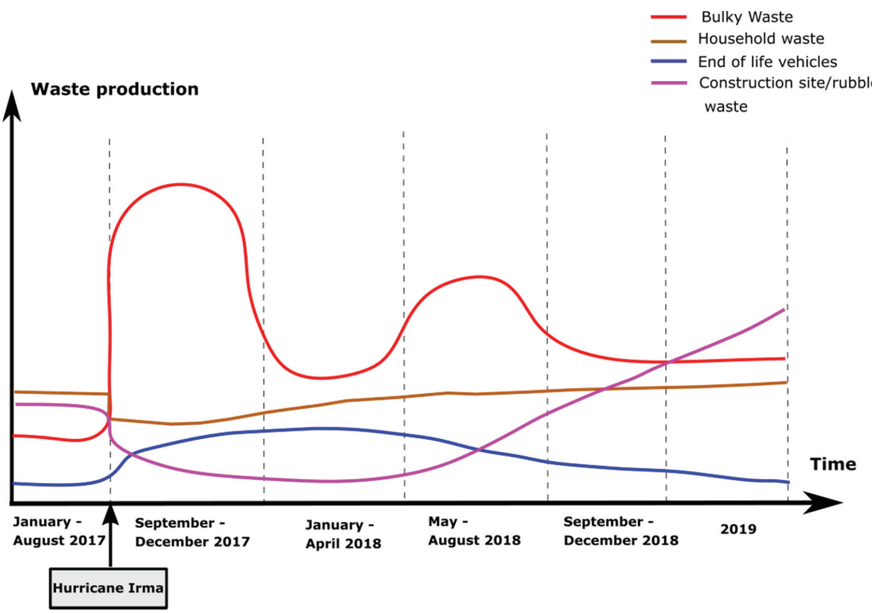

Figure 3. Evolution of waste flows after hurricane Irma in Saint Martin (Source: Verde SXM, field research, [2]) produced by DéPOs—2020).

The end-of-life vehicles were collected separately especially during the first year after Irma, thanks to a program financed by the government. The program took into consideration pre- and post-Irma cars as well. Although there are still abandoned vehicles to collect in public or private spaces, at present the volume is starting to decrease.

In addition to post-Irma waste, the evolution of the intensity of waste stocks and flows on Saint Martin's territory also depends on the so-called "normal" waste produced by the population and all the normal economic activities. Irma had important consequences on the way the island was run: the departure of many inhabitants and significantly reduced tourist activities, which used to be the island's principal source of income. F. Vinet et al. also show that the collection of household waste dropped by 20% during the post-Irma period [2]. Field interviews also confirmed this conclusion, showing that only 21% of the population used the official drop-off points in normal times to deposit their household waste, while others discharged it in the same drop-off areas for bulky waste or burned it.

4.2. Modification of the Spatial Structure of Waste Streams

The increase in waste production and the type of waste produced made the existing waste management system unsuitable for collecting and treating waste. Moreover, the technical waste management system itself was affected by the hurricane. A number of voluntary drop-off points, the basis for waste-collection under normal conditions, were damaged by Irma. The road leading to the Grandes Cayes Ecosite was cut, and machines present on the site were destroyed. An ad hoc organization was set up in a few days, which we will re-discuss in Section 4.3 in order to take a closer look at its design. At this point, we are more concerned by the network's spatial reorganization.

In the first few days after Irma, cleaning operations were intense. At the time, the urgency was to clear the roads blocked by the unending mass of waste resulting from house-clearing. Eleven temporary storage sites were created on sports grounds, car parks and waste land [38] for quickly removing house-clearing waste from public roads. The collected waste was transported to the temporary storage sites while waiting to be transferred to the Grandes Cayes Ecosite. In this way, these sites were more specifically intended to stock waste while waiting for the access roads to the ecosite to be reopened. As we will see in Section 4.3, the organization set up by Saint Martin's local authorities and building and public works companies was assisted by another spontaneous, informal spatial organization (Figure 4): drop-off storage sites that were spontaneously created close to temporary storage sites along the main roads, and in out-of-the-way zones, mostly by the population. These temporary storage sites and drop-off storage sites for disaster waste supplemented the normal voluntary drop-off points for normal waste. The collection of this waste was not carried out using the same organization as for collecting normal waste. The initial delimitation of the new collection sectors was done spontaneously by the local building and public works companies depending on their geographical localization. These sectors are also areas where they have been operating for a long time. Therefore, they had a very good knowledge of the terrain. As can be observed by comparing Figures 1 and 4, new waste collection sectors were created and finally decided by the local authorities together with the building and public works companies in charge of waste collection, the priority being to re-establish the access to critical infrastructures (hospital, public institutions, petrol stations, etc.). Once the urgent phase was over, intensive cleaning of the island continued until the end of October, with a sustained and regular supply of waste commingled on temporary storage sites.

Between mid-November and the end of December 2017, the destocking phase gave birth to another very intense flow of trucks transporting waste from temporary storage sites to the Grandes Cayes Ecosite.

Gradually, the organization for post-Irma waste management implemented in the last quarter of 2017 was brought to a stop by the end of December 2017. The temporary storage sites were then closed in order to prevent any further dumping. This situation led to an increased demand in drop-off sites close to these sites, as there was no interruption in waste production [41]. Building reconstruction operations began in January 2018. Certain affected inhabitants, in particular the owners of holiday homes, were only just beginning their cleaning operations. Although part of the population continued to use the normal collection infrastructure that was now functioning, (voluntary drop-off points, Galisbay collection site, Grande Caye Ecosite), another part continued to use the drop-off sites, although this practice was discouraged and declared illegal. Moreover, small construction companies that did not want to pay the tax for construction waste disposal at the Grande Caye landfill also discharged their waste to these drop-off sites. Therefore (Figure 3), the number of informal drop-off sites increased significantly from that time onward (Figure 5). As the clean-up operations were officially over, in December 2017, and the waste collection system returned to its initial functioning, the drop-off storage sites were considered illegal dumping areas. Therefore, private operators were not obliged to collect them. We can observe on Figure 5 a certain dynamic of these illegal dumping areas. While in 2018 some drop-off sites disappeared as a result of exceptionally public procurement processes for waste collection, other sites appeared nearby in 2019. Although one of the most important criteria that explains this phenomenon is cost-related, when looking at the island's scale, these informal drop-off sites continued to play the role of the temporary storage sites put in place during the crisis period, by storing secondary disaster waste flows generated mostly by the reconstruction but without becoming permanent illegal dumps. Although the clean-up process is slow, the waste at these sites tends to be collected and transported to the Grande Caye landfill.

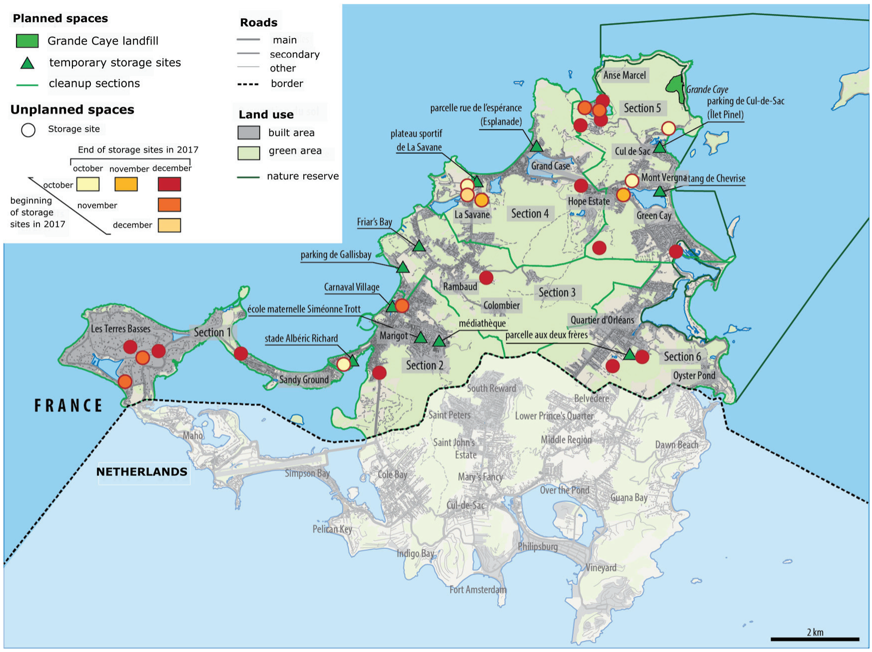

Figure 4. Spatial organization of post-Irma waste management in 2017: storage areas (Produced by: R. Popescu; DéPOs Project—2019).

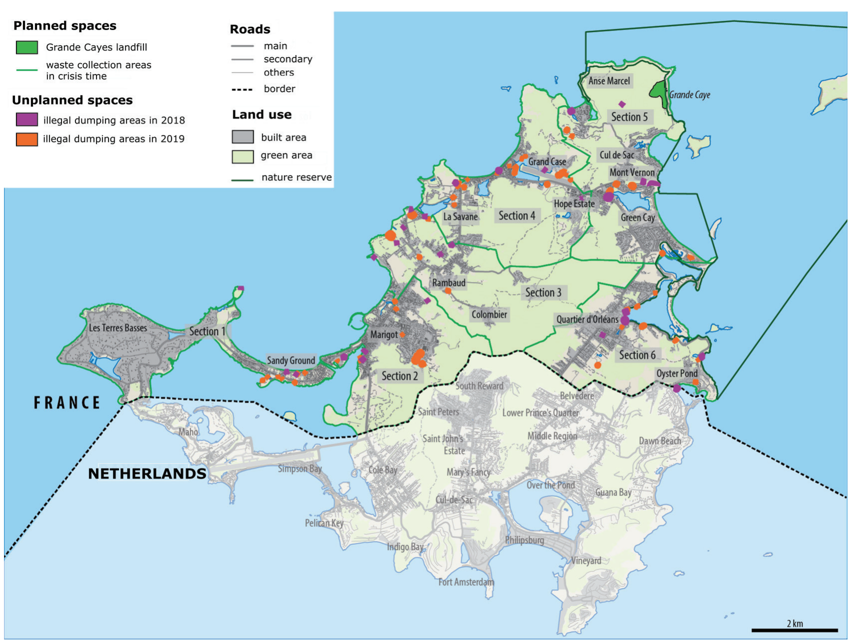

Figure 5. Spatial organization of post-Irma waste management after 2017: storage areas (Produced by: R. Popescu; DéPOs Project—2019).

Hence, the volume of waste produced by Irma, as well as the damage to collection and treatment resources, modified the circulation of waste flows, linked to the organization set up by the actors in waste and crisis management. Although, as we saw previously (Section 2.3), waste management was under the responsibility of Saint Martin's local authorities, which delegated waste collection to about ten different companies, new actors began to play a role after the passage of Irma.

4.3. Temporary Reorganization of Actors after Irma

Although no post-disaster waste management planning existed before Irma, and nothing in the post-disaster management plan (the ORSEC Plan) concerned disaster waste, it is interesting to note that the spontaneous organization which was set up on the day after the island was hit by Irma was the result of the know-how possessed by certain actors, inherited from Luis hurricane, which had hit the island hard in 1995. Certain construction contractors who were interviewed explained that the rapid intervention by companies in the building and public works sector and the creation of 11 temporary storage sites could be explained by vivid memories of this previous event [41].

As seen in other similar situations, the quantity and quality of waste produced does not allow normal waste collection actors to intervene in the collection of waste generated by a disaster, either because not all of their vehicles are suitable, or because they are not sufficiently equipped. Therefore, in the emergency period during the first week after Irma, it was first and foremost for technical reasons that participants were reorganized. Although the waste collection companies whose contracts were in force could have subcontracted to construction companies possessing appropriate equipment, post-crisis organization criteria were different. Building and public works companies played a crucial role in managing hurricane waste throughout the cleaning-up period. This can be explained for the most part by the important role played by building and public works companies in the past history of the island's development. As a result, a complex system of actors was set up—complex because it comprised public, private and civil society actors.

In the first days after Irma, building and public works companies worked alone in clearing up the main lines of communication and creating temporary storage sites. Subsequently, the "actor system" grew with the gradual spontaneous mobilization of additional resources (human, material and financial). The first players arriving from outside the island were companies in Guadeloupe's building and public works sector, mobilized by the "Société d'Economie Mixte de Saint Martin" (SEMSAMAR). Their mission was to take action on rented social housing on the island. The armed forces were also mobilized by the State in the framework of the ORSEC (Civil Security Response Organization) plan. For example, toward the end of September, the French Navy's Projection and Command Ship "Tonnerre" significantly increased the means of waste management thanks to its technical and human resources. They accelerated the clean-up speed and opened a new access route to the Grandes Cayes landfill. Subsequently, several small local companies were also created. They took part in the cleaning up process. As a result, the "actor system" reached its peak in terms of numbers during October, before starting to decrease.

October was also the most intense time for cleaning and transporting waste from drop-off storage sites to temporary storage sites. The new actors from the outside were perceived as a threat by local building and public works companies which wanted to monopolize the market for financial reasons. Once the access road to the landfill had been re-opened, temporary storage sites began to be destocked. The local building and public works companies wanted to regain control at this stage. The head of the risk management mission at the Saint Martin collectivity explained that around fifty companies from the local building and public works sector negotiated over-the-counter contracts with authorities for transporting waste stored on temporary storage sites to the Grandes Cayes landfill. The payment system was based on the number of rotations and not on the number of tonnes, which worked in favor of the building and public works companies. The overall cost of cleaning up the island was 15 million euros [41].

This new reorganization of the actor system was reflected by a visible drop in the level of cleanliness and the appearance of new drop-off sites on the island during the months of November and December

(Figure 4). This phenomenon can be explained in various ways: the departure of the armed forces, the end of funding for cleaning operations and the impossibility of continuing to pay the work forces, the attention paid by building and public works companies to the destocking phase rather than to cleaning the territory and the waste flows that continued to be generated by the population.

Therefore, at the end of the clean-up, after the last storage sites had been closed, the drop-off storage areas became illegal dumps, sources of projectiles for the next hurricane season. The Saint Martin collectivity had neither the technical nor the human resources for cleaning and collecting these dumps. Specific procurement procedures had to be drawn up for each cleaning operation.

From the beginning of 2018, the official waste management system started to run normally again, as before Irma. It was overwhelmed very quickly by the stream of waste that continued to be produced. This situation led to an informal waste management system. The new system was set up by a number of new actors: new citizen associations, actors who had to assume new responsibilities and cleaning campaigns organized by the community with the population's participation. They appeared spontaneously in the face of the need to clean up areas that were difficult to access, such as the seabed, mountains, natural areas, etc. Pre-existing informal actors and waste recycling and reuse streams also increased their activities as a result of this opportunity. Among the local recycling actors, we note the presence of three building and public works companies possessing crushers for grinding concrete. However, this activity was marginal and not officially recognized on the island. According to local actors' estimates, only 10% of the material was recycled on embankment, earthmoving and road base projects, 60% of the concrete was used to create surfaces between layers of household waste on the landfill and 30% was illegally dumped in the countryside [41].

Reusable building materials (steel sheeting and timber) were recovered by informal networks controlled by the Haitian and Dominican communities and sent back to their home countries. According to interviews held with heads of building companies, before Irma they sent back containers with building materials once or twice a year. After Irma, this export flow increased to several containers per week. If, quantitatively, this informal sector did not represent a great deal, it still played a role on materials that were exported, i.e., materials that left the island system [41]. In his works, [48] also calls for the need to integrate the informal recycling sector into the formal waste management system in order to make the social metabolism more circular. A first step is to improve our understanding of this sector in order to recognize its importance and inform public policies around ecological sustainability. Further research is needed not only in low-income countries, but also in high-income countries where informal recycling is becoming a growing phenomenon, that finds local authorities unprepared.

The importance of informal networks in disaster waste management has already been observed in several territories, such as Haiti after the 2010 earthquake, where 57.5% of the total volume of waste produced was managed by the informal sector and civil society [49,50]. These informal networks represent streams with interesting potential from the perspective of circularizing waste flows in Saint Martin's metabolism. They need to be accompanied by the authorities both financially and technically, so that they can last over time on the territory.

5. Conclusions

In conclusion, the analysis of the evolution of Saint Martin's metabolism following the impact of hurricane Irma shows a strong variation in its three short-term dimensions. Faced with the intensity of waste flows, a new spatial structure and a new system of actors reinforced by external resources was set up in order to control the waste streams. This change led to a transformation in the system's operation when compared to the way it operated previously. Once the crisis period was over, the waste management system did not return to its initial mode of operation. The intensity of the waste flows that continued to be generated remained much higher than before Irma. The capacities of existing official infrastructures proved to be insufficient for absorbing all the new waste flows, and this resulted in their spatial dissipation to illegal dumps or via informal streams. As a result, the metabolism evolved on the three dimensions under study: intensity, spatial dimension and actors and techniques.

These evolutions led to a lasting transformation of waste stocks. Most of the waste generated by Irma was buried, particularly furniture and electrical/electronic waste collected together during the crisis period. The condition for having this waste recovered by an eco-organization is that it is sorted and clean, an operation that is extremely difficult to set up during a crisis period if it has not been planned beforehand. Under these conditions, according to the manager of Verde SXM company, the Grandes Cayes landfill lost three years of its life as a result of Irma [41]. Three years after the crisis, new post-Irma waste flows continue to be generated by operations for cleaning, demolishing or reconstructing abandoned houses—operations that have only been 50% completed at present. These operations were essentially focused on building and public works.

On the other hand, the permanent transformation of the waste flow's circulation is less certain, a phenomenon that can be partly attributed to informal streams. The waste flows from the ELV (End-of-Life Vehicles) and BPHU (Out-of-Service Pleasure Boats) sector are the only ones whose structuring was supported by the authorities, through the assistance of DEAL Guadeloupe. The management of hazardous waste is the state's responsibility. After Irma, a DEAL territorial unit was created in Saint Martin with a risk and pollution officer, an evolution that has represented a lasting transformation in the management of hazardous waste flows. Two extra garages were installed on the territory for handling ELVs and accelerating their decontamination, crushing and compacting operations. Thanks to these measures, the collection rate went up from 40 ELV per month to around 200 ELV per month during 2018, but it did not reach the target imposed by the DEAL of 400 ELV per month. In 2019, one of these two garages was closed following controls due to non-compliance with pollution regulations, but the garage at Grandes Cayes is still in operation. Hence, by March 2019, 2900 ELV out of a total stock of 50,000 were evacuated from the territory (2000 before Irma). In 2019, a number of ELVs were identified on public land that had not yet been collected, and there were also a number of ELVs stored on private property that the population had kept for selling their spare parts. Concerning out-of-service pleasure boats, public tenders have been issued to find an operator capable of decontaminating and dismantling them. By 2019, 170 wrecks have been mapped and located, but they were still awaiting processing due to lengthy administrative procedures [41]. On the other hand, and despite the support of the Saint Martin prefecture, which recognizes the importance of structuring this type of activity, building and public works waste stream still operates under unofficial conditions. Even so, the system of actors in this sector has undergone a transformation, caused by the appearance of new actors or by the consolidation of a certain number of pre-existing actors. The management of the sector is under the responsibility of the collectivity. As far as management of household waste is concerned, it has returned to its initial mode of operation.

The lack of structured streams in Saint Martin before Irma and the difficulty in incorporating them into the structure of the official system after the crisis have given rise to difficulties in monitoring and accounting for these waste flows and to a low recycling rate. Some exports of waste were reported by the Verde SXM company. Up to 2019, two ships of 3700 tons each of crushed scrap metal and one container of 300 tons were shipped to the north of France [41]. Two years later, the Grandes Cayes ecosite had still not returned to normal operation, as it was still processing waste caused by Irma.

The Saint Martin case study highlights a metabolism that remains largely internalized. Despite its transformation following the disaster and the appearance of a few new recycling or re-use streams, waste flows remain relatively linear. This observation underlines the importance of working firstly on the circularity of these flows internally, and secondly on the scale of the Caribbean region, thereby tending toward outsourcing.

Author Contributions: Conceptualization, R.P., H.B. and B.B.; data curation, R.P.; funding acquisition, B.B.; investigation, R.P.; methodology, R.P. and H.B.; writing—original draft, R.P., H.B. and B.B.; writing—review & editing, H.B. and B.B. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the National Research Agency, which supports the research project Post Hurricane Waste (ANR-18-OURA-0003).

Acknowledgments: The authors thank to all the local public, private stakeholders as well as the civil society and the citizens of Saint Martin that offered us valuable information and support during the field research mission. The authors are also grateful to all the partners of the ANR DéPOs project: Gustave Eiffel University, Le Mans University, Avignon University, IFSTTAR, Robin des Bois Association and University of Mons (associated international partner).

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

References

1. Meteo France. Passage de l'Ouragan Exceptionnel Irma sur les îles Françaises des Antilles les 5 et 6 Septembre 2017. Available online: http://www.meteofrance.fr/espace-presse/53976142-passage-de-l-ouragan-exceptionnel-irma-sur-les-iles-francaises-des-antilles-les-5-et-6-septembre-2017 (accessed on 21 January 2019).
2. Vinet, F.; Peroche, M.; Palany, P.; Leone, F.; Gherardi, M.; Grancher, D.; Moatty, A.; Defossez, S. Collecte et gestion des débris post-cycloniques à Saint-Martin (Antilles françaises) après le passage du cyclone Irma (sept. 2017). *Cybergeo* **2020**. [CrossRef]
3. Lloréns, H. Ruin Nation. *NACLA Rep. Am.* **2018**, *50*, 154–159. [CrossRef]
4. Blake, E.S. The 2017 Atlantic Hurricane Season: Catastrophic Losses and Costs. *Weatherwise* **2018**, *71*, 28–37. [CrossRef]
5. FEMA. Public assistance. In *Debris Management Guide*; FEMA: Washington, DC, USA, 2007; p. 260.
6. Brown, C.; Milke, M.; Seville, E. Disaster management: A review article. *Waste Manag.* **2011**, *31*, 1085–1098. [CrossRef] [PubMed]
7. UNOCHA. *Disaster Waste Management Guidelines*; UNEP/OCHA: Geneva, Switzerland, 2011; p. 43.
8. Beraud, H. Initier la Résilience du Service de Gestion des Déchets aux Catastrophes Naturelles: Le cas des Territoires Urbains et de l'Inondation. Ph.D. Thesis, Université Paris est Marne-la-Vallée, Champs-sur-Marne, France, 2013.
9. Beraud, H.; Nithart, C.; Durand, M. The difficult disaster waste management: Case of Irma hurricane in Saint Martin. *Urban Risks* **2019**, *3*. [CrossRef]
10. Brown, C. Disaster Waste Management: A Systems Approach. Ph.D. Thesis, University of Canterbury, Christchurch, New Zealand, 2012.
11. Seraphin, H. Natural disaster and destination management: The case of the Caribbean and hurricane Irma. *Curr. Issues Tour.* **2019**, *22*, 21–28. [CrossRef]
12. Barroca, B.; Pacteau, C. Resilienza progetto urbano: Cosa ci insegnano le alluvioni del 2016 in Francia? *Techne* **2018**, *15*, 31–38.
13. Redon, M. Saint-Martin/Sint-Maarten, une petite île divisée pour de grands enjeux. *Cah. d'Outre-Mer* **2006**, *59*, 233–266. [CrossRef]
14. Préfecture de Guadeloupe. *Impact Économique des Fonds Européens 2007–2013 en Guadeloupe et dans les Ile du Nord. Préfecture de Guadeloupe. Rapport Final*; Technopolis-Amnyos Group: Guadeloupe, France, 2014; p. 149.
15. Collectivité de Saint-Martin. *Rapport des Services*; Collectivité de Saint Martin: Saint Martin, France, 2013; p. 250.
16. IEDOM. *Panorama 2017 de St-Martin.Note Expresse N°559*; IEDOM Guadeloupe Agency: Abymes, France, 2019; p. 4.
17. Verde Environnement. *Installation de Stockage des Déchets Non Dangereux des Grandes Cayes*; Rapport Annuel; Dossier d'information: Saint-Martin, France, 2015; p. 24.
18. Verde Environnement. Communiqué Concernant les Résultats de la Caractérisation des Déchets Présents dans l'alvéole de Stockage de la ISDND de Grande Caye; Collectivité de Saint Martin, France 2019. Available online: https://www.facebook.com/1499883603585492/photos/pcb.2382097448697432/2382091572031353/?type=3&theater (accessed on 19 August 2020).
19. Collectivité de Saint-Martin. *Rapport d'Activités*; Collectivité de Saint-Martin: Saint Martin, France, 2015; p. 245.
20. Collectivité de Saint-Martin. *Contrat de Développement 2014–2020*; Collectivité de Saint Martin: Saint Martin, France, 2014; p. 90.
21. Petridis, P.; Fischer-Kowalski, M.; Singh, S.J.; Noll, D. The role of science in sustainability transitions: Citizen science, transformative research, and experiences from Samothraki island, Greece. *Isl. Stud. J.* **2017**, *12*, 115–134. [CrossRef]

22. Barles, S. L'écologie territoriale et les enjeux de la dématérialisation des sociétés: L'apport de l'analyse des flux de matières. *Développement Durable Territ.* **2014**. [CrossRef]
23. Barles, S. Écologie territoriale et métabolisme urbain: Quelques enjeux de la transition socioécologique. *Rev. d'Économie Régionale Urbaine* **2017**, *5*, 819–836. [CrossRef]
24. Krausmann, F.; Fischer-Kowalski, M.; Schandl, H.; Eisenmenger, N. The Global Sociometabolic Transition. *J. Ind. Ecol.* **2008**, *12*, 637–656. [CrossRef]
25. Fischer-Kowalski, M. Society's Metabolism. *J. Ind. Ecol.* **1998**, *2*, 61–78. [CrossRef]
26. Fischer-Kowalski, M. Analyzing sustainability transitions as a shift between socio-metabolic regimes. *Environ. Innov. Soc. Transit.* **2011**, *1*, 152–159. [CrossRef]
27. Erkman, S. L'écologie industrielle, une stratégie de développement. *Le Débat* **2001**, *113*, 106–121. [CrossRef]
28. Deschenes, P.J.; Chertow, M. An island approach to industrial ecology: Towards sustainability in the island context. *J. Environ. Plan. Manag.* **2004**, *47*, 201–217. [CrossRef]
29. Eckelman, M.J.; Ashton, W.; Arakaki, Y.; Hanaki, K.; Nagashima, S.; Malone-Lee, L.C. Island Waste Management Systems: Statistics, Challenges, and Opportunities for Applied Industrial Ecology. *J. Ind. Ecol.* **2014**, *18*, 306–317. [CrossRef]
30. Athanassiadis, A.; Bouillard, P.; Crawford, R.H.; Khan, A.Z. Towards a Dynamic Approach to Urban Metabolism: Tracing the Temporal Evolution of Brussels' Urban Metabolism from 1970 to 2010. *J. Ind. Ecol.* **2017**, *21*, 307–319. [CrossRef]
31. Barles, S. The main characteristics of urban socio-ecological trajectories: Paris (France) from the 18th to the 20th century. *Ecol. Econ.* **2015**, *118*, 177–185. [CrossRef]
32. Buclet, N. (Ed.) *Essai d'Écologie Territoriale: L'Exemple d'Aussois en Savoie*; CNRS Editions: Paris, France, 2015; p. 218.
33. Rosado, L.; Kalmykova, Y.; Patricio, J. Urban metabolism profiles. An empirical analysis of material flow characteristics of three metropolitan areas in SWeden. *J. Clean. Prod.* **2016**, *126*, 206–217. [CrossRef]
34. Krausmann, F.; Richter, R.; Eisenmenger, N. Resource Use in Small Island States. *J. Ind. Ecol.* **2014**, *18*, 294–305. [CrossRef] [PubMed]
35. Eckelman, M.J.; Chertow, M.R. Using Material Flow Analysis to Illuminate Long-Term Waste Management Solutions in Oahu, Hawaii. *J. Ind. Ecol.* **2009**, *13*, 758–774. [CrossRef]
36. Symmes, R.; Fishman, T.; Telesford, J.N.; Singh, S.J.; Tan, S.Y.; Kroon, K. The weight of islands: Leveraging Grenada's material stocks to adapt to climate change. *J. Ind. Ecol.* **2019**. [CrossRef]
37. Quinn, D.J. Modeling the Resources Consumption of Housing in New Orleans Using System Dynamics. Master's Thesis, Massachusetts Institute of Technology, Cambridge, MA, USA, 2008.
38. Wildenberg, M.; Singh, S. Integrated modelling and scenario building for the Nicobar Islands in the aftermath of the Tsunami. In *Human—Nature Interaction in the Anthropocene*; Potentials for Socio-Ecological Systems Analysis; Glaser, M., Krause, G., Ratter, B.M.W., Welp, M., Eds.; Routledge: London, UK, 2012; pp. 161–189.
39. Kampelmann, S.; De Muynck, S. Les implications d'une circularisation des métabolismes territoriaux—Une revue de la littérature. *Pour* **2018**, *236*, 153–173. [CrossRef]
40. Robin des Bois. *Les Déchets de L'ouragan Irma*; ANR—Projet DéPOs; Robin des Bois: Paris, France, 2018; p. 106.
41. Perez, J.; Popescu, R. *La Gestion des Déchets Post-Ouragan « Irma » à Saint-Martin: Jeux d'acteurs et Transformation du Système Local d'avant, durant et d'après-Crise*; Rapport de Terrain, ANR—DéPOs; Université du Mans: Le Mans, France, 2019; p. 161.
42. Robin des Bois. *Les Déchets de la Tempête Xynthia*; Robin des Bois: Paris, France, 2010; p. 111.
43. Roper, W.E. Waste management policy revisions: Lessons learned from the Katrina disaster. *Int. J. Environ. Technol. Manag.* **2008**, *8*, 275–309. [CrossRef]
44. Marie, C. Deux ans Après Irma, la Décharge de Saint-Martin Toujours Débordée. Press Article; La 1ere France tv Info. Available online: https://la1ere.francetvinfo.fr/emissions-radio/planete-outre-mer/deux-ans-apres-irma-decharge-saint-martin-toujours-debordee-planete-outre-mer-743591.html (accessed on 17 August 2020).
45. Registre des Émissions Polluantes. Etablissement Verde SXM. Available online: https://www.georisques.gouv.fr/dossiers/irep/form-etablissement/details/13648#/ (accessed on 17 August 2020).
46. Gustin, P. Repenser les îles du nord pour une reconstruction durable. In *Délégation Interministérielle à la Reconstruction des îles de Saint-Barthélemy et Saint-Martin*; République Française: Paris, France, 2017; p. 34.
47. Délégation sénatoriale aux outre-mer. Risques naturels majeurs. In *Bâtir la Résilience des Outre-Mer*; République Française: Paris, France, 2019; p. 8.

48. Demaria, F. Social Metabolism, Cost—Shifting and Conflicts: The Struggles and Services of Informal Waste Recyclers in India. Ph.D. Thesis, Universitat Autonoma de Barcelona, Barcelona, Spain, 2017; p. 87.
49. Durand, M.; Popescu, R.; D'Ercole, R. Les déchets post-catastrophe à Haïti: Les jeux d'acteurs d'une gestion informelle. *VertigO* **2015**. [CrossRef]
50. Popescu, R.; Durand, M.; d'Ercole, R. La gestion des déchets post-catastrophe à Port-au-Prince: Entre relégation et proximité. *EchoGéo* **2014**. [CrossRef]

© 2020 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (http://creativecommons.org/licenses/by/4.0/).

sustainability

MDPI

Article

GIS-Based Material Stock Analysis (MSA) of Climate Vulnerabilities to the Tourism Industry in Antigua and Barbuda

Johnella Bradshaw [1], Simron Jit Singh [1,*], Su-Yin Tan [2], Tomer Fishman [3] and Kristen Pott [2]

1 School of Environment, Enterprise and Development, University of Waterloo, Waterloo, ON N2L3G1, Canada; jcbradsh@uwaterloo.ca
2 Department of Geography and Environmental Management, University of Waterloo, Waterloo, ON N2L3G1, Canada; su-yin.tan@uwaterloo.ca (S.-Y.T.); ke2dekroon@uwaterloo.ca (K.P.)
3 School of Sustainability, Interdisciplinary Center (IDC), Herzliya 4610101, Israel; tomer.fishman@idc.ac.il
* Correspondence: simron.singh@uwaterloo.ca

Received: 27 July 2020; Accepted: 28 September 2020; Published: 30 September 2020

Abstract: In the past decades, the Caribbean economy has transformed to rely primarily on tourism with a vast amount of infrastructure dedicated to this sector. At the same time, the region is subject to repeated crises in the form of extreme weather events that are becoming more frequent, deadly, and costly. Damages to buildings and infrastructure (or the material stocks) from storms disrupt the local economy by an immediate decline in tourists and loss of critical services. In Antigua and Barbuda (A&B), tourism contributes 80% to the GDP and is a major driver for adding new material stocks to support the industry. This research analyzes A&B's material stocks (MSs) in buildings (aggregates, timber, concrete, and steel) using geographic information systems (GIS) with physical parameters such as building size and footprint, material intensity, and the number of floors. In 2004, the total MSs of buildings was estimated at 4.7 million tonnes (mt), equivalent to 58.5 tonnes per capita, with the share of non-metallic minerals to be highest (2.9 mt), followed by aggregates (1.2 mt), steel (0.44 mt), and timber (0.18 mt). Under the National Oceanic and Atmospheric Administration's (NOAA's) 2 meter (m) sea level rise scenario, an estimated 4% of the island's total MSs would be exposed. The tourism sector would disproportionately experience the greatest exposure of 19% of its MSs. By linking stocks to services, our research contributes to the understanding of the complexities between the environmental and economic vulnerability of island systems, and the need for better infrastructure planning as part of resilience building.

Keywords: Antigua and Barbuda; tourism; climate change; small island developing states (SIDS); island sustainability; resource use and efficiency; material stock analysis; construction materials; geographical information systems (GIS); industrial ecology

1. Introduction

As economies develop, they stimulate the demand for essential services that are provided by the built environment (also referred to as "material stocks") in the production and consumption of goods and services, viewed as "the material basis of societal well-being" [1]. The growth and maintenance of these material stocks occur by mobilizing material and energy flows, either from domestic sources or through imports from other societies. The larger the stocks, the greater the flows required to maintain and reproduce these stocks, creating a feedback loop that has been termed as the "material–stock–flow–service nexus" (ibid.). This process of organizing and reproducing material stocks and flows by society is referred to as "social metabolism" [2].

Focusing on a small island state in the Caribbean, this research provides evidence on the extent to which the nation's built environment is vulnerable to the impacts of climate change. Utilizing the state-of-the-art spatially explicit material stock accounting (MSA), we highlight the economic impacts on Antigua and Barbuda's (A&B) tourism industry under a 1 m and 2 m sea level rise (SLR) scenario. Services including hotel accommodations, restaurants, real estate, yachting, and marina facilities are linked to the expansion of the tourism industry and the built infrastructure. With tourism contributing to approximately 80% to the GDP [3], the small island nation constantly experiences a heightened level of economic uncertainty due to its exposure to external economic shocks and climate-related events such as hurricanes. Based on our findings, we critique spatial planning and maladaptive practices such as coastal squeeze that need to be urgently considered for building system resilience. The Caribbean is the most tourism-reliant region in the world [4]. Tourism infrastructure and assets are mostly concentrated along the coasts and are subject to high risk from tropical storms. As such, tourism-dependent economies in the Caribbean face the highest risk worldwide [5]. Yet, growth and continued reliance on this climate-sensitive economic sector requires a continuous (re)accumulation of material stocks in buildings to meet growing demands. At the same time, the damages incurred from climate-related events are substantial in size in comparison to their economies. Ten percent of the worst impacted countries in terms of losses as a share of their GDP were Caribbean nations. For example, during the 2017 hurricane season, Sint Maarten's losses were estimated at 797% of the country's annual gross domestic product (GDP), the British Virgin Islands with 309% of their GDP, and Dominica with 259% of their GDP [6]. Sea level rise (SLR) is an imminent threat to small island developing states (SIDSs) as 26% of their land area is 5 m or less above sea level, equating to roughly 20 million people (or 30% of the SIDS population) living within these high-risk areas [7].

The high cost of loss and damage witnessed by these Caribbean islands is accompanied by excessive national debt, and the reliance on imports to supply new materials for infrastructure development and reconstruction [8,9]. Losses equate mostly to the damages caused to the built environment that delivers critical goods and services such as transport, health, food, and energy. By 2050, climate inaction is expected to cost Caribbean countries an estimated 10% of their GDP annually from hurricane damages and loss of tourism revenue alone, rising to 22% by 2100 [10]. By 2150, conservative estimates of SLR suggest that only a fraction of the current 66 million inhabitants of the small island developing states (SIDSs) will be spared from inundation [11]. In the face of these challenges and threats, achieving island sustainability is critical for these SIDSs [12,13]. In this study, island sustainability is defined as achieving a high quality of social and human wellbeing at the lowest environmental costs. Island sustainability also implies adapting and increasing resiliency to buffer against the adverse impacts of global environmental change and economic instabilities while maintaining resource security and self-reliance.

This study is part of a larger effort to study the metabolism of islands, an emerging research field within industrial ecology, that aims to seek solutions to sustainability challenges faced by small islands (see the initiative "Metabolism of Islands" (https://metabolismofislands.org) and the special issue Metabolism of Islands, Sustainability: https://www.mdpi.com/journal/sustainability/special_issues/metabolism_islands). The objectives of the research are two-fold. One is to contribute to the scant literature on the relationship of stocks and services, in particular tourism within an island context, and their exposure to climate vulnerability. We analyze these findings in the context of island sustainability by asking how can islands leverage spatial infrastructure planning as a way to build resilience and adapt to climate change, including sea level rise scenarios. Second, as a methodological contribution, this study introduces novelties to the geographical information systems (GIS)-based stock accounting method by presenting a building footprint-based identification of buildings and the use of Monte Carlo simulation in assigning material intensity typologies (MITs). In this study, the focus is directed towards classifying and estimating the material stock of construction materials including wood, non-metallic minerals, steel, and iron that are utilized for the growth and expansion of the building stocks.

2. Advances in Material Stock Accounting (MSA) Research

The 20th century has seen a massive increase in material flows that go into creating material stocks, from just over 20% in 1900 to over 50% in 2010 [14]. This has inspired several studies to focus on the dynamics and growth of anthropogenic stocks that require ever-increasing virgin materials [15]. Studies quantifying and characterizing the material composition of in-use material stocks as a potential pool of secondary resources for future material recovery are becoming important [16–19]. With the growing relevance of material stock accounting/analysis (MSA), researchers are constantly proposing additional approaches for improved material stock accounting. For example, Muller et al. [20] identified two main methodological approaches for material stock measurements, including a top-down and a bottom-up approach. Top-down approaches integrate historical data based on data availabilities on material inflows and material outflows determined by lifespan characteristics to quantify material stock [20,21]. In contrast, bottom-up approaches are data intensive and combine input parameters such as gross floor area, number of stories, and the average size of the dwelling area [22]. The bottom-up approaches require material end uses to be separated into categories sharing material intensities used to calculate material stock. This approach is mostly favored for the efficient use of GIS data [23] to explore spatial material stock accounts for local-scale studies worldwide [15,18,24–26]. Augiseau and Barles [27] analyzed thirty-one studies on material stocks and flows, along with distinguishing between six methodological approaches that were commonly used in such research.

Observing the surge of research related to the built environment within the past two decades, MSA is increasingly incorporating the use of GIS [16]. GIS comprises technology tailored to collecting, analyzing, and managing georeferenced data to produce location-specific information [23]. The application of GIS is not limited to calculating the size of the material stocks within a region but, from a spatial perspective, it can identify where material stocks have accumulated and how they are distributed within socio-economic systems. The applications of 4D-GIS and spatial data applied in previous studies focused on understanding the accumulation of material stocks on a temporal and spatial scale, in two different urban areas [24]. After a catastrophic earthquake and tsunami struck Japan, a material stock analysis (MSA) estimated the quantity of construction materials lost from the physical infrastructure (including buildings and roads) using GIS [25]. Wallsten et al. [28] combined a bottom-up material flow analysis (MFA) approach with GIS as an assessment tool to spatially characterize and examine hibernating metal stocks in urban infrastructure. Similarly, Kleemann et al. [15] utilized GIS data to quantify material stocks in buildings and map their spatial distribution within the city of Vienna through combining information about demolition activities to yield waste flow data. Mesta et al. [18] adopted a bottom-up approach to quantify the material stocks for residential buildings in Chiclayo (Peru) utilizing GIS data and data pertaining to the physical size of buildings. In Sweden, Heeren et al. [29] presented a bottom-up approach stock model with the use of geo-referenced building data to determine the building material stocks of Swiss residential buildings based on volumetric properties [29]. Symmes et al. [30] presented a bottom up GIS methodological approach to explore the vulnerability of material stock in buildings in Grenada [30]. Pott et al. [31] (paper submitted) adopt a spatial (bottom-up) GIS approach to study the relationship of in-use stocks and their services using a city and an island as cases.

3. Socio-Metabolic Research on Islands

Analyzing material stocks (MSs) plays an important and multifaceted role within socio-metabolic research, including functioning as service suppliers, wealth indicators, capital and resource repositories, and indicators for the spatial development of the built environment [32]. Small islands are ideal units of study for socio-metabolic research, with clear and distinct systems boundaries to track flows. At the same time, islands suffer from resource constraints due to their narrow resource base and limited waste absorption capabilities, causing sustainability problems both on the input side (scarcity and import dependency) and the output side (land and sea pollution) [17,33–37]. The lack of resources and relatively small populations limit the size of island economies and the ability to achieve economies of scale, thus pushing the overdependence of small island states on external markets to meet the majority of their resource needs. The openness of small island economies to external markets and their high dependency on trade to meet basic needs heighten their level of vulnerability.

Socio-metabolic research offers islands a unique perspective on sustainability, leveraging resource use patterns to build system resilience. Understanding the physical basis of island economies highlights areas of opportunities and constraints impacting sustainable development [38–40]. However, few socio-metabolic studies have been conducted on small islands. The first known material stock and flow account for an island was for Trinket (Nicobars, India) that portrayed the changing characteristic metabolic profile of an indigenous society subject to development programs from the Indian state [41], that was later compared with the rise in material and energy consumption due to the excessive aid following the 2004 Asian tsunami [42]. Krausmann et al. [43] focused on the application of a material flow analysis (MFA) for two high-income island states, Iceland and Trinidad and Tobago. The resource use patterns revealed that both islands heavily rely on domestic extractions, including fisheries, natural gas, and oil. Shah et al. [44] focused on institutional factors in Trinidad and Tobago and the challenges of implementing potential solutions tackling the island's waste metabolism of plastics and packaging material. Okoli [45] quantified biomass flows for Jamaica from 1961 to 2013 in the context of national food security from an island perspective. Marcos-Valls et al. [46] applied an integrated multi-scale socio-metabolic analysis for Menorca (Spain) to analyze the environmental and economic performance of major economic activities such as tourism in an island context.

Material stocks and flows were studied on the Greek island of Samothraki using a socio-metabolic approach [40,47]. More recently, Fischer-Kowalski et al. [48] focused on Samothraki's regime shift as the island transitions from an agriculture-based economy to a service (tourism) economy. In the Philippines, a material flow analysis was conducted to understand trends within a high-density country experiencing a shift from renewable to non-renewable materials as a result of ongoing development [49]. Symmes et al. [30] conducted the first material stock–flow analysis in the Caribbean, with a focus on Grenada's metabolism of construction materials, how they are distributed across the different sectors of the economy, and the potential impacts as a consequence of sea level rise [30]. Pott et al. [31] (paper submitted) explore the material stock–service relationship in Grenada and examines future material stock scenarios with consequences for island sustainability. The lack of proper waste management systems on islands is a growing concern as they undergo rapid development, with waste produced as a by-product of economic activities. Recently, a case study on the Faroe Islands focused on the practice of sustainable land management through the lens of social metabolism within a growing local economy [50].

4. Study Area: Antigua and Barbuda

A&B is one of the Leeward Islands situated in the eastern Caribbean Sea [51]. The country's political boundary consists of three islands: Antigua, Barbuda, and Redonda. Antigua functions as the mainland territory and is the largest of the three with an area of 280 sq. km. The sister isle of Barbuda is the second largest with an area of 161 sq. km. The smallest of the three, Redonda, is the only uninhabited island with an area of 1.6 sq. km [51]. Antigua's landscape is divided into seven parishes, with St. John's being Antigua's capital city and Codrington being the capital of Barbuda.

The coupled relationship between the ecosystem and the economy has proven to be beneficial in sustaining economic growth in A&B. The country's limited natural resources, distinct ecosystems, and its rich cultural heritage are all contributing factors in sustaining the island's economy. Historically, economic growth was driven by agricultural products such as rum and sugar, but within the past decades, both agricultural and manufacturing activities have been on a drastic decline [52]. Economic driving forces have transitioned towards a more service-based economy, with the provision of services on the island contributing to 90% of the country's GDP over the past forty years, as a result of the expanding tourism industry [9,52].

The World Bank Group reports that tourism accounts for approximately 80% of GDP, 85% of the foreign exchange, and contributes to 70% of direct and indirect employment in A&B [53]. A&B experiences high temperatures all year round ranging from (23 °C to 27 °C), as the climate is influenced by northeasterly trade winds distinguished by a dry and wet season [52]. The island's tropical climate and diverse ecosystems support its dominant and flourishing sand, sun, and sea tourism industry. A&B has the highest share of tourism in GDP amongst the other tourism-dependent islands within the SIDSs [54]. Historically from the 1960s to 2018, A&B has witnessed frequent periods of tourism booms and, as such, has experienced significant growth in tourism-related services including, but not limited to, construction, sand mining, transport, and communication [55,56].

However, this small island nation is highly vulnerable to climate change. Among the Caribbean island nations, A&B is ranked 1st in the composite vulnerability index (CVI), followed by the Bahamas (2nd), Dominica (3rd), Grenada (4th), and Jamaica (5th) [57]. By 2050, climate inaction will cost A&B 25.8% of its GDP [10]. The impacts of sea level rise and storm surges amongst the Caribbean and the Caribbean Community (CARICOM) states introduce both short-term and long-term major threats. Global sea level rise is projected to range between 1–2 m above present levels at the end of the 21st century. The impact of the projected sea level rise within the Caribbean will be uniform, however, for smaller islands, the magnitude of economic loss in comparison to the size of the economy will be more greatly felt in St. Kitts and Nevis, Grenada, and A&B [58].

5. Methods

The methodology was conducted in two phases. For this study, the first phase included the state-of-the-art bottom-up approach we selected as the most appropriate with respect to the study's objective. The alternative approach of quantifying material stocks that has been widely used in previous studies is a top-down method, that accounts for total quantities of stocked materials in a given system. This approach lacks information on the location of these stocks and their uses [59–61]. As our purpose is to highlight the vulnerabilities inherent in material stock patterns across the island, we opted for the bottom-up approach as the only other alternative. Alternative GIS datasets allowed us to quantify and map the spatial distribution and uses of the building material stock in A&B. In the second phase, a vulnerability assessment estimates the quantity of MSs threatened by various sea level rise scenarios.

5.1. Material Stock Analysis (MSA) of Buildings

The building shapefile for A&B provided by the Department of Environment (DOE) consisted of 60,000 building footprints (BFs). The first step involved the creation of a classification system to categorize the BFs for the entire island into their respective building use type classes. It consisted of two main components: the interpretation and analysis of remote sensing satellite imagery and local knowledge of the physical infrastructure in A&B. Image interpretation included the analysis of basic elements, such as the shape, size, pattern (spatial distribution), and association of the BFs on external mapping platforms, such as OpenStreetMap (OSM) and Google Maps, as shown in Figure 1. The distinctive shapes of specific building typologies such as cathedrals and stadiums enabled for clear identification of buildings from the OSM data layers to the DOE data layer. Buildings within residential and commercial areas usually follow distinctive spatial patterns that can be identified by their size and layout. Understanding the contrast in sizes amongst different classes of buildings introduces a scale factor that allows for the recognition of buildings that are less easily identified than others. Association involved the observation that the presence of specific building use type classes influences the presence of others. Each village or parish in A&B has present their group of churches, healthcare clinics, and small shops.

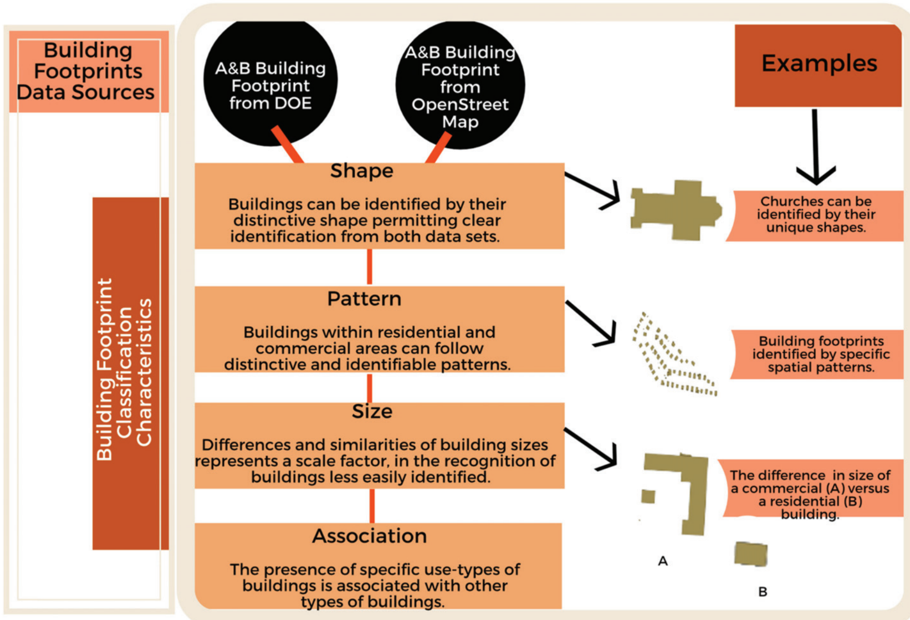

Figure 1. Schematic of the building footprint classification process adopted for Antigua and Barbuda. Image interpretation required the use of a base map provided by the Department of Environment (DOE) which was compared and contrasted to a reference map from OpenStreetMap. The four main characteristics guiding the classification process included: shape, pattern, size, and association.

The 2004 BF layer was sourced from the DOE in A&B [62] and used as a base map during the building classification process. The original BFs dataset only provided information on the area, perimeter, and feature attributes of each building footprint, resulting in all BFs to be considered as "unclassified" in the absence of assigned categories describing their specific use type role. To accurately compare and analyze the base map, a reference map was provided by OSM that provided greater details (e.g., supplementary geographic data at more defined scales, road networks, location tags of basic areas and other points of interest) during the classification process. Physical data were collected during empirical evaluations of a sample size of 303 building footprints, which were randomly selected within each of the seven parishes in A&B. These data included height measurements and the study of local construction styles for the material intensity typologies (MITs). The generation of material intensity typologies (MITs) is based on the local construction styles practiced within the country under the varying building use type classes. The MIT separates the material intensities (MIs) into four main categories of construction materials (aggregates, wood, concrete, steel). The adoption of GIS tools facilitated the calculation of the total estimated material stock within the island and generated maps of its spatial distribution.

In the absence of actual height measurements of the BFs, the number of stories or floors within each building was used as a proxy. A sensitivity analysis of the original floor estimates of +/− floor change in each building use type shows the fluctuations in the material stock (MS) estimates in Table S4 of the Supporting Information.

To calculate the gross floor area (*GFA*) for each building footprint (represented by *b*), the equation is as follows:

$$GFA_{(b)} = Building\ Footprint\ Area_{(b)} \times The\ number\ of\ floor\ stories_{(b)} \quad (1)$$

MS, measured per material category *m* (aggregate, timber, concrete, or steel), for a building footprint *b* is calculated as follows:

$$MS_{(b,m)} = GFA_{(b)} \times MI_{(m)} \tag{2}$$

Total *MS* (MS_{sum}) for the GFA of a building footprint *b* is calculated by the sum of the material stock measured per material category *m* (aggregate, timber, concrete, and steel):

$$MS_{sum} = \Sigma\, MS_{(b,m)} = MS\ Aggregate_{(b,m)} + MS\ Timber_{(b,m)} + MS\ Concrete_{(b,m)} + MS\ Steel_{(b,m)} \tag{3}$$

To calculate the total MSs for all the BFs from the 2004 BF layer, the MS_{sum} is summed for each BF.

5.2. Residential Material Intensity Distribution

The residential sector accounts for the majority of the material stock estimate, as after classifying the BFs of the entire island, residential dwellings constitute 90% of the BFs in A&B. As a result, the MITs distributed within the residential sector were determined using housing statistics in the 2001 National Census [63]. The ratio of the outer wall materials of household dwellings stated in the census was the determining factor in distributing the corresponding MITs. In the absence of on-site empirical evaluations, material intensities were assigned by a Monte Carlo simulation coded in R. To evaluate the level of uncertainty, the margin of error was assessed through running multiple iterations of the code. This step illustrates how the material stock estimates are affected by the random assignment of MITs that may result in the potential overestimation or underestimation of material stock estimates.

5.3. Estimating Vulnerable Building Stocks

Sea level rise (SLR) assessments in the study were based on 1 m and 2 m scenarios. These values were derived from four scenarios presented by Parris et al. [64], including an intermediate–low scenario measured at 0.5 m, and the highest scenario measured at 2 m. A triangulated irregular network (TIN) file containing elevation data for Antigua was sourced from the DOE [62] and converted into a 1 m resolution raster file. The 0–2 m elevation levels were extracted, while the resulting raster layer contained areas measured at 1 m or less in elevation. An overlay analysis of the elevation polygon file and the BF data layer identified buildings falling within the 1 m and 2 m boundary. These steps were repeated for the 2 m level rise analysis. This methodology was adopted in the absence of shoreline data and accounting for hydrological connectivity to the sea, as utilized in previous research [65–67].

6. Results

6.1. Material Intensity Typologies, Height Assumption, and Residential MITs

Table 1 shows the material intensities of the six different material intensity typologies (MITs) examined in this study, which reflect A&B's local construction styles verified through on-site empirical evaluation observations. The table summarizes the different building use type classes that are categorized under each material typology class.

Table 1. Material intensity typologies (MITs) for Antigua and Barbuda (kg/m^2) based on local construction styles. All numbers are rounded to one significant digit.

Construction Style	Aggregate (kg/m^2)	Wood (kg/m^2)	Concrete (kg/m^2)	Steel (kg/m^2)	Building Use Type Classes
Concrete Structure 1					
Foundation pad footing	76.2	0.9	91.5	30.5	❖ Hotels; ❖ Rural area single-family dwelling; ❖ Urban area single-family dwelling ❖ Rural residential area family dwelling; ❖ Double house family; ❖ Business and dwelling; ❖ Townhouse.
Foundation—column and beam	0.0	0.0	0.0	0.0	
Ground slab	0.0	0.0	227.3	13.8	
Floors (suspended)	0.0	0.0	227.3	13.8	
Walls	110.0	7.7	9.0		
Roof frame	0.0	15.4	55.8	5.6	
Roof covering	0.0	0.0	0.0	3.9	
Total	**186.2**	**24.0**	**610.9**	**67.6**	

Table 1. *Cont.*

Construction Style	Aggregate (kg/m^2)	Wood (kg/m^2)	Concrete (kg/m^2)	Steel (kg/m^2)	Building Use Type Classes
Concrete Structure 2					
Foundation—strip foundation	110.0	1.6	116.8	45.4	❖ Churches; ❖ Schools; ❖ Hospitals; ❖ Health clinics; ❖ Commercial; ❖ Police stations; ❖ Fire station; ❖ Government Offices; ❖ Airport; ❖ Bus terminals; ❖ Stadium; ❖ Sports complex; ❖ Rural area single-family dwelling; ❖ Urban area single-family dwelling; ❖ Rural residential area family dwelling; ❖ Double house family; ❖ Business and dwelling; ❖ Townhouse.
Foundation—concrete blocks	0	0	9.0	0	
Ground slab	0	0	227.3	13.8	
Floors (suspended)	0	0	227.3	13.8	
Walls	110.0	7.7	9.0	0	
Roof frame	0	15.4	55.8	5.6	
Roof covering	0	0	0	3.9	
Total	**220.0**	**24.7**	**645.2**	**82.5**	
Concrete Structure 3					
Foundation—pile	0	1.2	152.6	30.1	❖ Rural area single-family dwelling; ❖ Urban area single-family dwelling; ❖ Rural residential area family dwelling; ❖ Double house family; ❖ Business and dwelling; ❖ Townhouse.
Foundation—pile cap and beam	0	0	0	0	
Ground slab	0	0	227.3	13.8	
Floors (suspended)	0	0	227.3	13.8	
Walls	110.0	7.7	9.0	0	
Roof frame	0	15.4	55.8	5.6	
Roof covering	0	0	0	3.9	
Total	**110.0**	**24.3**	**672.0**	**67.2**	

Table 1. *Cont.*

Construction Style	Aggregate (kg/m^2)	Wood (kg/m^2)	Concrete (kg/m^2)	Steel (kg/m^2)	Building Use Type Classes
Timber					
Foundation—strip foundation/concrete pillars	110.0	1.6	117.4	45.4	❖ Business and dwelling mixed use. ❖ Rural area single-family dwelling; ❖ Urban area single-family dwelling; ❖ Rural residential area family dwelling; ❖ Double house family; ❖ Business and dwelling; ❖ Townhouse.
Floors	0	4.6	0	0	
Walls	0	6.2	0	0	
Roof frame	0	15.4	0	0.8	
Roof covering	0	0	0	3.9	
Total	**110.0**	**27.7**	**117.4**	**50.0**	
Concrete/Timber Mixed Structure					
Foundation—strip foundation	110.0	1.6	116.8	45.4	❖ Rural area single-family dwelling; ❖ Urban area single-family dwelling; ❖ Rural residential area family dwelling; ❖ Double house family; ❖ Business and dwelling; ❖ Townhouse.
Foundation—concrete blocks	0	0	3.0	0	
Ground slab	0	0	115.4	6.2	
Floors	0	0	115.4	6.2	
Walls	111.7	3.9	3.0	0	
Roof frame	0	15.4	55.8	5.6	
Roof-Covering	0	0	0	3.9	
Total	**221.7**	**20.9**	**409.4**	**67.3**	
Cut-stone Historical Buildings					
Foundation—strip footing	110.0	1.6	116.8	45.4	❖ Historical buildings; ❖ Cathedral.
Ground slab—concrete	0	0	227.3	13.8	
Floors (suspended)	0	0	0	0	
Walls—cut stone and concrete	0	0	0	0	
Roof frame—timber	0	15.4	55.8	5.6	
Roof covering—galvanized	0	0	0	3.9	
Total	**110.0**	**17.0**	**399.9**	**68.7**	

Table 1. *Cont.*

Construction Style	Aggregate (kg/m²)	Wood (kg/m²)	Concrete (kg/m²)	Steel (kg/m²)	Building Use Type Classes
Steel Structure					
Foundation—column beam and foundation pad	76.2	0.9	91.5	30.5	❖ Industrial; ❖ Seaport.
Floor slab	0	0	0	0	
Walls—concrete block walls	0	0	0	0	
Roof covering—galvanized sheeting and steel	0	0	0	0	
Roof frame—steel	0	0	0	0	
Roof covering	0	0	0	3.9	
Total	**76.2**	**0.9**	**91.5**	**34.4**	

6.2. Material Stock (MS) of Buildings

In 2004, the total material stock for buildings in A&B was calculated at 4.7 million tonnes (mt), which is equivalent to 58.5 t/cap. Concrete accounts for more than half the total MS in buildings, at 62%. Aggregates consume the second-largest amount of materials at 25%, followed by steel and timber with 9% and 4%, respectively.

In terms of the building use type classes, Figure 2 shows that the residential building class dominated with 53% of the total material stock, accounting for 2.5 mt. Tourism and commercial buildings represented the next largest class, accounting for approximately 18% and 17% of the total material stocks, respectively.

Figure 3 shows the density (represented by the standard deviation) of the total material stocks by dividing the island into 100 m^2 cells. The densest cells of material stocks are represented by blue and red, while the gray cells correspond to the low accumulation of material stocks.

The hotspots of building material stocks are located mainly around the coastal areas in high developmental areas and main tourism districts. There are a few dense cells located inland on the northern side of the island which are mostly associated with commercial and transport services.

St. John's city is the main commercial district and the primary port of entry for both the trading of goods and cruise ship arrivals in A&B. The area demonstrated the highest accumulation of building material stocks concentrated within the city core. Other areas, such as Jolly Harbour and English Harbour, indicated high amounts of material stocks and are considered to be intensive tourism areas. The two locations are major tourist hubs with surrounding small-scale and large-scale hotels and restaurants located around the areas' perimeter.

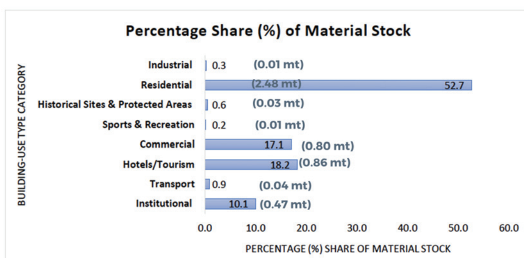

Figure 2. The percentage share of material stock illustrated by the building use type categories in Antigua and Barbuda for 2004.

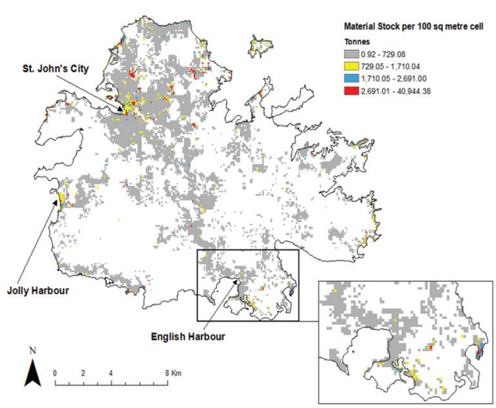

Figure 3. A standard deviation map of the spatial distribution of the total material stock (MS) of construction materials within buildings in Antigua and Barbuda (2004).

6.3. Sea Level Rise (SLR) Scenario

The vulnerability of the building material stocks in A&B was assessed in terms of a SLR analysis. This analysis identified the number of buildings, material stock, and the respective building use type categories that are exposed under a 1 m and 2 m sea level rise scenario based on global predictions for 2100 [64]. Tourism was the most impacted building use type under the 2 m sea level rise projections, as shown in Table 2 and Figure 4. The tourism industry accounted for approximately 81% of the total material stock exposed in A&B under a 2 m SLR scenario. This is equivalent to approximately 19% of the tourism industry's material stock exposed and 16% of the country's GDP.

Table 2. The percentage of exposed material stock within the affected building use type categories identified in the sea level rise analysis and flood risk assessment.

Building Use Type	1 m Sea Level Rise Scenario		2 m Sea Level Rise Scenario	
	MS Exposed (kt)	% of Use Type MS Exposed	MS Exposed (kt)	% of Use Type MS Exposed
Institutional	3.0	0.6%	5.1	1.1%
Transport	7.4	17.0%	6.2	14.3%
Tourism	143.3	16.7%	161.4	18.8%
Commercial	7.7	1.0%	13.3	1.7%
Sports and Recreation	0.1	0.7%	0.1	0.7%
Historical Sites and Protected Areas	2.4	14.7%	2.3	14.5%
Residential	7.7	0.3%	9.4	0.4%
Industrial	0.1	0.4%	0.1	0.4%

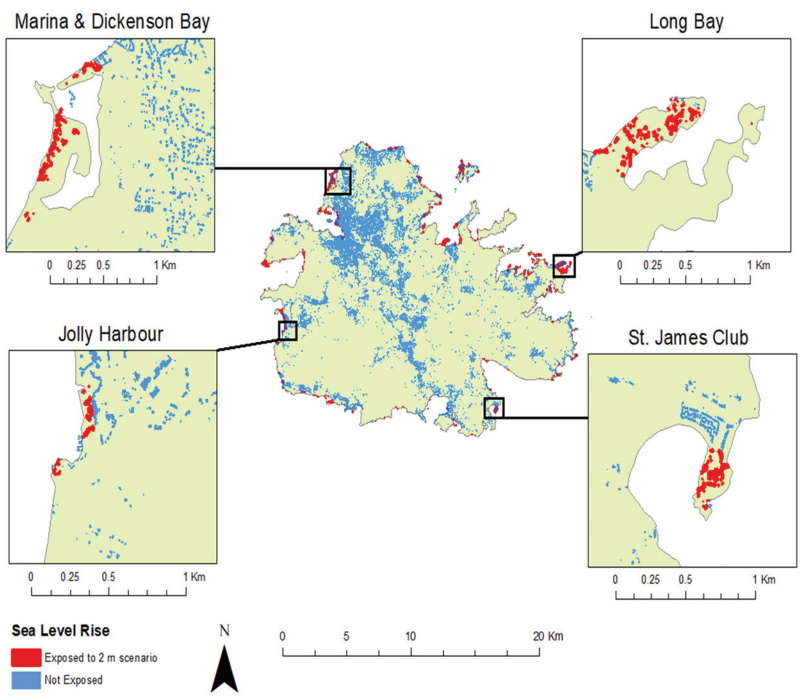

Figure 4. Four impacted areas on the island that would be exposed under a 2 m sea level rise scenario including Marina and Dickenson Bay, St. James's Club, Jolly Harbour, and Long Bay. Exposed areas are highlighted in orange.

The majority of the tourism facilities in A&B are situated on the coast and are directly exposed to the threat of SLR. Residential buildings located near the coast are also threatened and consist of 15% of the exposed buildings. In Table 2, tourism, historical sites, and transport-based buildings were most vulnerable as they accounted for the largest proportion of buildings exposed, assessed at 18.8%, 14.5%, and 14.3%, respectively.

7. Discussion

7.1. Resource Efficiency in the Tourism Sector: Maintenance and Replacement Requirements

The role of tourism for A&B is significant, accounting for approximately 80% of the country's GDP [3], and remains the most productive sector in the constant reconstruction of the economy after a crisis. Before the economic recession in 2008, the island's economic activity experienced positive growth rates of GDP, with 12% recorded in 2006 and 9% in 2007 [9]. This growth was in direct response to both the tourism and construction sectors that function as drivers of income and employment generation [68]. Apergis and Payne [69] studied the causal relationship between tourism and economic growth for nine Caribbean islands from 1995–2007 and found a bidirectional causality relationship between tourism and economic growth from both a long-term and short-term perspective.

Construction material production is a major driver of environmental and economic burdens, exacerbated in a SIDS like A&B which imports much of its construction materials, and so it is imperative to utilize the existing stock and plan future stock accumulation in a way that reduces demands for further inflows. Material extraction and imports are required to an extent for improving wellbeing and supporting the economy, and the inflows required for stock expansion to meet growing societal and economic demands is considered a characteristic of development [14,70]. Inflows for these ends may plateau and eventually perhaps even decline once material stocks reach a level of sufficiency or "saturation" [60,71,72]. Policy towards lowering this ultimate level using resource efficiency measures to "get more service from less material" [73], i.e., to minimize the need to further accumulate stocks, would be of high priority, especially in the context of a SIDS which, as an importer rather than a producer of materials, has little control over supply-side technical resource efficiency measures [73].

In this regard, our results show that the importance of tourism to A&B's economy is physically reflected in its high share of nearly 20% of the country's material stocks and brings to the forefront several otherwise obscured resource efficiency challenges. With visitors comprising 8–11 times the population of A&B, huge volumes of material stocks are needed to support the industry but are only in use for a few months of the year during the tourism season. This under-usage of buildings, infrastructure, and materials is perhaps not a serious issue for the bottom line of the tourism industry and developers. However, it stands as a resource utilization inefficiency and therefore perhaps represents a market failure from the sustainability perspective, similar to the case of idle vehicles recognized elsewhere [74].

Beyond the expansion of the stock, a second demand for inflows is for the maintenance, replacement, and operation of the already existing stock. As material stocks accumulate and eventually reach their end of life, this second type of demand increases [75], and even in economies with relatively steady levels of stock, substantial inflows are still required for these ends [76]. The extension of the useful life of buildings and infrastructure can lower the scales of these maintenance and replacement demands and concurrently also demolition outflows. However, in A&B's recent history and perhaps its future, a substantial portion of the stock requires constant replacement not because of reaching its end of life but because of disasters, which means constant reliance on imports just to maintain current stock levels. This is extremely environmentally and economically unsustainable and requires measures involving integrated policy, planning, and construction of more resilient buildings and infrastructure to avoid these throughputs of materials. For any remaining unavoidable outflows, local technical and institutional capacities to reuse materials are required. Our results can directly inform the formulation of such policy.

7.2. The Influence of Tourism Material Stocks on the Growth of Island Services

At the same time, a spatial analysis of the distribution of material stocks in A&B highlights the hotspots of the location of the built environment and their associated services. The concentration is in areas of increased commercial centers and tourism-based services, where most physical infrastructure development also takes place. The main hotspots are close to the island's coastal areas. The capital, St. John's, shows a high material stock accumulation within its core, and this location also hosts one of the island's central business hubs, in addition to accommodating the passage of all the cruise ships docking on the island and the main seaport. The high accumulation of material stocks with St. John's city (Figure 4) can be connected to the many services that are provided by the built environment within the city core, thus building upon the material stock–flow–service nexus, a feedback loop recently explored by Pott et al. [31] (paper submitted) in Grenada.

The outskirts of the city core are surrounded by a growing urban residential area where a smaller quantity of MSs can be found. Residential development has favored the northern side of the island where pockets of medium–high material stocks are distributed, as well as where the airport is situated. MS is present with low–medium levels in the middle of the island where primary and secondary roads are used to travel to the southern end of the island. This type of development is referred to as ribbon development and, according to Davies (as cited in Cohen, [77]), (p. 226), ribbon developments are "beaded clusters of activities strung out alongside major roads . . . that may contain a high incidence of services and sometimes a mixture of small wholesale and manufacturing establishments". Figure 4 also illustrates secondary hotspots on the island which coincide with major tourist hubs including Jolly Harbour and English Harbour. Both tourism hotspots are identified as "intensive tourism activity areas" and the developmental pattern is reinforced for areas that are already economically successful in A&B [52]. Such a model of development stimulates additional services (outside the focus of hotels and restaurants) which can be easily accessible to visitors such as non-resident villas, marinas, car rentals, shopping centers, and banking facilities.

7.3. The Importance of Building Resilience

The spatial distribution of material stocks and services raises concerns about the levels of vulnerability the tourism industry faces with climate change. As illustrated by Figure 4, the concentration of material stocks for tourism is primarily located along coastal areas. Beachfront properties are ideal locations for access to beaches, resorts, and other tourist accommodations. As a result of this concentration of development on the coast, SLR and extreme climatic events can result in abruptions and disturbances within the tourism sector [78]. Tourism is identified as the most vulnerable building use type exposed under a 2 m sea rise scenario. The study takes a conservative approach on the SLR vulnerability assessment, based on estimates of the global SLR by 2100, with the highest scenarios measured at 2 m. Emerging studies show estimates of global SLR ranging below 2 m [79] and after a revision of the NOAA SLR scenarios in 2017, the worst-case scenario increased by 0.5 m, with the current estimates measured at 2.5 m by 2100 [80]. While estimates continue to change with ongoing research and evidence, the key message in this paper does not change: SIDSs are faced with major threats to their infrastructure with a 2 m SLR [26,30,81]. In fact, under a 1 m sea level rise scenario, 29% of the major resorts in the Caribbean would be partially or fully inundated [82]. Moreover, the economic evaluation conducted by Moore et al. [83] of various climate change scenarios for Caribbean destinations estimated a projected loss of USD 118–156 million in tourist expenditure by 2100 as a result of projected climatic shifts.

In addition to SLR, hurricanes and the higher frequency of strong weather systems is another area of concern [84]. A&B has experienced severe category 5 hurricanes in the past, causing widespread damage. The 2017 category 5 hurricane Irma resulted in significant destruction of Barbuda, both by being in the direct path of the storm, as well as by virtue of its low elevation of 3 m above sea level [85]. The aftermath left behind high volumes of debris from the dysfunctional infrastructure, which accounted for 90% of the total buildings in Barbuda, resulting in the loss of essential services such as transport, health, and education. Between 1851 and 2017, A&B has experienced 128 storms and hurricanes, and the financial cost due to this has been USD 950 million in the past 12 years alone [85,86].

Tourism is both weather dependent and reliant on natural ecosystem services (beaches, coral reefs, waterfalls, etc.), and impacted by climate change [78,87,88]. In fact, tourism is one of the most climate-sensitive sectors globally, impacted by all 10 types of climate change impacts (such as floods, droughts, warming, heatwaves, precipitation, and sea level rise) [89]. Moreover, the development of tourism itself threatens the fragile ecosystem on which it depends. In A&B, for example, the YIDA International development project gained the public's immediate attention when over 2000 acres of coastal land, one of the largest marine protected areas (MPAs), were sold to establish an "economic zone". This area included mangroves and nesting grounds for endangered and threatened species. The loss of 75% of mangroves resulted in a loss of local livelihoods depending on these resources, but also increased exposure to the impact of hurricanes and flooding [88,90], creating a negative feedback loop for the economy. At the same time, tourism relies on the international transport industry and the high level of interconnectivity by air or sea to global markets. In A&B, the majority of the visiting tourist population originates from the US, Canada, and Europe [91]. In 2017, tourists from the USA accounted for 39% of total air arrivals, Europe 37%, and Canada 9%. Therefore, for the island's tourism sector to be operational, the country depends on international airlines and the cruise industry. However, in situations where the country is in shutdown and transport is suspended due to a natural disaster or a worldwide pandemic (such as COVID-19), the sector comes to a standstill. Besides the loss of jobs, large portions of the built infrastructure for tourism will remain further underutilized. Transport infrastructure located on the coast is highly threatened by the effects of climate vulnerability and change [81], as observed in A&B. Table 2 illustrates that in an under 2 m SLR scenario, approximately 14% of transportation material stocks would be exposed, including airports and seaports.

Thus, small island states like A&B, where tourism is a high contributor to the GDP, are among the most vulnerable nations, with climate change posing significant barriers to tourism's contribution to the Sustainable Development Goals (SDGs) [5]. In 2014, the UN World Tourism Organization [92] outlined core challenges facing the survival of the tourism industry, from climate change to the need to conserve the stressed and fragile local ecosystems, to the drain on foreign exchange of recurring imports of construction material. The Caribbean Group for Cooperation in Economic Development [93] explains that natural disasters are inherently a developmental issue, as there is evidence of unsustainable planning and investment decisions in the aftermath that contributes to vulnerability. Although tourism is the main economic driver in A&B, it is also the most vulnerable and volatile industry. All of this questions the sustainability of material stock accumulation within A&B's tourism sector, and the urgent need for economic diversification.

8. Conclusions and Outlook

Socio-metabolic research on small islands in the context of sustainability is still an emerging field, and the body of literature surrounding this field is only now beginning to show. As reviewed in Section 3, most socio-metabolic studies so far have been "flow" focused, and very few on "material stocks". This paper is a novel contribution to our understanding of societal services (tourism in this case) from the perspective of material stocks and flows (referred to as the "material stock–flow–service nexus"). A socio-metabolic perspective on tourism can offer relevant information to policymakers to identify opportunities to decouple the tourism sector from resource requirements and build system resilience [1].

In a single-driven service based-economy like A&B and other Caribbean countries, the material stock–flow–service nexus is an instrumental approach in understanding local-scale resource flows, material stock growth, and determining resource requirements for achieving the Sustainable Development Goals (SDGs), in particular SDG 12 (responsible consumption and production) and 13 (climate action). The material stock–flow–service nexus approach has the potential to offer insights to better understand island economies and their overall sustainability. By focusing on the interrelationship between stocks, flows, and service, policymakers can identify those services that are driving biophysical growth, who benefits from them, and to accordingly foster inclusive sustainable development. It is argued that tourism can also create spatial disparities in terms of social and economic development, where an island's spatial distribution impacts the island's societal development which can differ amongst islands [94–96]. For example, decisions that restrict access of local residents to beaches located within tourism hotspots or the amount of land made available for tourism expansion versus the amount of land catered towards societal development. In addition to the volume of infrastructure attributed to tourists compared to local residents, tourist-centered areas can become "islands within islands" that restrict the use and access to services by residents from the surrounding communities. Local development projects must take into consideration these concerns before future tourism-related construction takes place on the island. The government and policymakers will need to create greater inclusivity and sustainable growth within the sector [97], asking whether the costs and benefits of building stocks and related services are equally distributed across society. In other words, sustainable infrastructure development and the allocation of material stocks should consider the resident population and their social and economic wellbeing (SDG 13—sustainable communities) [98].

There is no doubt that SIDSs are threatened by a heightened risk from climate change. Increasing disaster preparedness and to protect the socio-economic services delivered by the tourism sector, the combined use of geospatial analysis, material stock–flow–service accounting approaches, and scenario exercises can assist island governments and businesses in improved planning and dealing with uncertainties [99]. SIDSs will benefit from further research incorporating new data sets with the study's methodology to expand on the sea level rise and climate vulnerability analysis. Sustainable tourism must include several core principles such as economic viability, physical integrity, community wellbeing, and resource efficiency [78]. A holistic and inclusive approach is likely to enhance tourism's ability to contribute to the SDGs and, to some degree, shield it from the negative impacts of climate change. However, factors such as geographic location and the country's ability to build adaptive capacities to cope with expected changes will also be key in increasing the sector's resiliency.

Supplementary Materials: The Supplementary Information provides greater detail on the methodology section of the research including the material stock analysis (MSA) of buildings, building footprint classification, empirical evaluation and data collection, building use type classes and height assumption, material intensity typology, and residential material intensity: Monte Carlo simulation. Available online: http://www.mdpi.com/2071-1050/12/19/8090/s1.

Author Contributions: Conceptualization, J.B., S.J.S., S.-Y.T., and T.F.; methodology, J.B., S.-Y.T., K.P., and T.F.; validation, J.B., S.J.S., S.-Y.T., and T.F; writing—original draft preparation, J.B. and S.J.S.; writing—review and editing, J.B., S.J.S., S.-Y.T., and T.F.; visualization, J.B. and S.-Y.T.; supervision, S.J.S., S.-Y.T., and T.F. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

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

References

1. Haberl, H.; Wiedenhofer, D.; Erb, K.H.; Görg, C.; Krausmann, F. The Material Stock–Flow–Service Nexus: A New Approach for Tackling the Decoupling Conundrum. *Sustainability* **2017**, *9*, 1049. [CrossRef]
2. Fischer-Kowalski, M.; Weisz, H. The Archipelago of Social Ecology and the Island of the Vienna School. *Soc. Ecol.* **2016**. [CrossRef]
3. Thomas, D. The Caribbean Tourism Industry in the 21st Century: An Assessment. In *Kimberley Green Latin American and Public Affairs*; Caribbean Center: Miami, FL, USA, 2015.
4. Economic Impact|World Travel & Tourism Council (WTTC). Available online: https://wttc.org/Research/Economic-Impact (accessed on 24 August 2020).
5. Scott, D.; Hall, C.M.; Gössling, S. Global tourism vulnerability to climate change. *Ann. Tour. Res.* **2019**, *77*, 49–61. [CrossRef]

6. CRED. UNISDR Economic Losses, Poverty & Disasters: 1998–2017—UNDRR. Available online: https://www.unisdr.org/we/inform/publications/61119 (accessed on 1 January 2019).
7. UNDESA Partnerships Briefs for Small Island Developing States Climate Change & Disaster Risk Management Division for Sustainable Development UNDESA 2014 UN Conference on Small Island Developing States. 2014. Available online: https://sustainabledevelopment.un.org/content/documents/1344SIDS_BRIEFS_ClimateChange.pdf (accessed on 2 January 2020).
8. Caribbean Small States—Challenges of High Debt and Low Growth. *Policy Pap.* **2013**, *2013*. [CrossRef]
9. Eastern Caribbean Central Bank DashboardDatas|Eastern Caribbean Central Bank. Available online: https://www.eccb-centralbank.org/statistics/dashboard-datas/ (accessed on 1 January 2020).
10. Bueno, R.; Herzfeld, C.; Stanton, E.; Ackerman, F. *The Caribbean and Climate Change: The Costs of Inaction*; Stockholm Environment Institute, US Center and Global Development and Environment Institute, Tufts University: Medford, MA, USA, 2008.
11. Rasmussen, D.J.; Bittermann, K.; Buchanan, M.K.; Kulp, S.; Strauss, B.H.; Kopp, R.E.; Oppenheimer, M. Extreme sea level implications of 1.5 °C, 2.0 °C, and 2.5 °C temperature stabilization targets in the 21st and 22nd centuries. *Environ. Res. Lett.* **2018**, *13*, 034040. [CrossRef]
12. Popescu, R.; Beraud, H.; Barroca, B. The Impact of Hurricane Irma on the Metabolism of St. Martin's Island. *Sustainability* **2020**, *12*, 6731. [CrossRef]
13. Van der Ploeg, J.; Sukulu, M.; Govan, H.; Minter, T.; Eriksson, H. Sinking Islands, Drowned Logic; Climate Change and Community-Based Adaptation Discourses in Solomon Islands. *Sustainability* **2020**, *12*, 7225. [CrossRef]
14. Krausmann, F.; Lauk, C.; Haas, W.; Wiedenhofer, D. From resource extraction to outflows of wastes and emissions: The socioeconomic metabolism of the global economy, 1900–2015. *Glob. Environ. Change* **2018**, *52*, 131–140. [CrossRef]
15. Kleemann, F.; Lederer, J.; Rechberger, H.; Fellner, J. GIS-based Analysis of Vienna's Material Stock in Buildings. *J. Ind. Ecol.* **2017**, *21*, 368–380. [CrossRef]
16. Lanau, M.; Liu, G.; Kral, U.; Wiedenhofer, D.; Keijzer, E.; Yu, C.; Ehlert, C. Taking Stock of Built Environment Stock Studies: Progress and Prospects. *Environ. Sci. Technol.* **2019**, *53*, 8499–8515. [CrossRef]
17. Schiller, G.; Müller, F.; Ortlepp, R. Mapping the anthropogenic stock in Germany: Metabolic evidence for a circular economy. *Resour. Conserv. Recycl.* **2017**, *123*, 93–107. [CrossRef]
18. Mesta, C.; Kahhat, R.; Santa-Cruz, S. Quantification of lost material stock of buildings after an earthquake. A case study of Chiclayo, Peru. In Proceedings of the 16th World Conference on Earthquake Engineering, 16WCEE, Santiago, Chile, 9–13 January 2017; pp. 1–12.
19. Kalcher, J.; Praxmarer, G.; Teischinger, A. Quantification of future availabilities of recovered wood from Austrian residential buildings. *Resour. Conserv. Recycl.* **2017**, *123*, 143–152. [CrossRef]
20. Müller, E.; Hilty, L.M.; Widmer, R.; Schluep, M.; Faulstich, M. Modeling metal stocks and flows: A review of dynamic material flow analysis methods. *Environ. Sci. Technol.* **2014**, *48*, 2102–2113. [CrossRef] [PubMed]
21. Moynihan, M.; Allwood, J. The flow of steel into the construction sector. *Resour. Conserv. Recycl.* **2012**, *68*, 88–95. [CrossRef]
22. Sartori, I.; Bergsdal, H.; Müller, D.; Brattebø, H. Towards modelling of construction, renovation and demolition activities: Norway's dwelling stock, 1900–2100. *Build. Res. Inf.* **2008**, *36*, 412–425. [CrossRef]
23. Zhu, X. GIS and Urban Mining. *Resources* **2014**, *3*, 235–247. [CrossRef]
24. Tanikawa, H.; Hashimoto, S. Urban stock over time: Spatial material stock analysis using 4d-GIS. *Build. Res. Inf.* **2009**, *37*, 483–502. [CrossRef]
25. Tanikawa, H.; Managi, S.; Lwin, C.M. Estimates of Lost Material Stock of Buildings and Roads Due to the Great East Japan Earthquake and Tsunami. *J. Ind. Ecol.* **2014**, *18*, 421–431. [CrossRef]
26. Merschroth, S.; Miatto, A.; Weyand, S.; Tanikawa, H.; Schebek, L. Lost Material Stock in Buildings due to Sea Level Rise from Global Warming: The Case of Fiji Islands. *Sustainability* **2020**, *12*, 834. [CrossRef]
27. Augiseau, V.; Barles, S. Studying construction materials flows and stock: A review. *Resour. Conserv. Recycl.* **2017**, *123*, 153–164. [CrossRef]
28. Wallsten, B.; Magnusson, D.; Andersson, S.; Krook, J. The economic conditions for urban infrastructure mining: Using GIS to prospect hibernating copper stocks. *Resour. Conserv. Recycl.* **2015**, *103*, 85–97. [CrossRef]

29. Heeren, N.; Fishman, T. A database seed for a community-driven material intensity research platform. *Sci. Data* **2019**, *6*, 23. [CrossRef] [PubMed]
30. Symmes, R.; Fishman, T.; Telesford, J.N.; Singh, S.J.; Tan, S.; De Kroon, K. The weight of islands: Leveraging Grenada's material stocks to adapt to climate change. *J. Ind. Ecol.* **2019**, *24*, 369–382. [CrossRef]
31. Pott, K.; Tan, S.-Y.; Singh, S.; Symmes, R.; Fishman, T.; Telesford, J. A Study of Building Material Stocks and the Service-Nexus in the City of Kitchener from a 4D GIS perspective. *J. Ind. Ecol.* **2020**.
32. Pauliuk, S.; Müller, D.B. The role of in-use stocks in the social metabolism and in climate change mitigation. *Glob. Environ. Change* **2014**, *24*, 132–142. [CrossRef]
33. Mohammadi, E.; Singh, S.J.; Habib, K. Electronic waste in the Caribbean: An impending environmental disaster or an opportunity for a circular economy? *Resour. Conserv. Recycl.* **2020**, *164*, 105106. [CrossRef]
34. Taylor, M.A.; Clarke, L.A.; Centella, A.; Bezanilla, A.; Stephenson, T.S.; Jones, J.J.; Campbell, J.D.; Vichot, A.; Charlery, J. Future Caribbean Climates in a World of Rising Temperatures: The 1.5 vs 2.0 Dilemma. *J. Clim.* **2018**, *31*, 2907–2926. [CrossRef]
35. Hay, J.E. Small island developing states: Coastal systems, global change and sustainability. *Sustain. Sci.* **2013**, *8*, 309–326. [CrossRef]
36. Pichler, A.; Striessnig, E. Differential Vulnerability to Hurricanes in Cuba, Haiti, and the Dominican Republic: The Contribution of Education. *Ecol. Soc.* **2013**, *18*. [CrossRef]
37. Pelling, M.; Uitto, J.I. Small island developing states: Natural disaster vulnerability and global change. *Environ. Hazards* **2001**, *3*, 49–62. [CrossRef]
38. Wallner, H.P.; Narodoslawsky, M.; Moser, F. Islands of Sustainability: A Bottom-up Approach towards Sustainable Development. *Environ. Plan. Econ. Space* **1996**, *28*, 1763–1778. [CrossRef]
39. Deschenes, P.J.; Chertow, M. An island approach to industrial ecology: Towards sustainability in the island context. *J. Environ. Plan. Manag.* **2004**, *47*, 201–217. [CrossRef]
40. Noll, D.; Wiedenhofer, D.; Miatto, A.; Singh, S.J. The expansion of the built environment, waste generation and EU recycling targets on Samothraki, Greece: An island's dilemma. *Resour. Conserv. Recycl.* **2019**, *150*, 104405. [CrossRef]
41. Singh, S.J.; Grünbühel, C.M.; Schandl, H.; Schulz, N. Social metabolism and labour in a local context: Changing environmental relations on Trinket Island. *Popul. Environ.* **2001**, *23*, 71–104. [CrossRef]
42. Singh, S.J.; Fischer-Kowalski, M.; Haas, W. The Sustainability of Humanitarian Aid: The Nicobar Islands as a Case of 'Complex Disaster. *Asian Tsunami Post-Disaster Aid* **2018**. [CrossRef]
43. Krausmann, F.; Richter, R.; Eisenmenger, N. Resource Use in Small Island States. *J. Ind. Ecol.* **2014**, *18*, 294–305. [CrossRef] [PubMed]
44. Shah, K.U.; Niles, K.; Ali, S.H.; Surroop, D.; Jaggeshar, D. Plastics Waste Metabolism in a Petro-Island State: Towards Solving a "Wicked Problem" in Trinidad and Tobago. *Sustainability* **2019**, *11*, 6580. [CrossRef]
45. Okoli, A. Socioeconomic Metabolism of Biomass in Jamaica in the Context of Trade and National Food Security: A Time Series Biophysical Analysis (1961–2013). Master's Thesis, University of Waterloo, Waterloo, ON, Canada, 2016.
46. Marcos-Valls, A.; Kovacic, Z.; Giampietro, M.; Kallis, G.; Rieradevall, J. Isolated yet open: A metabolic analysis of Menorca. *Sci. Total Environ.* **2020**, *738*, 139221. [CrossRef]
47. Petridis, P.; Fischer-Kowalski, M. Island Sustainability: The Case of Samothraki. *Soc. Ecol.* **2016**. [CrossRef]
48. Fischer-Kowalski, M.; Löw, M.; Noll, D.; Petridis, P.; Skoulikidis, N. Samothraki in Transition: A Report on a Real-World Lab to Promote the Sustainability of a Greek Island. *Sustainability* **2020**, *12*, 1932. [CrossRef]
49. Martinico-Perez, M.F.G.; Fishman, T.; Okuoka, K.; Tanikawa, H. Material Flow Accounts and Driving Factors of Economic Growth in the Philippines. *J. Ind. Ecol.* **2016**, *21*, 1226–1236. [CrossRef]
50. Bogadóttir, R. The Social Metabolism of Quiet Sustainability in the Faroe Islands. *Sustainability* **2020**, *12*, 735. [CrossRef]
51. The Commonwealth Antigua and Barbuda|The Commonwealth. Available online: https://thecommonwealth.org/our-member-countries/antigua-and-barbuda (accessed on 1 January 2020).
52. UNEP Sustainable Island Resource Management Zoning Plan for Antigua and Barbuda (Including Redonda). 2011. Available online: https://www.unenvironment.org/resources/report/sustainable-island-resource-management-zoning-plan-antigua-and-barbuda-including (accessed on 2 February 2020).
53. World Bank Group World Bank Climate Change Knowledge Portal. Available online: https://climateknowledgeportal.worldbank.org/country/antigua-and-barbuda (accessed on 1 January 2020).

54. UN-OHRLLS SIDS in Numbers Climate Change Edition 2015. Available online: http://unohrlls.org/sids-in-numbers-climate-change-edition-2015/ (accessed on 2 January 2020).
55. De Albuquerque, K.; McElroy, J.L. Antigua and Barbuda: A Legacy of Environmental Degradation, Policy Failure, and Coastal Decline. 1995. Available online: https://ageconsearch.umn.edu/record/11913 (accessed on 1 January 2020).
56. Montevago, J. Antigua and Barbuda Tourism Boom Continues. Available online: https://www.travelmarketreport.com/articles/Antigua-and-Barbuda-Tourism-Boom-Continues (accessed on 1 January 2020).
57. Atkins, J.P.; Mazzi, S.; Easter, C.D. *A Commonwealth Vulnerability Index for Developing Countries*; Economic Paper; OECD Publishing: London, UK, 2000; ISBN 978-1-84859-716-7.
58. Simpson, M.C. Quantification and Magnitude of Losses and Damages Resulting from the Impacts of Climate Change: Modelling the Transformational Impacts and Costs of Sea Level Rise in the Caribbean (Key Points and Summary for Policy Makers Document). In *Quantification and Magnitude of Losses and Damages Resulting from the Impacts of Climate Change: Modelling the Transformational Impacts and Costs of Sea Level Rise in the Caribbean (Key Points and Summary for Policy Makers Document)*; United Nations Development Programme (UNDP): Barbados, Caribbean, 2010.
59. Daigo, I.; Igarashi, Y.; Matsuno, Y.; Adachi, Y. Accounting for Steel Stock in Japan. *ISIJ Int.* **2007**, *47*, 1065–1069. [CrossRef]
60. Fishman, T.; Schandl, H.; Tanikawa, H.; Walker, P.; Krausmann, F. Accounting for the material stock of nations. *J. Ind. Ecol.* **2014**, *18*, 407–420. [CrossRef] [PubMed]
61. Condeixa, K.; Haddad, A.; Boer, D. Material Flow Analysis of the Residential Building Stock at the city of Rio de Janeiro. *J. Clean. Prod.* **2017**, *149*, 1249–1267. [CrossRef]
62. Department of Environment Building. *Footprint of Antigua & Barbuda-Shapefile*; Department of Environment: St. Johns, Antigua & Barbuda, 2012.
63. Statistics Division Population and Housing Census Antigua & Barbuda. 2001. Available online: https://statistics.gov.ag/wp-content/uploads/2017/11/2011-Antigua-and-Barbuda-Population-and-Housing-Census-A-Demographic-Profile.pdf (accessed on 4 October 2018).
64. Parris, A.S.; Bromirski, P.; Burkett, V.; Cayan, D.R.; Culver, M.E.; Hall, J.; Horton, R.M.; Knuuti, K.; Moss, R.H.; Obeysekera, J. Global sea level rise scenarios for the United States National Climate Assessment. NOAA Technical Report OAR CPO-1 2012. Available online: https://scenarios.globalchange.gov/sites/default/files/NOAA_SLR_r3_0.pdf (accessed on 5 May 2020).
65. Lichter, M.; Felsenstein, D. Assessing the costs of sea-level rise and extreme flooding at the local level: A GIS-based approach. *Ocean Coast. Manag.* **2012**, *59*, 47–62. [CrossRef]
66. Poulter, B.; Halpin, P.N. Raster modelling of coastal flooding from sea-level rise. *Int. J. Geogr. Inf. Sci.* **2008**, *22*, 167–182. [CrossRef]
67. Gesch, D.B. Analysis of Lidar Elevation Data for Improved Identification and Delineation of Lands Vulnerable to Sea-Level Rise. *J. Coast. Res.* **2009**, *53*, 49–58. [CrossRef]
68. Urosevic, Z. *Making Tourism Work for Small Island Developing States*; World Tourism Organization (WTO): Madrid, Spain, 2004; ISBN 92-844-0782-6.
69. Apergis, N.; Payne, J.E. Tourism and Growth in the Caribbean—Evidence from a Panel Error Correction Model. *Tour. Econ.* **2012**, *18*, 449–456. [CrossRef]
70. Guo, J.; Fishman, T.; Wang, Y.; Miatto, A.; Wuyts, W.; Zheng, L.; Wang, H.; Tanikawa, H. Urban development and sustainability challenges chronicled by a century of construction material flows and stocks in Tiexi, China. *J. Ind. Ecol.* **2020**. [CrossRef]
71. Bleischwitz, R.; Spataru, C.; VanDeveer, S.D.; Obersteiner, M.; van der Voet, E.; Johnson, C.; Andrews-Speed, P.; Boersma, T.; Hoff, H.; van Vuuren, D.P. Resource nexus perspectives towards the United Nations Sustainable Development Goals. *Nat. Sustain.* **2018**, *1*, 737. [CrossRef]
72. Cao, Z.; Shen, L.; Liu, L.; Zhao, J.; Zhong, S.; Kong, H.; Sun, Y. Estimating the in-use cement stock in China: 1920–2013. *Resour. Conserv. Recycl.* **2017**, *122*, 21–31. [CrossRef]
73. Allwood, J.M. Unrealistic techno-optimism is holding back progress on resource efficiency. *Nat. Mater.* **2018**, *17*, 1050–1051. [CrossRef] [PubMed]
74. Cabrera Serrenho, A.; Allwood, J.M. Material Stock Demographics: Cars in Great Britain. *Environ. Sci. Technol.* **2016**, *50*, 11403–11413. [CrossRef]

75. Nguyen, T.C.; Fishman, T.; Miatto, A.; Tanikawa, H. Estimating the Material Stock of Roads: The Vietnamese Case Study. *J. Ind. Ecol.* **2018**, *23*, 663–673. [CrossRef]
76. Wiedenhofer, D.; Steinberger, J.K.; Eisenmenger, N.; Haas, W. Maintenance and Expansion: Modeling Material Stocks and Flows for Residential Buildings and Transportation Networks in the EU25. *J. Ind. Ecol.* **2015**, *19*, 538–551. [CrossRef]
77. Cohen, E. Touristic craft ribbon development in Thailand. *Tour. Manag.* **1995**, *16*, 225–236. [CrossRef]
78. Eco-union. Sustainable Blue Tourism Blue Tourism Study. 2019. Available online: http://www.ecounion.eu/wp-content/uploads/2019/06/TRIPA_Angles_2_p.pdf (accessed on 10 February 2020).
79. Kulp, S.A.; Strauss, B.H. New elevation data triple estimates of global vulnerability to sea-level rise and coastal flooding. *Nat. Commun.* **2019**, *10*, 1–12.
80. Sweet, W.V.; Kopp, R.E.; Weaver, C.P.; Obeysekera, J.; Horton, R.M.; Thieler, E.R.; Zervas, C. Global and regional sea level rise scenarios for the United States. In *NOAA Technical Report NOS CO-OPS 083*; National Oceanic and Atmospheric Administration: Washington, DC, USA, 2017; 75p.
81. Monioudi, I.N.; Asariotis, R.; Becker, A.; Bhat, C.; Dowding-Gooden, D.; Esteban, M.; Feyen, L.; Mentaschi, L.; Nikolaou, A.; Nurse, L.; et al. Climate change impacts on critical international transportation assets of Caribbean Small Island Developing States (SIDS): The case of Jamaica and Saint Lucia. *Reg. Environ. Change* **2018**, *18*, 2211–2225. [CrossRef]
82. Scott, D.; Simpson, M.C.; Sim, R. The vulnerability of Caribbean coastal tourism to scenarios of climate change related sea level rise. *J. Sustain. Tour.* **2012**, *20*, 883–898. [CrossRef]
83. Moore, W.R. The impact of climate change on Caribbean tourism demand. *Curr. Issues Tour.* **2010**, *13*, 495–505. [CrossRef]
84. Burgess, C.P.; Taylor, M.A.; Spencer, N.; Jones, J.; Stephenson, T.S. Estimating damages from climate-related natural disasters for the Caribbean at 1.5 °C and 2 °C global warming above preindustrial levels. *Reg. Environ. Change* **2018**, *18*, 2297–2312. [CrossRef]
85. United Nations Environment Program. *Green Climate Fund-GCF Resilience to Hurricanes, Floods and Droughts in the Building Sector in Antigua and Barbuda*; United Nations Environment Program: Antigua and Barbuds, Caribbean, 2017.
86. Destin, D. Antigua and Barbuda Meteorological Services- Hurricanes and Storms- 1851 to 2019. Available online: http://www.antiguamet.com (accessed on 1 January 2020).
87. Pang, S.F.H.; McKercher, B.; Prideaux, B. Climate Change and Tourism: An Overview. *Asia Pac. J. Tour. Res.* **2013**, *18*, 4–20. [CrossRef]
88. Brown, N.A.; Rovins, J.E.; Feldmann-Jensen, S.; Orchiston, C.; Johnston, D. Exploring disaster resilience within the hotel sector: A systematic review of literature. *Int. J. Disaster Risk Reduct.* **2017**, *22*, 362–370. [CrossRef] [PubMed]
89. Mora, C.; Spirandelli, D.; Franklin, E.C.; Lynham, J.; Kantar, M.B.; Miles, W.; Smith, C.Z.; Freel, K.; Moy, J.; Louis, L.V.; et al. Broad threat to humanity from cumulative climate hazards intensified by greenhouse gas emissions. *Nat. Clim. Change* **2018**, *8*, 1062–1071. [CrossRef]
90. Handy, G. Antigua: Sprawling "Chinese Colony" Plan across Marine Reserve Ignites Opposition. The Guardian. 2019. Available online: https://www.theguardian.com/world/2019/jun/20/antigua-yida-project-chinese-colony-controversy (accessed on 25 May 2020).
91. Antigua Hotel and Tourist Association-AHTA Tourism Statistics for Antigua & Barbuda: Tourist Arrivals by Country. Available online: http://members.antiguahotels.org/tourism-statistics-for-antigua-and-barbuda/ (accessed on 1 January 2020).
92. UNWTO. *Tourism in Small Island Developing States (SIDS)—Building a more Sustainable Future for the People of Islands*; World Trade Organization: Madrid, Spain, 2014. [CrossRef]
93. *Caribbean Group for Cooperation in Economic Development Caribbean Economic Overview 2002: Macroeconomic Volatility, Household Vulnerability, and Institutional and Policy Responses*; World Bank: Washington, DC, USA, 2002.
94. Weaver, D.B. The evolution of a 'plantation' tourism landscape on the caribbean island of antigua. *Tijdschr. Voor Econ. En Soc. Geogr.* **1988**, *79*, 319–331. [CrossRef]
95. Grydehøj, A.; Hayward, P. Social and economic effects of spatial distribution in island communities: Comparing the Isles of Scilly and Isle of Wight, UK. *J. Mar. Isl. Cult.* **2014**, *3*, 9–19. [CrossRef]

96. Rutty, M.; Gössling, S.; Scott, D.; Hall, C. *The Global Effects and Impacts of Tourism. An Overview in the Routledge Handbook of Tourism and Sustainability*; Hall, C.M., Gössling, S., Scott, D., Eds.; Routledge: Abingdon, UK, 2015; pp. 36–62.
97. Schandl, H.; Marcos-Martinez, R.; Baynes, T.; Yu, Z.; Miatto, A.; Tanikawa, H. A spatiotemporal urban metabolism model for the Canberra suburb of Braddon in Australia. *J. Clean. Prod.* **2020**, *265*, 121770. [CrossRef]
98. Adenle, A.A.; De Steur, H.; Hefferon, K.; Wesseler, J. Two Decades of GMOs: How Modern Agricultural Biotechnology Can Help Meet Sustainable Development Goals. In *Science, Technology, and Innovation for Sustainable Development Goals*; Oxford University Press: Oxford, UK, 2020; ISBN 0-19-752890-2.
99. Gössling, S.; Scott, D. Scenario planning for sustainable tourism: An introduction. *J. Sustain. Tour.* **2012**, *20*, 773–778. [CrossRef]

© 2020 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (http://creativecommons.org/licenses/by/4.0/).

sustainability

Article

Lost Material Stock in Buildings due to Sea Level Rise from Global Warming: The Case of Fiji Islands

Simon Merschroth [1,2], Alessio Miatto [3], Steffi Weyand [1], Hiroki Tanikawa [2] and Liselotte Schebek [1,*]

1 Material Flow Management and Resource Economy, Institute IWAR, Technische Universität Darmstadt, Franziska-Braun-Strasse 7, 64287 Darmstadt, Germany; simonmerschroth@googlemail.com (S.M.); S.Weyand@iwar.tu-darmstadt.de (S.W.)
2 Graduate School of Environmental Studies, Nagoya University, Furo-cho, Chikusa-ku, Nagoya 464-8601, Japan; tanikawa@nagoya-u.jp
3 School of Forestry & Environmental Studies, Yale University, 195 Prospect Street, New Haven, CT 06511, USA; alessio.miatto@yale.edu
* Correspondence: l.schebek@iwar.tu-darmstadt.de

Received: 6 December 2019; Accepted: 19 January 2020; Published: 22 January 2020

Abstract: This study developed a methodology to estimate the amount of construction material in coastal buildings which are lost due to climate change-induced sea level rise. The Republic of Fiji was chosen as a case study; sea level rise is based on predictions by the Intergovernmental Panel on Climate Change for the years 2050 and 2100. This study combines the concept of a geographic information system based digital inundation analysis with the concept of a material stock analysis. The findings show that about 4.5% of all existing buildings on Fiji will be inundated by 2050 because of an expected global sea level rise of 0.22 m (scenario 1) and 6.2% by 2100 for a sea level rise of 0.63 m (scenario 2). The number of buildings inundated by 2050 is equivalent to 40% of the average number of new constructed buildings in Fiji Islands in a single year. Overall, the amount of materials present in buildings which will be inundated by 2050 is 900,000 metric tons (815,650 metric tons of concrete, 52,100 metric tons of timber, and 31,680 metric tons of steel). By 2100, this amount is expected to grow to 1,151,000 metric tons (1,130,160 metric tons of concrete, 69,760 metric tons of timber, and 51,320 metric tons of steel). The results shall contribute in enhancing urban planning, climate change adaptation strategies, and the estimation of future demolition flows in small island developing states.

Keywords: island metabolism; material stock analysis; demolition of buildings; GIS; climate change; global warming

1. Introduction

Anthropogenic activities have changed the Earth's temperature by approximately 1 °C between the period of 1850–1900 and the year of 2017 [1]. This has led to an average global sea level rise (SLR) of 3.20 mm/year. It is expected with 67% confidence that by 2100, the global average sea level will rise by 0.28 m to 0.98 m relative to the mean sea level of the years 1986–2005 [2].

The effects of SLR include the salinization of coastal agricultural areas and water storages, the destruction of coastal eco-systems, the erosion of shorelines, and the destruction of buildings and infrastructure [1]. SLR affects coastal countries all over the world, such as China, the Netherlands, Nigeria and the United Kingdom [3]. Some of the most impacted regions are the islands located in the Caribbean Sea and in the South Pacific, the so-called Small Island Developing States, as well as southern and eastern parts of Asia [4]. The Intergovernmental Panel on Climate Change (IPCC) developed four Representative Concentration Pathways (RCPs). They refer to four different pathways of Greenhouse Gas (GHG) emissions and atmospheric concentrations, air pollutant emissions and land use. While RCP 4.5 and RCP 6.0 refer to intermediate scenarios, RCP 2.6 refers to very low GHG emissions keeping global warming likely below 2 °C. RCP 8.5 refers to a very high GHG emissions pathway [5]. Kulp and Strauss [6] estimated that a global warming of 2 °C in relation to RCP 4.5 results in an increase of 40 million additional people to live permanently below the high tide line until 2050 and an increase of 90 million people until 2100.

In particular, Small Island Developing States are affected by this since their geomorphology is often characterized by low-elevation islands with population concentrated along their coasts [7]. In addition, Small Island Developing States heavily depend on the functioning of coastal ecosystems, and their economies are highly sensitive to slight changes [7,8]. Furthermore, they are more vulnerable to the effects of SLR because most of them lack institutional, financial and technical structures to adapt to it [7].

Vulnerability assessment studies for Small Island Developing States have been carried out within various states, such as islands in the Caribbean Sea [9,10], in South-East Asia [11,12] and in the Southern Pacific [13,14]. In 2008, Gravelle and Mimura [13] conducted a vulnerability assessment for the Republic of Fiji aiming to point out areas that are threatened by the SLR for different SLR scenarios. This study illustrated that most urban centers will face partial inundation within this century and that a proportional increase between the SLR and the total inundated area can be observed. Other vulnerability assessments estimated the total flooded area of specific regions [15], the number of inundated households and buildings being inhabitable within a certain area [16], the length of affected roads by the SLR [17] as well as the financial value of lost built structure [18].

Based on such vulnerability assessments, adaptation measurements incorporating SLR are being developed on the city, region or country level [7,19–21]. These include direct protection actions, such as the construction of barriers in the sea, and preventive actions, such as the relocation of houses or entire villages [21]. Relocations are fairly drastic solutions and generally require large economic and human resources. Moreover, they tend to destroy social structures, cultural traditions, as well as causing emotional stress [22]. Forced demolitions of coastal buildings and infrastructure result in large amounts of construction and demolition waste, which cause environmental stress. On top of this environmental pressure, the new facilities being built to replace the demolished ones will require new materials for the reconstruction. Nevertheless, information on the demolition waste streams from inundated coastal buildings is crucial for Small Island Developing States in two aspects: first, waste management is demanding due to limited land availability, remoteness, and high costs [23,24]; second, possibility of reuse of materials enables waste mitigation and contributes to the overcoming of resource shortages on Small Island Developing States [25,26].

However, while the effects of the SLR on the number of buildings inundated have already been studied by vulnerability assessment studies [16], these studies have not estimated demolition waste streams and materials required for reconstructions caused by SLR. The information on demolition waste streams and materials required for reconstructions can be extracted by the concept of material stock analysis (MSA). MSA is a method developed in the field of Industrial Ecology that allows the estimation of the amount of materials in use in the socio-economic sphere of our societies [27,28]. This tool has been used for estimating the mass of materials lost during the Great East Japan Earthquake [28]; waste flows coming from demolitions [29,30]; or the potential for urban mining [31]. To date, the concept of MSA has yet to be combined with vulnerability assessments that focus on SLR.

This study develops a novel methodology for an estimation of construction material amounts through a hybrid combination of geospatial analysis and material stock analysis, applying and evaluating it to the case study of the Republic of Fiji. This novel methodology can be applied to small islands/coastal regions for the estimation of lost material stock (MS) caused by the SLR. The Republic of Fiji was chosen as a case study area because it represents a typical Small Island Developing State due to a relatively high population density living along the coast, as well as the country's limited climate adaptation capacity. In the following section (Materials and Methods), data sources and an introduction to the case study area, as well as a detailed explanation of the methodology are provided. In Section 3 (Results), the results of the spatial analysis are provided, along with a quantification of the construction materials (number of buildings and total mass) that will be permanently inundated. The results are separated by province in rural and urban dwellings. Additionally, high risk areas were identified. Section 4 (Discussion) provides insights and considerations on the findings. Section 5 (Conclusions) draws conclusions, discusses the limits of this methodology and points out future research steps.

2. Materials and Methods

This study's research approach consists of two parts: firstly, a Geographic Information System-Digital Inundation Analysis Model (GIS-DIAMs) to calculate the number of flooded buildings and secondly an MSA to estimate the construction material stocked in those. Figure 1 represents a conceptualization of how the models were combined, while data sources are listed in Table 1.

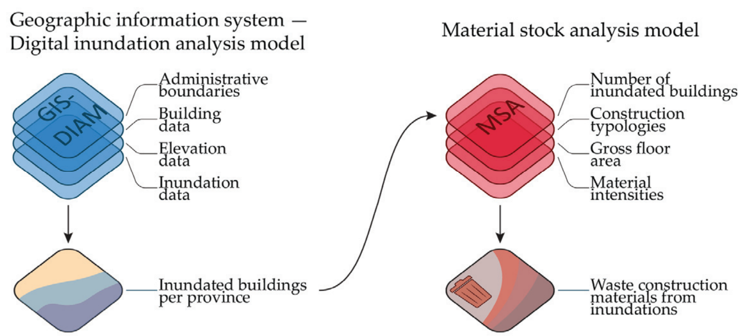

Figure 1. Schematic representation of the methodological approach of this study.

Table 1. Data sources used for the Geographic Information System-Digital Inundation Analysis Model (GIS-DIAM) and the material stock analysis (MSA).

Area of Interest	Specification	Reference
Administrative boundaries	Enumerations	[32]
	Provinces	[32]
	Towns and Cities	[33]
Building data	Open Street Map data	[34]
	Satellite imagery	[35]
	Buildings per province	[36,37]
Elevation data	Government data	[38]
Inundation data	Permanent sea level rise based on Intergovernmental Panel of Climate Change (IPCC) prediction	[2]
Construction typologies	Construction types commonly used on Fiji	[39]
Gross floor area	Area of a building	[34]
	Number of floors in urban areas	Please refer to Supplementary Information Table S1 for the references on the determination of the number of floors within urban areas
Material intensities	Material intensities in kg/m^2	[28,31,39–44]
	Spatial distribution per province and construction type	[32]

The GIS-DIAM analysis enabled the identification of the number and location of buildings, subdivided per province and into rural and urban areas, subjected to inundation due to SLR. Using this result, the percentage of buildings inundated was estimated in comparison to the total number of buildings per province, also subdivided into rural and urban areas. The MSA was then conducted by assigning for each inundated building a construction typology, which carries information on the typical material intensities per m^2. This information was then crossed with data on building size to estimate the amount of the materials concrete, steel and timber potentially lost due to SLR.

2.1. Case Study Area

The Republic of Fiji is a group of islands located in the South Pacific. Its population accounts for 881,000 people living on 18,000 km^2, subdivided on 300 islands, of which 100 are inhabited [45]. Fiji's coastline measures around 1130 km [45] where 90% of the population lives and where the biggest urban regions, Lautoka, Nadi, Labasa and the capital Suva, are located [46]. This study focuses on the two main islands of Fiji, Viti Levu and Vanua Levu, where 96% of the population lives [33].

In 2017 and 2018, on average, 626 buildings valued US$73.63 million were constructed each year [36,37]. In 2014, the village of Vunidogoloa, located in the Republic of Fiji, had to be relocated due to coastal erosion and storm surges caused by climate change induced SLR [22,47]. It cost approximately US$500,000 to relocate the residents 2 km inwards from the coast [22]. It is predicted that until 2050, with reference of a SLR of 0.26 m relative to the years 1986–2005, 30,000 Fijians occupy land vulnerable to the SLR. Until 2100, with a predicted SLR of 0.59 m relative to the years 1986–2005, 80,000 Fijians occupy land vulnerable to SLR [6].

In 2017, the government of Fiji began planning adaptation actions to counter the effects of SLR. Highly affected areas were identified and the relocation of several settlements was forecast. The government additionally plans to secure funds, to focus on better management of natural resources and to increase their human capital by investing in the education of engineers and by training existing technical stuff [21]. Moreover, it plans to increase resilience in communities by identifying the most vulnerable villages [14] and by protecting urban coastlines from the effects of SLR [19]. According to The World Bank [14], the Fijian government foresees the relocation of settlements where storms are happening in a frequency that makes the settlements unable to live in on a long-term view. The government further plans on improving the current Digital Elevation Model of Fiji using LiDAR (Light Detection And Ranging) data, which will enable more detailed and accurate inundation analyses [14].

2.2. GIS-Based Digital Inundation Analysis Model (GIS-DIAM)

A digital elevation model of the two main islands of Fiji was taken as primary data. This model carries orographic information of the islands. Further data include a detailed 2D representation of the existing buildings. Moreover, metadata on the administrative boundaries of the region was used. Using ArcGIS, a popular software for GIS analyses, a simulation of the inundation areas due to SLR was conducted. Predictions on SLR are based on predictions by the IPCC [2]. Results are calculated for the years 2050 (scenario 1) and 2100 (scenario 2). This simulation generated two GIS-DIAMs which highlighted the number of inundated buildings per province, further discerned in rural and urban areas.

2.2.1. Elevation Data

Height information to was directly provided by the Geospatial Division of the Ministry of Lands & Mineral Resources Fiji [38]. The data's spatial resolution is not reported in the document, and, when inquired, the Ministry did not provide an answer. To overcome this limitation, we assumed that this data is generally based on satellite data displaying surface elevation rather than terrain height. This is due to a constantly displayed height difference when comparing densely forested areas with open spaces located in close proximity. Additionally, the Fijian DEM was compared regarding its accuracy to elevation data by the United States Geological Survey, Shuttle Radar Topography Mission (SRTM) data [48] and to data by the Japan Aerospace Exploration Agency, Advanced Land Observing Satellite (ALOS) data [49].

2.2.2. Inundation Data

Inundation is predicted for the years 2050 (scenario 1) and 2100 (scenario 2). The dates were chosen to provide an overview on two different epochs in future time, one happening relatively soon and one relevant for long-term planning. Maximum tide inundation, including storm surges, were not incorporated in this study, because it is unable to accurately predict for which inundation interval a building is unusable. For the inundation data, only the permanent SLR is incorporated into the GIS-DIAM, which means that it does not take into consideration tidal effects.

This permanent SLR is based on the global SLR predictions by the IPCC's Fifth Assessment Report. SLR was chosen on a global scale, relative to the period 1986–2005. It was chosen in reference to RCP 2.6 and RCP 8.5. The likelihood of the SLR refers to a 'likely range' as referred to by the IPCC, meaning a probability of 66%–100% [2].

The IPCC [2] predicts, for the period 2046–2065, a minimum SLR of 0.17 m (RCP 2.6) and a maximum SLR of 0.38 m (RCP 8.5). As the report does not provide tabular data for the year 2050, the authors assumed an SLR of 0.22 m for the year 2050 (scenario 1). The value for 2100 was determined as the average of the lowest value predicted for RCP 2.6 (SLR of 0.28 m) and the highest value predicted for RCP 8.5 (SLR of 0.98 m). Thus, an SLR of 0.63 m is expected on average [2].

2.2.3. Administrative Boundaries and the Spatial Localization of Buildings

The Fiji are divided into 15 provinces and 1602 enumeration areas. Data on administrative boundaries were downloaded from the PopGIS 2.0 platform which is managed by the Fiji Bureau of Statistics, based on the 2007 Census [32]. GIS data locating 89,628 Fijian buildings were taken from the Geofabrik platform, which retrieves data from Open Street Maps [34]. The data were then tested for their accuracy using satellite imagery by Esri et al. [35]. It was evident that Open Street Maps data do not cover all the buildings on Fiji's coastline. Therefore, an additional 6979 buildings were manually drawn as points in ArcGIS based on the satellite imagery by Esri et al. [35].

2.2.4. Separation between Urban and Rural Areas

The number of inundated buildings was calculated according to the province a building is constructed, subdivided in urban and rural areas. In this study, an area was classified as urban when it is listed as 1st category urban area in the 2007 Census of Population and Housing [33]. The government defines cities and towns by their urban attributes, their economic activity and their population size [50]. In the 2007 census, twelve areas are listed as 1st category urban area. The enumeration areas which are located within urban zones were subsequently manually assigned using the satellite imagery by Esri et al. [35].

2.3. MSA-Based Construction Material Stocked Model

To calculate the materials stocked in buildings subject to inundation, an MSA was conducted for characterizing the structural materials typically used for buildings on Fiji: concrete, steel, and timber. Using the 'Select By Location' tool by ArcGIS, a building was referred to as inundated if its polygon or point was within the features of the inundation layer. To proceed, an equation first described by Tanikawa et al. [28] was modified as in the following Equation (1):

$$MS_K = \sum_{j=1}^{4}\left(MI_{K,J}\cdot\sum_{i=1}^{n}\left(GFA_{i,j}\right)\right) \tag{1}$$

where MS_k is the stocked amount of a specific construction material k, $MI_{k,j}$ is the material intensity of the construction type j and material k, and $GFA_{j,n}$ is the gross floor area of the i-th building per construction type j. Note that the index j goes from 1 to 4 as there are 4 building typologies, while i goes up to n as there is a variable number of buildings for each typology.

2.3.1. Construction Types

Buildings in Fiji can be classified into 4 building typologies, depending on the material used for their walls: cement block masonry, timber frame cladded by timber panels, timber frame cladded by steel panels [39], and reinforced concrete [44]. Traditionally, Fijian buildings have one story, concrete foundations and steel based sheets as roof [39]. While cement block masonry, timber cladded and iron cladded buildings appear in both rural and urban areas, buildings based on reinforced concrete are only constructed in cities where houses typically have more than one story. This includes the city of Suva (three floors) as well as the cities Nadi, Labasa, Ba and Lautoka (all with two floors). See Supplementary Materials §1 for a list of the data sources used to determine the number of floors per city.

The Fiji Bureau of Statistics provides the average distribution of construction typologies used in each one of the 1602 enumeration areas [32]. This served as a basis for allocating to each province the share of each construction type, separated in rural and urban areas. As it is impossible to know exactly the actual construction type for a specific building from an aerial photo, we assumed the typologies of inundated buildings as proportional to the share of typologies in a certain enumerated area. Please see Supplementary Materials §2 for more information on the distribution of construction typologies per province.

2.3.2. Material Intensities

Table 2 shows the material intensities used for the MSA. To date, no typical material intensities for the construction types defined have been published, for Fiji nor for any other region in the world. Thus, material intensities were calculated by the authors manually. The material intensities of buildings with walls based on cement block masonry, timber sheets and steel based corrugated iron sheets were based on a housing construction manual provided by the Habitat for Humanity [40] in combination with baseline data on local building structure and materials published by Caimi et al. [39]. Details on calculations can be retrieved in Supplementary Materials §3.

Table 2. Material intensity per construction type (kg/m^2 of gross floor area) [28,31,39–44].

Construction Type	Layer	Concrete	Steel	Timber
Cement bricks	Foundation	1200	0	0
	Wall	624	0	0
	Roof	0	5	1
	Total	1824	5	1
Reinforced concrete	Total	1416	104	0
Steel cladded	Foundation	108	0	56
	Wall	0	4	4
	Roof	0	4	1
	Total	108	8	61
Timber cladded	Foundation	108	0	56
	Wall	0	0	36
	Roof	0	5	1
	Total	108	5	94

Information that helps with calculating the material intensity of multi-storied reinforced concrete buildings is not reported in Habitat for Humanity [40], nor in Caimi et al. [39]. It was assumed that multi-storied reinforced concrete buildings on Fiji are built in a similar way as they are in other regions of the world. Therefore, data was retrieved from research previously conducted by Cheng et al. [31] for buildings in Taipei, Taiwan. Here, Cheng and colleagues cite research by Chang [41]. Subsequently, all material intensities were compared to the values published by Tanikawa et al. [28], which lists material intensities by Nagaoka et al. [42] and Tanikawa and Hashimoto [43].

2.3.3. Gross Floor Area (GFA)

The total gross floor area of inundated buildings was not directly retrievable from the GIS data, as we identified over 7000 buildings that were not mapped. For this reason, a probabilistic approach had to be implemented.

The estimation of the total footprint of inundated buildings is reported in Equations (2) and (3):

$$FP_{total,urban,p} = FP_{avg,urban,p} \cdot n_{urban,p} \tag{2}$$

$$FP_{total,rural,p} = FP_{avg,rural,p} \cdot n_{rural,p} \tag{3}$$

where $FP_{total,\ urban,\ p}$ indicates the total building footprint (expressed as m^2) of inundated buildings located in urban areas of the province p; $FP_{avg,urban,p}$ reports the average footprint (expressed in m^2) of an inundated building in urban areas of the province p; and $n_{urban,p}$ is the number of buildings that are inundated in urban areas of the province p. Equation (3) is identical to Equation (2), the only difference being that it refers to rural areas rather than urban ones.

The average area of a building was estimated based on the average area of those buildings that were withdrawn as polygons from Geofabrik GmbH and OpenStreetMap Contributors [34]. Please see Supplementary Materials §2 for a list of the average area of a building per province.

The calculation of the total gross floor area of inundated buildings in a certain province is shown in Equation (4):

$$GFA_{total,p} = FP_{total,urban,p} \cdot Floors_{urban} + FP_{total,rural,p} \tag{4}$$

where $GFA_{total,p}$ is the total floor area which is going to be inundated in the province p; and $Floors_{urban}$ indicates the average number of floors present in buildings in the urban area of the province p. Note that there is not a term floors for the rural area, as buildings in rural areas are always limited to a single story.

The total gross area of a province is then discerned into typologies as per Equation (5):

$$GFA_{j,p} = GFA_{total,p} \cdot v_{j,p} \tag{5}$$

where $GFA_{j,p}$ is the gross floor area of the construction type j in province p; and $v_{j,p}$ is the ratio of building having type j in province p, as calculated in Equation (6).

$$v_{j,p} = \frac{n_{j,p}}{n_{total,p}} \tag{6}$$

where $v_{j,p}$ is calculated as the fraction between the number of buildings having type j in the province p ($n_{j,p}$) over the total number of buildings in the province p ($n_{total,p}$).

The overall gross floor area is the calculated as in Equation (7):

$$GFA_j = \sum_{p=1}^{15} GFA_{j,p} \tag{7}$$

where GFA_j is the overall gross floor area for the construction type j. Note that p goes from 1 to 15, as there are 15 provinces in this case study.

3. Results

The following Section 3.1 illustrates the results of the spatial analysis of the sea level rise, while Section 3.2 displays the results of the material stock analysis. A machine-readable Supplementary Data File with the values used to plot Figure 2, Figure 3, and Figure 8 is provided.

Figure 2. Number of inundated buildings in urban and rural areas of Fiji by province. Scenario 1 refers to projections to 2050 (+ 0.22 m), scenario 2 refers to projections to 2100 (+ 0.63 m).

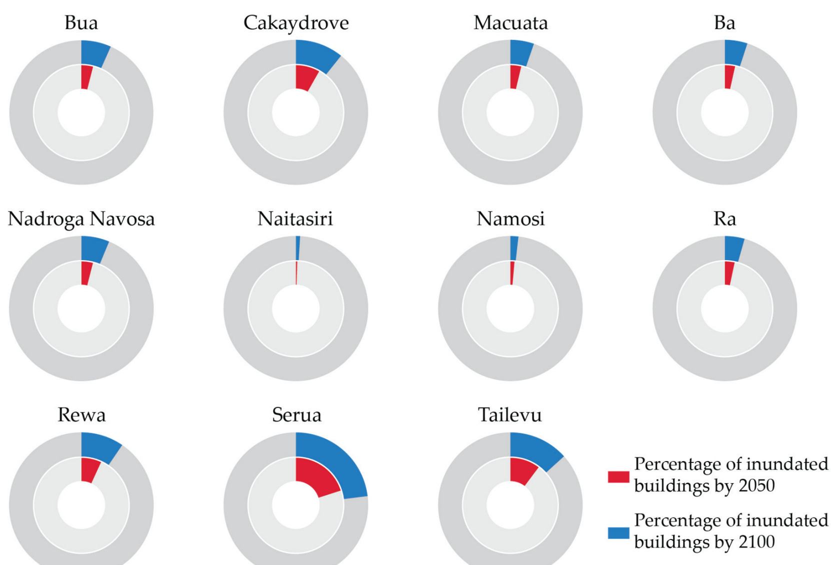

Figure 3. Percentage of inundated buildings compared to the total buildings currently standing. The inner circle represents the percentage for 2050 (+ 0.22 m); the outer circle represents the percentage for 2100 (+ 0.63 m).

3.1. Results of the GIS-DIAM

Figure 2 displays the number of inundated buildings per province in both scenarios, separated in rural and urban areas, while Figure 3 indicates the percentage of all existing buildings that will be lost in scenarios 1 and 2. The results illustrate that buildings along coastlines will be affected and that every province will suffer losses, albeit to different extents. In total, 7472 buildings will be inundated by 2050 and 10,304 by 2100. This is equivalent to 4.5% of the overall number of currently existing buildings in scenario 1 and 6.2% in scenario 2. Until 2050, the average number of inundated buildings per year will be 241. After that, the rate decreases 57 buildings per year on average.

The rural proportion accounts for about 80% in both scenarios. Nevertheless, Fiji's major urban areas Suva, Lautoka, Lami, Labasa, Nasinu and the suburban region in Nadi will be heavily affected. Of all the inundated buildings in Serua, Cakaudrove, Nadroga Navosa, Namosi, Ra, and Tailevu, over 90% is located in rural areas. Conversely, the provinces of Naitasiri and Macuata are expected to experience the majority of their inundated buildings in urban areas.

The spatial distribution of the inundated buildings in 2050 is plotted in Figure 4 (Vanua Levu) and Figure 5 (Viti Levu). The total number of inundated buildings is the highest in Ba (1737 buildings), Rewa (1450 buildings), and Tailevu (1127 buildings). Yet, the percentage of buildings inundated in comparison to the total number of buildings is the highest in Serua (20%), with one out of five buildings flooded. It is remarkable that less than 2% of the buildings in Naitsairi and in Namosi will be directly affected.

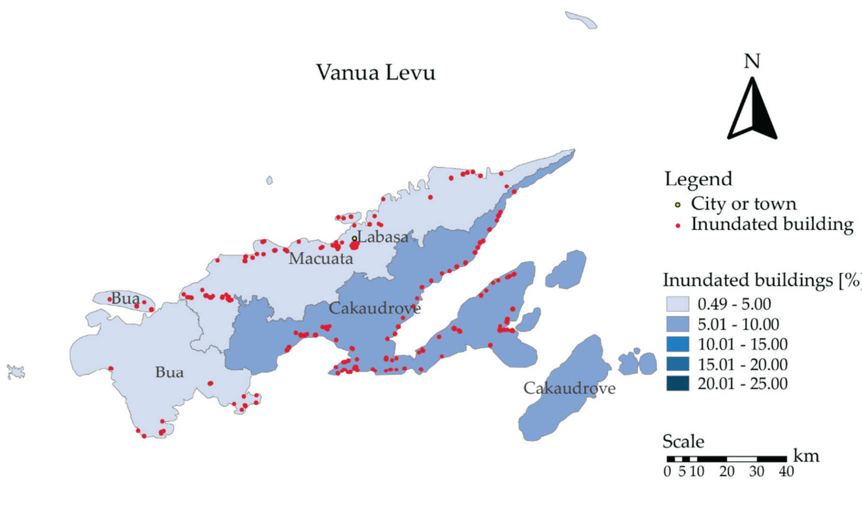

Figure 4. Distribution of permanently inundated buildings in Vanua Levu in 2050. Each province is colored according to the percentage of inundated buildings compared to the total existing ones.

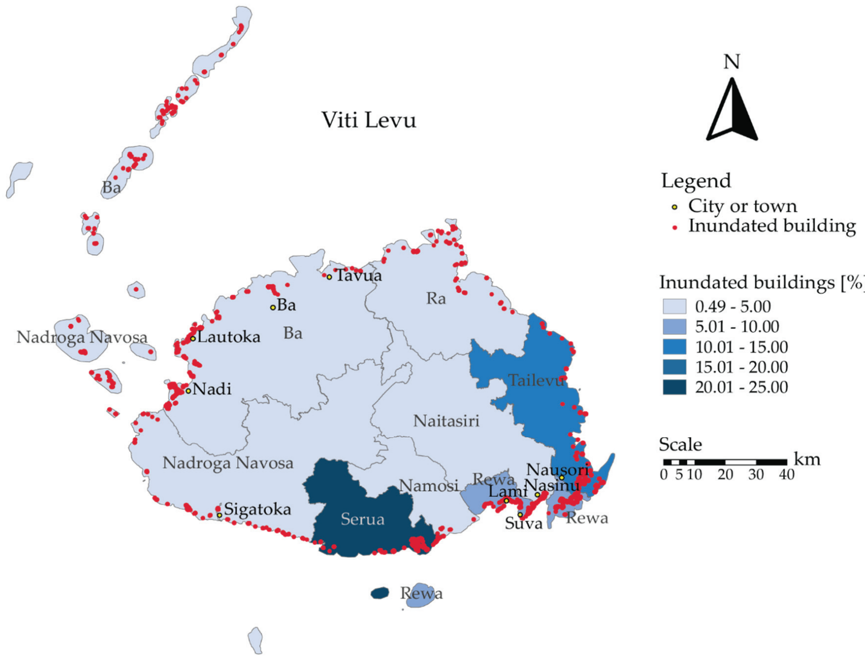

Figure 5. Distribution of permanently inundated buildings in Viti Levu in 2050. Each province is colored according to the percentage of inundated buildings compared to the total existing ones.

Areas with many buildings being inundated in a relatively small spatial frame can be identified in the town centers of Lami and Labasa, as well as in the peri-urban areas of Nadi, Nasinu, and Lautoka, including industrial and touristic locations. Additionally, the south eastern part of Viti Levu, which is broadly and relatively densely settled, is expected to face large inundations.

The spatial distribution of the submerged buildings for 2100 is plotted in Figures 6 and 7. There is a relatively low difference in regard to the amount of buildings predicted to be inundated in 2050 and 2100: compared to a SLR difference of 182% between the two, the number of inundated buildings increases by only 38%. Nevertheless, the rise of inundated buildings in urban areas increases by 58%, with Ba (146%) and Naitasiri (90%) being affected the most. Naitasiri, and furthermore, Bua and Nadroga Navosa also show a relatively high rise regarding the additional inundation of rural buildings in 2100.

The province with the highest number of inundated buildings is still Ba (2500 buildings), followed by Rewa (2009 buildings) and Tailevu (1460 buildings). Serua remains the most affected province, with 23% of its currently standing buildings expected to be permanently underwater by 2100.

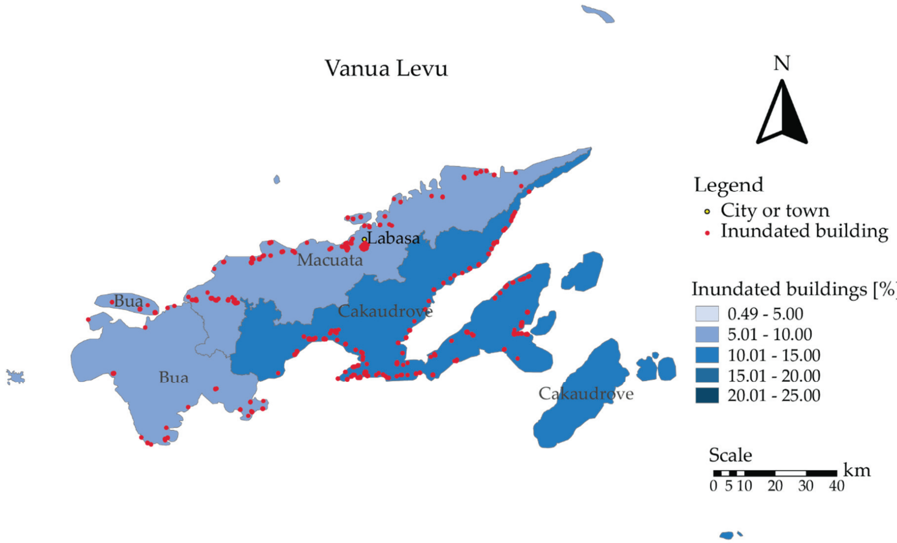

Figure 6. Distribution of permanently inundated buildings in Vanua Levu in 2100. Each province is colored according to the percentage of inundated buildings compared to the total existing ones.

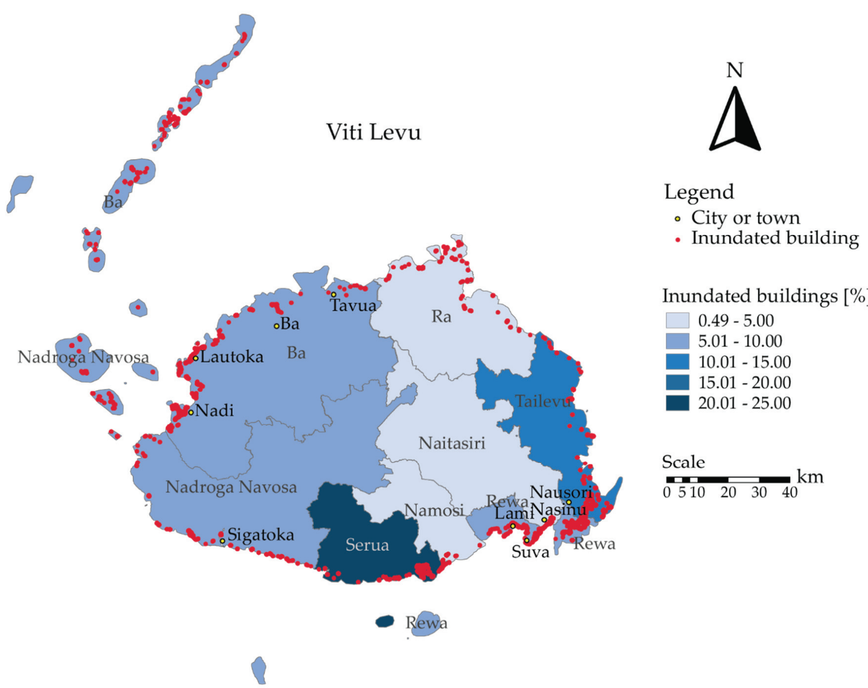

Figure 7. Distribution of permanently inundated buildings in Viti Levu in 2100. Each province is colored according to the percentage of inundated buildings compared to the total existing ones.

3.2. Results of the MSA

Figure 8 plots the lost material stock for the 2050 and 2100 scenarios (an equivalent table can be retrieved in the Supplementary Materials §4, and in the supporting data file for a machine-readable format). Our simulation predicts that, by 2050, 816 gigagrams (Gg) of concrete, 52 Gg of timber and 32 Gg of steel is stocked in buildings that are likely to be inundated. On average, every year will see 26 Gg of concrete, 1.7 Gg of timber, and 1 Gg of steel rendered unusable because of SLR.

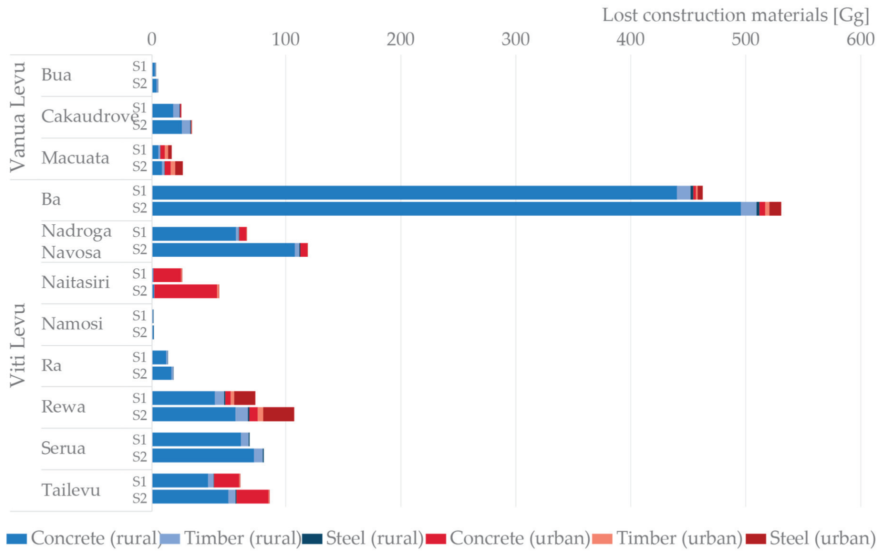

Figure 8. Amount of construction materials lost in gigagrams (Gg) due to sea level rise in Fiji. S1 refers to the 2050 scenario (+ 0.22 m); S2 refers to the 2100 scenario (+ 0.63 m). The blue colors indicate materials located in rural areas, while the red colors represent urban areas.

In both scenarios, concrete accounts for about 90% of the total material lost by mass, followed by timber and steel, with 6% and 4% respectively. Steel will be mainly lost in urban areas while timber and concrete mainly occur in rural areas, due to the prevalence of this construction type in more urbanized areas. In total, most material will be lost in the provinces of Ba, Tailevu, Serua, Nadroga, Navosa, and Rewa.

The differences between the 2050 scenario and the 2100 scenario are proportional to the number of buildings that are additionally inundated in scenario 2. While steel rises by 62%, concrete rises by only 26% and timber by 34%. Those values are similar to the increases that can be seen when observing the changes of buildings being inundated in rural areas (33%) and urban areas (58%). The amount of lost material grows more than 100% in the urban areas of Naitasiri and Ba.

4. Discussion

It is unknown to which extent SLR induced by man-made climate change will influence future resource demand and waste flows. However, this aspect needs to be considered in regard to adaptation actions, especially in countries characterized by large coastal regions with limited economic possibilities and resource availability. One first step in trying to fill this knowledge gap is to estimate the material stock that will be lost due to the permanent inundation of buildings. This study is a first attempt at quantifying the amount of materials rendered unusable by SLR. By explicitly quantifying the number of buildings and amount of materials that will be under water, policymakers have a valid dataset which can contribute to planning adaptation actions to climate change.

The results show that the main material that will be lost is concrete, a structural material which is notorious for its high carbon emissions and energy requirements [51,52]. This is bad news for the environment but it is also an opportunity for transitioning towards more sustainable building solutions. Fijian policy makers are in time for planning relocations, incentivize the use of alternative structural materials, and consider appropriate actions for the large amount of concrete that will need to be demolished. Concrete can be recycled into new concrete [53–55], or downcycled for the formation of road beddings and railway ballasts [56–58]. Timber can be carefully disassembled and used in new constructions [59–61], or it can be used for generating energy [62–64]. Steel should be brought to smelting facilities and remanufactured into new steel products [65]. The fraction of materials that cannot be kept within the economy should be opportunely disposed in landfills, whose number, location, and size should be discussed with local communities and waste managers. The discussed waste treatment would require the establishment of new recycling and incineration facilities. Therefore, reusing and recycling demolition materials should be considered and will likely bring benefits to the environment in the long term, but will add to the costs of relocation in the short term (e.g., operation costs, facility costs, labor costs).

By 2050, the total expected demolition flows due to SLR are 900 Gg, averaging 30 Gg per year. Considering that in 2017 and 2018, the amount of construction materials in new buildings was on average 1170 Gg per year [36,37], SLR demolition flows equate to 2.6% of the total yearly material requirements for new constructions. Such a small fraction has the potential for being absorbed into new constructions without the need for dumping materials into landfills—albeit this does not consider demolition flows coming from normal activities not related to SLR. Fijian policymakers should consider facilitating the inclusion of construction and demolition waste into new buildings by legislating opportune regulations.

While concrete and timber are mainly lost in rural areas, urban areas show a large amount of steel loss. Nevertheless, adaptation policies might prevent urban areas from being flooded (e.g., constructing dams), which would thus protect existing buildings and prevent their demolition.

In both scenarios, rural buildings account for more than 80% of the inundated buildings. This is indicative of the fact that largest settlements are located inland, while coastlines are characterized by scattered buildings. The retreat of coastlines will push people further inland, likely increasing urbanization rates and shifting material demands toward reinforced concrete, as this is the preferred structural material used in cities. Future research shall include the influence climate change has on migration patterns in Fiji.

The relocation of Vunidogoloa cost US$15,625 per house [66]. If applied to the number of inundated rural buildings in this study, this would tally to US$96.13 million for scenario 1 and US$128.42 million for scenario 2. Yet, this simple estimation does not take into account the full impact of SLR, as aside of relocating, people will lose agricultural land. Considering that over 80% of inundated buildings are in rural areas, the people affected by SLR will have either to purchase or be assigned new land, or find different occupations in cities. A thorough analysis of the economic implications of the impacts of SLR on the Fijian economy should be addressed by future research.

The overall difference between scenario 1 and scenario 2 (+ 28%) is relatively low in comparison to the difference of SLR between the two (+ 182%). These findings shed new light on the results of Gravelle and Mimura [13]. While any increase in SLR will results in a proportional reduction of land, the same does not hold for buildings, as losses are dependent on their spatial distribution. This shows that there is not necessarily a relation between the total area inundated and the number of buildings flooded, and that for an accurate assessment of the techno-economic impacts of SLR on human settlements specific studies are needed.

5. Conclusions

5.1. Conclusions

This study presents an estimation of the lost construction material stock due to the permanent rise of sea levels caused by man-made climate change. The results are designed to provide governments, research institutions, non-government organizations and residents a statistical foundation for sustainable long-term planning. In particular, they can be used as baseline data for processes of spatial planning, especially to identify highly affected areas and to plan potential resettlements.

This methodology can be easily applied to other regions and can be fairly simply automated through the use of ArcGIS ModelBuilder or similar applications. This would provide vital information to local and national policymakers for deciding on the best course of actions to adapt to climate change and prepare for the consequences of SLR.

The present study could be expanded in various directions. The GIS-DIAM showed that infrastructure, especially the coastal highways on Viti Levu, are threatened by inundation. While this will not generate demolition flows, as roads are rarely removed [67], new roads will need to be constructed. To plan future material consumption even more sufficiently, future viability plans and associated material requirements should be considered. Additionally, more precise material indicators which include additional materials such as glass, aluminum, or copper, should be calculated to increase the robustness of the results.

Relocations, waste flows, loss of agricultural land, and future resource demands could be placed in a more encompassing economic model to quantify the overall costs associated to SLR. If possible, integrating the current digital terrain model with a digital elevation model which includes buildings could allow for the calculation of the exact height of constructions. Moreover, a highly detailed LiDAR map should be used to analyze in more detail the inundation pattern. This would allow for the possibility of simulating water barriers, allowing for the study of different solutions in relation to their cost and effectiveness. For better predictions, future research should consider increasing the epochs in future time where inundation maps are generated for. By doing so, trends can be better analyzed and the study's predictions could be compared to what has actually happened in the future. The present study's results could be additionally used on Fiji to create maps with secondary resources including an approximate date on which they would become available.

5.2. Limitations and Assumptions

The main limitation of this study comes from the limited data available in relation to building typologies and construction techniques, which is a common problem when conducting research in developing regions [68]. Material intensities differ for each building, while construction typologies are not provided in official maps. The spatial distribution of the typologies, as well as material intensities, were thus assigned on a provincial level rather than being specifically assigned to each building. Additionally, official maps do not report the number of floors for each building, and digital elevation maps only report the terrain height instead of the actual ground elevation. Moreover, over 7000 buildings that were visible from aerial photos were not included in the vectorized digital maps, and had to be manually added.

Additional limitations occur from the DEM and the predicted SLR in regard of a certain point of time. The choice of the years the study was conducted for is to give an overview on two periods in time, one relevant on short-term planning and one relevant on long-term planning. The results stay relevant even if SLR predictions change and therefore provide a good orientation. The accuracy of the DEM is unknown, which unfortunately limits the accuracy of the results. However, this DEM was the best accessible DEM for Fiji during the time this research was conducted (June 2019). Further, this study is meant to provide an overview on the situation and identify the most critical areas rather than presenting highly detailed results on MS. Manual observation was used as a comparative method to verify whether the federal data are more suitable than the SRTM data or the ALOS data. Using

ArcMap, it was proven that the governmental data are more consistent and furthermore, less restricted by the limitation of displaying surface elevation heights rather than ground elevation heights. This is particularly due to the fact that the governmental data incorporate the limitation of showing surface elevation more precisely than the SRTM data and the ALOS data. Research was performed to identify whether lost material stock in buildings inundated due to climate change induced SLR is an issue that should be considered in further climate change adaptation research and policies.

Further limitations can be found regarding the implications of actions to adapt to climate change. The construction of water barriers can significantly change the predicted inundated areas, rendering buildings that were predicted to be underwater still usable. As it is not possible to forecast if and when a water barrier will be constructed, this study disregards this option and presents results as if no water barriers will be erected.

In addition, results account only for buildings which will be actually inundated. Buildings which are not inundated might be included in relocation processes, especially in those cases where the majority of the buildings in a village will be flooded. This decision has to be considered from case to case and is therefore not possible to be included in this study.

Storms, coastal erosion, and the salination of agricultural land and water storages might cause additional relocations. Models on the permeation of seawater in agricultural land and aquifers are required to include these aspects for a more accurate prediction.

This study neglects approximately 36,000 people (about 4% of the national population) that are not living on the two main islands. These primarily rural residents could cause further challenges because relocations can eventually not happen on smaller islands and therefore increase the density of the larger islands.

In spite of its limitations, this study was conducted to provide an overview on the situation and its significance for climate change adaptation. The limitations do not influence the goodness of results in a way that would result in significant differences.

Supplementary Materials: The following are available online at http://www.mdpi.com/2071-1050/12/3/834/s1, Table S1: Typical number of floors in buildings by province, including references, Table S2: Distribution of construction typologies per province for scenario 1 (2050), Table S3: Distribution of construction typologies per province for scenario 2 (2100), Table S4: Material intensities of cement block masonry walls, construction typology based on [13], measurements based on [14] densities according to [15] (concrete), [16] (steel), [14] (timber). Note that GFA = Gross Floor Area, Table S5: Material intensities of corrugated iron walls and steel frame buildings, construction typology based on [13], measurements based on [14], densities according to [15] (concrete), [16] (steel), [14] (timber). Note that GFA = Gross Floor Area, Table S6: Material intensities of timber frame buildings, construction typology based on [13], measurements based on [14], densities according to [15] (concrete), [16] (steel), [14] (timber). Note that GFA = Gross Floor Area, Table S7: Results of the material stock analysis. Unit: Gg (note: 1 Gg = 109 g = 103 t = 1 kt).

Author Contributions: Conceptualization, S.M., A.M., S.W., H.T. and L.S.; Data curation, A.M.; Formal analysis, S.M. and A.M.; Funding acquisition, S.W. and L.S.; Investigation, S.M.; Methodology, S.M., A.M. and S.W.; Project administration, A.M. and S.W.; Resources, S.M.; Software, S.M.; Supervision, H.T. and L.S.; Validation, A.M., S.W., H.T. and L.S.; Visualization, S.M., A.M. and S.W.; Writing—original draft, S.M., A.M. and S.W.; Writing—review & editing, S.M., A.M., S.W., H.T. and L.S. All authors have read and agreed to the published version of the manuscript.

Funding: The authors acknowledge the financial support by the DFG (German Research Foundation) in the framework of the Excellence Initiative, Darmstadt Graduate School of Excellence Energy Science and Engineering (GSC 1070) as well as by the Open Access Publishing Fund of Technische Universität Darmstadt.

Acknowledgments: The authors are grateful to the staff at Geospatial Division of the Ministry of Lands & Mineral Resources Fiji, in particular M. Hicks, V. K. Raqona and N. N. Kumar for their kind assistance in providing data.

Conflicts of Interest: The authors declare no conflict of interest. The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript, or in the decision to publish the results. Maps throughout this paper were created using ArcGIS® software by Esri. ArcGIS® and ArcMap™ are the intellectual property of Esri and are used herein under license. Copyright © Esri. All rights reserved. For more information about Esri® software, please visit www.esri.com.

References

1. IPCC. *Global Warming of 1.5 °C*; An IPCC Special Report on the impacts of global warming of 1.5 °C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate-change, sustainable development, and efforts to eradicate poverty; Masson-Delmotte, V.M., Zhai, P., Pörtner, H.-O., Roberts, D., Skea, J., Shukla, P.R., Pirani, A., Moufouma-Okia, W., Péan, C., Pidcock, R., et al., Eds.; IPCC: Geneva, Switzerland, 2018; In Press.
2. Church, J.A.; Clark, P.U.; Cazenave, A.; Gregory, J.M.; Jevrejeva, S.A.; Levermann, A.; Merrifield, M.A.; Milne, G.A.; Nerem, R.S.; Nunn, P.D.; et al. Sea Level Change. In *Climate Change 2013: The Physical Science Basis*; Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change; Stocker, T.F., Qin, D., Plattner, G.-K., Tignor, M., Allen, S.K., Boschung, J., Nauels, A., Xia, Y., Bex, V., Midgley, P.M., Eds.; Cambridge University Press: Cambridge, UK; New York, NY, USA, 2013.
3. Dasgupta, S.; Meisner, C.; Laplante, B.; Wheeler, D.; Yan, J. *The Impact of Sea Level Rise on Developing Countries*; WPS-4136; The World Bank: Washington, DC, USA, 2007.
4. Barbier, E.B. Climate Change Impacts on Rural Poverty in Low-Elevation Coastal Zones. *Estuar. Coast. Shelf Sci.* **2015**, *165*, A1–A13. [CrossRef]
5. IPCC. *Climate Change 2014: Synthesis Report*; Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change; IPCC: Geneva, Switzerland, 2014.
6. Kulp, S.A.; Strauss, B.H. New elevation data triple estimates of global vulnerability to sea-level rise and coastal flooding. *Nat. Commun.* **2019**. [CrossRef]
7. Climate Change Secretariat. *Climate Change: Small Island Developing States*; Climate Change Secretariat: Bonn, Germany, 2005.
8. Golden, C.D.; Allison, E.H.; Cheung, W.W.L.; Dey, M.M.; Halpern, B.S.; McCauley, D.J.; Smith, M.; Vaitla, B.; Zeller, D.; Myers, S.S. Nutrition: Fall in Fish Catch Threatens Human Health. *Nature* **2016**, *534*, 317–320. [CrossRef] [PubMed]
9. Mercer, J.; Kelman, I.; Alfthan, B.; Kurvits, T. Ecosystem-Based Adaptation to Climate Change in Caribbean Small Island Developing States: Integrating Local and External Knowledge. *Sustainability* **2012**, *4*, 1908–1932. [CrossRef]
10. Turvey, R. Vulnerability Assessment of Developing Countries: The Case of Small-island Developing States. *Dev. Policy Rev.* **2007**, *25*, 243–264. [CrossRef]
11. Kurniawan, F.; Adrianto, L.; Bengen, D.G.; Prasetyo, L.B. Vulnerability Assessment of Small Islands to Tourism: The Case of the Marine Tourism Park of the Gili Matra Islands, Indonesia. *Glob. Ecol. Conserv.* **2016**, *6*, 308–326. [CrossRef]
12. Blasiak, R.; Spijkers, J.; Tokunaga, K.; Pittman, J.; Yagi, N.; Österblom, H. Climate Change and Marine Fisheries: Least Developed Countries Top Global Index of Vulnerability. *PLoS ONE* **2017**, *12*. [CrossRef]
13. Gravelle, G.; Mimura, N. Vulnerability Assessment of Sea-Level Rise in Viti Levu, Fiji Islands. *Sustain. Sci.* **2008**, *3*, 171–180. [CrossRef]
14. The World Bank. *Climate Vulnerability Assessment: Making Fiji Climate Resilient*; The World Bank: Suva, Fiji, 2017.
15. Wu, S.Y.; Najjar, R.; Siewert, J. Potential Impacts of Sea-Level Rise on the Mid- and Upper-Atlantic Region of the United States. *Clim. Chang.* **2009**, *95*, 121–138. [CrossRef]
16. Heberger, M.; Cooley, H.; Herrera, P.; Gleick, P.H.; Moore, E. *The Impacts of Sea-Level Rise on the California Coast*; California Climate Change Centre: Oakland, CA, USA, 2009.
17. Sadler, J.M.; Haselden, N.; Mellon, K.; Hackel, A.; Son, V.; Mayfield, J.; Blase, A.; Goodall, J.L. Impact of Sea-Level Rise on Roadway Flooding in the Hampton Roads Region, Virginia. *J. Infrastruct. Syst.* **2017**, *23*, 05017006. [CrossRef]
18. Hallegatte, S.; Ranger, N.; Mestre, O.; Dumas, P.; Corfee-Morlot, J.; Herweijer, C.; Wood, R.M. Assessing Climate Change Impacts, Sea Level Rise and Storm Surge Risk in Port Cities: A Case Study on Copenhagen. *Clim. Chang.* **2011**, *104*, 113–137. [CrossRef]
19. Ministry of Health and Ministry of Economy. *5- Year to 20- Year National Development Plan for Fiji*; Ministry of Health and Ministry of Economy: Suva, Fiji, 2017.

20. California Coastal Comission. *California Coastal Comission Sea Level Rise Policy Guidance: Interpretive Guidelines for Addressing Sea Level Rise in Local Coastal Programs and Coastal Development Permits*; California Coastal Comission: San Francisco, CA, USA, 2015.
21. Ministry of Economy. *Fiji's National Adaptation Plan Framework Ministry of Economy*; Ministry of Economy: Suva, Fiji, 2017.
22. Charan, D.; Kaur, M.; Singh, P. Customary Land and Climate Change Induced Relocation—A Case Study of Vunidogoloa Village, Vanua Levu, Fiji. In *Climate Change Adaptation in Pacific Countries Forstering Resilience and Improving the Quality of Life*; Leal Filho, W., Ed.; Springer International Publishing: Cham, Switzerland, 2017. [CrossRef]
23. Fuldauer, L.I.; Ives, M.C.; Adshead, D.; Thacker, S.; Hall, J.W. Participatory Planning of the Future of Waste Management in Small Island Developing States to Deliver on the Sustainable Development Goals. *J. Clean. Prod.* **2019**, *223*, 147–162. [CrossRef]
24. United Nations Environment Programme. *Small Island Developing States Waste Management Outlook*; United Nations Environment Programme: Nairobi, Kenya, 2019. [CrossRef]
25. Ali, S.; Darsan, J.; Singh, A.; Wilson, M. Sustainable Coastal Ecosystem Management – An Evolving Paradigm and Its Application to Caribbean SIDS. *Ocean Coast. Manag.* **2018**, *163*, 173–184. [CrossRef]
26. Mackay, S.; Brown, R.; Gonelevu, M.; Pelesikoti, N.; Kocovanua, T.; Iaken, R.; Iautu, F.; Tuiafitu-Malolo, L.; Fulivai, S.; Lepa, M.; et al. Overcoming Barriers to Climate Change Information Management in Small Island Developing States: Lessons from Pacific SIDS. *Clim. Policy* **2019**, *19*, 125–138. [CrossRef]
27. Tanikawa, H.; Fishman, T.; Okuoka, K.; Sugimoto, K. The Weight of Society over Time and Space: A Comprehensive Account of the Construction Material Stock of Japan, 1945–2010. *J. Ind. Ecol.* **2015**, *19*, 778–791. [CrossRef]
28. Tanikawa, H.; Managi, S.; Lwin, C.M. Estimates of Lost Material Stock of Buildings and Roads Due to the Great East Japan Earthquake and Tsunami. *J. Ind. Ecol.* **2014**, *18*, 421–431. [CrossRef]
29. Kleemann, F.; Lehner, H.; Szczypińska, A.; Lederer, J.; Fellner, J. Using Change Detection Data to Assess Amount and Composition of Demolition Waste from Buildings in Vienna. *Resour. Conserv. Recycl.* **2017**, *123*, 37–46. [CrossRef]
30. Miatto, A.; Schandl, H.; Forlin, L.; Ronzani, F.; Borin, P.; Giordano, A.; Tanikawa, H. A Spatial Analysis of Material Stock Accumulation and Demolition Waste Potential of Buildings: A Case Study of Padua. *Resour. Conserv. Recycl.* **2019**, *142*, 245–256. [CrossRef]
31. Cheng, K.L.; Hsu, S.C.; Li, W.M.; Ma, H.W. Quantifying Potential Anthropogenic Resources of Buildings through Hot Spot Analysis. *Resour. Conserv. Recycl.* **2018**, *133*, 10–20. [CrossRef]
32. H2. Main Material for Construction of Walls—Proportion of Wood—Pie Chart—2007 Census (Households). Available online: http://fiji.popgis.spc.int/#z=211120,8600481,1039511,939237;l=en;v=map1 (accessed on 26 November 2018).
33. Fiji Bureau of Statistics. *Census 2007 Results: Population Size, Growth, Structure, and Distribution*; Fiji Bureau of Statistics: Suva, Fiji, 2008.
34. Fiji. Available online: https://download.geofabrik.de/australia-oceania/fiji.html (accessed on 22 November 2018).
35. ArcGIS—World Imagery Mit Metadaten. Available online: https://www.arcgis.com/home/webmap/viewer.html?webmap=268c1b2fe17842758476f4e002d19ef4&extent=12.0492,52.0048,13.9938,52.8464 (accessed on 30 June 2019).
36. Building Statistics December Quarter and Annual 2018. Available online: https://www.statsfiji.gov.fj/index.php/latest-releases/establishment-surveys/building-statistics/931-building-statistics-december-quarter-annual-2018?highlight=WyJidWlsZGluZyIsImFubnVhbCIsMjAxOCwiYW5udWFsIDIwMTgiXQ== (accessed on 30 August 2019).
37. Building Statistics—December Quarter & Annual 2017. Available online: https://www.statsfiji.gov.fj/index.php/latest-releases/establishment-surveys/building-statistics/818-building-statistics-december-quarter-and-annual-2017?highlight=WyJidWlsZGluZyIsMjAxN10= (accessed on 30 August 2019).
38. Raqona, V. *Personal Communication*; Geospatial Division of the Ministry of Lands & Mineral Resources Fiji: Suva, Fiji, 2019.
39. Caimi, A.; Moles, O.; Joffroy, T.; Serlet, M. *Fiji/Baseline Data on Local Building Culture & Coping Strategies*; International Centre for Earthen Construction: Villefontaine, France, 2016. [CrossRef]
40. Habitat for Humanity Fiji. *Construction Manual*; Habitat for Humanity Fiji: Suva, Fiji, 2013.

41. Chang, Y.-S. *Life Cycle Assessment on the Reduction of Carbon Dioxide Emission of Buildings*; Chenggong University: Tainan, Taiwan, 2002.
42. Nagaoka, K.; Tanikawa, H.; Yoshida, N.; Higashi, O.; Onishi, A.; Feng, S.; Imura, H. Study of Accumulation (Distribution Tendency to the Material Stock of the Construction Sector in All Prefectures and Mega Cities in Japan. *Environ. Sci.* **2009**, *23*, 83–88.
43. Tanikawa, H.; Hashimoto, S. Urban Stock over Time: Spatial Material Stock Analysis Using 4D-GIS. *Build. Res. Inf.* **2009**, *5–6*, 483–502. [CrossRef]
44. Google Maps. Suva City. Available online: https://www.google.com/maps/@-18.1394616,178.424621,3a,75y,96.46h,110.5t/data=!3m7!1e1!3m5!1sAF1QipNCJNPOQ8u1FqqGFOpm5jq-ztenE-FzsWw0-ORt!2e10!3e11!7i5376!8i2688 (accessed on 10 April 2019).
45. Fiji Key Facts. Available online: http://thecommonwealth.org/our-member-countries/fiji (accessed on 30 October 2018).
46. Pacific Islands Climate Change Assistance Programme. *Climate Change the Fiji Islands Response*; Pacific Islands Climate Change Assistance Programme: Suva, Fiji, 2005.
47. Fiji: Building Resilience in the Face of Climate Change. Available online: https://www.unocha.org/story/fiji-building-resilience-face-climate-change (accessed on 23 October 2019).
48. USGS Earth Explorer. Available online: https://earthexplorer.usgs.gov/ (accessed on 7 January 2019).
49. ALOS Science Project. Available online: https://www.eorc.jaxa.jp/ALOS/en/aw3d30/index.htm (accessed on 7 January 2019).
50. *Fiji 2017 Population & Housing Census*; Fiji Islands Bureau of Statistics: Suva, Fiji, 2018.
51. Solutions, Green Cement: Concrete. Available online: https://www.nature.com/news/green-cement-concrete-solutions-1.12460 (accessed on 8 November 2019).
52. Barcelo, L.; Kline, J.; Walenta, G.; Gartner, E. Cement and Carbon Emissions. *Mater. Struct.* **2014**, *47*, 1055–1065. [CrossRef]
53. Hansen, T.C. *Recycling of Demolished Concrete and Masonry*, 1st ed.; CRC Press: London, UK, 1992. [CrossRef]
54. Oikonomou, N.D. Recycled Concrete Aggregates. *Cem. Concr. Compos.* **2005**, *27*, 315–318. [CrossRef]
55. Tam, V.W.Y. Comparing the Implementation of Concrete Recycling in the Australian and Japanese Construction Industries. *J. Clean. Prod.* **2009**, *17*, 688–702. [CrossRef]
56. Courard, L.; Michel, F.; Delhez, P. Use of Concrete Road Recycled Aggregates for Roller Compacted Concrete. *Constr. Build. Mater.* **2010**, *24*, 390–395. [CrossRef]
57. Schimmoller, V.E.; Taylor Eighmy, T.; Smith, M.; Rohrbach, G.J.; Helms, G.; Van Deusen, C.H.; Almborg, J.A.; Holtz, K.; Wiles, C.; Malasheskie, G. *Recycled Materials in European Highway Environments: Uses, Technologies, and Policies*; DIANE Publishing: Washington, DC, USA, 2000. [CrossRef]
58. Herrador, R.; Pérez, P.; Ordónez, J. Use of Recycled Construction and Demolition Waste Aggregate for Road Course Surfacing. *J. Transp. Eng.* **2012**, *138*. [CrossRef]
59. Ormondroyd, G.A.; Spear, M.J.; Skinner, C. The Opportunities and Challenges for Re-Use and Recycling of Timber and Wood Products Within the Construction Sector. In *Environmental Impacts of Traditional and Innovative Forest-based Bioproducts*; Kutnar, A., Muthu, S., Eds.; Springer: Singapore, 2016; pp. 45–103. [CrossRef]
60. Hafner, A.; Ott, S.; Winter, S. Recycling and End-of-Life Scenarios for Timber Structures. Mater. *Joints Timber Struct.* **2014**, *9*. [CrossRef]
61. Addis, B.; Addis, W. *Building with Reclaimed Components and Materials: A Design Handbook for Reuse and Recycling*; Routledge: London, UK, 2006.
62. Kaziolas, D.N.; Zygomalas, I.; Stavroulakis, G.E.; Baniotopoulos, C.C. Environmental Impact Assessment of the Life Cycle of a Timber Building. In Proceedings of the Fourteenth International Conference on Civil, Structural and Environmental Engineering Computing, Cagliari, Sardinia, Italy, 3–6 September 2013; Topping, B.H.V., Ivány, P., Eds.; Civil-Comp Press: Stirlingshire, Scotland, 2013. Available online: http://repository.edulll.gr/2516 (accessed on 06 November 2019).
63. John, S.; Buchanan, A. *Review of End-of-Life Options for Structural Timber Buildings in New Zealand and Australia*; University of Canterbury: Christchurch, New Zealand, 2013; Available online: http://hdl.handle.net/10092/10296 (accessed on 06 November 2019).
64. Macineasa, S.G.; Entuc, I.S.; Taranu, N.; Florenta, I.; Secu, A. *Environmental* Performances of Different Timber Structures for Pitched Roofs. *J. Clean. Prod.* **2018**, *175*, 164–175. [CrossRef]

65. Tam, V.W.Y.; Tam, C.M. A Review on the Viable Technology for Construction Waste Recycling. *Resour. Conserv. Recycl.* **2006**, *47*, 209–221. [CrossRef]
66. McNamara, K.E.; Des Combes, H.J. Planning for Community Relocations Due to Climate Change in Fiji. *Int. J. Disaster Risk Sci.* **2015**, *6*, 315–319. [CrossRef]
67. Switalski, T.; Bissonette, J.; DeLuca, T.; Luce, C.; Madej, M. Benefits and Impacts of Road Removal. *Front. Ecol. Environ.* **2004**, 2. [CrossRef]
68. Nguyen, T.C.; Fishman, T.; Miatto, A.; Tanikawa, H. Estimating the Material Stock of Roads: The Vietnamese Case Study. *J. Ind. Ecol.* **2019**, *23*, 663–673. [CrossRef]

© 2020 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (http://creativecommons.org/licenses/by/4.0/).

sustainability

MDPI

Article

The Social Metabolism of Quiet Sustainability in the Faroe Islands

Ragnheiður Bogadóttir

Department of History and Social Sciences, University of the Faroe Islands, Jónas Broncks gøta 25, FO-100 Tórshavn, Faroe Islands; ragnheidurb@setur.fo

Received: 3 October 2019; Accepted: 1 January 2020; Published: 20 January 2020

Abstract: This paper investigates the interrelations between social metabolism and socio-ecological sustainability in the Faroe Islands in a long-term perspective. It traces the trajectory and changes in socio-metabolic configurations from the time of settlement until today and shows how social metabolism has increased to very high per capita levels during the past century. The analysis departs from the recognition that a decrease in social metabolism, i.e., a net reduction in throughput of natural resources in human economies, is necessary in order to curb the impending ecological crisis. It is argued that parallel to the growth oriented formal Faroese economy, economic food-provisioning practices rooted in the traditional, and ecologically sustainable, land management system continue to be practiced by Faroese people. These practices can be conceptualized as practices of so-called "quiet sustainability" and their contribution is estimated in bio-physical metrics of weight. The analysis shows that practices of "quiet sustainability" contribute significant quantities of certain food items to the local population thereby enhancing food security and food sovereignty. Moreover, these practices are an integral element in the biocultural diversity, which has constituted the Faroe Islands for close to two millennia. Therefore, they should be considered real alternatives to import-based consumption and taken into account in sustainability discourse and policy to a higher degree than is currently the case.

Keywords: social metabolism; island metabolism; quiet sustainability; Faroe Islands; landesque capital; historical political ecology

1. Introduction

On a global scale, and in a long-term perspective, current levels of resource use in human economies are not sustainable. As natural capital is spent at a faster pace than it is replenished, the capabilities of the earth system to provide vital ecosystem service are undermined, and critical planetary boundaries for a safe human operating space are transgressed [1–4]. The scale of global environmental change is unprecedented in human history [5] and the consequences on the climate and other crucial ecosystem functions have long been reported. More recently, this research is synthesized by the IPCC (Intergovernmental Panel on Climate Change) and the IPBES (Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services). Achieving a high quality of life for more than seven billion people without destabilizing planetary processes and undermining fundamental ecosystem services remains a formidable challenge, and it requires a reduction in absolute resource use and thereby a reduction in social metabolism [6].

Islands are "good to think with" [7], and the paper addresses the above mentioned challenge thinking with the case of the Faroe Islands, or the Faroes, a small island nation in the North Atlantic. As boundaries are more easily discernible on islands, they offer great potential in the study of crucial issues pertaining to sustainability such as biocultural diversity, and the social organization of material and energy flows [8–11].

This particular case study offers an opportunity to think about sustainability and human well-being by looking at social metabolism in the Faroes in a long-term perspective. It traces the emergence of an ecologically sustainable land management system from the time of settlement around 300 AD and identifies economic practices carried out by Faroese people today rooted in this system. It also briefly traces the emergence and development of industrial metabolism during the twentieth century. As has been shown to be the case for other island societies [12], the Faroes experienced substantial transformations after the 1950s, which entailed increased resource dependence beyond the islands' geographical borders. The Faroese trajectory can be compared with the metabolic profiles of other small island states such as Iceland and Trinidad and Tobago, which have been described by Krausmann et al. [11] as examples of high-income island economies with very specific resource use patterns. In the case of the Faroes, an export-oriented fishing industry (and in later decades also aquaculture) is driving very high, and increasing, levels of material and energy use per capita [13]. The geographical isolation combined with a metabolic profile of high-level resource extraction, and high dependence on imports, makes island societies vulnerable to economic and ecological flux. One extreme case to illustrate this point is Nauru, where phosphate mining devastated local ecosystems to a very large degree and where the social and cultural consequences of such devastation are evident [14]. To counter this development of increasing dependency, many island societies have consciously sought to reconnect their island economies to their natural systems, but such recoupling presents several challenges related to questions of resilience, vulnerability, and sustainability [12].

Social Metabolism, Biocultural Diversity, and Diverse Practices of Quiet Sustainability

Reversing the trend of growing social metabolism without compromising human well-being is arguably the key challenge for sustainability science. While much focus remains on technological solutions, the cultural dimensions of sustainability are often neglected, together with the realization that the process of increasing social metabolism is also a process of increasing biodiversity and cultural loss. In other words, increasing social metabolism is very often a process of decontextualization [15] and of biocultural homogenization [16,17] often entailing environmental and social injustices and tradeoffs [18]. As Rozzi [16] has argued, in the context of global socio-environmental change, the world views, knowledge, and practices of sustainable cultures should be respected and eventually adapted through intercultural exchange. This article explores how practices rooted not in other cultures, but in an ecologically sustainable cultural past may be adapted, or reevaluated and enhanced in a modern, high-resource use context. In a recent review of Pacific small island knowledge-practice-belief systems, McMillen et al. [19] argue that such systems include valuable insights on ecological processes and management of biocultural diversity relevant for resilience and adaptability, particularly regarding the effects of climate change. The argument put forward here is that such knowledge systems are not only crucial for adaptability to climate change, but also in mitigation. The recognition of the importance of traditional and indigenous knowledge in land and resource management is not new [20] and is visible, for instance, in article eight in the Convention of Biological Diversity and the accompanying Akwé: Kon guidelines, but in most policy context it remains at the margin of mainstream development discourse. However, as the consequences of mainstream "development" become evident, the importance of nurturing and conserving local and culturally specific economic practices and habits is increasingly recognized.

In the following analysis, economic practices in the Faroes, rooted in the traditional land management system, are identified as practices of "quiet sustainability." Smith and Jehlicka [21] have defined quiet sustainability as long-standing forms of food self-provisioning, i.e., the growing and sharing of food as common practices carrying environmental and social benefits, yet it receives little consideration in academic literature and policy discourse on sustainability. Practices of quiet sustainability are everyday practices with low environmental impacts. Such practices, in the Faroese context, can also be conceptualized as a form of diverse or alternative economic practice, as defined by Gibson-Graham [22]. From a physical perspective they are rooted in a traditional socio-economic system where nutrients and biomass were recycled, and which was primarily oriented towards local consumption and self-provisioning. From an ideological perspective, they are rooted in land management traditions, which were governed by a so-called limited-good world view [23]. These characteristics distinguish them from the economic practices and moral principles characterizing and organizing the growth oriented industrial metabolism of the Faroes.

In order to illuminate the distinctions between industrial social metabolism and the social metabolism of quiet sustainability, the analysis draws on theoretical discussions on socio-metabolic constellations/configurations, and the implications for long-term sustainability. Additionally, the analysis draws on theoretical insights from long-term socio-ecological research, environmental history, and historical political ecology, such as the concept of landesque capital [24–31], in order to investigate how different socio-metabolic configurations produce distinct forms of capital stocks, and the role of these capital stocks in resource flow path dependencies [32–34]. One key insight gained from this body of research and literature is that humans can organize society and social metabolism in ways that contribute to both sustainability and equality. Accepting this proposition avoids the analytical confinement to the idea that there is a fundamental contradiction between human society and the natural environment [35]. Humans, however, can also organize social metabolism in ways that undermine the very ecological and social foundation of their (or others') society. Endeavors to establish and maintain balanced relations between environmental sustainability and social and economic equality are a central question in (historical) political ecology [36], and the urgency of this question is becoming ever more apparent as both social metabolism and economic inequality are increasing [37,38]. Such endeavors towards ecological sustainability and economic equity may arguably be seen as processes of "islanding" [39]: of perceiving, discerning, and negotiating the boundaries that define human–human and human–nature interrelations. One way of doing this, in practice, is to organize economies into separate spheres of exchange. The principle of separate spheres of exchange has been identified ethnographically in many cultures, and it has been suggested as a way to "insulate local sustainability and resilience from the deleterious effects of globalization and financial speculation" [40]. Departing from this point, the aim here is to identify and delineate distinct spheres or modes of social metabolism co-occurring on the Faroes. The implication is a deliberate emphasis on the fact that distinct modes of social metabolism do not only belong to certain historical time periods defined as metabolic regimes [41,42], but that such modes co-occur, and that people, in their daily practices, switch between socio-metabolic modalities [43,44]. The fact that they are coeval is of relevance for sustainability science because it demonstrates that alternatives to unsustainable resource use patterns and strategies are already (quietly) present in society.

One of the traits defining practices of quiet sustainability is that they contribute to sustainability but without explicitly seeking to do so. These practices are thus already contributing to sustainability but are not counted as such. The main contribution of this article is to count some of these practices, and thereby make them count. In other words, to quantify the contribution of the people practicing "quiet sustainability" in the Faroes to highlight the relevance of these activities as already existing and potential forces of sustainability, and their importance to food security and food sovereignty in an island context.

2. Materials and Methods

The Faroe Islands are an island nation in the North Atlantic Ocean comprising 18 islands, 17 of which are inhabited. The population is approximately 51,000, and the land area is 1399 square kilometers. Ocean territory or EEZ (exclusive economic zone) is almost 274,000 square kilometers. The Faroes were probably first settled around 300 AD and became part of the Norwegian Kingdom in the 13th century. Together with Greenland and Iceland, the Faroes were under the Norwegian and later the Danish crown but gained Home Rule in 1948 and are a self-governing nation with extensive autonomous powers and responsibilities within the kingdom of Denmark. The Faroes are often popularly described as a welfare society of the so-called Nordic model, and GDP per capita ranks among the highest in the world [45]. Fish has been the main export item for the past century, and fish products make out 90–95% of the export value.

As the primary ambition with this paper is an investigation of social metabolism in the Faroe Islands, it draws on methods and methodology in the field of social metabolism [46,47]. While the official statistics agency of the Faroes produces much relevant statistical material, physical statistics are not prioritized, and this makes more established methods of material and energy flows, such as MEFA and MFA, less feasible. Regarding informal economic practices that would fall under the definition of "quiet sustainability," even those that contribute significant volumes of food, these are often classified as "hobbies" within Faroese administration [48], and statistics are not available.

The methods used in this analysis have therefore been adapted to the specific context of the field and the aim of the study. To provide a metabolic profile and a schematic assessment of Faroese industrial metabolism, relevant statistical material has been collected from peer-reviewed literature and publicly available statistical records. The method used to make quantitative estimates of quiet sustainability practices has been to conduct searches in peer-reviewed literature, gray literature, and statistical records. In some cases, official statistics are available, for instance statistical records on the Faroese pilot whale catch go back to the year 1584 and are therefore among the best documented hunting practices in the world. For other alternative and traditionally rooted economic practices, information is more obscure and most of the data has been found in gray literature, mostly from government and agency reports. Data on fowling has been obtained through personal communication with experts in the field. The practices included in the analysis are therefore those where data were found to base estimates on. These practices were sheep rearing, potato cultivation, fowling, and whaling. This selection and methodological approach means that many other practices are excluded, such as the raising of geese, ducks, and chicken, other forms of hunting and gathering, and more.

The methodology also implies a gendered approach to the economy, emphasizing the male sphere and excluding food items that are mostly produced by women, such as various kinds of sausages made from the parts of sheep that are not meat. Likewise, limiting practices of quiet sustainability to food provisioning practices means excluding other traditional and essential provisioning strategies such as the production of yarn and clothes through the practices of spinning, weaving, and particularly knitting, which many Faroese women continue to engage in on a daily basis.

3. Results

3.1. Industrial and Traditional Social Metabolism on the Faroes

Prior to around 1950, Faroese society was sustained to a large degree by material and energy flows originating within its geographical borders. After 1950, as the Faroes have been increasingly incorporated into the wider and emerging extractive global economy and global food system, the size of material and energy flows crossing its geographical borders has increased dramatically. The Faroese economy is a very clear example of how inclusion into the global market and the development of an export-oriented industry, in this case fisheries, has led to growing per capita levels of material and energy use. During the 20th century total catch figures grew from an estimated 1200 tons in 1903 to more than 700,000 tons in 2017 [49] (Figure 1). Per capita, fish catches went from 80 kg in 1903 to almost 14 tons in 2017, corresponding to a 175-fold increase. A large proportion of this catch is exported, more than 500,000 tons in 2017, corresponding to more than 10 tons per capita. In the quarter century between 1993 and 2017 total physical exports grew from 176,000 tons in 1993 to 589,093 tons in 2017 [50]. Physical export in 2017 corresponds to more than 11 tons per capita. In comparison, physical export in the EU is approximately 1 ton per capita [51].

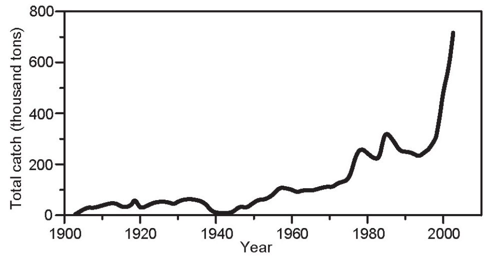

Figure 1. Total Faroese fisheries catch in the century between 1903 and 2003. Adapted from Jákupstovu [49].

The revenues from these high levels of export enable a high material standard of living in the Faroes, but as has been the case for many other island societies, it has also created dependence on imports to sustain basic human needs and modern economic functions [12]. Revenues likewise enable large investments and build-up of industrial infrastructure. Much of this infrastructure requires high levels of resource and energy use to be sustained and to maintain productivity, and the fossil fuel requirements of Faroese industrial fisheries are very high. Generally speaking, the energy efficiency performance of industrial fisheries has worsened over time [52], and as fish stocks are becoming overexploited, greater effort and energy inputs are required. In 2018, the fishing fleet contributed 44% of total Faroese CO_2 emissions from the burning of fossil fuels. Another 6% of emissions can also be attributed to the fishing fleet through the use of greenhouse gases in cooling systems and other industrial processes. Emissions from fisheries have increased from approximately 200,000 tons in 1990 to more than 500,000 tons in 2018 [53]. Export revenues similarly enable imports of all kinds of artefacts and consumer goods. Statistics on physical imports are not available, but statistical information on CO_2 emissions and waste production may be seen as indicators of a high import level, since most consumption goods and all fossil energy are imported. A portion of these goods accumulates in capital stocks (people, livestock, and infrastructure), and the rest dissipates into various kinds of pollution and waste. CO_2 emissions were as high as approximately 20 tons per capita in 2017 [54], and waste production in the same year was more than 1 ton per capita [55]. In comparison, the production of municipal waste in Europe was 486 kg per capita in 2017 [56] (See Figure 2 and Table 1).

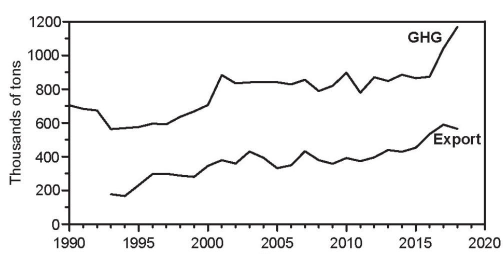

Figure 2. Growth in greenhouse gas (GHG) emission in CO_2 equivalents and total physical exports since the early 1990s. Source: Statistics Faroe Islands and the Faroese Environment Agency.

The dramatic increase in CO_2 emissions and in fish biomass extracted from the sea (illustrated in Figures 1 and 2) attest to the increasing flows of exhaustible resources required to sustain these industrial processes and the resulting net increase in social metabolism.

Table 1. Socio-metabolic characteristics of the Faroe Islands for European and global comparison for the year 2017.

Indicator	Faroe Isl.	EU	World
Population density (people/km^2)	36	118	51
CO_2 emission per capita (tons CO_2/year)	20	7	5
Waste generation per capita (kg/day)	2.9	1.3	1.1

Sources: Environment Agency of the Faroe Islands, Eurostat, and the World Bank.

The argument pursued in this paper is that the informal or diverse economy, carried out by people engaging in practices of "quiet sustainability," should not be ignored or neglected as part of the solution to the sustainability challenges of reducing greenhouse gas emissions, and more generally, of reducing net social metabolism, as well as of conserving and enhancing biodiversity. Dominant discourses on economy and sustainability in the Faroes are governed by an ideology of growth, an ideology that is in turn materializing in growing social metabolism. However, alongside or parallel to this "real" industrial economy is the alternative or diverse economy, which is arguably governed by different logics and moral principles. The practices associated with the alternative economy are not necessarily framed as sustainable, often quite the contrary, they are considered backward and unnecessary. Informal and non-commercial food provisioning practices are not seen as alternatives to industrially based production and consumption, and they are mostly either ignored or neglected in policy and physical planning. Many of these practices of quiet sustainability in the Faroes are rooted in the traditional land management system.

The system and cultural principles organizing traditional Faroese society and social metabolism is often referred to as the infield/outfield system. The cultivated infields surrounding the villages were cleared and marked from the outfields with stonewalls and were used to produce hay for winter fodder for the cows. It has been estimated that around 85–90% of the infield was used for making hay [57]. The remaining plots were cultivated with barley and swedes. Manure was collected and used in the barley plots that were worked using the practice of *reinavelting* (Faroese words in this text are in italics). This form of tilling, using only hand power, improved the productivity of the land and increased grass yields in the following years. The practice of *reinavelting*, first mentioned in historical sources from the 17th century, seems to have been a method exceptionally well adapted to the Faroese geography and climate to grow barley under very limiting climatic circumstances, to avoid soil erosion, and for improving the quality of the soil [58].

The outfields were used for grazing. Sheep grazed all year round, and the cattle grazed from around May or June until October and were kept in the byre during winter. Based on the information in farmers journals and other historical material, Guttesen [57,59–62] has suggested that dairy production constituted more than 40% of caloric intake. Imported grain made up close to 25%, and locally grown grain made up 8%. Although sheep rearing and sheep products had high cultural prestige, it contributed less than 20% to the diet, and fish was only 8%. These staple food items were supplemented with whale, seal, and seabird. The percentages presented above should of course be taken with caution, and there will have been significant variety during different time periods and in different geographic locations in the islands, but it underlines the importance of dairy production for food security in traditional Faroese society. Trade with the outside world was, however, always an element of the Faroese economy. In return for fish and/or wool products, the Faroese imported grain, which was a staple in the Faroese diet, timber, which was always in shortage on the treeless islands, soapstone, and a number of luxury goods [63].

In many respects, Faroese society, from settlement and up until around 1800 can be seen as an example of a steady state economy. After settlement, the population is believed to have steadily increased up until around 3000–4000 people and to have remained stable for the next five centuries. The land, and what it produced, was divided and organized in units of value, which ultimately measured the material stocks and flows comprising Faroese society in *mørk*, *gyllin* and *skinn*. *Mørk*, *gyllin* and *skinn* were traditional measures of land area, weight, and value, and they continue to govern traditionally rooted food provisioning practices. One *mørk* is 16 *gyllin*, and one *gyllin* is 20 *skinn*. One *skinn* was the value of a sheepskin, and one *mørk* of land could sustain between 40 and 48 sheep. Half a *mørk* was the minimum requirement to sustain a family. As all land and resources were measured according to this system, the total number of *mørk* was the calculated and culturally negotiated carrying capacity of traditional Faroese society [64].

3.2. The Sustainable Roots of Current Faroese Land Use Management Practices

From a long-term socio-ecological perspective, it makes sense to divide Faroese history into three periods. The first period runs from the initial settlement of the islands around 300 AD and up until around 1300 AD, when the so-called Sheep Letter *Seyðabrævið*, a royal decree dating to 1298 AD, codified land management practices that came to dominate and regulate Faroese society during the following centuries and largely into the modern period. The third period is the period of modernization setting off around 1800 and during which Faroese society and economy underwent fundamental changes, going from an agrarian regime to an industrial regime.

It is uncertain when the Faroes were first settled and by whom, but archaeological evidence dates settlement back to around 300 AD. During the 8th and 9th centuries, historical records document the arrival of Norse migrants who brought with them their agricultural and cultural traditions. The first settlement period indicates a larger reliance on the hunting of seals, whales, seabirds, while the grazing lands were used as a common-pool resource to manage herds of sheep, cattle, and pigs [65,66]. Around 1300, there is evidence of a restructuring of land management and the establishment of the so-called infield/outfield system. Analyses of the historical ecology of the Faroes have shown that the Faroese adopted a distinct approach to economy and land management early on, investing in landesque capital that improved agricultural yields and largely avoided deterioration of grazing lands [67]. The infield/outfield model also governed sustainable catches of wild seabirds and fish, whale, and seal, thus creating a sustainable cultural landscape.

The Sheep Letter probably reinforced and formalized the control of resources by the landowner elite, allowing regulation of resource exploitation and enforcing certain restrictions on the access to common resources. These management practices were remarkably efficient in avoiding so-called "tragedies of the commons," and the management system must be defined as a successful commons governance regime [68,69]. To acknowledge this achievement should not be understood as any kind of glorification of traditional Faroese society as these management practices entailed economic and social inequalities. Social power, hierarchy, and access to resources was intimately associated with land ownership. However, although the system manifested inherent social differences between people, there is evidence that people are likely to have had adequate access to food regardless of their social status [69]. Everyone also had the right to cut peat, which was the only fuel source in the Faroes [63]. Nevertheless, there were also periods of starvation. The reliance on a variety of food sources and production systems (herding, hunting, gathering and cultivation) made Faroese society relatively resilient, but when one or more of these sources failed, and it co-occurred with insufficient imports of grain, people starved. One such period was reported for the years 1808 and 1809 when the grain harvest was poor, fish catches were limited, and there were no pilot whale catches for a period of many years.

3.3. From an Agrarian to an Industrial Socio-Metabolic Regime

In 1801 the population had reached 5000 people and systematic efforts to change the traditional production system were pushed by the colonial authorities in order to intensify and increase production. The introduction of potato cultivation (which eventually replaced barley cultivation and the practice of *reinavelting*), the appropriation of tracts of the outfields for cultivation, and the systematic attempts to establish an export-oriented fishing industry were colonial projects, which were met with considerable local protest and resistance [70,71]. With the changes occurring during the 19th century, with a considerable portion of the outfields taken into cultivation, the traditional balance between the infield and the outfield was disrupted. The new cultivated plots were the so called *traðir* and the people who cultivated them emerged as a new social category of people, *traðarmenn* (men of the cultivated plot), formerly landless people, who were now able to feed themselves. This social category did not have access to the outfield grazing areas and other land-based resources, but fishing was open-access and everyone also had rights to whale meat. The cow was still the crucial element in food security, and one cow per family or one cow between two families, supplemented with fishing and potato cultivation, provided the required caloric base for poor families. The *traðir* may be seen as a form of urban gardening developing during the 19th century and as a source of resilience for long-term urban food security [72,73].

Although, as has already been stressed, this traditional land and resource management system is not considered part of the "real" formal economy, it continues to operate alongside the industrial system, and it continues to provide people with food and other services. Only two food provisioning practices in the Faroes have become fully industrialized and mechanized; fisheries and dairy production. The traditional form of fishing in the Faroes was *útróður*, which was carried out in wooden oar boats. Cod fishing, for instance, was typically carried out in wooden boats fitting eight rowers *áttamannafar*, and resources from the sea were common and open access [63]. Fisheries became the main industry in the Faroes during the 20th century, but the practice of *útróður*, that is, small-scale coastal fisheries, has continued, both as a commercial practice and as a household and community food provisioning practice. In a census of the Faroese population carried out in 2011, 28% of Faroese households were reported to have access to a boat [74]. There is little doubt that *útróður* and other non-commercial and informal modes of food provisioning and distribution contribute significantly to the Faroese diet, but making estimates is difficult, so it is not included in this analysis. However, with the commercialization and marketization of fisheries, direct access to fish has declined for some groups or sections of people in the Faroes. Paradoxically, although catch figures have increased dramatically during the past century, direct access to fish has been reduced.

While the industrial exploitation of the marine environment is largely oriented towards export, industrial agriculture is oriented towards supplying the local Faroese market. Dairy production is the only part of Faroese agriculture that has become fully commercialized and incorporated into the formal market economy. Dairy production in the Faroes was 148 L per capita in 2017 or 0.4 L per day per capita, corresponding well with daily recommended intake. The Faroes are therefore more or less self-sufficient in this respect, but production has become centralized with fewer and fewer producers and more mechanization, and increasingly dependent upon imported feed and fossil energy. From a biodiversity perspective, industrialization has entailed a replacement of endemic livestock breeds with imported breeds suited for industrial milk production. Endemic breeds were smaller and better adapted to the Faroese landscape [75], and contributed to the improvement of grazing pastures.

3.4. Quantifying Practices of Quiet Sustainability

The resource management practices and principles that have co-evolved from the human–nature interaction on the Faroes throughout the centuries have proven remarkably resilient. Allowing flexibility and building on intimate local knowledge, these community level management systems continue to benefit Faroese people today [69]. The practices, or habits, descending from this system are visible in the daily practices of quiet sustainability in the Faroes; the cultivation of potatoes and rhubarb in gardens or *traðir*, sheep rearing, fowling, and hunting. These are all practices that a large proportion of Faroese people engage in, some on a daily basis, others less frequently. More than 70% of the population have been reported to have "supplemented food source available" [74], indicating that a very large percentage of the population engage in self-provisioning food practices or at least benefit from them. It is outside the scope of this paper to estimate the total production of "quiet sustainability" practices in the Faroes. In the following, estimates are made for selected informal economic practices and results are summarized in Table 2.

Table 2. Estimated contribution of informal food provisioning practices. Figures refer to estimated average annual production during the past decades and do not refer to any specific year. Per capita calculations are based on a total population figure of 50,000 people.

Food Category	Total Amount [1]	Per Capita
Sheep	900 tons	18 kg
Potatoes	700 tons	14 kg
Sea bird	70 tons	1.4 kg
Whale meat	186 tons	3.6 kg
Whale blubber	167 tons	3.3 kg
Total	2023 tons	40.3 kg

[1] Sources to the figures are provided in the text.

3.4.1. Sheep Rearing

Sheep rearing in the Faroes is to a large extent still based on the principles codified in the Sheep Letter more than seven centuries ago. Sheep rearing is largely non-commercial and organized by community or kinship, and sheep meat is not exported but consumed locally. The most commonly quoted figures on sheep numbers in the Faroes is that there are 70,000 mother sheep, and that 50,000 sheep are slaughtered every year. There are historical sources indicating higher numbers of mother sheep in earlier periods. 18th and 19th century sources mention figures of 75,000, 96,000 and 100,000 mother sheep [48], but changes in the volume of production have not been dramatic. Traditionally, sheep were vulnerable to drastic climatic conditions, severe winters, or particularly devastating storms. While climatic conditions still affect the mortality rate of sheep in the outfield, other factors affecting mortality have been minimized. Use of medication and winter feeding has lowered mortality. The lowered mortality means that more sheep graze in the outfield, especially during the winter period, which in turn increases pressure on the grazing areas resulting in soil erosion and deteriorating quality of the pastures [76]. In summary, while production is perhaps the same or higher than in previous periods, it is increasingly dependent upon imported animal feed. In addition, as a result of the increasing pressure placed on the pastures, the bio-productive capacity of the land is eroded, undermining the potential for future sustainable pastoral food production. As has been shown in other cases of agricultural industrial intensification, the increase in production can entail negative sustainability consequences, both locally and in other territories [77]. The estimated yearly production of sheep meat is around 900 tons, corresponding roughly to around 18 kg per capita [78].

3.4.2. Cultivation (Potatoes)

Traditionally, the main crops cultivated in the Faroes were barley and swedes (brassica), but from the 19th century potatoes became the staple and more or less replaced other crops. It is difficult to assess how large formal and informal cultivation of potatoes is, but commercial potato production is limited. Many people keep their own potato fields in their gardens, for example, or in infield plots. A few farmers cultivate and sell potatoes, but locally produced potatoes cannot be produced at a lower cost than imported potatoes. It is estimated that around 700 tons of potatoes are cultivated every year, corresponding to around 20% of total potato consumption, while the rest is imported [78].

3.4.3. Fowling

Seabirds and seabird eggs were a significant supplement to the traditional Faroese diet, particularly on islands that had bird cliffs and were so-called birdplaces known as *fuglapláss* in Faroese. The species that were harvested were most commonly Atlantic puffin (*Fratercula arctica grabae*) and common guillemot (*Uria aalge*). However, numbers have declined drastically. It is believed that the numbers of guillemot on the island of Skúvoy were as many as two million in the 1950s. Today, it is estimated that only around 180,000 guillemot nest in all of the Faroe Islands. The reasons for the decline are debated, but local communities have, in some cases, significantly reduced or totally banned harvesting of some seabird species. The most commonly harvested seabird today in the Faroes is the northern fulmar (*Fulmarus glacialis*). Fulmar eggs are harvested on the bird cliffs on some islands, and this harvest is regulated through the traditional land management system. As the young fulmars leave the bird cliffs in autumn for the first time and are not yet able to fly, they can be more or less picked out of the sea from a boat. Since the young fulmars are at sea, they have entered the commons and the catch is not regulated. No reliable statistics are available, but an estimate of total seabird catch in 2007 (including fulmar, puffin, guillemot, northern gannet, and more) was approximately 140,000 birds [79]. If every bird provided on average half a kg of food, the total contribution would be 70 tons or 1.4 kg per capita.

3.4.4. Whaling

Whale meat has most likely been consumed in the Faroes since the time of settlement, and community organized hunting of pilot whales has continued on the Faroes till this day. The fact that whale drives and distribution of whale catch is mentioned in the Sheep Letter indicates that the practice of pilot whale hunting or *grindadráp* goes back to at least the 14th century. Historical documentation and statistics of *grindadráp* catches go back to 1584, making it one of the best documented hunting practices in the world. The whale species hunted by the Faroese is the long-finned pilot whale (*Globicephala melas*). When a pod is spotted close enough to the coast, the whales are driven ashore and killed on the beaches. Pilot whales are not considered a threatened species by the IUCN (International Union for Conservation of Nature), but because of environmental and animal rights concerns, the practice of *grindadráp* has been highly controversial since the mid-1980s. In spite of this, the Faroese have so far continued the food provisioning practice of *grindadráp*. The size and distribution of a whale catch is measured in the traditional unit of *skinn*, and during the past two decades, the yearly average size of the whale catch has been approximately 4900 *skinn*. Using the *skinn* value of 38 kg for meat and 34 kg for blubber proposed by Bloch and Zahariassen [80], this can be calculated into an average annual contribution of 186 tons of whale meat and 167 tons of blubber.

4. Discussion

Even if the figures listed in Table 2 represent only a part of alternative local food provisioning practices, their contribution is significant. Adding together the sources of meat (sheep, pilot whale meat, and sea bird), the estimated annual amount of meat per person is 23 kg, corresponding to the world average annual meat consumption per person in 1961 [81]. Globally, meat consumption has surged, particularly in the more affluent regions of the world, and reached 43 kg per person in 2014. Current levels of meat consumption in the Faroes are very high, but returning to a local and more marine-based diet would bring both health and environmental benefits [82]. At the same time, local consumption of fish has probably declined and has to a large degree been replaced with imported meat. Considering the nutritional value of fish and the declining access to this local resource, it is mind provoking to reflect on that fact that if every Faroese inhabitant was provided with half a kilo of fish per day every day of the year, this amount would still only make out little more than 1% of what the total Faroese industrial fisheries catch. From a human health perspective as well as from a sustainability perspective, the consumption of locally caught fish should be encouraged. Here the framework of quiet sustainability can guide policy initiatives to re-evaluate and support traditional and alternative principles of resource distribution, such as informal and traditional food networks and forms of sharing, rather than continuing the process of increased marketization of local (marine) resources.

While the contribution of meat and fat is significant, the food items listed in Table 2 provide only a few percent of the necessary caloric requirements of the Faroese population, to say nothing of modern dietary preferences for food items exotic to the Faroes such as fruits and vegetables. The results in Table 2 also show that although potato production is relatively large (around 20% of total consumption), the Faroese agricultural landscape is almost exclusively used for meat and dairy production and very little space is dedicated to cultivation of food crops for direct human consumption. This pattern reflects the traditional land use described in the previous sections, where imported grain was an integral element in the traditional Faroese economy and diet, supplemented with local grain and brassica production. While local meat and dairy production has remained relatively stable into modern times, cultivation of food crops for human consumption has probably decreased. Many people still keep a potato plot, but recently there have also been attempts, both commercial and non-commercial, to introduce new crops and cultivation practices and to reintroduce traditional practices in order to increase local production of vegetables and grains. New initiatives more in line with mainstream global sustainability discourses are also emerging. For instance, urban gardens of a more metropolitan appearance than the common potato and rhubarb gardens are popping up, and locally produced food is increasingly promoted as sustainable, healthy, and of a higher quality than imported food. Here, the Faroese case can be seen in comparison to another island study of dietary change and quiet sustainability practices. In their study on the Greek island of Samothraki, Petridis and Huber [83] (p. 263) propose to reinforce the sustainable elements of traditional practices by "associating them with values that find resonance within the community, such as health, localness, and quality." In the Faroese case this strategy has been successful, at least to some extent. One particularly interesting example is the member group called *Veltan*, an initiative on the Faroese island of Sandoy, where a group of community members have organized themselves around the ambition to cultivate and grow vegetables, and also to preserve and build new knowledge. *Veltan* members produce food for their own household, and production is also commercial aiming to provide the Faroese market with local produce. Some of the recent initiatives can be seen as elements of purposive transitioning and of enhancing resilience and local production, but not necessarily with ecological sustainability as a primary goal. As in Samothraki, the desire for healthy, local, "organic" food may be a promising avenue for sustainability transitions of the food and land management system.

Another aspect of traditional food production, or quiet sustainability practices, which becomes evident in the analysis, is the fact that production has remained relatively stable during the past century even if population grew more than three-fold. The number of sheep has remained relatively stable, as have whale catches. Catches of sea bird have probably decreased, but this is mostly a result of the dramatic global decline in seabird. This characteristic of agricultural food provisioning practices in the Faroes may be contrasted with the changes occurring in the exploitation of the marine environment in the export-oriented industrial fisheries (and aquaculture), where production has increased dramatically, both in absolute numbers and per capita. In the Faroese case, two distinct spheres of social metabolism are arguably discernible in the differences between industrial and export-oriented production, and food provisioning practices that are oriented towards local production and distribution. Moreover, these distinct modes of social metabolism are producing very different cultural landscapes. The industrial metabolism of the Faroes consists of large material and energy flows, and further investments in industrial capital stocks, i.e., infrastructure, serve to reinforce a process of increasing metabolism that cannot be considered viable, at least not in a long-term perspective, and neither does it comply with the official sustainability goals of the Faroese Government. (The Faroese government has signed the Paris agreement and the Faroese parliament also in 2009 unanimously voted for passing a resolution to reduce greenhouse gas emissions by at least 20% relative to the 2005 emissions level in the decade between 2010 and 2020. In spite of these intentions, greenhouse gas emissions have increased by almost 10% relative to the 2005 emissions level.) In other words, maintaining this industrial landscape requires an ongoing and unsustainable flow of resources.

In contrast, traditional social metabolism in the Faroes produced a sustainable, diverse, and bio-productive landscape. The traditional Faroese land and resource management system presented in the previous section enhanced the bio-productive potential and capacity of the land to continually provide vital ecosystem services. This success was partly based on the ongoing investment in appropriate capital stocks including so-called landesque capital. The concept of landesque capital has been developed within the field of historical political ecology and may be understood as a specific form of capital stock, i.e., "enduring, non-alienable anthropogenic modifications of landscapes that increase physical productivity per unit of space" [84]. It enables an analytical discussion and separation between two forms and strategies of growth, namely growth as a result of net increase of in-situ bio-physical growth, photosynthesis for instance, and growth as a result of resource appropriation from other systems. As the term of landesque capital enables analysis of this dimension of human-nature interaction, it is useful for investigating the long-term sustainability and productivity of land management systems, both in the past and in the future.

Various forms of landesque capital associated with the traditional land management system are still visible in the Faroese landscape. The stone walls, which marked the border between the infield and the outfield, are one example. Another typical form of landesque capital are the agricultural terraces, *bríkar* in Faroese, on the steep slopes of the infield. Reducing the steepness of the land made them easier to work and prevented soil erosion. A less visible form of landesque capital is the improved quality of soil and pastures through cultivation and grazing practices. All these forms of landesque capital required considerable and continuous investments of labor, as well as intimate knowledge of the environment. The Faroese landscape has been intensively exploited for close to two millennia, even the least accessible cliffs being used for grazing. And yet, most of the ecosystem services available to the first settlers were sustained or enhanced through the centuries and well into the twentieth century [67,69]. Even the biodiversity of the Faroese landscape may be considered a form of landesque capital, the ecosystem co-evolving with people to produce the Faroese cultural landscape. In this sense, the high levels of biodiversity and productivity of the traditional Faroese landscape should be seen as a result of human activity, not as something remaining in spite of it. Policy attempts at increasing food production or enhancing biodiversity that are not attentive to this crucial role of culture in processes of homogenization and diversification of ecosystems are bound to fail their goal.

The concept of landesque capital helps to illuminate the distinctions between different forms of capital stocks, and the implications of these for (island) sustainability and resilience. Material stocks, or capital, can materialize as commercial artefacts, such as disposable consumer goods, or as improved soil, depending on the cultural organization of social metabolism. The implications for sustainability and the bio-productive capacity of the natural system are compelling. While certain forms of industrial stocks, such as the industrial fishing fleet in this case, obviously serves to increase production, it also relies on very large volumes of external resource flows. When it comes to the fossil energy required to sustain Faroese industrial fisheries, the access to this energy is ultimately dependent upon global market relations or monetary relations. Changes in these relations are largely out of local control and may cause capital stock in the form of an industrial fishing vessel to become immediately unproductive. In comparison, investments in landesque capital, for instance in improved pastures and soil, is less vulnerable to external factors. As Widgren [85] (p. 61) puts it, landesque capital has a tendency to survive in different social contexts because "unlike monetary capital, which is fluid in space but fixed in time, landesque capital is fixed in space, but 'fluid' in time." This makes landesque capital hard to appropriate in comparison to capital and resources that can be transported away. The formation of capital stocks as landesque capital or as some other form of stock has a lot to do then with how the social metabolism of a society is related to the outside world [9,86]. Interestingly, Petridis and Huber [83] (p. 282) in their discussion of quiet sustainability on the island of Samothraki direct attention to this potential association between landesque capital, dietary changes, and sustainability transformations. They propose that a reevaluation of older farming systems, such as agricultural terraces, and its association with changing dietary demands for local produce can work to increase both ecological and human health. A reevaluation of these older farming systems would, however, have to entail a reevaluation of the time required to maintain such forms of landesque capital, and more generally of maintaining biocultural landscapes. The issue of time and sustainability is also mentioned by Smith and Jelicka [21] in their discussion on policy changes to promote quiet sustainability. They suggest that more radical steps towards enhancing quiet sustainability would require consideration of economies of time within households and communities, for example, the length of the working week. The fundamental question of how people spend their time, how monetary value is attributed to different modes of time use, and how that relates to both ecological and human well-being is generally overlooked in mainstream sustainability discourse.

5. Conclusions

The practices here defined as practices of quiet sustainability are rooted in a traditional land management system that was ecologically sustainable out of necessity. As they have coevolved in a society that has been increasingly connected to the global market economy and dominated and colonized by industrial social metabolism, they are also changing. Food provisioning practices such as sheep, livestock, and poultry rearing increasingly rely on imported animal feed, and the production of local feed, mostly straw fodder, is increasingly mechanized. The question of how a sustainable local food system can be organized in an open economy context requires a deepened and transdisciplinary understanding of how production is coupled to local ecosystems as well as to foreign ecosystems, and how this pertains to issues of resiliency, vulnerability, and sustainability. Chertow et al. [12] have explored these relevant themes in a discussion of four island societies that have consciously attempted to reconnect vital aspects of their economies to their natural systems. It is, however, crucially important that such processes are guided by adequate analytical insight into the complexity of sustainable coevolution as both a bio-physical process and a cultural process. While a recoupling of the natural system is always intended to enhance self-sufficiency and resilience, such efforts are not necessarily sustainable in the long term. As an example, efforts at reconnecting Faroese dairy production to the local natural system rather than to rely on imported feed could potentially entail a radical transformation of the Faroese cultural landscape into an agro-industrial landscape. Such transformation towards greater intensification and industrialization of agriculture would increase local production of feed, but considering the very limited land area suitable for mechanized cultivation, it would also contribute to the erosion and abandonment of what Tello et al. [87] (p. 52) have called "true biocultural landscapes," entailing a loss of crops, breeds, knowledge, practices, and people.

In conclusion, distinct modes of social metabolism are discernible in the Faroes. An unsustainable industrial metabolism, governed by ideologies of growth, is colonizing and homogenizing the Faroese landscape. Another mode, which is rooted in the traditional land management system involves a direct metabolic connection between people and their landscape through food provisioning practices such as hunting and gathering, cultivation, and animal husbandry. It has been asserted here that these practices can be conceptualized as practices of quiet sustainability and that they should be acknowledged, guided, protected, and promoted, and in a concrete sense be given space in physical and land use planning, both in rural and urban settings. Rather than focusing too narrowly on sustainability transitions that are difficult to overcome and require large restructuring of society and technological infrastructure, as well as behavioral change, practices of quiet sustainability are already in place and deeply meaningful for people to engage in [88]. In Faroese policy discourse, traditional and alternative food-provisioning practices are perceived at best as supplementary to the "real economy," but their dietary contribution has been shown to be significant in quantitative terms, and a considerable expansion of local food production could arguably be achieved within a quiet sustainability framework, particularly regarding fisheries and cultivation for direct human consumption. Such a trajectory would contribute to both human and ecological health, and would enhance biocultural diversity, resilience, food security, and food sovereignty. It would simultaneously expand the alternatives to the growth-oriented industrial production strategies currently dominating the islands. Further research into diverse and alternative food provisioning practices in the Faroes could provide important insight into how alternative modes and spheres of social metabolism are organized, maintained, and culturally negotiated, and how they can be expanded in order to reduce the social metabolism of human society without undermining human well-being. Thinking with this specific Faroese case and other cases of island metabolism(s), and through the metaphor of islanding, might also provide more general insight into how sustainable socio-metabolic spheres can be protected and enhanced in a context of globalization and financial speculation in the struggle of forging less resource-intensive paths into the future.

Funding: This research received no external funding.

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

References

1. Krausmann, F.; Gingrich, S.; Eisenmenger, N.; Erb, K.-H.; Haberl, H.; Fischer-Kowalski, M. Growth in global material use, GDP and population during the 20th century. *Ecol. Econ.* **2009**, *68*, 2696–2705. [CrossRef]
2. Steffen, W.; Broadgate, W.; Deutsch, L.; Gaffney, O.; Ludwig, C. The trajectory of the Anthropocene: The Great Acceleration. *Anthr. Rev.* **2015**, *2*, 81–98. [CrossRef]
3. Schandl, H.; Fischer-Kowalski, M.; West, J.; Giljum, S.; Dittrich, M.; Eisenmerger, N.; Geschke, A.; Lieber, M.; Wieland, H.; Schaffartzik, A.; et al. Global Material Flows and Resource Productivity: Forty Years of Evidence. *J. Ind. Ecol.* **2018**, *22*, 827–838. [CrossRef]
4. Steffen, W.; Richardson, K.; Rockström, J.; Cornell, S.E.; Fetzer, I.; Bennett, E.M.; Biggs, R.; Carpenter, S.R.; de Vries, W.; Wit, C.A.; et al. Planetary boundaries: Guiding human development on a changing planet. *Science* **2015**, *347*. [CrossRef]
5. McNeill, J.R. *Something New under the Sun. An Environmental History of the Twentieth Century*; Penguin Books: London, UK, 2000.
6. O'Neill, D.W.; Fanning, A.L.; Lamb, W.F.; Steinberger, J.K. A good life for all within planetary boundaries. *Nat. Sustain.* **2018**, *1*, 88–95. [CrossRef]
7. Gillis, J.R. *Islands of the Mind. How the Human Imagination Created the Atlantic World*; Palgrave Macmillan: London, UK, 2004.
8. Clark, E. The ballad dance of the Faroese: Island biocultural geography in an age of globalization. *Tijdschr. Econ. Soc. Geogr.* **2004**, *95*, 284–297. [CrossRef]
9. Clark, E.; Tsai, H.-M. Islands: Ecologically unequal exchange and landesque capital. In *Ecology and Power, Struggles over Land and Material Resources in the Past, Present and Future*; Hornborg, A., Clark, B., Hermele, K., Eds.; Routledge: New York, NY, USA, 2012; pp. 52–67.
10. Deschenes, P.J.; Chertow, M. An island approach to industrial ecology: Towards sustainability in the island context. *J. Environ. Plan. Manag.* **2004**, *47*, 201–217. [CrossRef]
11. Krausmann, F.; Richter, R.; Eisenmerger, N. Resource Use in Small Island States: Material Flows in Iceland and Trinidad and Tobago, 1961–2008. *J. Ind. Ecol.* **2014**, *18*, 294–305. [CrossRef]
12. Chertow, M.; Fugate, E.; Ashton, W. The intimacy of human-nature interactions in islands. In *Long-Term Socio-Ecological Research. Studies in Society-Nature Interactions across Spatial and Temporal Scales*; Singh, S.J., Haberl, H., Chertow, M., Mirtl, M., Schmid, M., Eds.; Springer: Dordrecht, The Netherland, 2013; Volume 2, pp. 315–338.
13. Bogadóttir, R. Blue Growth and its discontents in the Faroe Islands: An island perspective on Blue (De) Growth, sustainability, and environmental justice. *Sustain. Sci.* **2019**. [CrossRef]
14. Gowdy, J.M.; McDaniel, C.N. The physical destruction of Nauru: An example of weak sustainability. *Land Econ.* **1999**, *75*, 333–338. [CrossRef]
15. Hornborg, A. Ecology as semiotics: Outlines of a contextualist paradigm for human ecology. In *Nature and Society Anthropological Perspectives*; Descola, P., Palsson, G., Eds.; Routledge: London, UK, 1996.
16. Rozzi, R. Biocultural Ethics: From Biocultural Homogenization Toward Biocultural Conservation. In *Linking Ecology and Ethics for a Changing World: Values, Philosophy, and Action*; Rozzi, R., Pickett, S., Palmer, C., Armesto, J.J., Callicot, J.B., Eds.; Springer: New York, NY, USA, 2013; pp. 9–32.
17. Sánchez-Bayo, F.; Wyckhuys, K.A.G. Worldwide decline of the entomofauna: A review of its drivers. *Biol. Conserv.* **2019**, *232*, 8–27. [CrossRef]
18. Hegmon, M. *The Give and Take of Sustainability: Archaeological and Anthropological Perspectives on Tradeoffs*; Cambridge University Press: New York, NY, USA, 2017.
19. McMillen, H.L.; Ticktin, T.; Friedlander, A.; Jupiter, S.D.; Thaman, R.; Campbell, J. Samll islands, valuable insights: Systems of customary resource use and resilience to climate change in the Pacific. *Ecol. Soc.* **2015**, *19*, 44. [CrossRef]

20. Gadgil, M.; Berkes, F.; Folke, C. Indigenous Knowledge for Biodiversity Conservation. *Ambio* **1993**, *22*, 151–156.
21. Smith, J.; Jehlicka, P. Quiet sustainability: Fertile lessons from Europe's productive gardeners. *J. Rural Stud.* **2013**, *32*, 148–157. [CrossRef]
22. Gibson-Graham, J.K. Diverse economies: Performative practices for 'other worlds'. *Prog. Hum. Geogr.* **2008**, *32*, 613–632. [CrossRef]
23. Trawick, P.; Hornborg, A. Revisiting the Image of Limited Good: On Sustainability, Thermodynamics, and the Illusion of Creating Wealth. *Curr. Anthropol.* **2015**, *56*, 1–27. [CrossRef]
24. Blakie, P.; Brookfield, H. *Land Degradation and Society*; Routledge: New York, NY, USA, 1987.
25. Widgren, M.; Håkansson, N.T. Landesque Capital: What is the Concept Good For? In *Landesque Capital. The Historical Ecology of Enduring Landscape Modifications*; Håkansson, N.T., Widgren, M., Eds.; Left Coast Press: Walnut Creek, CA, USA, 2014; pp. 9–30.
26. Håkansson, N.T.; Widgren, M. (Eds.) *Landesque Capital. The Historical Ecology of Enduring Landscape Modifications*; Left Coast Press: Walnut Creek, CA, USA, 2014.
27. Winiwarter, V.; Schmid, M.; Haberl, H.; Singh, S.J. Why Legacies Matter: Merits of a Long-Term Perspective. In *Social Ecology, Society-Nature Interaction across Space and Time*; Haberl, H., Fischer-Kowalski, M., Krausmann, F., Winiwarter, V., Eds.; Springer International: Cham, Switzerland, 2016; pp. 149–168.
28. Gingrich, S.; Schmid, M.; Dirnbock, T.; Dullinger, I.; Garstenauer, R.; Gaube, V.; Haberl, H.; Kainz, M.; Kreiner, D.; Mayer, R.; et al. Long-Term Socio-Ecological Research in Practice: Lessons from the Inter- and Transdisciplinary Research in the Austrian Eisenwurzen. *Sustainability* **2016**, *8*, 743. [CrossRef]
29. Balée, W. *Advances in Historical Ecology*; Columbia University Press: New York, NY, USA, 1998.
30. Haberl, H.; Winiwarter, V.; Andersson, K.; Ayres, R.U.; Boone, C.; Castillo, A.; Cunfer, G.; Fischer-Kowalski, M.; Freudenburg, W.R.; Furman, E.; et al. From LTER to LTSER: Conceptualizing the Socioeconomic Dimension of Long-Term Socioecological Research. *Ecol. Soc.* **2006**, *11*, 13. [CrossRef]
31. González de Molina, M.; Toledo, V.M. *The Social Metabolism: A Socio-Ecological Theory of Historical Change*; Springer: London, UK, 2014.
32. Haberl, H.; Wiedenhofer, D.; Erb, K.-H.; Görg, C.; Krausmann, F. The Material Stock-Flow-Service Nexus: A New Approach for Tackling the Decoupling Conundrum. *Sustainability* **2017**, *9*, 1049. [CrossRef]
33. Weisz, H.; Suh, S.; Graedel, T.E. Industrial Ecology: The role of manufactured capital in sustainability. *Proc. Natl. Sci. Acad. USA* **2015**, *112*, 6260–6264. [CrossRef]
34. Lin, C.; Liu, G.; Müller, D.B. Characterizing the role of built environment stocks in human development and emission growth. *Resour. Conserv. Recycl.* **2017**, *123*, 67–72. [CrossRef]
35. Hornborg, A.; McNeill, J.R.; Martinez-Alier, J. *Rethinking Environmental History: World-System History and Global Environmental Change*; Altamira Press: Plymouth, UK, 2007.
36. Widgren, M. Slaves: Inequaliy and sustainable agriculture in pre-colonial West Africa. In *Ecology and Power: Struggles over Land and Material Resources in the Past, Present, and Future*; Hornborg, A., Clark, B., Hermele, K., Eds.; Routledge: London, UK, 2012; pp. 97–107.
37. Piketty, T. *Capital in the Twenty-First Century*; Harvard University Press: Cambridge, MA, USA, 2014.
38. Hickel, J. Is global inequality getting better or worse? A critique of the World Bank's convergence narrative. *Third World Q.* **2017**, *38*, 2208–2222. [CrossRef]
39. Baldacchino, G.; Clark, E. Guest editorial introduction: Islanding cultural geographies. *Cult. Geogr.* **2013**, *20*, 129–134. [CrossRef]
40. Hornborg, A. How to turn an ocean liner: A proposal for voluntary degrowth by redesigning money for sustainability, justice, and resilience. *J. Political Ecol.* **2017**, *24*, 623–632. [CrossRef]
41. Fischer-Kowalski, M. Analyzing sustainability transitions as a shift between socio-metabolic regimes. *Environ. Innov. Soc. Transit.* **2011**, *1*, 152–159. [CrossRef]
42. Haberl, H.; Fischer-Kowalski, M.; Krausmann, F.; Martinez-Alier, J.; Winiwarter, V. A socio-metabolic transition towards sustainability? Challenges for another Great Transformation. *Sustain. Dev.* **2011**, *19*, 1–14. [CrossRef]
43. Graeber, D. *Debt the First FiveThousand Years*; Melville House: New York, NY, USA, 2011.
44. Wengrow, D.; Graeber, D. Farewell to the 'childhood of man': Ritual, seasonality, and the origins of inequality. *J. R. Anthropol. Inst.* **2015**, *21*, 597–619. [CrossRef]

45. House of Industry. 2019. Available online: https://www.industry.fo/international-edition/about-the-faroe-islands/economic-situation (accessed on 20 September 2019).
46. Fischer-Kowalski, M.; Weizs, H. Society as a hybrid between material and symbolic realms: Toward a theoretical framework of society-nature interaction. *Adv. Hum. Ecol.* **1999**, *8*, 215–251.
47. Fischer-Kowalski, M.; Haberl, H. Social metabolism: A metrics for biophysical growth and degrowth. In *Handbook of Ecological Economics*; Martinez-Alier, J., Muradian, R., Eds.; Edward Elgar: Cheltenham, UK, 2015; pp. 100–138.
48. Ministry of Trade (Vinnumálastýrið). *Álit um Landbúnaðarviðurskifti Føroya*; Appointed Committee under the Ministry of Trade: Tórshavn, Faroe Islands, 1997.
49. Jákupstovu, H. *Fiskiskapur við Førpyar í 100 ár*; Fiskirannsóknarstovan: Tórshavn, Faroe Islands, 2004.
50. SFI2019. Available online: https://statbank.hagstova.fo/pxweb/en/H2/H2__UH__UH01/uh_uthbolk.px/ (accessed on 18 November 2019).
51. Eurostat. 2019. Available online: https://ec.europa.eu/eurostat/statistics-explained/index.php/Physical_imports_and_exports (accessed on 23 September 2019).
52. Guillen, J.; Cheilari, A.; Damalas, D.; Barbas, T. Oil for Fish: An Energy Return on Investment Analysis of Selected European Union Fishing Fleets. *J. Ind. Ecol.* **2016**, *20*, 145–153. [CrossRef]
53. Environment Agency of the Faroe Islands. 2019. Available online: http://www.us.fo/Default.aspx?ID=14068 (accessed on 28 September 2019).
54. Environment Agency of the Faroe Islands. 2019. Available online: http://umhvorvisstovan.fo/Default.aspx?ID=14086 (accessed on 23 September 2019).
55. Environment Agency of the Faroe Islands. 2019. Available online: http://www.us.fo/Default.aspx?ID=14217 (accessed on 18 November 2019).
56. Eurostat. 2019. Available online: https://ec.europa.eu/eurostat/statistics-explained/index.php?title=File:Municipal_waste_landfilled,_incinerated,_recycled_and_composted,_EU-28,_1995-2017.png (accessed on 23 September 2019).
57. Guttesen, R. Animal production and climate variation in the Faeroe Islands in the 19th century. *Geogr. Tidsskr. Dan. J. Geogr.* **2003**, *103*, 81–91. [CrossRef]
58. Christiansen, S. Faroese Spade-Cultivation, Reinavelta, Its Practice, Function, and History. *Fróðskaparrit* **1989**, *38–39*, 143–152.
59. Guttesen, R. Veðurlag, framleiðsla, og fólkatal í 1800-talinum og fyrr. In *Brot úr Føroya Søgu*; Nolsøe, L., Ed.; Fróðskapur: Tórshavn, Faroe Islands, 2010; pp. 43–65.
60. Guttesen, R. Commander Loebner's tables and vital necessities in the Faeroe Islands in 1813. *Geogr. Tidsskr.* **1999**, *1*, 75–80.
61. Guttesen, R. Plant production on a Faroese farm 1813–1892, related to climate fluctuations. *Geogr. Tidsskr. Dan. J. Geogr.* **2001**, *101*, 67–76. [CrossRef]
62. Guttesen, R. Food production, climate and population in the Faeroe Islands 1584–1652. *Geogr. Tidsskr. Dan. J. Geogr.* **2004**, *104*, 35–46. [CrossRef]
63. Thorsteinsson, A. Land Divisions, Land Rights, and Land Ownership in the Faeroe Islands. In *Nordic Landscapes: Region and Belonging on the Northern Edge of Europe*; Jones, M., Olwig, K.R., Eds.; University of Minnesota Press: Minneapolis, MN, USA, 2008; pp. 77–105.
64. Thorsteinsson, A. Merkur, alin og gyllin—Gomul føroysk virðismeting. *Frøði* **1993**, *1*, 4–9.
65. Church, M.J.; Arge, S.V.; Brewington, S.; McGovern, T.H.; Woollett, J.M.; Perdikaris, S.; Lawson, I.T.; Cook, G.T.; Amundsen, C.; Harrison, R.; et al. Puffins, Pigs, Cod and Barley: Paleoeconomy at Undir Junkarinsfløtti, Sandoy, Faroe Islands. *Environ. Archaeol.* **2005**, *10*, 179–197. [CrossRef]
66. Mahler, D.L. The Stratigraphical Cultural Landscape. In *Outland Use in Preindustrial Europe*; Anderson, H., Ersgård, L., Svensson, E., Eds.; Lund Studies in Medieval Archaeology 20; Institute of Archaeology, University of Lund: Lund, Sweden, 1998; pp. 49–62.
67. Lawson, I.T.; Church, M.J.; McGovern, T.H.; Arge, S.V.; Wollett, J.; Edwards, K.J.; Gathorne-Hardy, J.; Dugmore, A.J.; Cook, G.; Mairs, K.-A.; et al. Historical Ecology on Sandoy, Faroe Islands: Palaeoenvironmental and Archaeological Perspectives. *Hum. Ecol.* **2005**, *33*, 651–684. [CrossRef]
68. Ostrom, E. *Governing the Commons. The Evolution of Institutions for Collective Action*; Cambridge University Press: Cambridge, UK, 1990.

69. Brewington, S. Tradeoffs and Human Well-Being: Achieving Sustainability in the Faroe Islands. In *The Give and Take of Sustainability. Archaeological and Anthropological Perspectives on Tradeoffs*; Hegmon, M., Ed.; Cambridge University Press: New York, NY, USA, 2017; pp. 222–243.
70. Isholm, E. Eplaskipið 1840—Tá tað almenna fór at keypa eplir. *Frøði* **2014**, *3*, 26–31.
71. Isholm, E. Fiskivinna sum Broytingaramboð hjá Amtmanninum. Ph.D. Thesis, Fróðskaparsetur Føroya, Tórshavn, Faroe Islands, 8 February 2019.
72. Barthel, S.; Isendahl, C. Urban gardens, agriculture, and water management: Sources of resilience for long-term food security in cities. *Ecol. Econ.* **2013**, *86*, 224–234. [CrossRef]
73. Lin, B.B.; Chappell, M.J.; Vandermeer, J.; Smith, G.; Quintero, E.; Benzner-Kerr, R.; Griffith, D.M.; Ketcham, S.; Latta, S.C.; McMichael, P.; et al. Effects of industrial agriculture on climate change and the mitigation potential of small-scale agro-ecological farms. *CAB Rev. Perspect. Agric. Vet. Sci. Nutr. Nat. Resour.* **2011**, *6*, 1–18. [CrossRef]
74. SFI2019. Available online: https://statbank.hagstova.fo/pxweb/en/H2/H2__MT__MT08__MT0802/MT306.px/ (accessed on 18 November 2019).
75. Austrheim, G.; Asheim, L.J.; Bjarnason, G.; Feilberg, J.; Fosaa, A.M.; Holand, Ø.; Høegh, K.; Jonsdottir, I.S.; Magnússon, B.; Mortensen, L.E.; et al. Sheep grazing in the North Atlantic region: A long term perspective on management, resource economy and ecology. *Rapport Zoologisk Serie* **2008**, *3*, 86.
76. Ross, L.C.; Austrheim, G.; Asheim, L.J.; Bjarnason, G.; Feilberg, J.; Fosaa, A.M.; Hester, A.J.; Holand, Ø.; Jónsdóttir, I.S.; Mortensen, L.E.; et al. Sheep grazing in the North Atlantic region: A long-term perspective on environmental sustainability. *Ambio* **2016**, *45*, 551–566. [CrossRef] [PubMed]
77. González de Molina, M.; Soto Fernández, D.; Infante-Amate, J.; Aguilera, E.; Vila Traver, J.; Guzmán, G.I. Decoupling Food from Land: The Evolution of Spanish Agriculture from 1960 to 2010. *Sustainability* **2017**, *9*, 2348. [CrossRef]
78. Randbøll Wolff, M. Belysning af de Konkurrencemæssige Vilkår, Som Færøsk Landbrug er Konfronteret Med fra Importerede Landbrugs-og Fødevarer, Særlig fra Overføringsstøttet Produktion i EU og EØS. En Rapport Udarbejdet på Opdrag af Búnaðarstovan 2016. Available online: http://www.bst.fo/Admin/Public/DWSDownload.aspx?File=%2fFiles%2fFiler%2fBunadarstovan%2fBelysning+af+de+konkurrencem%c3%a6ssige+vilk%c3%a5r+for+f%c3%a6r%c3%b8sk+landbrug_M_R_Wolff_juni+2016.pdf (accessed on 18 November 2019).
79. Olsen, B.; Havstovan, Faroe Marine Research Institute, Tórshavn, Faroe Islands. Personal communication, 11 October 2019.
80. Bloch, D.; Zachariassen, M. The "skinn" values of Faroe Islands pilot whales: An evaluation and corrective proposal. *JN Atl. Stud.* **1989**, *1*, 38–56.
81. Sans, P.; Combris, P. World meat consumption patterns: An overview of the last fifty years (1961–2011). *Meat Sci.* **2015**, *109*, 106–111. [CrossRef]
82. Westhoek, H.; Lesschen, J.P.; Rood, T.; Wagner, S.; De Marco, A.; Murphy-Bokern, D.; Leip, A.; Van Grinsven, H.; Sutton, M.A.; Oenema, O. Food choices, health and environment: Effects of cutting Europe's meat and dairy intake. *Glob. Environ. Chang.* **2014**, *26*, 196–205. [CrossRef]
83. Petridis, P.; Huber, J. A Socio-metabolic Transition of Diets on a Greek Island: Evidence of "Quiet Sustainability". In *Socio-Metabolic Perspectives on the Sustainability of Local Food Systems*; Frankova, E., Haas, W., Singh, S.J., Eds.; Springer International Publishing: Cham, Switzerland, 2017; Volume 7, pp. 263–289.
84. Hornborg, A.; Eriksen, L.; Bogadóttir, R. Correlating Landesque Capital and Ethno-Political Integration in Pre-Columbian South America. In *Landesque Capital: The Historical Ecology of Enduring Landscape Modifications*; Håkansson, N.T., Widgren, M., Eds.; Left Coast Press: Walnut Creek, CA, USA, 2014; pp. 215–231.
85. Widgren, M. Precolonial Landesque Capital: A Global Perspective. In *Rethinking Environmental History: World-System History and Global Environmental Change*; Hornborg, A., McNeill, J.R., Martinez-Alier, J., Eds.; Rowman Altamira: Lanham, MD, USA, 2007; pp. 61–77.
86. Bayliss-Smith, T. From Taro Garden to Golf Course? Alternative Futures for Agricultural Capital in the Pacific Islands. In *Environment and Development in the Pacific Islands*; Burt, B., Clerk, C., Eds.; National Centre for Development Studies, Research School of Pacific and Asian Studies, the Australian National University: Canberra, Australia, 1997; pp. 143–170.

87. Tello, E.; González de Molina, M. Methodological Challenges and General Criteria for Assessing and Designing Local Sustainable Agri-Food Systems: A Socio-Ecological Approach at Landscape Level. In *Socio-Metabolic Perspectives on the Sustainability of Local Food Systems*; Frankova, E., Haas, W., Singh, S.J., Eds.; Springer International Publishing: Cham, Switzerland, 2017; Volume 7, pp. 27–67.
88. Bogadóttir, R.; Olsen, E.S. Making degrowth locally meaningful: The case of the Faroese grindadráp. *J. Political Ecol.* **2017**, *24*, 504–518. [CrossRef]

© 2020 by the author. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (http://creativecommons.org/licenses/by/4.0/).

MDPI
St. Alban-Anlage 66
4052 Basel
Switzerland
Tel. +41 61 683 77 34
Fax +41 61 302 89 18
www.mdpi.com

Sustainability Editorial Office
E-mail: sustainability@mdpi.com
www.mdpi.com/journal/sustainability

MDPI
St. Alban-Anlage 66
4052 Basel
Switzerland

Tel: +41 61 683 77 34
Fax: +41 61 302 89 18

www.mdpi.com

ISBN 978-3-0365-0937-2