Is Fiji's Metabolism Built for Resilience? A Socio-Metabolic Risk Perspective.

by

Bhargav Singh Thakur

A thesis

presented to the University of Waterloo

in fulfillment of the

thesis requirement for the degree of

Master of Environmental Studies

in

Sustainability Management

Waterloo, Ontario, Canada, 2025

Author’s Declaration

This thesis consists of material all of which I authored or co-authored: see Statement of Contributions included in the thesis. This is a true copy of the thesis, including any required final revisions, as accepted by my examiners.

I understand that my thesis may be made electronically available to the public.

Statement of Contributions

I am the sole author of Chapter 1, Chapter 2, Chapter 3 and Chapter 5 of this thesis. Chapter 4 is based on academic work and the paper that was co-authored with other academics.

Chapter 4 has been incorporated within a paper that has been submitted for publication. The paper is co-authored by my supervisor (Dr. Simron Singh) and co-supervisor (Dr. Michael Wood). Dr. Singh, Dr. Wood and I developed methodology, conceptualization, and visualization of results. I carried out the collection and formal analysis of the data, as well as writing. All co-authors contributed to reviewing and editing the manuscript. Revisions to the paper, based on reviewer feedback, have also been completed and submitted. Bibliographic citation:

> Thakur, B. S., Singh, S. J., Wood, M. O. (2025). "How prepared is Fiji to climate and geopolitical risks? Insights from a socio-metabolic risk (SMR) analysis." Submitted to the *Journal of Industrial Ecology.* Submission date: 3rd July 2025.

Abstract

Small Island Developing States (SIDS), despite contributing less than 1% of global greenhouse gas emissions, are among the most affected by the climate crisis. They face rising sea levels and climate-related economic losses averaging 2.1% of GDP, seven times the global average. This vulnerability is not limited to environmental exposure; it is further intensified by compounding factors such as a heavy reliance on external resources and limited material circularity. Most SIDS import over 60% of their food, and nearly all fossil fuels and construction materials, leaving them highly exposed to global supply chain disruptions and price fluctuations. To analyze this nexus of environmental and economic fragility, the Socio-Metabolic Risk (SMR) concept links a nation's resilience to its material metabolism, its patterns of resource extraction, trade, consumption, and waste. SMR assesses risk across three pillars: secure resource access, circular material use, and equitable distribution of services. While pioneering studies have validated SMR's utility, applications remain limited to single-year snapshots. This leaves a critical gap, as a static view cannot capture the path-dependent dynamics, material lock-ins, and potential tipping points that evolve over time. Addressing this gap, this thesis uses Fiji as a case study to ask: Has the country's material use from 2000 to 2022 mitigated or accumulated its SMR? To answer this, the study constructs the first multi-decadal (2000–2022), economy-wide material flow analysis (ew-MFA) mass balance account from a SMR lens, for a SIDS. Over two decades, Fiji underwent a profound metabolic transformation. Domestic biomass extraction, once the economy's cornerstone, fell by 42% (driven by a decline in the sugarcane industry), while biomass imports surged by 80%, eroding food self-sufficiency. Concurrently, imports of non-metallic minerals (e.g., cement, aggregates) increased more than fivefold (+436%), with surges for reconstruction following major cyclones like Cyclone Winston in 2016. Reliance on imported fossil fuels remained absolute, with total inflows growing by 26%. Fiji's overall import dependency climbed from 27% in 2000 to 46% in 2022. The analysis also shows a steady buildup of material assets, likely concentrated in hazard-prone coastal areas. This occurs within an overwhelmingly linear system, where material circularity is negligible and recycling practices are largely absent. The study concludes that Fiji's development path has intensified its SMR, creating a material lock-in marked by growing reliance on imports and limited progress toward circular resource use. This creates a vicious cycle where climate shocks destroy vulnerable stocks, driving further import-heavy reconstruction that deepens vulnerability. By operationalizing SMR with a longitudinal dataset, this research provides a robust empirical foundation for evidence-based policy.

The findings highlight the urgent need for interventions aligned with Fiji’s national development goals to strengthen the circular economy, accelerate the transition to renewable energy, promote local food systems, and enforce disaster-resilient 'build-back-better' standards. Ultimately, steering SIDS toward a more sustainable and resilient future requires a fundamental transformation of their resource use patterns.

Acknowledgements

I would like to express my heartfelt gratitude to my supervisors, Dr. Simron Jit Singh and Dr. Michael O. Wood, for their unwavering support, guidance, and encouragement throughout every stage of this thesis. Their mentorship has not only shaped the academic quality of this work but also provided invaluable personal support during challenging times. This journey would not have been possible without their understanding, trust, and commitment.

This study contributes to the project “Resilience to Climate Vulnerability and Environmental Risk” (RECOVER), part of the CLARE (Climate Adaptation & Resilience) program (Project link), co-funded by the UK’s Foreign, Commonwealth & Development Office (FCDO) and Canada’s International Development Research Centre (IDRC). I am also grateful to the University of Waterloo and the Faculty of Environment for providing the academic environment and resources that supported this research.

My thanks also go to RECOVER team members, Sateesh Kumar Pisini and Swetha Thammadi for their thoughtful engagement with my work and for offering valuable suggestions during its development.

A special thank-you goes to my mother, whose resilience, love, and sacrifices have been the backbone of this journey. While caring for my father’s medical needs and managing everything back home in India, she ensured I could remain focused on completing my studies.

I am also thankful to Jasleen, Gaurav, Kratika, Vardaan, Scotch, and Piku, for their constant motivation, unconditional love, encouragement, and honest feedback. Their presence and support have meant a great deal to me throughout this process.

To all who stood by me, offered their time, insights, or simply believed in me, thank you. Your support has made this thesis not only possible, but meaningful.

Dedication

To my father, whose quiet courage in recovery steadies my own; to my mother, whose unwavering care and selfless sacrifice made this journey possible; to Piku, my brave companion, whose unconditional love lives on in my memory; and to Scotch, whose gentle comfort continues to warm our family. To the people of Small Island Developing States, whose resilience in the face of adversity inspires this work.

This work is for you.

Table of Contents

List of Figures

List of Tables

List of Abbreviations

C&D. *Construction and Demolition*
DE. *Domestic Extraction*
DMC. *Domestic material consumption*
DMI. *Direct material inputs*
DPO. *Domestic processed outputs*
DRS. *Deposit-Return Schemes*
EoL. *End-of-life*
EPR. *Extended producer responsibility*
eUse. Energetic use
ew-MFA. *Economy-wide Material Flow Analysis*
FAO. *Food and Agricultural Organization*
GAS. *Gross additions to stocks*
GDP. *Gross Domestic Product*
GIS. *Geographical Information System*
INCr. *Input non-circularity rate*
IntOut. *Interim outputs*
IRENA. *International Renewable Energy Agency*
ISCr. *Input socio-economic cycling rate*

LOS. *Large ocean states*
MFA. *Material flows accounting*
MSA. *Material stocks accounting*
MSW. Municipal solid waste
mUse. *Material use*
MVI. *Multidimensional Vulnerability Index*
NAS. *Net additions to stock*
ND-GAIN. *Notre Dame Global Adaptation Initiative*
ONCr. *Output non-circularity rate*
OSCr. *Output socio-economic cycling rate*
PIOT. *Physical Input Output Table*
PM. *Processed materials*
SIDS. *Small Island Developing States*
SLR. *Sea-level rise*
SM. *Secondary materials*
SMD. *Structural Metabolic Dependency*
SMRs. *Socio-metabolic Risks*

Chapter 1

Introduction

1.1 Background - Disproportionate Risk Faced by SIDS

Small Island Developing States (SIDS) are a group of low-lying coastal and island countries that collectively have a population of roughly 65–70 million people and contributes under 1% of global greenhouse gas emissions (IRENA, 2024; UNDRR, 2024). Despite this negligible share of emissions, these islands are on the frontlines of climate change, experiencing some of the earliest and most severe impacts. SIDS consistently rank among the world's most climate-vulnerable nations, with many located in tropical cyclone belts and composed of narrow coastal zones that are highly exposed to storms and SLR (World Bank, 2024). For instance, out of 192 countries assessed by the Notre Dame Global Adaptation Initiative (ND-GAIN) for climate change exposure, 10 of the 19 countries in the most-exposed decile are SIDS (Figure 1) (Notre Dame, 2024). This outsized exposure is further captured by the new UN Multidimensional Vulnerability Index (MVI), which shows that most of the SIDS are far more vulnerable than their income level would suggest (UNDP, 2024b). On average, SIDS incur annual economic losses from climate-related disasters equivalent to about 2.1% of their GDP, compared to a global average of just 0.3% (UNDRR, 2024). This means an island economy can lose roughly seven times in one year the share of output that a non-island economy loses to disasters. Such outsized losses highlight the acute fragility of SIDS in the face of intensifying storms, droughts, and other climate stresses.

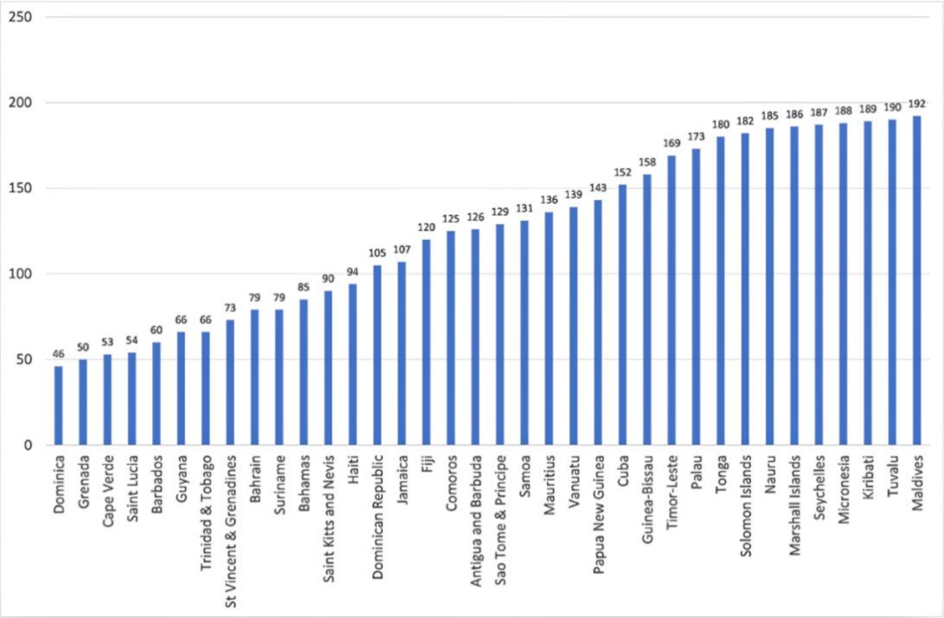


Figure 1.1: Ranking of 36 SIDS in the ND-GAIN sub-index of Exposure to Climate Change. (Notre Dame, 2024)

Geography amplifies this vulnerability. Sea levels around SIDS are rising at approximately 3.7–4 millimeters per year, encroaching on densely settled coasts and critical infrastructure and much of the population, infrastructure, and productive land in SIDS lies only a few meters above present sea level (IPCC, 2021; UN, 2015; UN DESA, 2020; UNDRR, 2024). In fact, in extremely low-lying atoll nations like Kiribati, the Maldives, and Tuvalu, 99% of land area is under five meters elevation (UNCTAD, 2024). On average across all SIDS, roughly one-third of the population lives on land below the five-meter mark, areas highly prone to coastal flooding, erosion, and storm surges (UNDP, 2017). This topographic exposure means that even moderate rises in sea level or minor shifts in storm tracks can have catastrophic effects (IPCC, 2021). Already, SIDS are among the most disaster-prone countries worldwide, with disaster mortality and affectation rates several times the global average (UNDRR, 2023). The combination of rising hazards and high exposure creates a perilous outlook for these islands' communities and economies. Climate scientists warn that without ambitious adaptation efforts, some low-lying atolls could become uninhabitable by later this century (IRENA, 2024). Indeed, SIDS are being forced to contend not only with stronger cyclones and marine heatwaves, but also with the slow-motion crisis of creeping sea levels and shoreline loss. The combination of high exposure and limited protective land area creates a perilous situation in which even a single extreme event can have catastrophic humanitarian and economic consequences for SIDS (IMF, 2018). This reality has made SIDS important voices in international climate negotiations, where they advocate for urgent mitigation by major emitters and for dedicated support to build their resilience (IRENA, 2024; UNDP, 2024).

1.2 Structural Dependence and Increasing Climate Vulnerability

Compounding these climate pressures and geographic vulnerabilities is a structural economic weakness rooted in resource dependence. Many SIDS rely heavily on external sources, importing more than 60% of their food, up to 90% of their construction materials, and nearly all of their fossil fuel energy (UN-OHRLS, 2020; Singh et al., 2020). This import-heavy, linear economy leaves SIDS acutely sensitive to external shocks in global supply and commodity markets (Martin del Campo et al., 2023). For example, the 2007–2008 global fuel price crisis, when oil prices surged to historic highs, sent diesel and electricity costs soaring virtually overnight in many Pacific and Caribbean islands, straining households and government budgets (EIA 2008; Treasury 2011; RMI 2015). Such shocks expose the precarious position of SIDS: because they must import energy and goods at great cost, any volatility abroad can instantly become a domestic emergency.

Recent climate-related disasters have further illustrated the risks of this economic structure. When Tropical Cyclone Winston struck Fiji in 2016 – the strongest cyclone ever recorded in the South Pacific – it affected 62% of the population, destroyed over 30,000 homes, and caused about US$900 million in damage (IMF, 2018; Government of Fiji, 2016). This toll was equivalent to roughly 31% of Fiji's GDP, a staggering setback for a developing economy (Government of Fiji, 2016). Just one year later, Cyclone Maria devastated Dominica in the Caribbean, inflicting losses estimated at 226% of Dominica's GDP (about $1.3 billion) in a matter of hours (Government of Dominica & GFDRR, 2018). These extreme events not only wreck physical assets but also trigger a surge in demand for imported food, fuel, cement and other recovery supplies at the very moment when local systems are most strained. In Dominica's case, post-Maria reconstruction required massive inflows of materials and capital, contributing to a spike in public debt and years of fiscal stress (IMF, 2018; Government of Dominica & GFDRR, 2018). The same pattern holds across SIDS: after disasters, governments must often borrow heavily to finance imports for rebuilding, locking them into a cycle of vulnerability and indebtedness. Crucially, recent studies indicate that an island's resource-use patterns – what it imports, produces, consumes, and discards – can either cushion these shocks or amplify them (IPCC, 2022; Martin del Campo et al., 2023). Heavy reliance on extended global supply chains has been shown to amplify small islands' exposure to external price and logistics shocks (UNCTAD, 2024). By contrast, evidence indicates that bolstering local self-sufficiency, diversifying procurement, and embedding circular-economy principles can significantly strengthen resilience to disruptions (UNEP & IRP, 2022).

1.3 The Socio-Metabolic Risk (SMR) Concept

These combined shocks and dependencies point to deeper structural vulnerabilities, a nexus that the Socio-Metabolic Risk (SMR) concept seeks to unravel by linking material flows to adaptive capacity. The SMR concept was first introduced by Singh et al. (2020) and further developed in Singh et al. (2022). It builds upon earlier work in social metabolism by the Vienna School of Social Ecology, particularly the foundational contributions of Haberl et al. (2016). Drawing on this perspective, SMR focuses on three key levers in the metabolism of an island or any socio-ecological system: (1) secure access to critical resources (availability and reliability of supply), (2) circular and efficient use of those resources (integrity of material circulation, minimizing waste), and (3) fair distribution of the services and benefits they provide (Singh et al., 2022). If any of these pillars is weak, for instance, if an island is import-dependent for fuel, exhibits linear economy, or allocates resources inequitably, then the overall system is at greater risk of collapse when stressed. In essence, SMR offers a systemic lens to assess how the biophysical structure of an economy (its patterns of extraction, import, consumption, stock-building, and waste) underpins its capacity to withstand or adapt to shocks.

In the context of SIDS, the SMR concept has proven especially illuminating. SIDS offer stark examples of how specific configurations of material flows and stocks can drive vulnerability or resilience (Martin del Campo et al., 2023; Singh et al., 2022). For instance, the first mass balance SMR analysis of The Bahamas for the year 2018 revealed a linear and undiversified metabolic profile, characterized by extreme dependence on external resources (Martin del Campo et al., 2023). The study found that imports constituted 60% of the nation's annual direct material input and that the country was almost 100% reliant on imported fossil fuels for its energy needs. This high throughput of materials results in significant outflows, with high masses of waste (1.4 t/cap/yr) remaining unrecovered due to a near-total lack of recycling. Such findings underscore how an island's metabolism, in this case, a linear system with high import dependency and low circularity, creates profound socio-metabolic risks, including high vulnerability to external supply-chain shocks, commodity price fluctuations, and threats to local ecosystems. By quantifying these factors, the SMR approach moves beyond qualitative statements of vulnerability and pinpoints why certain islands remain trapped in risk-prone development trajectories. There is growing recognition in the climate adaptation community that SMR offers a powerful diagnostic tool for island systems. However, to date only a few studies have attempted to operationalize SMR in SIDS, notably, the work of Martin del Campo et al. (2023). These pioneering studies remain new and rare, and not a single SIDS have been analyzed through a complete mass balanced time series SMR lens – revealing a clear gap in both research and practice.

1.4 Research Question and Objectives

Building on the above context, this thesis addresses a central research question: Have the past two decades of material inflows, outflows, and stock accumulation in a SIDS, in this case, Fiji, contributed to reducing SMR, or have they instead intensified it? In other words, is Fiji's material use trajectory becoming more circular and resilient or more linear and vulnerable when examined through the SMR lens? To answer this question, the research pursues four interrelated objectives:

1. To construct the first multi-decadal (2000–2022), economy-wide material flow analysis (ew-MFA) mass balance account for a SIDS, using Fiji as a case study, and covering all major material categories including biomass, fossil fuels, metal ores, non-metallic minerals, and waste.
2. To operationalize the SMR concept through quantifiable indicators, such as import dependency ratios, net additions to stock, and input/output circularity rates, based on harmonized and cross-verified material flow data.
3. To analyze long-term shifts in Fiji's material-use patterns, including trends in domestic extraction vs. imports, waste generation, and assess their implications for climate adaptation, circularity, and systemic risk in small island contexts.
4. To generate empirical, time-series-based insights into SMR dynamics by providing a longitudinal analysis of Fiji's resource-use trajectory and its implications for resilience and vulnerability.

This thesis, by developing a time-series ew-MFA mass balance account, through an SMR lens, contributes to both the empirical evidence base and methodological advancement necessary for adaptive planning in vulnerable island economies.

Chapter 2

Socio-Metabolic Research – A Literature Review

To systematically explore the biophysical foundations of island societies, the field of Industrial Ecology leverages a diverse suite of analytical tools designed to quantify and interpret the flows and stocks of materials and energy. This chapter charts the evolution of these tools, tracing the development of methodologies, from ew-MFA to material stock analysis (MSA), and ultimately to the emerging lens of SMR. It synthesizes key empirical insights while illuminating the distinct challenges posed by island systems, including data scarcity, geographic isolation, and acute resource dependencies. A central finding of this review is the persistent absence of multi-decadal ew-MFA mass balance accounts conducted from SMR perspective. This critical gap constrains our ability to understand the historical, path-dependent trajectories of island metabolisms, how past material choices and infrastructural investments have locked in present vulnerabilities and limited adaptive futures. Addressing this data void is essential for developing informed strategies that enhance long-term resilience and sustainability in SIDS.

2.1 The Foundations: Industrial Ecology and the Concept of Social Metabolism

At its core, Industrial Ecology (IE) systematically investigates the flows of materials and energy within society (Frosch & Gallopoulos, 1989; Graedel & Allenby, 2003). This fundamental concept, often termed 'Socio-metabolism' or 'socio-economic metabolism,' applies a biological analogy to human societies to understand how they process resources (Fischer-Kowalski et al., 2011). It conceptualizes a society, be it a city, a nation, or the entire globe, as a living organism that requires a constant flow of materials and energy to function, grow, and reproduce its structures. This analytical framework quantifies these flows, meticulously accounting for all the resources a society draws from the environment (inputs like minerals, biomass, and fossil fuels), how it processes and accumulates them as physical "stocks" (such as buildings, infrastructure, and machinery), and what it releases back into the environment (outputs like emissions, solid waste, and wastewater) (Haberl et al., 2019; Krausmann et al., 2018). By mapping these biophysical flows, socio-metabolic research provides a powerful diagnostic tool to assess a society's resource efficiency, its dependency on external resources, its overall environmental impact, and its long-term sustainability (Haberl et al. 2019; Singh et al., 2022).

Early scholars recognized that the clearly demarcated physical and geopolitical boundaries of islands simplify the complex task of tracking material flows. This led Deschenes and Chertow (2004) to famously characterize islands as ideal "natural laboratories" for Material Flow Analysis (MFA). In these contained systems, imports and exports are channeled through a limited number of ports and airports, making data collection and accounting more manageable than in continental regions with porous borders. This unique characteristic allows for a clearer and more accurate picture of a society's complete metabolic profile, its inputs, outputs, and internal accumulations.

2.2 Quantifying Inflows: Material Flow Analysis (MFA) on Islands

The initial wave of island MFA studies focused on validating the methodology and demonstrating its policy relevance. A methodological precursor is Sundkvist et al. (1999), who applied an energy-flow analysis with selective material-flow accounting to the Swedish island of Nämdö, mapping societal metabolism across local production, imports, and wastes to evaluate self-sufficiency and carrying capacity. An important micro-island bridge in this evolution is the Trinket Island case, which combined field-based Material and Energy Flow Accounting with Human Appropriation of Net Primary Production (HANPP) to articulate a ‘biophysical transition’ lens linking MFA indicators to society–nature relations and policy levers (Singh et al., 2001; Singh & Grünbühel, 2003). Another seminal study by Eckelman and Chertow (2009) on the Hawaiian island of O‘ahu was pivotal in this regard. By meticulously accounting for all material inputs and outputs, they demonstrated that MFA could provide concrete, actionable data to inform critical policy decisions regarding waste management and import-reduction strategies. Their work established a practical precedent, showing that a metabolic analysis was not merely an academic exercise but a vital tool for island governance.

Following these foundational studies, the literature evolved from methodological proof-of-concept to more nuanced, material-specific, and temporally expansive analyses. Researchers began to investigate how the unique economic structures of different islands shaped their metabolic profiles. For example, Bahers et al. (2020) analyzed the socio-metabolism of New Caledonia, revealing an economy overwhelmingly dominated by its nickel industry. Within SIDS specifically, Krausmann et al. (2014) conducted one of the earliest multi-decade, economy-wide MFAs for Trinidad and Tobago (1961–2008), illustrating how a limited domestic resource base and reliance on one or two key export commodities have shaped long-term trajectories of Domestic Material Input (DMI) and Domestic Material Consumption (DMC). Rahman et al. (2022) reconstructed several decades of biomass flows across four Caribbean SIDS (Barbados, Jamaica, Dominica, Grenada), reinforcing that limited domestic resource bases commonly translate into high, and rising, import dependence, particularly for food and energy.

The scope of analysis also broadened in both time and space. Seeking to understand long-term developmental trajectories, Noll et al. (2021) conducted a ninety-year historical reconstruction of material flows for the Greek island of Samothraki. Their analysis documented a profound metabolic transition from a largely self-sufficient, circular agrarian society to a modern, tourism-driven economy characterized by high material intensity and linearity. On the spatial front, Chertow et al. (2020) proposed a "holarchic" approach in their study of Hawaiʻi, using nested MFAs to capture material leakages and transfers across different scales, from individual households to the entire archipelago.

More recently, the field has progressed towards using MFA to identify common patterns and systemic risks. A landmark SIDS study by Martin del Campo et al. (2023) presents the first mass-balance socio-metabolic account for The Bahamas, explicitly diagnosing SMR and cascading effects in a linear, import-dependent metabolism; the paper also situates The Bahamas in relation to other island territories. Together with Rahman et al. (2022), Noll et al. (2021), and Krausmann et al. (2014), it highlights why multi-year MFAs are critical for revealing structural lock-ins and transition (or non-transition) pathways in SIDS, yet no multi-decade, ew-MFA mass balance series explicitly framed through an SMR perspective currently exists for any SIDS.

2.3 Quantifying Outflows: The Growing Burden of Island Waste

A fundamental principle of mass balance dictates that rising material inflows inevitably lead to growing outflows in the form of waste and emissions. As island economies consume more, they must dispose of more. A comprehensive two-decade review by Singh et al. (2023) charts the evolution of island waste research, noting a progression from simple tonnage counts to more sophisticated analyses that frame these outflows as a complex socio-economic driver. Indeed, underdeveloped waste management systems are now understood as a primary source of SMR with the potential for cascading failures that impact both human and environmental health (Singh et al., 2023)

A growing body of case studies vividly illustrates the consequences of this rising tide of waste. On Samothraki, the shift to a tourism-based economy led to a fifteen-fold increase in construction-and-demolition waste, with very limited capacity for recycling or reuse (Noll et al., 2019). In Grenada, a municipal solid waste stream of 46 kilotonnes per year highlights the immense financial constraints that SIDS face in developing and maintaining adequate treatment infrastructure (Elgie et al., 2021). The challenge is particularly acute for modern waste streams; for instance, e-waste generation in the Caribbean is already double the global per capita average and continues to rise, posing a significant toxic hazard (Mohammadi et al., 2021). Even in small territories with relatively modest material throughputs, such as Ndzuwani in the Comoros, significant disposal gaps and environmental contamination persist (Bahers et al., 2022).

These contemporary challenges were anticipated in earlier work. Eckelman & Chertow (2009) had noted on Oʻahu that severe landfill space limitations were incentivizing the innovative use of local construction debris as a secondary aggregate material. More recent studies have situated these local waste management challenges within a broader geopolitical context, linking the flow of waste to small island territories to concerns over "waste colonialism," where islands become destinations for waste from larger, wealthier nations (Manglou et al., 2022).

2.4 Quantifying In-Use Stocks: Material Accumulated and Embedded Risks

Material that enters an island economy and does not immediately leave as waste or emissions accumulates in long-lived in-use stocks, buildings, roads, utilities, vehicles, and industrial facilities, that deliver essential societal services while also anchoring risk in place (Bradshaw et al., 2020; Symmes et al., 2020; Bahers et al., 2022; Merschroth et al., 2020; Martin del Campo et al., 2023). The first island MSA was conducted on Trinket (Nicobar Islands), where researchers directly inventoried stocks, often by physically weighing artefacts and structures, and compiled a companion material-flow account distinguishing domestic extraction from imports (Singh et al., 2001; Singh & Grünbühel, 2003).

From these beginnings, the mainstream trajectory of MSA moved from top-down accounting toward spatially explicit, field-informed inventories as data, GIS, and remote sensing improved and as research goals shifted from “how much stock?” to “what is it for, where is it, and how exposed is it?” (Augiseau & Barles, 2017; Dai et al., 2025). In the Caribbean, Symmes et al. (2020) produced the region’s first spatially explicit MSA for Grenada, linking construction stocks to climate hazards and reconstruction dynamics; Bradshaw et al. (2020) mapped Antigua & Barbuda’s built environment and explicitly linked stocks to the tourism services they underpin; and in the Pacific, Merschroth et al. (2020) integrated inundation modeling with MSA to estimate stock losses under sea-level-rise scenarios for Fiji, extending earlier disaster-loss MSA concepts demonstrated for Japan (Tanikawa et al., 2014). Most recently, a national, spatially explicit MSA for The Bahamas mapped building and transport stocks and their exposure to sea-level rise, consolidating MSA's role as a risk-diagnostic companion to ew-MFA in SIDS (Martin del Campo et al., 2023).

Conceptually, the field has shifted from quantification to sustainability: recent syntheses frame material stocks not merely as quantities to be measured but as leverage points for resilience, circularity, and service provision, though these reviews remain largely industry-oriented rather than island-focused (Dai et al., 2025). Culminating this evolution, the stock–flow–service nexus emphasizes the services enabled by stocks and the flows they require; early island applications operationalize this perspective by linking mapped stocks to tourism and mobility services and by assessing climate-hazard exposure in Antigua & Barbuda, Fiji, and The Bahamas (Haberl et al., 2017; Haberl et al., 2021; Bradshaw et al., 2020; Merschroth et al., 2020; Martin del Campo et al., 2023).

2.5 The Emergence of Socio-Metabolic Risk (SMR) studies

The field of disaster studies has shifted from a hazard-centric view to one that emphasizes societal choice and vulnerability. Scholars widely agree there is no such thing as a "natural disaster": hazards such as cyclones or earthquakes become disasters only when they overwhelm societal capacity, exposing long-term structural vulnerabilities (Wisner et al., 2025; Lewis & Kelman, 2025). Disasters are thus the outcome of chronic socio-economic and political processes, not random shocks. This framing has led to the argument that disasters are "by choice," arising from development and governance decisions that place people at risk and constrain response options (Kelman, 2021). A common mnemonic expresses this relationship as $R = (H \times V / C) - M$, where Risk depends on Hazard and the ratio of Vulnerability to Capacity, offset by Mitigation; this is not a quantitative model but a teaching device to highlight the social construction of risk (Wisner et al., 2025).

Socio-metabolic research has progressively enhanced our capacity to measure the physical dimensions of economies (Fischer-Kowalski et al., 2011; Krausmann et al., 2018; Haberl et al., 2019), but descriptive stock-and-flow accounts alone cannot explain how and why certain metabolic configurations become fragile, lock in maladaptive pathways, or approach critical thresholds (Haberl et al., 2017; Markolf et al., 2018; Singh et al., 2022; Scheffer, 2010). A crucial recent development has been the introduction of an analytical lens that moves beyond quantification toward an explicit assessment of systemic vulnerability: the concept of socio-metabolic risk (SMR).

The SMR concept argues that a society's metabolic profile, its patterns of resource use, trade, and waste, is a primary driver of its vulnerability to both environmental and geopolitical shocks (Singh, 2020; Singh et al., 2022; Martin del Campo et al., 2023; Wisner et al., 2025). A linear, import-dependent metabolism, as is common in many SIDS, is an expression of structural vulnerability that increases the "V" and decreases the "C" in the risk equation (Wisner et al., 2025; Martin del Campo et al., 2023). Therefore, SMR is not a separate category of risk, but a sub-set of systemic risk that diagnoses how the biophysical structure of an economy creates the conditions for disaster (Singh et al., 2022; Singh, 2020). SMR is more specifically defined as the "systemic risk associated with the availability of critical resources, the integrity of material circulation, and the (in)equitable distribution of derived products and societal services in a socio-ecological system" (Singh et al., 2022). This framing builds on the earlier work on social-metabolism research by the Vienna school of social ecology, offers a systemic lens on the biophysical structures that underpin island economies (Haberl et al. 2016).

What the SMR concept contributes is the conceptual bridge between what material stock-flow analysis measure (flows, stocks, and their spatial patterns) and what those patterns imply for a system's exposure, sensitivity, and adaptive capacity. While composite frameworks such as the ND-GAIN Index, the MVI, and the Sendai Framework evaluate exposure, sensitivity, and outcomes through aggregated indicators (Notre Dame Global Adaptation Initiative, 2015; UNDESA & UNDP, 2021; UNDRR, 2015), SMR focuses instead on the structural drivers of vulnerability. It highlights how material and resource flows shape systemic fragility or resilience. Heavy import dependence for food and fuel, mono-commodity export specialization, linear “take–make–dispose” throughputs with low recovery, or the spatial concentration of material stocks and critical infrastructures in hazard-prone coastal zones, form “metabolic traps” (Martin del Campo, 2023; Noll et al., 2021). In resource-constrained, trade-dependent SIDS, these traps are not merely inefficient; they are existential, threatening a polity’s ability to maintain essential services (energy, water, mobility, shelter) in the face of price shocks, supply-chain disruptions, and climate-amplified hazards (Singh et al., 2022; Bahers et al., 2022; Martin del Campo et al., 2023). Thus, a low per-capita DMC, often celebrated as “resource efficient”, can mask extreme fragility if that low throughput is overwhelmingly imported, tied to volatile international markets, and embedded in a linear, low-recovery regime. SMR therefore urges analysts to interrogate the quality, configuration, and control of flows and stocks (e.g., import ratios, self-sufficiency ratios, circularity gaps, domestic vs. foreign extraction shares), not merely their aggregate quantity.

Because metabolic dynamics are path-dependent (i.e., today's stocks and infrastructures condition tomorrow's options), only multi-decade, time-series can reveal the cumulative stock–flow feedbacks that drive risk (Haberl et al., 2019; Krausmann et al., 2018; Kullmann et al., 2021; Noll et al., 2021). The mass balance identity (Inputs = Outputs + ΔStocks) is fundamentally temporal; ΔStocks accumulate across years, creating lock-ins that can gradually steer systems toward socio-metabolic tipping points, thresholds beyond which small perturbations produce disproportionately large, and potentially irreversible, shifts in system behaviour (Scheffer, 2010; Franzke et al., 2022; Juhola et al., 2022; Singh et al., 2022). Single-year snapshots, while diagnostic, cannot capture these slow-burn dynamics, for example, the progressive erosion of self-sufficiency, the deepening of import dependence, or the escalating exposure of coastal stocks to SLR as urban expansion hardens into the built environment. Therefore, SMR when combined with longitudinal ew-MFA, these dynamics translate into measurable indicators, such as import dependence ratios and circularity gaps, that can inform forward-looking resilience planning (Circular Economy, 2025).

The Bahamas national account by Martin del Campo et al. (2023) illustrates the SMR concept in practice: using a mass balance, indicator-driven assessment of resource availability, access, consumption, and self-sufficiency, it shows how a linear, import-dependent metabolism (9.4 t cap^{-1}, 60% imported, 1.4 t cap^{-1} unrecovered waste in 2018) translates into concrete risks such as food insecurity, energy poverty, and recovery bottlenecks. However, the paper also exposes a methodological ceiling: because it is single-year, it cannot observe how the system arrived at this configuration, or which structural inflections (e.g., trade liberalization, tourism expansion, catastrophic cyclones) mattered most. This is precisely why continuous, harmonised, SMR-focused multi-year ew-MFA mass balance accounts are indispensable for adaptation planning, they let us track trajectories, not just states.

2.6 Synthesizing the Research Gap

Taken together, the literature reviewed above shows a clear methodological arc: from early, policy-oriented island ew-MFAs that validated the usefulness of strict mass balance accounting (e.g., O‘ahu), to spatially explicit MSAs that map where vulnerability is physically anchored, and finally to the SMR concept, which interprets metabolic patterns explicitly through a systemic risk lens. Yet, despite these advances, the evidence base for SIDS remains fragmented and temporally thin. While there are a few multi-decade SIDS material accounts that do exist (e.g., Trinidad & Tobago; Caribbean biomass flows, etc.) do not operationalize SMR. Consequently, we lack the very thing the literature argues is indispensable: long, mass balanced time series viewed from a SMR lens, that can reveal path-dependent lock-ins, structural breaks, and tipping-point dynamics in island metabolisms.

This constitutes the central research gap: No SIDS has, to date, a harmonised, multi-decade, mass balanced ew-MFA that is explicitly designed, read, and interpreted through an SMR lens. Without such a record, scholars and policymakers cannot properly trace how import dependence, self-sufficiency, and circularity gaps co-evolve over time; detect when and where material lock-ins emerge as stocks accumulate and infrastructures harden; quantify how successive shocks (storms, price spikes, pandemics) alter metabolic trajectories; or identify socio-metabolic tipping points.

Addressing this gap matters substantively and methodologically. Substantively, SIDS confront compound risks: extreme import dependence, mono-commodity specialization, rising waste burdens, and spatially concentrated stocks exposed to SLR and cyclones. These characteristics are not static; they are historically produced and path-dependent. The absence of multi-year SMR-oriented ew-MFAs thus blinds adaptation planning to trajectories, forcing decision-makers to plan on states rather than the processes that generate them. This thesis operationalizes SMR by constructing the first multi-decade, harmonized, mass balanced ew-MFA for a SIDS (2000-2022), explicitly analyzed through SMR lens.

Chapter 3

Research Design and Analytical Methodology

3.1 The Pacific Context: A Region of Acute Vulnerability

The Pacific is the epicentre of climate-related economic loss among SIDS. Recent ESCAP analyses show that Pacific SIDS lose on average, up to 9% of GDP every year to climate-related hazards (2015–2020), around four times the SIDS average of 2.1% of GDP and about 30 times the global average of 0.3% of GDP. This makes the Pacific not just more vulnerable than other SIDS groupings, but an outlier on a global scale. (ESCAP, 2020; UNDRR, 2024).

This extreme, structural loss profile is compounded by the fact that Pacific SIDS face the highest adaptation costs in Asia–Pacific, about 1.41% of GDP annually (ESCAP, 2023, 2022), and well over 40% of SIDS are already at, or near, unsustainable debt levels/debt distress (UNDP, 2024; IIED, 2023; Reuters, 2024). Studying a Pacific SIDS within this hyper-vulnerable context therefore offers a uniquely revealing lens on how socio-metabolic lock-ins, fiscal stress, and climate hazards co-produce systemic risk, and why forward-looking, SMR-oriented, multi-decade ew-MFAs are essential for credible resilience planning.

3.2 The Rationale for Focusing on Fiji

Within the highly vulnerable Pacific region, Fiji presents a particularly compelling single-case study for several intersecting reasons. Its selection is justified by its regional significance, progressive policy landscape, pronounced vulnerability, and, crucially for empirical research, its robust data availability. Fiji is a significant player in the South Pacific. With a population nearing one million, it has the second-largest economy in the subregion and functions as a vital hub for transportation, diplomacy, and education, notably hosting the main campus of the University of the South Pacific (World Bank, 2025; UNDESA, 2024). This leadership role is also reflected in its proactive climate diplomacy; Fiji was the first country globally to ratify the Paris Agreement, signaling its commitment to climate action on the world stage (Jenkins, 2016).

Second, Fiji has articulated ambitious national goals for sustainability and resilience. Its national 2050 Climate Adaptation Roadmap, for example, outlines a vision to reduce dependency on volatile import markets and achieve full circularity in waste management (Government of Fiji, 2024).

However, this ambition exists in stark contrast to its on-the-ground reality. Despite its proactive stance, Fiji remains exceptionally vulnerable. The Notre Dame Global Adaptation Initiative ranks Fiji 120th out of 192 countries, placing it among the most vulnerable nations globally (Notre Dame, 2024). Similarly, the UNDP's Multidimensional Vulnerability Index identifies Fiji as the fourth most vulnerable Pacific nation and the sixth most vulnerable among all SIDS (UNDP, 2024b). This "aspiration-reality gap" makes Fiji a critical case for examining the barriers that prevent ambitious policies from translating into tangible resilience.

Fiji epitomises hyper-vulnerability among Pacific SIDS. Tropical Cyclone (TC) Winston (2016) caused FJ$1.99 billion (US$0.9 billion) in damages and losses, affecting about 62% of the population and cutting projected growth by 2.5 percentage points (Government of Fiji, 2016; World Bank, 2017). The country was struck again by Category 5 TC Yasa (2020), which generated an additional approximately US$245 million (5% of 2020 GDP) in losses, followed just weeks later by TC Ana (2021), compounding fiscal stress and recovery costs (Refugees International, 2021). These shocks are not isolated: TC Harold (2020) also impacted Fiji, adding to reconstruction needs across already strained sectors (WMO, 2020).

Finally, from a methodological standpoint, Fiji offers a distinct advantage: data availability. The country has maintained near-continuous and reliable records of trade and material extraction since 2000. This provides a solid empirical foundation for the longitudinal analysis required to conduct a comprehensive material flow and circularity assessment. This unique combination of robust data, urgent policy ambitions, and acute, well-documented vulnerability makes Fiji an ideal "test bed" for understanding the challenges of implementing a circular economy under the constant threat of climate change. The insights derived from Fiji's experience are poised to offer valuable lessons not only for its Pacific neighbors but for all island economies striving for a sustainable future.

3.3 Analytical Framework: ew-MFA

The analytical core of this study is the application of the ew-MFA framework. This methodology provides a systematic and comprehensive means of quantifying the physical metabolism of a national economy, serving as a powerful tool for biophysical monitoring and sustainability assessment.

3.3.1 Core Indicators for Biophysical Monitoring

The ew-MFA framework generates a suite of aggregated indicators that provide a comprehensive overview of the national metabolism. These indicators, defined in Table 3.1, and illustrated in the Figure 3.1, which provides the general framework for the ew-MFA in Fiji, serve as the primary variables for the biophysical monitoring of Fiji's economy. They are categorized by their position in the material flow process: inputs, use, in-use stocks, and outputs. In the context of a SIDS economy, certain indicators carry particular significance.

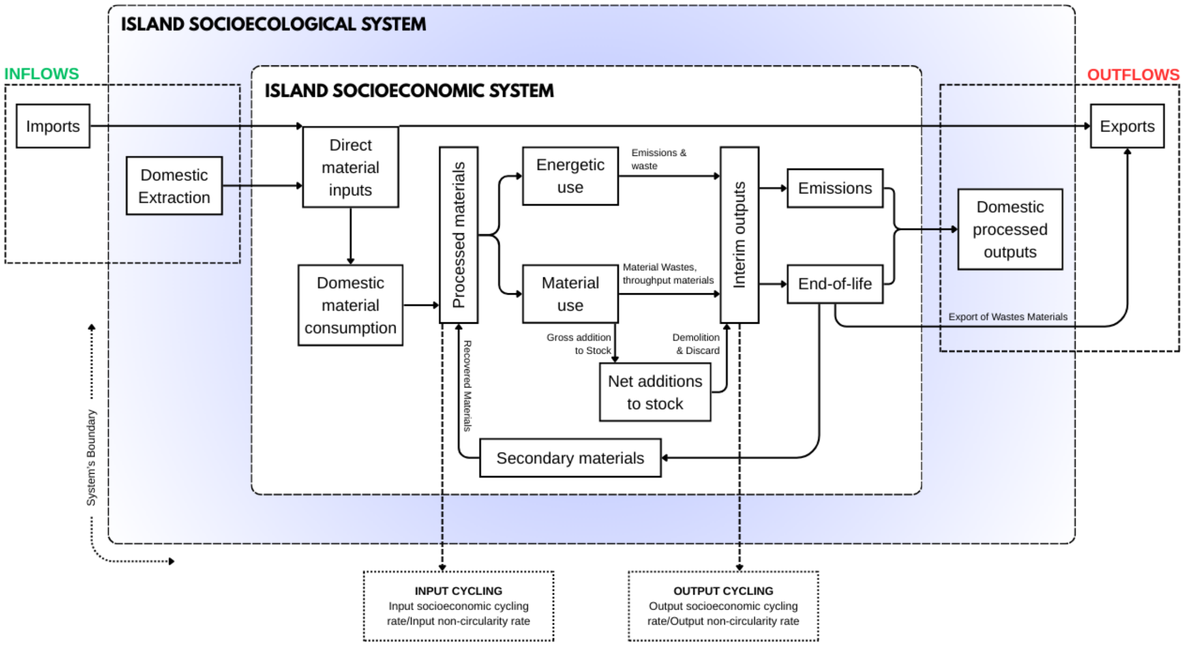


Figure 3.1: Economy-wide material flow framework used in this study

For instance, Direct Material Input (DMI) and the Import Dependence Ratio (IDR) are critical for quantifying the economy's reliance on external resources. Domestic Material Consumption (DMC) provides the measure of the total mass of materials used within the national territory, reflecting the scale of domestic resource consumption. Net Additions to Stock (NAS) is a crucial indicator of the physical growth of the economy, tracking the annual accumulation of materials in long-lived infrastructure, buildings, and durable goods, a key process in a developing nation undergoing urbanization and infrastructure expansion.

Table 3.1 provides a comprehensive overview of the key scale and circularity indicators employed for the biophysical monitoring of Fiji's economy, along with their definitions and formulas.

Domain	Name / Sub-category	Description
Material Category	Biomass	Biomass encompasses all organic materials originating from plants, animals, and micro-organisms, namely crop products (e.g., cereals, fruits, vegetables), forestry and logging residues (roundwood, bark, sawdust), animal products (meat, dairy, hides), and processing by-products (agricultural residues, food waste) (Eurostat (European Commission), 2018). Beyond serving as a source of energy, biomass can be processed into a variety of products: it provides food and animal feed, serves as raw material for paper, textiles, construction, etc.
	Metals	Metal ores are naturally occurring mineral aggregates from which metals are extracted which includes ferrous ores (iron, manganese), non-ferrous ores (aluminium/bauxite, copper, lead, zinc), and precious-metal ores (gold, silver) (Eurostat (European Commission), 2018).

		These ores serve as the primary feedstock for metal production and downstream manufacturing of steel, aluminium, copper alloys, and other metal products used in construction, transportation, machinery, and electronics. Metal ores are non-renewable resources whose extraction, processing, and end-of-life management have significant environmental footprints.
	Non-metallic minerals	Non-metallic minerals comprise inorganic, non-metallic substances extracted from the earth, such as sand, gravel, crushed stone, clays, gypsum, phosphate rock, and other industrial minerals, that serve as raw materials in construction, glass and ceramic production, chemical manufacturing, and various industrial applications. These minerals are essential for foundational and surfacing functions: they form concrete aggregates, provide fillers for asphalt and building materials, supply raw feedstocks for cement and clinkers, and enable the

		manufacture of ceramics and glass products (Eurostat (European Commission), 2018).
	Fossil fuels	Fossil fuels comprise non-renewable, carbon-rich energy carriers such as coal, crude oil, natural gas, and derived products (e.g., petrol, diesel, heavy fuel oil). These fuels serve as primary inputs for electricity generation, transportation, industrial processes (e.g., steel and cement production), and residential heating (Eurostat (European Commission), 2018).
	Wastes	Wastes encompasses all materials that is discarded, including MSW, C&D debris, and industrial by-products. MSW comprises household, commercial, and institutional refuse, whereas C&D waste consists of materials from building activities such as concrete, timber, and steel.
MFA Indicator – Input (kt/yr)	Domestic Extraction (DE)	All materials extracted from the domestic environment

	Imports	Inputs of goods originating from outside the national economy
	Direct material inputs (DMI) = DE + Imports	Input of materials into the national economy originating from the domestic environment and the rest of the world
MFA Indicator – Use (kt/yr)	Domestic material consumption (DMC) = DMI – Exports	Total amount of materials that are directly used in a national economy
	Processed materials (PM) = DMC + SM	All materials processed domestically
	Secondary materials (SM)	Includes materials recovered from end-of-life waste which are reintroduced into the domestic economy
	Energetic use (eUse)	Share of PM that provide energy for technical applications as well as for livestock and human metabolism (feed and food)
	Material use (mUse)	Share of PM that is used for its material properties
MFA Indicator – Stock (kt/yr)	Net additions to stock (NAS) = GAS – Demolition and discard	Net amount of material added to the stocks per year

	Gross additions to stocks (GAS)	All materials going into material stocks (lifetime greater than 1 year)
MFA Indicator – Output (kt/yr)	Exports	Outputs of goods and materials to other economies
	Demolition and discard (D&D)	Quantity of materials removed from material stocks after their service lifetime
	Interim outputs (IntOut)	Includes all materials that are accounted as an output from the socioeconomic system before divided into emissions and end-of-life waste
	Domestic processed outputs (DPO) = DPOe + DPOw	All materials that are released back into the environment as a result of consumption and production processes
	Emissions (DPOe)	The part of the DPO corresponding to emissions, whether from combustion processes or metabolic processes of livestock and humans
	End Of Life (EoL) DPO Wastes (DPOw = EoL - SM)	EoL: Wastes including materials that are sent back into the economic system for material recovery. DPOw: The part of the DPO

		corresponding to solid materials that can no longer be cycled back to the economic system as secondary materials and have reached the end of their service lifetimes.
Circularity – Input (%)	Input socioeconomic cycling rate (ISCr) = (Secondary materials ÷ PM) × 100	Share of secondary materials reintroduced through socioeconomic processes into the economic system
	Input circularity rate (INCr) = (Fossil energy carriers ÷ PM) × 100	Fossil energy carriers as share of PM
Circularity – Output (%)	Output socioeconomic cycling rate (OSCr) = (Secondary materials ÷ IntOut) × 100	Share of secondary materials present in DPO
	Output non-circularity rate (ONCr) = (Fossil energy carriers ÷ IntOut) × 100	Fossil energy carriers as share of DPO
Trade dependence (%)	Import Dependence Ratio (IDR) = Imports ÷ DMI	Quantifies how much of a country's material consumption is dependent on imports, as opposed to domestic extraction.

3.3.2 Measuring Circularity and Linearity

To assess Fiji's progress towards a circular economy, this study employs a set of four key indicators adapted from prior circular economy and socio-metabolic research literature (Haas et al., 2015; Martin Del Campo et al., 2023; Mayer et al., 2019). This approach moves beyond simplistic metrics like aggregate recycling rates to provide a more nuanced and balanced assessment of material loop-closing. The framework simultaneously quantifies both the positive aspects of circularity (the recovery and reuse of materials) and the persistent aspects of linearity (the reliance on virgin, non-renewable resources). The four indicators, expressed as percentages of relevant material flows, are defined as follows:

- Input Non-Circularity Rate (INCr): The share of fossil energy carriers in total processed materials (PM) on the input side, expressed as a percentage. INCr captures the extent to which virgin fossil resources (e.g. coal, petroleum fuels) contribute to the economy's material inputs. A higher INCr indicates a heavier reliance on non-renewable, linear inputs.
- Output Non-Circularity Rate (ONCr): The share of fossil energy carriers in interim outputs (IntOut), expressed as a percentage. This measures the proportion of material outputs leaving the socioeconomic system that is attributable to fossil resource use – for example, carbon-containing emissions from burning fossil fuels, or fossil-based materials ending up as waste. A higher ONCr signifies that a large part of the outputs are non-circular (destined to dissipate into the environment rather than being recovered).
- Input Socioeconomic Cycling Rate (ISCr): The share of secondary (recycled) materials in total processed materials (PM) inputs, expressed as a percentage. ISCr indicates how much of the material input into the economy comes from socioeconomic cycling – i.e. reuse or recycling of materials within the economy rather than new extraction or imports. A higher ISCr means a greater fraction of the inputs are coming from recycled sources, reflecting a more circular input profile.
- Output Socioeconomic Cycling Rate (OSCr): The share of secondary materials in interim outputs (IntOut), expressed as a percentage. OSCr reflects the portion of outgoing material flows that are captured for recycling or reuse instead of being disposed of. In other words, it shows how much of the waste/emission output stream is actually looped back as a resource. A higher OSCr signifies that more output is being cycled back into economic use (for

instance, materials collected for recycling), indicating better circular performance on the output side.

These four indicators together provide a balanced view of circularity: INCr and ONCr quantify the non-circular (linear) portion of inputs and outputs, respectively, while ISCr and OSCr quantify the circular (recycled) portion of inputs and outputs. Tracking these metrics allows us to assess Fiji's progress toward a circular economy from both the consumption/input perspective and the waste/output perspective.

3.4 Data Processing Workflow for Replicability

To ensure the methodological transparency and exact replicability of this study, a rigorous, multi-stage data processing workflow was designed and executed. This protocol documents every step of the process, from the initial identification of raw data sources to the final compilation of the mass balance model, allowing for a complete audit and reproduction of the final dataset.

3.4.1 Data Scoping and Inventory Construction

The initial phase involved a systematic scoping of all potential national and international data sources containing information on material flows relevant to Fiji for the 23-year period from 2000 to 2022. A structured data inventory was compiled for all material categories, meticulously logging the source, specific flow type (e.g., domestic extraction, import, export), temporal coverage, and original unit conventions for each candidate dataset, in accordance with the principles outlined in the Eurostat (2018) ew-MFA handbook. This comprehensive inventory, presented in Table 3.2, formed the foundational architecture for the entire data collection and harmonization process.

Table 3.2: Comprehensive Data Source Inventory for Fiji's ew-MFA (2000–2022)

Material Category (MF Class)	**Flow Type**	**Specific Variable**	**Primary Source**	**Secondary Source(s)**	**Temporal Coverage**

MF1. Biomass	Domestic Extraction	Crop Production, Livestock, Forestry Products, Fish Catch	Fiji Bureau of Statistics (FBoS)	Food and Agriculture Organization (FAOSTAT)	2000–2022
	Import / Export	Agricultural goods, wood products, processed foods	UN COMTRADE	FBoS	2000–2022
MF2. Metal Ores	Domestic Extraction	Gold, Silver, other mineral production	FBoS	United States Geological Survey (USGS), British Geological Survey (BGS)	2000–2022
	Import / Export	Raw metals, semi-finished and finished metal products	UN COMTRADE	FBoS	2000–2022
MF3. Non-	Domestic Extraction	Sand, Gravel, Limestone, Clay	FBoS	USGS, BGS	2000–2022

metallic minerals					
	Import / Export	Cement, Fertilizers, Salt, other mineral products	UN COMTRADE	FBoS	2000–2022
MF4. Fossil Fuels	Import / Export	Crude oil, Petroleum products, Coal, Gas	UN COMTRADE	FBoS, International Renewable Energy Agency (IRENA)	2000–2022
MF6. Waste	Domestic Processed Output (Waste)	Municipal Solid Waste, C&D Waste, Recycled Waste	FBoS	Secretariat of the Pacific Regional Environment Programme (SPREP) Audits	2006–2022
	Domestic Processed Output (Emissions)	Agricultural emissions (enteric fermentation, manure)	FAOSTAT	N/A	2000–2021

3.4.2 Data Extraction, Harmonization, and Standardization

Following the inventory construction, raw data were systematically extracted from their original sources. For datasets published in non-editable formats, such as PDF reports, data was manually copied to the excel sheets, and cross checked for accuracy. For trade data, a comprehensive list of Harmonized System (HS) codes was compiled for all relevant material items, enabling precise and consistent queries of the UN COMTRADE database across the entire time series.

All extracted raw data were organized into a dedicated Excel workbook with separate spreadsheets for each major material category (Biomass, Metals, Non-metallic minerals, Fossil fuels, and Outflows). Within each sheet, a consistent structure was maintained, with columns for material sub-category, flow type (domestic extraction, import, export), HS code, item description, and separate columns for values from each data source. During this stage, each material item was also classified according to its primary end-use function as either energetic use (eUse) or material use (mUse). A critical step in this phase was the rigorous standardization of units. As sources reported flows in various units (kilograms, tonnes, cubic meters), all mass-based data were converted to tonnes to ensure consistency and allow for meaningful aggregation and comparison. All conversion factors used were documented in a dedicated notes column to maintain a transparent audit trail.

3.4.3 Data Triangulation and Reconciliation Protocol

A core component of ensuring the quality and integrity of the final dataset was a systematic data triangulation and reconciliation protocol. This process involves using multiple data sources to corroborate and validate individual data points, thereby enhancing the reliability of the final accounts. A hierarchical principle of source prioritization was applied. For any given material flow and year, the official national statistics provided by the Fiji Bureau of Statistics (FBoS) were considered the primary and most authoritative source.

In instances where FBoS data were unavailable for a specific year or material, the value was filled using data from a designated secondary source, typically a major international agency database (e.g., UN COMTRADE for trade, FAOSTAT for biomass). If values from primary and secondary sources were both available but showed discrepancies, they were investigated by cross-referencing definitions and reporting methodologies. In general, the FBoS value was retained, with the international data serving as a validation check. This meticulous process of comparison and reconciliation was conducted for every material item across the entire 23-year time series. Once a final value was selected, it was entered into a dedicated "Final Value" column, and the specific source from which it was derived was explicitly recorded. This ensures that every single data point in the final mass balance model can be traced back to its original source.

3.4.4 Mass Balance Model Construction and Analysis

With a complete, standardized, and reconciled dataset established for all primary flows, the final analytical steps were undertaken. First, pivot tables were created in Excel for each material category. These tables served as a powerful tool for preliminary data validation, allowing for the rapid summarization and visualization of flows by year, flow type, and material sub-category. This step helped to identify any remaining outliers, inconsistencies, or classification errors before the final calculations were performed.

Next, a new workbook was constructed to serve as the definitive mass balance model. Within this workbook, separate sheets were dedicated to each material category, and the key MFA indicators (e.g., DMI, DMC, PM, NAS) were calculated year-by-year from 2000 to 2022 using the formulas specified in Table 3.1. Finally, a series of time-series visualizations were developed using both Excel and Tableau to analyze trends and patterns in the calculated indicators over the study period. To streamline the reporting of results in subsequent chapters, a final master reporting sheet was compiled, aggregating all key indicators from the five material categories into a single, unified table. This master sheet serves as the single, authoritative source for all quantitative results presented in this thesis, ensuring consistency and traceability.

3.5 Mapping ew-MFA to SMR

To move the Socio-Metabolic Risk (SMR) concept from a theoretical framework to an analytical tool, we operationalize it by mapping specific, quantifiable indicators from the economy-wide material flow analysis (ew-MFA) onto SMR’s core levers of vulnerability. First, the Import Dependence Ratio (IDR) serves as a direct measure of a nation's exposure to external supply chain disruptions and price shocks; a rising IDR signals greater dependence on foreign resources and thus, a heightened SMR. Second, the Input and Output Socioeconomic Cycling Rates (ISCr and OSCr) quantify the integrity of material circulation. Persistently low or declining rates indicate a more linear, "take-make-dispose" system, which elevates SMR by increasing reliance on virgin inputs and creating larger waste burdens. Finally, Net Additions to Stock (NAS), particularly when understood to be accumulating in hazard-prone coastal zones, tracks the physical build-up of vulnerable assets like buildings and infrastructure; a sustained increase in NAS within these exposed areas signifies a growing concentration of risk that can be locked in for decades. While existing composite vulnerability indices, such as the ND-GAIN or the MVI, provide a crucial snapshot of a country's overall vulnerability, our operationalization of SMR reveals the underlying biophysical mechanisms that produce that vulnerability. It shows precisely how a nation's patterns of resource consumption and accumulation either amplify or cushion its exposure to risk. Only a multi-decadal view can uncover the deeper, structural shifts occurring over time, such as the gradual erosion of self-sufficiency and the quiet accumulation of external dependencies. This long-term analysis exposes the path-dependent nature of risk, revealing how economies can drift into "metabolic traps" that are invisible in a static snapshot.

3.6 Data Quality Assurance and Management of Limitations

This study employed a rigorous data harmonization and quality assurance protocol to manage the inherent complexities of compiling a comprehensive dataset from a variety of sources, including national statistics, international databases, regional audits, and academic literature. While a complete and perfectly consistent dataset is an ideal, the reality of research, particularly in SIDS contexts, involves navigating data gaps and inconsistencies. This section transparently documents the key limitations encountered and details the systematic strategies employed to mitigate them, thereby ensuring the final analysis is as robust and reliable as possible.

The most significant data limitations were encountered in the accounting of material outflows, specifically for waste and recycling streams. Key challenges included:

- Municipal Solid Waste (MSW) Data: Official FBoS statistics on MSW generation were only available for the period 2006–2022. Furthermore, these figures aggregate multiple waste streams, including household, commercial, and some construction and demolition (C&D) debris, making disaggregation difficult.
- C&D Waste: Dedicated records for C&D waste were sparse, with separate data reported only from 2014 onwards and limited to specific construction-related activities.

- Recycling Data: Official data on the quantities of materials recovered for recycling were only available from 2013 onwards, leaving a significant gap in the earlier years of the study period.
- Waste Composition: Comprehensive, long-term national data on the material composition of different waste streams (e.g., the percentage of plastics, organics, or metals in MSW) were not available.

To manage these limitations, a data triangulation and proxy-based estimation strategy was implemented, as summarized in Table 3.3. This involved leveraging the best available context-specific information from external sources to estimate the material composition of aggregate waste flows. For the composition of MSW, this study utilized the findings of the most recent and detailed waste audit available for a Fijian urban center: a 2023 audit of Labasa Town conducted by the Secretariat of the Pacific Regional Environment Programme (SPREP, 2023). This audit, which surveyed 118 households and businesses, provides a robust, empirically grounded snapshot of Fijian MSW composition. According to this audit, MSW is composed of approximately 37% organic matter, 18% plastic, and 17% paper and cardboard by weight.

For the composition of C&D waste, where local data were particularly scarce, this study referenced the peer-reviewed findings of Merschroth et al. (2020). Their detailed material stock analysis of buildings in Fiji estimated that C&D debris is composed of roughly 90% concrete, 6% timber, and 4% steel. These externally derived, but context-specific, composition percentages were then applied to the available aggregate waste tonnage data from FBoS to disaggregate the total waste outflows into their respective material categories within the ew-MFA model. This approach, while reliant on estimation, is transparently documented and grounded in the best available scientific evidence for the Fijian context.

Table 3.3: Data Gap Mitigation and Triangulation Strategy

Data Limitation	**Identified Gap**	**Mitigation Strategy**	**Proxy Data Source & Justification**
Municipal Solid Waste	Lack of official, long-	Application of proxy composition percentages	**SPREP (2023).** Justification: This is the

(MSW) Composition	term national data on the material breakdown of MSW streams.	based on the most recent, localized empirical audit.	most detailed and context-specific waste audit available for a Fijian urban center, providing the best available empirical estimate for MSW composition.
C&D Waste Composition	Lack of official, time-series data on the material breakdown of C&D waste streams.	Application of proxy composition percentages derived from a peer-reviewed academic study specific to Fiji.	**Merschroth et al. (2020).** Justification: This study provides a specific material stock analysis for buildings in Fiji, offering a scientifically robust estimate for the material composition of C&D waste in the absence of official statistics.
Pre-2013 Recycling Data	Absence of official records on the quantity of materials recovered for recycling before 2013.	Linear back-casting was not performed due to lack of a reliable basis. The analysis acknowledges this gap, and circularity indicators (ISCr, OSCr) are calculated only for the period where data is available (2013–2022).	**Fiji Bureau of Statistics (FBoS).** Justification: Acknowledging the data gap is more methodologically sound than introducing significant uncertainty through unsupported extrapolation.

Chapter 4

Results[1]

This chapter presents the results of Fiji's core resource-use indicators from 2000 to 2022. It begins with an overview of Domestic Material Consumption (DMC), providing a general picture of resource use during the study period. Subsequent sections present results for other indicators disaggregated by material categories. A discussion then situates these findings in a comparative, risk-oriented perspective, and the chapter concludes with a concise summary.

4.1 Domestic Material Consumption (DMC) of Fiji from year 2000 to 2022

From 2000 to 2022, Fiji's total Domestic Material Consumption (DMC) fell from 5.7 Mt to 4.3 Mt, despite growth in selected categories. The contraction was driven primarily by a steep fall in biomass extraction, which outweighed increases in non-metallic minerals and fossil fuels. Early on, domestic extraction of sugarcane and marine catch dominated inflows, but over time these subsided and were progressively replaced by imported food, construction materials, and energy carriers. Imports grew steadily, with IDR rising from 27% in 2000 to 46% in 2022. Fossil fuel and construction material imports spiked multiple times but show volatility.

Figure 4.1 shows clear shifts in Fiji's metabolism. Biomass DMC fell 38% (4,462→2,779 kt) as biomass IDR rose from 6% to 16%. Non-metallic minerals DMC rose 51% (499→753 kt) and IDR climbed from 11% to 39% (with peaks >30% after 2014). Fossil-energy DMC increased 26% (663→836 kt) and IDR stayed at 100% throughout. Metal-ore DMC was low except for the 2012–2015 bauxite spike; outside that window, IDR remains 100%. Figure 4.2 illustrates this transition visually through a sequence of Sankey diagrams. The panels show how thick biomass flows at the start of the period gradually thin, while fossil fuels and non-metallic minerals expand. The five years selected (2000, 2010, 2013, 2016, 2022) capture key turning points: from a biomass-dominated baseline, through the pre-bauxite and bauxite-boom years, to cyclone-driven rebuilding, and finally

---

[1] The contents of this section of the Chapter have been incorporated within a paper that has been submitted for publication. Thakur, B. S., Singh, S. J., Wood, M. O. (2025). "How prepared is Fiji to climate and geopolitical risks? Insights from a socio-metabolic risk (SMR) analysis." Submitted to the *Journal of Industrial Ecology.* Minor editorial changes are applied for being consistent with the University of Waterloo thesis format.

the 2022 endpoint where imported flows dominate, underscoring Fiji's systemic reorientation toward external dependence.

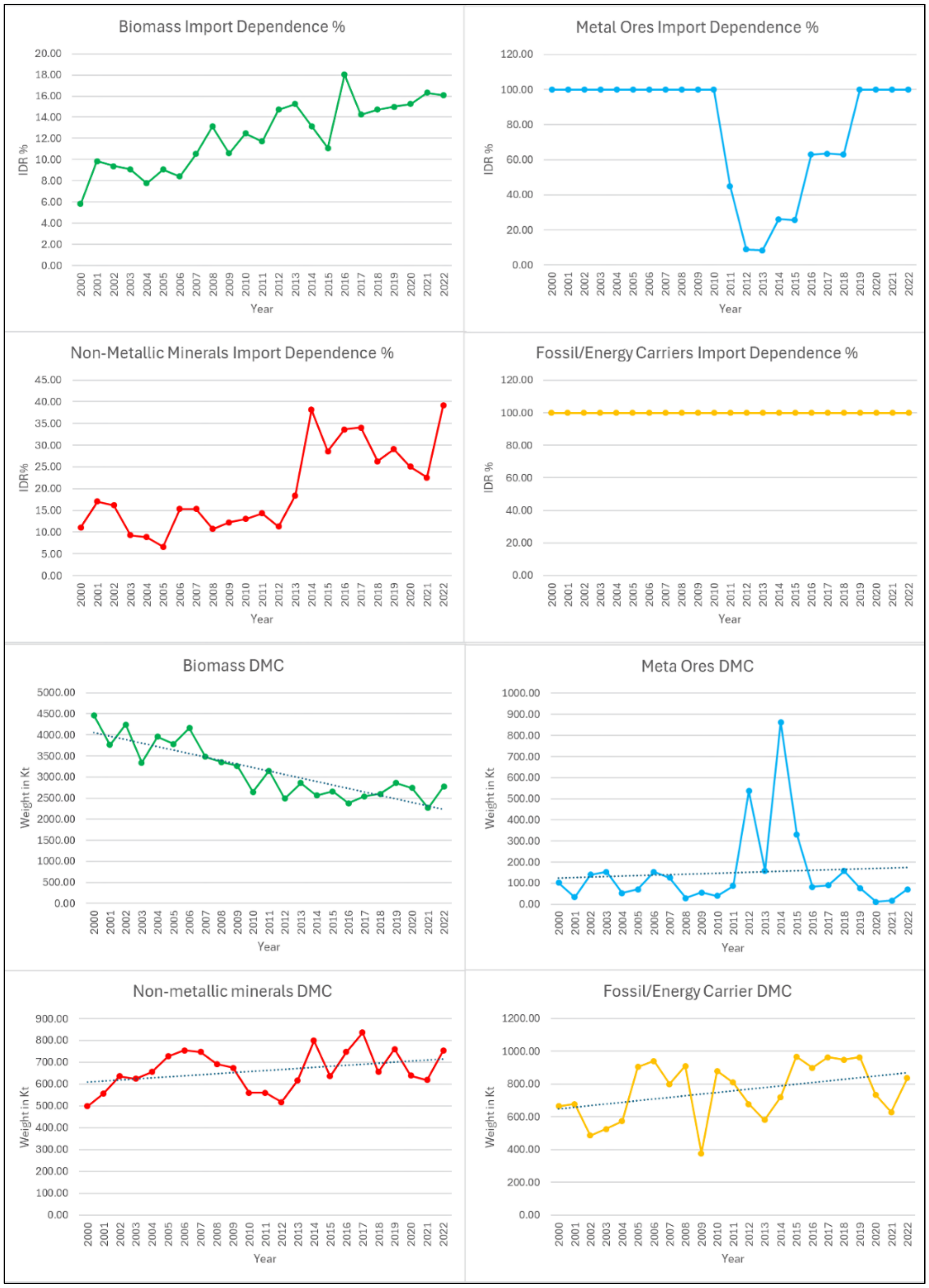


Figure 4.1: *Import Dependence Ratio (IDR) & Domestic Material Consumption (DMC) across the four material categories (2000 to 2022)*

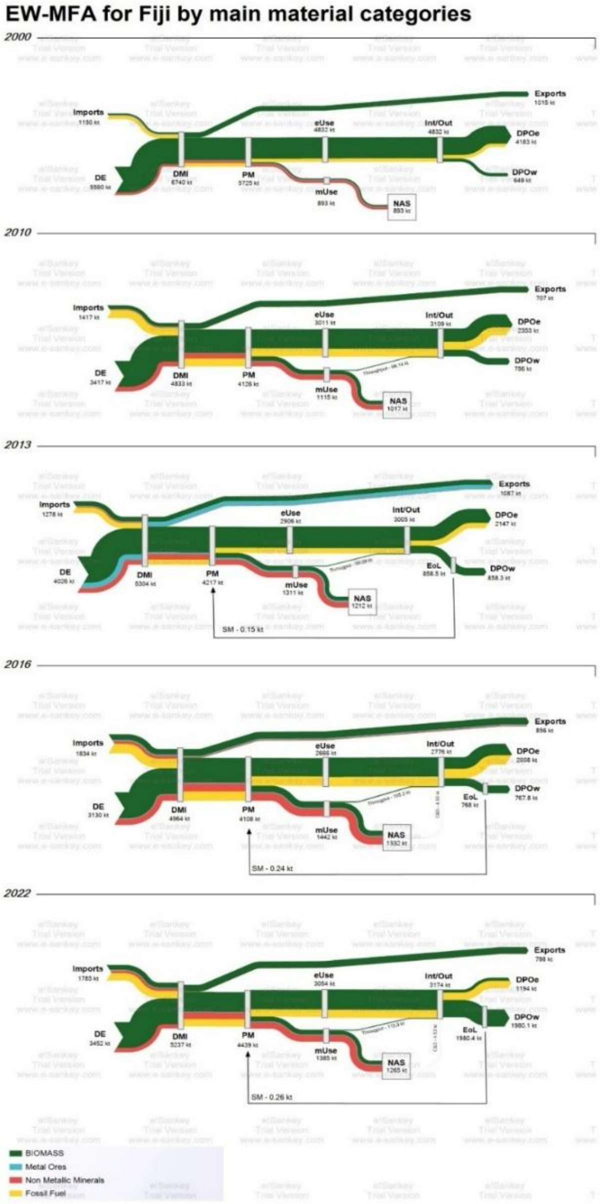


Figure 4.2: *Sankey diagram of ew-MFA for Fiji from 2000 to 2022 by main material categories. (The five years selected (2000, 2010, 2013, 2016, 2022) capture key turning points, from a biomass-dominated baseline, through the pre-bauxite and bauxite-boom years, to cyclone-driven rebuilding, and finally the 2022 endpoint where imported flows dominate, underscoring Fiji's systemic reorientation toward external dependence (*see *Table 1 in supporting information S1).*

4.2 Results across the four material categories

In the sections that follow, we turn from the big picture to the details of each material category. Section 4.1.1 examines biomass flows, 4.1.2 unpacks metal ores, 4.1.3 non-metallic minerals, 4.1.4 traces fossil-fuel flows, and 4.1.5 explores waste generation. Together, these deep dives will reveal how each stream contributes to Fiji's evolving socio-metabolic profile.

4.2.1 Biomass

Between 2000 and 2022 Fiji's biomass metabolism both contracted and externalized. DE dropped from about 5,137 kt to 2,982 kt (-42%) (Figure 4.4), majorly because sugar-cane harvests more than halved from around 3,800 kt to 1,600 kt; sugar cane is processed into raw sugar, molasses and bagasse for cogeneration, and its share in total DE slipped from three-quarters to a little over half (Figure 4.3).

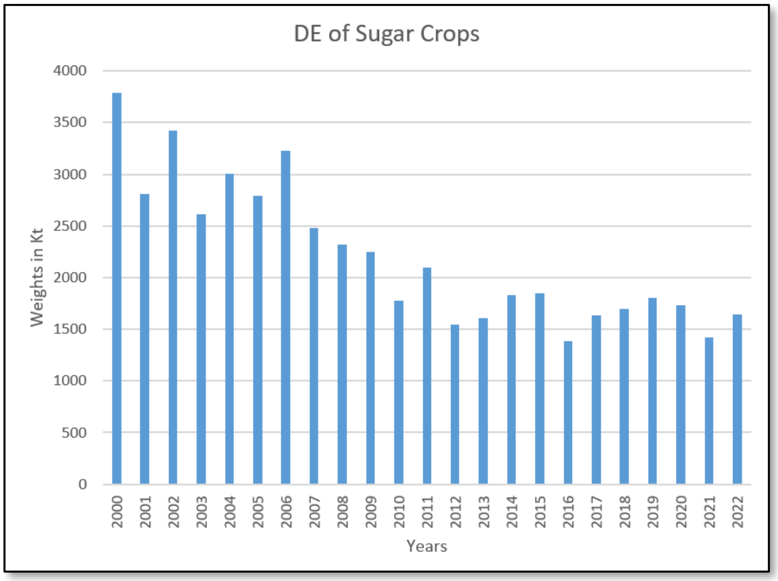


Figure 4.3: Domestic extraction of Sugar Crops

Marine catches of tuna, grouper and other finfish, declined by one third (49 kt → 33 kt), while domestic livestock DE (beef, pork, poultry and dairy for meat and milk supply) stayed near 75 kt yr^{-1}, suddenly declining to 38 kt in 2016 before climbing back to the mid-70 kt range by 2022. In contrast, vegetables (cabbage, tomatoes, root vegetables) DE more than tripled (18 kt → 66 kt) and fruits grew from 19 kt to 48 kt, partially cushioning the overall downturn (Figure 4.4).

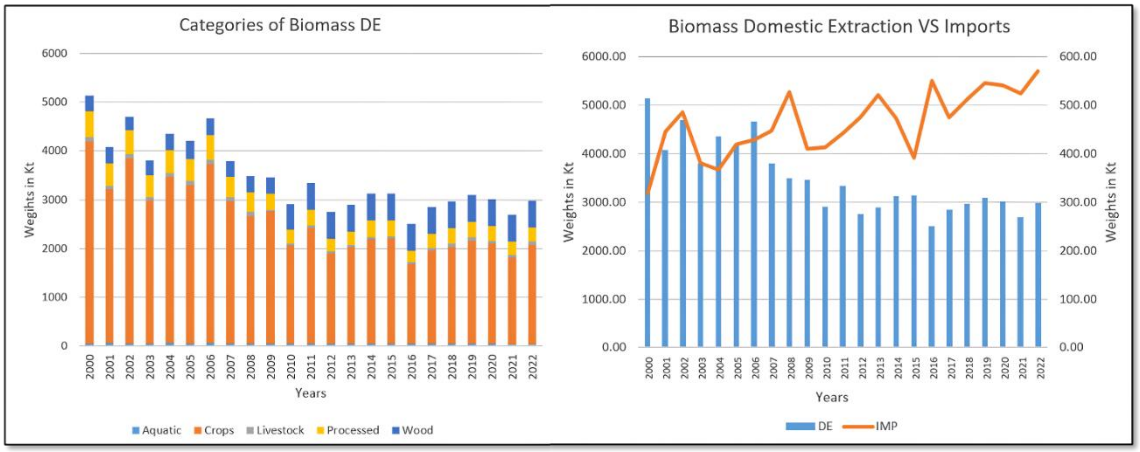


Figure 4.4: Categories of Biomass DE & Biomass DE Vs Imports

DMC mirrored extraction, contracting from 4,462 kt to 2,779 kt (38%) (Figure 4.5). External trade partly offset the slide: biomass imports climbed from 317 kt to 571 kt (+80%), led by cereals, soy cake, and processed foods, whereas exports slipped from 990 kt to 770 kt (22%) (Figure 4.4). As a result, imported biomass now supplies roughly 21% of national DMC, up from just 7% in 2000. NAS rose from 294 kt in 2000 to 457 kt in 2022, peaking at 518 kt in 2017.

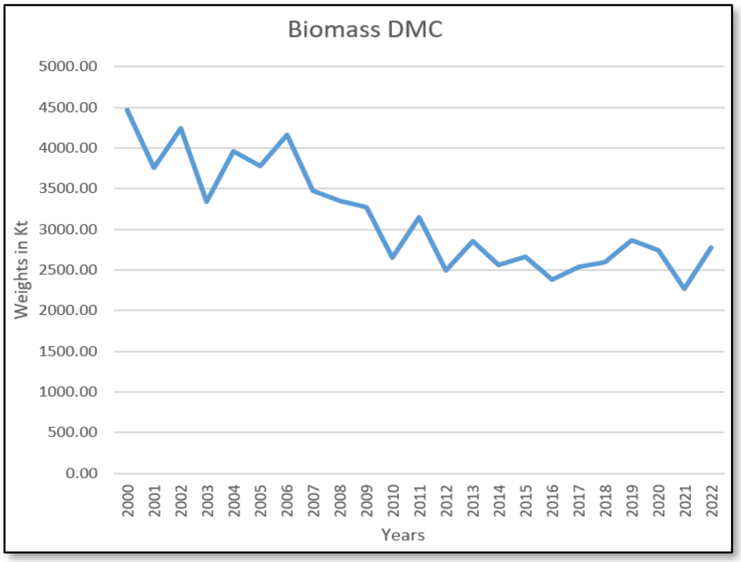


Figure 4.5: Biomass DMC

4.2.2 Metal Ores

Between 2000 and 2022, Fiji's metal-ore flows were import-driven, with DE 0.01 kt in 2000, and imports of 111.6 kt. A bauxite-mining phase from 2011 to 2015 briefly altered this pattern: DE rose from under 1 kt in 2010 to 50 kt in 2011, then to 500 kt in 2012, 600 kt in 2013, and peaked at 640 kt in 2014, at which point DE accounted for roughly 74% of total inflows (864 kt) and DMC reached 863.5 kt. After 2014, the bauxite boom faded: by 2018 DE had fallen to 60 kt and returned to near-zero after 2019, while DMC declined in parallel to 157.8 kt in 2018 and 70.6 kt in 2022. Imports likewise receded from 228 kt in 2014 to 74.3 kt in 2022. Throughout the period, precious-metal production remained a niche activity: total gold and silver output fell from 5.27 t in 2000 to 1.01 t in 2022 (gold: 3.81 t → 0.53 t, –86%; silver: 1.46 t → 0.48 t, –67%). Since 2019, domestic metal-ore extraction has stayed below 10 kt yr^{-1}, indicating that Fiji's current metal sector relies almost entirely on imports and semi-finished products. NAS surged from 101 kt in 2000 to a boom-time peak of 857 kt in 2014, before collapsing to just 63 kt in 2022 as bauxite extraction wound down.

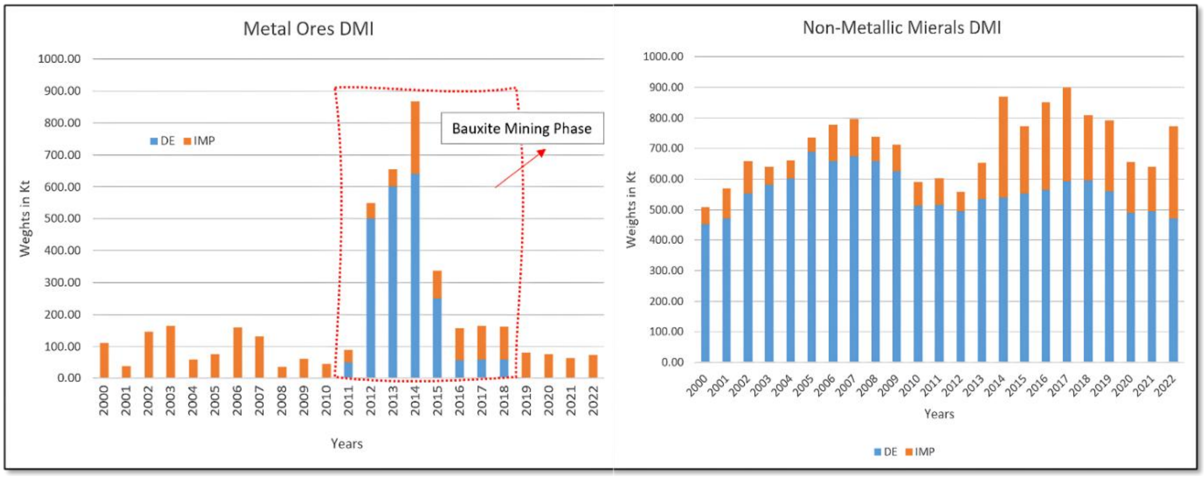


Figure 4.6: Metal Ores DMI & Non-Metallic Minerals DMI

4.2.3 Non-Metallic Minerals

The non-metallic mineral sector has experienced significant growth, with domestic material input (DMI) increasing by 52% from 510 kt in 2000 to 773 kt in 2022 (Figure 4.6). DMC has moved in parallel, rising 51% from 499 kt to 753 kt (Figure 4.7). DE oscillated between 450 kt and 780 kt, ending only slightly above its 2000 level. Imports have expanded more than five-fold, peaking at 332 kt in 2014 and landing at 303 kt in 2022 (+436%). Even more striking is the surge in imports of finished products made from these minerals, like cement & clinkers, which skyrocketed by 1,674% (14.8 kt in 2000 → 263.12 kt in 2022), driven largely by sharp increases in 2006 and between 2014 – 2018. NAS increased from 499 kt in 2000 to 744 kt in 2022, with a high of 827 kt in 2017, driven mainly by cement, aggregates, and other construction inputs accumulating in urban and coastal infrastructure.

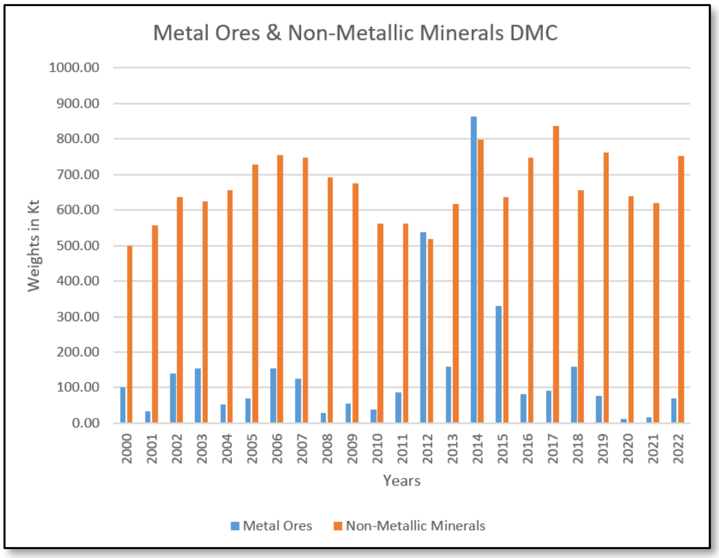


Figure 4.7: Metal Ores & Non-Metallic Minerals DMC

4.2.4 Fossil Fuels

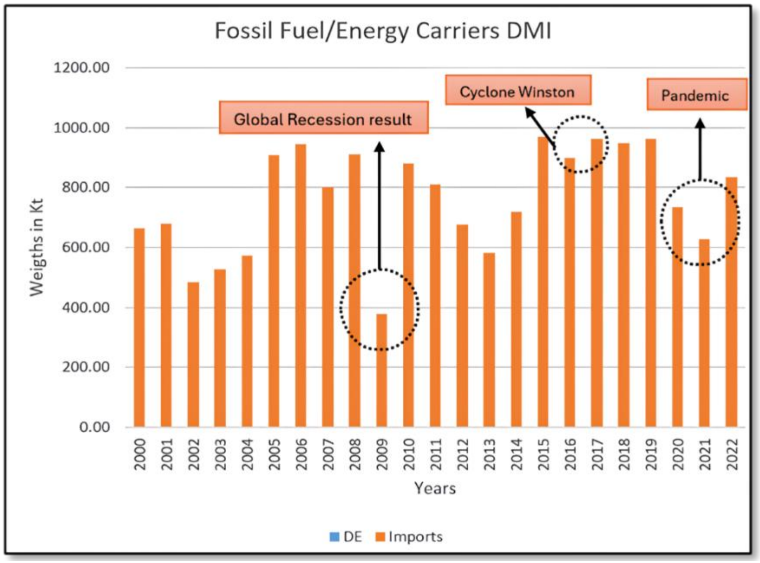


Figure 4.8: Fossil Fuel/Energy Carriers DMI

Between 2000 and 2022 Fiji's fossil-fuel metabolism, primarily diesel, petrol, coal, and heavy fuel oil, used across multiple sectors, was driven entirely by imports, with no recorded DE. DMI (and therefore Consumption) rose from 665 kt in 2000 to 836 kt in 2022, a net increase of about 26%, but the path was volatile. Imports first surged in 2005, then peaked at 943 kt in 2006, and experienced another increase in 2008, touching 911 kt, then collapsed to just 377 kt in 2009 during the global downturn. A rapid rebound carried inflows back to the 880-970 kt range, where they hovered through 2015-2019, before falling to 628 kt in 2021; a partial recovery followed in 2022 (Figure 4.8). Trade detail data reveal a profound compositional shift. Imports of gaseous fuels, principally liquefied petroleum gas (LPG) and other bottled gases, expanded steadily, climbing 29% (24 kt → 31 kt) and setting successive records between 2016 and 2019. Solid fuel inflows were far more episodic: large coal consignments in 2002-2003 (>16 kt each) and again in 2012-2018, plus intermittent deliveries of oil shale and peat, pushed the solid total from just 0.13 kt in 2000, to 5.58 kt in 2022.

The most dramatic movement, however, occurred in refined petroleum and related fossil energy products. These imports peaked at roughly 920 kt in 2006, stayed above 770 kt through 2011, except for the dramatic drop reported in 2009 to 350 kt. These fossil-energy products imports saw a steady uptrend, peaking 934 kt in 2015, before falling back to 599 kt in 2021. Exports remained negligible, though a few re-export spikes suggest Fiji occasionally acted as a trans shipment hub rather than a producer. With nearly all imports entering immediate use, Domestic Processed Output (DPO) rose by 26% from 664 kt in 2000 to 836 kt in 2022.

4.2.5 Waste

MSW outflows have risen steadily since systematic recording began in 2006. Annual tonnage grew from 151 kt in 2006 to 190 kt in 2022, a 26% increase, equivalent to an average gain of 2.5 kt yr ^{1}. Growth was largely incremental. Waste climbed through 2008, levelled off during 2009-11, then nudged upward again from 2012 onward. The largest single year jump was reported in 2018 when MSW leapt 4% (178.9 kt → 186.6 kt), and third, a contraction in 2020 shaved roughly 8.5 kt off the 2019 peak, but the system rebounded to a near peak levels in 2022. Data on material recovery are available only from 2013, and the quantities are modest.

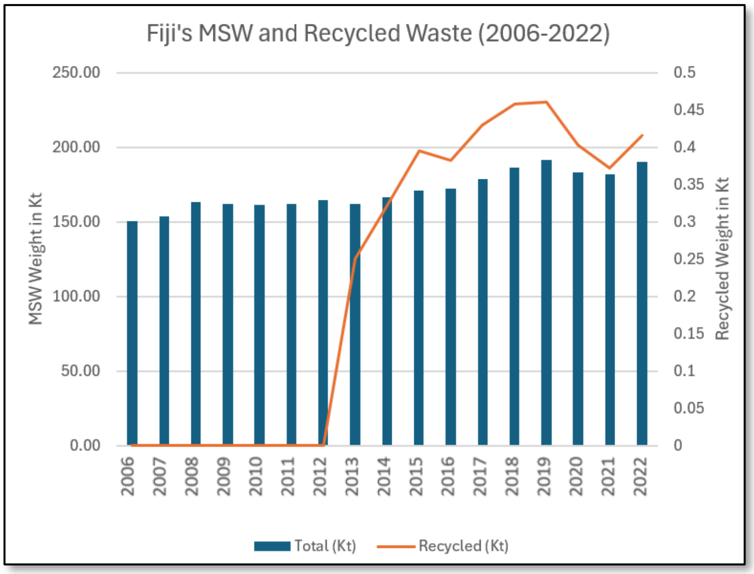


Figure 4.9: Fiji's MSW (2006–2022)

Collected recyclables rose from 0.25 kt in 2013 to just 0.42 kt in 2022, representing only 0.2% – 0.24% of MSW (Figure 4.9). Dedicated C&D statistics begin in 2014. Between 2014 and 2019, the floor area of new and renovated buildings expanded from 92 000 m² to 129 000 m², driving C&D waste from 3.86 kt to a peak of 6.64 kt (+72%). Concrete dominates the stream, averaging 90% by mass; timber (6%) and steel (4%) comprise the remainder (Merschroth et al., 2020). Activity slowed sharply in 2020 21, cutting C&D waste to 3.85 kt in 2021. A partial rebound occurred in 2022 (4.53 kt), yet volumes remained 32% below the 2019 peak, hinting at an uneven recovery in the building sector (Figure 4.10).

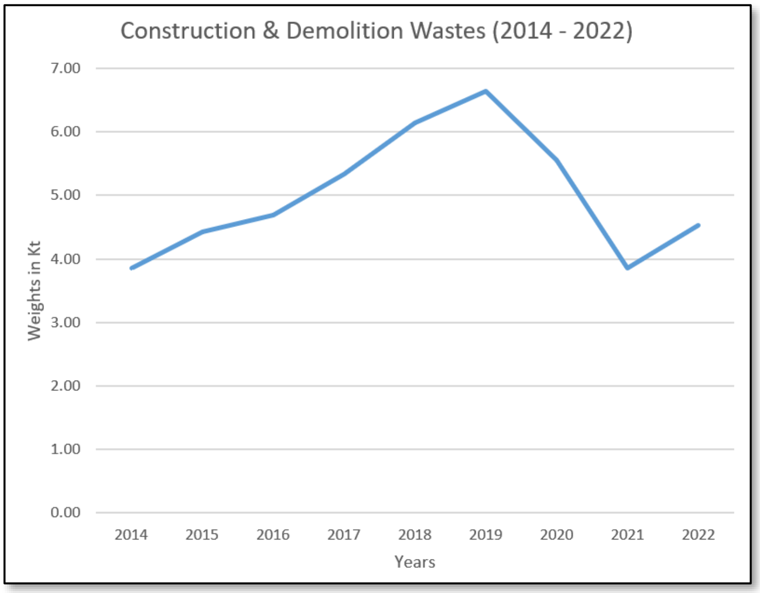


Figure 4.10: Construction & Demolition Wastes (2013–2022)

4.3 Circularity Indicators

Biomass flows are linear: ISCr never exceeds 0.01, and the OSCr is fixed at 0.01 throughout 2013-2022, showing that barely 1% of residues return to use (see table C.1 in supporting information S1). Metal ores ISCr oscillates between zero and low single-digit values, punctuated by a one-off spike to 0.14 in 2020. Metals OSCr stays within 0.16-0.27, indicating that roughly one-quarter of metal-bearing outputs are captured for recycling (see table C.2 in supporting information S1). In stark contrast, non-metallic minerals remain almost wholly virgin-material dependent: ISCr is zero every year, and OSCr hovers in a narrow 0.11-0.16 band, suggesting that most construction-and-demolition debris still heads straight to landfill (see Table C.3 in supporting information S1). Fossil fuels dominate Fiji's material throughput, but linear: both the INCr and the ONCr stood at a constant 100% in 2013-2022, with all combusted and none recirculated (see table C.4 in supporting information S1).

4.4 DISCUSSION

Our analysis shows that Fiji's traditional agro-export base, once dominated by sugarcane production, has eroded substantially, from over 4 Mt in the mid-1990s to around 1.6 Mt in 2022 (Dean, 2022).

Biomass extraction fell while IDR tripled from 6% in 2000 to 16% in 2022, increasing reliance on imported food and feed**.**

Concurrently, Fiji's economy pivoted to services, especially tourism. By the mid-2010s, tourist arrivals exceeded Fiji's population, driving construction of hotels, roads, and airports (World Bank, 2020). Non-metallic minerals show the sharpest IDR jump, from 11% in 2000 to 39% in 2022, with peaks above 30% after Cyclone Winston (2016) and again in 2022 as rebuilding continued. Imports of cement, clinkers, and aggregates surged, facilitated by port upgrades such as the Lautoka ship-loading tower (ADB, 2008; ADB 2011; Lal, 2013), translating into sustained NAS growth. A significant share of these materials is likely embedded in coastal and urban infrastructure exposed to sea-level rise and cyclones. Long-lived stocks deliver services but simultaneously anchor risk, since extreme events can rapidly convert them to debris, triggering new import wave and reinforcing lock-in and external dependence.

Fiji briefly pursued extractive diversification via bauxite boom, exporting 1.2 Mt to China between 2012–2015 (USGS, 2015), enabled by reopening Bua Port in 2012; the 2013 Sankey (Figure 4.2) shows the spike in metal ore flows (Biswas, 2017; Papua New Guinea Mine Watch, 2016). Depletion and price drops ended the boom, yielding minimal benefits and leaving environmental damage in Bua province (AL Circle, 2020; 2014; USGS, 2016). Unlike resource-rich SIDS like Trinidad and Tobago, where fossil extraction dominates metabolism (International Trade Administration, 2022; Krausmann et al., 2014), Fiji's extractive phase was modest and unsustained. Fossil fuels remain fully imported, cementing its role as the core material vulnerability.

Low circularity compounds these risks. Recycling remains negligible, and lack of systematic outflow accounting hides future liabilities. Together, rising import dependence, growing NAS in hazard-prone zones, and low circularity undermine resilience. Only a long-term perspective reveals this structural reorientation from a biomass-based metabolism toward an externally dependent, high-stock, low-circularity configuration that deepens systemic vulnerability.

4.4.1 Comparative Insights from Other Island Economies.

Table 4.1 places Fiji among SIDS with differing dominance of non-metallic minerals, fossil fuels, or biomass. In 2019 Fiji’s DMC was still biomass-led, similar to Samothraki (Noll et al., 2021). But our longitudinal SMR lens shows steady erosion of Fiji’s biomass base since the early 2000s, mainly from collapse of sugarcane outputs, while fossil fuels and construction imports expanded. This trajectory is a shift away from self-sufficiency toward heightened external dependence.

Table 4.1: *Comparison of per-capita MFA indicators, numbers in [tonnes/cap/yr]*

Island Territory	Year	DE	Import	Export	DMI	DMC	Main DMC Contributor	Source
Republic of Fiji	2019	4.08	2.03	0.92	6.11	5.19	Biomass	Present Study
The Bahamas	2018	5.5	3.9	3.3	9.4	6.1	Fossil fuel, Non-metallic minerals	(Martin Del Campo et al., 2023)
Samothraki	2018	13.8	5.0	2.3	18.8	16.5	Biomass	(Noll et al., 2021)
Iceland	2008	14	15.1	6.1	29.1	23	Biomass, Non-metallic minerals	(Krausmann et al., 2014)
Trinket Island	2000	N.D.	N.D.	2.4	6.2	3.8	Biomass, Non-metallic minerals	(Singh et al., 2001)
Trinidad and Tobago	2008	34.7	8.8	26.2	17.3	17.4	Fossil fuels	(Krausmann et al., 2014)
Oahu, Hawaii	2005	3.7	16.6	6.7	20.3	13.6	Fossil fuels	(Eckelman & Chertow, 2009)
New Caledonia	2016	N.D.	10.6	N.D.	N.D.	29.3	Non-metallic minerals	(Bahers et al., 2020)

Santa Cruz (Galapagos)	2012	16.3	4.4	0.1	20.7	20.8	Non-metallic minerals	(Cecchin, 2017)
Japan	2015	4.6	6.13	1.4	10.7	9.3	Non-metallic minerals	(Tanikawa et al., 2021)
Global Average	2019	12.5	1.9	1.8	14.4	12.4	Non-metallic minerals	(UNEP & IRP, 2022)
Europe Average	2019	16.4	7.9	5.8	24.3	18.5	Non-metallic minerals	(UNEP & IRP, 2022)
LAC Average	2019	16.9	1.2	2.3	18.1	15.8	Biomass	(UNEP & IRP, 2022)

Other islands show different metabolic structures. In Trinidad and Tobago, fossil fuel extraction and processing account for large share of material flows (Krausmann et al., 2014), and on Oahu, tourism and residential demand drive high petroleum imports (Eckelman & Chertow, 2009; U.S. Energy Information Administration, 2024). For Fiji, rising imports of cement, clinkers, and fuels, especially during cyclone-driven reconstruction, and eroding self-sufficiency underscore that a one-year snapshot conceals growing structural risks. Longitudinal MFA+SMR approach reveals how cumulative changes in flows and stocks shape vulnerability and resilience in ways that outcome-based indices and static analysis alone cannot.

4.4.2 Uncovering dynamic risks in Fiji

Fiji's material flow profile over the past two decades reveals how extreme events and external pressures disrupt long-term trends and shape systemic vulnerability. Cyclone Winston (2016), the strongest Southern Hemisphere storm, destroyed 130,000 homes and caused losses equal to 31% of GDP (World Bank, 2016). Port damage at Suva and Lautoka temporarily halted sugar and timber exports (Government of Fiji, 2016). This surged imports, especially non-metallic minerals, with temporary import duty relief and international loans supporting the influx of cement, steel, and other supplies (Government of Fiji, 2016). Similar "build-back" dynamics occurred in Samoa after Cyclone Evan (2012) which caused damage equal to 30% of GDP and triggered a spike in construction material imports (UNFCCC, 2014). Such events highlight cascading risks as destruction triggers sudden material inflows, which are often debt-financed (Martin Del Campo et al., 2023). In 2016–17, Fiji's agricultural and industrial output fell, increasing reliance on imported essentials (World Bank, 2016). These shocks strain both material and economic systems, as Cyclone Winston showed with waste, reconstruction, and fiscal stress. Similar disruptions followed Cyclones Harold and Yasa in 2020 in Fiji amid the COVID-19 crisis, compounding stress on material flows and the economy.

Other external shocks such as global market fluctuations and political instability have also shaped Fiji's material profile. The mid-2000s oil-price spike, a domestic coup, and COVID-19's tourism collapse; each left clear peaks and troughs in material inflows and widened trade deficits. Between 2007 and 2009, Fiji's trade deficit rose from 1.05 billion USD to 1.34 billion USD, a 296 million USD increase, driven largely by oil prices and fuel import (Country Economy, 2024). In 2008 fuel bills were nearly 29% of total imports and over 15% of GDP, pressuring reserves and inflation (Davies & Sugden, 2010). COVID-19 in 2020 collapsed tourism, cutting fuel imports and throughput, evident in our data findings. These shifts underscore that Fiji's material flows are tightly coupled to global systems, commodity markets, finance, and tourism.

Very low circularity amplifies exposure. Despite various recycling efforts, such as Mission Pacific, JICA-supported 3R programs, and campaigns led by the Pacific Recycling Foundation, Fiji's economy remains overwhelmingly linear due to an underdeveloped recycling infrastructure (International Union for Conservation of Nature, 2022; J-PRISM II Project, 2022). High throughput, minimal looping, and rising import dependency leave Fiji exposed to shocks and chronic liabilities. These patterns illustrate the mechanisms of SMR: growing import lock-in, long-lived stocks in hazard-prone areas that create path dependence, extreme events that trigger rebuilding cycles driving up demand for virgin materials, and persistently low circularity that limits recovery options, all of which deepen vulnerability. Understanding how these dynamic risks have evolved and interacted with the material flows would not have been possible without a time-series approach. In Fiji's case, these dynamics, compounding reliance on imports, accumulation of vulnerable stocks, and limited material recovery, collectively signal an evolving and elevated SMR

4.4.3 Can Fiji transform its socio-metabolic profile to adapt to climate risks?

Fiji’s socio-metabolic resilience is undermined by three interlinked dynamics: rising import dependence, accumulation of vulnerable stocks, and critically low circularity. Fiji’s 2025–2029 and 2050 vision National Development Plan (NDP) echoes these vulnerabilities and outlines interventions on agriculture, energy, construction, and waste that directly respond to the patterns identified in our analysis (Government of Fiji, 2024). Fiji’s biomass IDR rose from 6% in 2000 to 16% in 2022, aligning with the NDP’s recognition of food insecurity and its proposal for a national food stockpile mechanism, alongside renewed investment in rice and root crop farming. Strengthening domestic agriculture is thus a direct response to the structural decline in biomass DE documented in our analysis.

Sustained NAS growth of non-metallic minerals, likely near coastal areas where 90% of population lives, represents another vulnerability (Merschroth et al., 2020). The NDP acknowledges rising costs of imported construction materials and calls for domestic aggregates and retrofitting housing stock. These measures target build-back cycles revealed in our analysis, where cyclones convert long-lived assets into debris, triggering virgin imports. Fiji’s “build back better” approach since Cyclone Winston, with updated building codes and investment in nature-based defenses, responds to the need to prevent stocks from becoming a repeating liability (Government of Fiji, 2024; World Bank, 2016).

Another major vulnerability lies in energy dependency. Fiji relies heavily on imported fossil fuels, which leaves the economy exposed to global oil price shocks. Fuel imports have, at times, accounted for over 20% of GDP. The NDP admits Fiji’s high imported fossil fuels dependence and targets 2050 to achieve 100% renewable electricity (Government of Fiji, 2024). Our evidence underscores Fiji’s growing energy demand, and transition to hydro, solar, wind, and biomass is not only a climate imperative but also a matter of economic security, cushioning Fiji from oil price volatility and supply disruptions.

Fiji needs a shift toward circularity. ISCr and OSCr near zero, and NDP reports that only 0.2% of waste was recycled in 2021 (Government of Fiji, 2024). Biomass makes up about 54% of Fiji’s MSW, yet most organics are landfilled and barely recovered. Supporting bio-based startups and incentivizing waste-to-resource pilots could create exportable products and green jobs. Recent breakthroughs underscore the opportunity: Orange Fiber spins discarded citrus peels into luxury cellulose yarn used by Ferragamo (Aishwariya, 2020); Circular Systems' Agraloop™ converts banana stems and pineapple leaves into "BioFibre" threads sold through H&M's Conscious collections (Circular Systems, 2025); and Alt TEX, a Canadian startup, ferments food waste into biodegradable bioplastic fibre that can be molded into items such as plastic pallets (BetaKit, 2021). Complementary pilot projects are already under way in the Pacific, for example, IUCN-supported pilots in the Pacific use recycled plastic in pavement blocks (IUCN, 2022); scaling them will require regional cooperation to pool recyclables, cut logistics costs, and reach viable volumes. The successful implementation of such circular economy initiatives in Fiji could represent a "positive tipping point" for the region. As described by Flor et al. (2025), a positive tipping point is a critical threshold where targeted interventions can trigger self-reinforcing feedback loops that accelerate a system-wide transition toward sustainability. For Fiji, successfully converting organic waste into high-value exports or using recycled plastics in public infrastructure could create a demonstration effect, spurring regional cooperation, policy adoption, and private investment that scales these practices across other Pacific SIDS.

However, this transition toward greater self-sufficiency and circularity must navigate an increasingly complex geopolitical landscape that presents new dimensions of socio-metabolic risk. The trend toward de-globalization and rising geopolitical tensions can create new vulnerabilities for SIDS that are deeply integrated into global supply chains. For instance, a key challenge for a circular economy is managing residual waste streams that cannot be processed locally. In a more fragmented world, the question of "who will accept the wastes?" becomes critical. Island nations may find fewer viable export markets for their recyclables or face higher costs for disposing of hazardous materials, potentially leading to local environmental burdens if not managed proactively. These global dynamics reinforce the urgency for Fiji to reduce its overall material throughput and maximize domestic circularity, thereby minimizing its exposure to volatile international trade and waste management systems. Such actions are no longer just environmental policy but a core component of national security and resilience strategy.

Import policies should promote product circularity by favoring durable, repairable goods or those with take-back schemes, thereby easing waste burden and reducing imports. Stock-and-flow counterfactuals for Japan, the Netherlands, and Australia show national circularity plateauing near 14–15% (Miatto et al., 2025). Achieving similar levels would still relieve pressure on primary supplies and overflowing landfills. Adapting wet-processing techniques to sugar-cane bagasse, coconut husk, or breadfruit waste could reduce the gap in the biomass loop, cut landfill methane, and advance the NDP's mandate for innovation-driven, inclusive growth. For island economies like Fiji, circularity is a practical adaptation strategy.

Food and water security are equally crucial. Declining biomass production and climate threats from droughts, floods, and saltwater intrusion challenge self-reliance. Fiji is reviving rice farming, promoting root crops, and protecting freshwater, forests, and fisheries (Government of Fiji, 2024). Community-level buffers, such as local stocks of food, fuel, and materials, can sustain people when external aid is delayed after a disaster. These stockpiles serve as critical buffers in material flows, allowing countries to meet urgent needs without instant imports. Ultimately, building resilience in Fiji means shifting from a reactive, high-throughput model to one that is adaptive, circular, and locally anchored, ensuring the island can better withstand climate shocks and global uncertainties.

4.5 Summary of chapter 4

This study presents the first application of SMR concept via multi-decade (2000–2022) ew-MFA mass-balance account for a SIDS, using Fiji as a case study. Linking 23 years of extraction, trade, stock and waste data demonstrates why time-series application of SMR matters? it reveals patterns and feedbacks that remain hidden in single-year snapshots and captures the directionality of risk, whether resource-use trajectories move islands toward resilience or deeper traps of dependence. The work therefore represents a substantive methodological advance for island industrial ecology and for climate change adaptation analysis. The vulnerabilities uncovered here resonate with Fiji's 2025–2029 and 2050 vision NDP, which calls for strengthening domestic food security, expanding renewable energy, and accelerating waste recycling (Government of Fiji, 2024). Our analysis provides a metabolic map that can inform and reinforce these policy ambitions, helping to steer Fiji toward a more resilient and circular future.

Across the period, Fiji's metabolism shifted from local provisioning toward heavier reliance on imported food, building materials and fuel. Repeated cyclones erased stocks, generated new waste and triggered fresh waves of imports, locking the country into a costly "recovery loop." The finding underscores that climate shocks, trade dependence and limited waste capacity now reinforce one another. While there are nascent signs of adaptive potential, such as modest increases in material recovery and recycling, Fiji's current trajectory leaves it highly exposed to SMR. Fiji's experience is emblematic of broader patterns across SIDS, where similar structural vulnerabilities and linear resource dependencies prevail. To transform these vulnerabilities into pathways for sustainable resilience, critical interventions are urgently needed: strengthening domestic resource stocks, scaling up circular economy practices, and reorienting trade policies to prioritize long-lasting, repairable inputs. In parallel, promoting sustainable and material recovery businesses and startups can play a pivotal role in localizing value chains and generating green employment.

However, a major bottleneck is the widespread lack of robust, disaggregated databases on waste materials across SIDS. Without detailed and longitudinal data on material stocks, inflows, and outflows, including what is lost during and after disasters, it is difficult to track progress, identify leakage points, or design targeted circularity initiatives.

Advancing adaptation in SIDS will also require deeper research into how disasters reshape material flows across key sectors such as construction, energy, transport, and agriculture. Mapping these intersectoral linkages can reveal systemic fragilities as well as leverage points for intervention. Ultimately, building a resilient and circular metabolism in SIDS demands not only technical and infrastructural upgrades but also a scientific commitment to understanding how materials move, accumulate, and recover over time, especially in the wake of increasing shocks.

Chapter 5

Summary, contributions, and future research directions

5.1 Thesis Summary

This thesis addresses why a long-term, mass balanced account of SIDS analyzed from SMR lens matters? SIDS face systemic risk because their essential services increasingly depend on external material flows while local ecosystems and waste sinks are limited. Viewing Fiji's metabolism through the concept of SMR enables a systems diagnosis of where and how vulnerabilities accumulate, across supply dependence, shock sensitivity, and environmental loading, rather than a mere tally of material quantities. The core question is therefore risk-oriented: has Fiji's material use (2000–2022) steered its metabolism toward greater resilience or deeper vulnerability?

Answering this from a systems perspective required more than measuring tons. The analysis traces how structural shifts in inflows (domestic extraction vs. imports), net additions to stock, and low circularity interact with external shocks to shape the reliability of services and the exposure of people, infrastructure, and public finance. Findings show a transition away from self-sufficiency toward import-intensive construction minerals, fuels, and finished goods, with shock-driven reconstruction surges reinforcing linear consumption pathways. Concurrently, negligible circularity and rising waste outflows intensify pressure on limited absorptive capacities. Together, these dynamics signal growing import dependency, persistence of linear stock accumulation, and heightened sensitivity to disruption, distinct drivers of SMR.

The contribution of this thesis lies in reorienting island metabolism from quantification to sustainability actionability. Specifically, it: (i) provides a transparent, multi-decadal, mass balanced ew-MFA for a SIDS that is explicitly interpreted through an SMR lens; (ii) operationalizes a risk-focused indicator set, import dependence, net additions to stock, and circularity gap, to locate where risk concentrates in the system; and (iii) links metabolic patterns to policy levers for resilience (diversifying critical inflows, demand-side efficiency, targeted substitution, and end-of-life recovery). By centering why metabolism matters, service reliability, shock response, and environmental constraints, this study reframes material use as a sustainability problem with tractable interventions, not just a measurement exercise.

5.2 Key Findings and their Implications for SMR

The study provides a clear, empirically grounded answer to the central research question: Fiji's material metabolism between 2000 and 2022 has trended toward greater, not lesser, SMR. The key dynamics underpinning this conclusion are the erosion of domestic self-sufficiency, the accumulation of vulnerable material stocks through linear pathways, and the compounding effect of climate shocks on an already strained system.

5.2.1 The Erosion of Self-Sufficiency and Rising Import Dependency

A primary driver of Fiji's heightened SMR is its increasing reliance on external resources for essential functions. The 42% decline in domestic biomass extraction, driven by the contraction of the sugarcane sector, has been paralleled by an 80% rise in biomass imports. This signifies a structural shift in the nation's food system, moving away from domestic production and toward a greater dependency on imported cereals and processed foods. Similarly, the near-total reliance on imported fossil fuels and the fivefold increase in imported non-metallic minerals highlight a deep-seated dependency on global supply chains for energy and construction.

This metabolic profile constitutes a classic "metabolic trap" for SIDS. High import dependency makes the national economy acutely vulnerable to external shocks beyond its control, such as global commodity price volatility, geopolitical conflicts that disrupt shipping routes, and trade policy shifts in supplier nations. The 2008 global fuel crisis and the supply chain disruptions during the COVID-19 pandemic are stark reminders of how quickly these external factors can translate into domestic economic stress. By externalizing its resource base, Fiji's development path has amplified its exposure to systemic risks that threaten its ability to provide fundamental services to its population.

5.2.2 Stock Accumulation and "Lock-In"

Fiji's NAS (2000–2022) shows non-metallic minerals dominating stock additions, with pronounced surges in 2014 and 2017, indicating an infrastructure-led expansion of long-lived assets and associated path-dependence. Given the spatial concentration of people and services along shorelines, 90% of Fiji's population lives in coastal areas and 76% live within 5 km of the coast (91% within 10 km), new stock could have concentrated in hazard-exposed coastal corridors (Republic of Fiji, 2018; DFAT, 2021). This exposure is mirrored in services: in Fiji, 41% of medical facilities lie within 500 m of the shoreline (Taylor, 2021), while regionally 67% of infrastructure in Pacific islands is within 500 m of the coast (IPCC, 2022). Together, the NAS signal and siting evidence strongly suggest a material lock-in of risk: coastal siting hardens exposure to sea-level rise, storm surge, and compound flooding over asset lifetimes. To better understand and manage these risks, a time-series spatial MSA should map annual NAS data onto coastal zones (e.g., within 50 m, 100 m, 500 m, and 1 km from the shore) and low-lying areas below 10 m elevation. This can then be compared with SLR and flooding scenarios to identify which areas need to be prioritized for protection, upgrades, or relocation.

5.2.3 Take – Make – Dispose Metabolism

The evidence on waste and recycling indicates an overwhelmingly linear metabolism: materials move from extraction (domestic or imported) to use and disposal with minimal recovery or cascading reuse. With municipal solid waste recycling rates near zero, Fiji's loops remain effectively open. This linearity intensifies SMR because service provision becomes contingent on a constant inflow of virgin materials, exposing the economy to price volatility, port disruptions, and foreign-exchange constraints, while unrecovered outflows accumulate as disposal burdens that compress limited landfill capacity, elevate leachate and marine-litter risks, and shift costs onto communities, especially on outer islands with minimal infrastructure. Post-shock debris surges (cyclones, floods) further amplify linear pathways by triggering emergency imports for reconstruction at the same time as large, poorly sorted waste streams overwhelm existing systems.

Policy implications follow directly from these mechanisms. Priority should be given to closing loops where risk is most concentrated. In C&D, this means introducing deconstruction standards, mandating recycled-aggregate specifications in public projects, and piloting a central sorting and recycling hub proximate to major ports to leverage backhaul logistics. For organics, source separation and distributed composting or anaerobic digestion can reduce landfill loads, mitigate methane risk, and lower transport costs on outer islands. Metals and e-waste require stabilizing finance and predictable flows created by extended producer responsibility (EPR) and deposit-return schemes (DRS), while packaging can be addressed through phased EPR/DRS that dampens import-linked throughput and litter. Parallel support for repair and reuse enterprises, particularly for appliances and construction components, extends product lifetime, reduces replacement imports, and builds local skills.

Because climate shocks are recurrent, debris management must be integrated into emergency planning rather than treated as an ad-hoc, post-event problem. Pre-contracted surge capacity for sorting, designated temporary staging sites, and protocols to salvage reusable components can prevent one-off linear spikes that erode future resilience by locking in additional import dependence.

Data limitations are themselves a policy signal and a lever. Standardizing waste reporting by material category and by island, installing weighbridges at key facilities, and aligning categories with the ew-MFA structure (biomass, construction minerals, metals, fossil-derived products, etc.) would create the information backbone for circularity. Linking waste records to NAS enables anticipation of "waste waves" as building cohorts age, supporting forward planning for capacity, siting, and procurement.

Finally, demand creation is essential. Green public procurement can underwrite markets for recycled aggregates, compost, and remanufactured components, reducing perceived risk for private investment in recovery infrastructure and translating measurement into action. Progress should be tracked with a risk-aligned indicator set that includes import dependence for priority materials, circularity or diversion rates by category and island, DPOw per capita alongside estimated years of remaining landfill capacity, stock longevity for key asset classes to forecast end-of-life surges, and shock-sensitivity metrics that quantify reconstruction-driven inflow spikes. Read together, these indicators convert a "take–make–dispose" diagnosis into a practical agenda for de-risking Fiji's metabolism.

5.2.4 Climate Shocks and Resource Vulnerability

The longitudinal account reveals how extreme events amplify underlying SMRs. The 2016 spike in construction-material imports following Tropical Cyclone Winston functions as a natural experiment: destruction of in-use stocks (buildings, roads, utilities) immediately translated into extraordinary demand for replacement materials, fuels, and manufactured components. Because local recovery capacity and secondary materials markets are limited, that demand was met largely through imports, intensifying foreign-exchange exposure, straining public finances, and pushing port and logistics systems to their limits. In short, the shock accelerated a pre-existing linear metabolism in which services are restored by drawing on virgin, externally sourced materials.

This "rebuild cycle" also creates path dependence. Emergency procurement prioritizes speed and availability, which often favors conventional, import-intensive materials and like-for-like replacement. The result is a surge in net additions to stock that reproduces prior vulnerabilities: short lifetimes, high maintenance needs, and limited repairability. Simultaneously, disaster debris arrives as a large, poorly sorted “waste wave,” overwhelming collection and landfill capacity and foreclosing reuse or recycling opportunities. The combination of reconstruction inflows and unmanaged outflows raises SMR on two fronts, by deepening import dependence and by loading already constrained environmental sinks.

The broader implication is that climate adaptation and resource management cannot be treated as separate agendas in SIDS. Resilience hinges not only on hazard-proofing assets but on altering the material profile of recovery itself: extending lifetimes through higher durability standards and design-for-repair; substituting toward materials with lower import and environmental risk; pre-positioning secondary materials (e.g., recycled aggregates) and modular components; and integrating debris-management protocols that salvage, sort, and reinject materials into local use. Policies such as green public procurement and contingency contracts for sorting and remanufacturing shift reconstruction from a linear throughput to a circular, service-oriented response. Practically, progress can be assessed by tracking reconstruction import intensity, the share of recovery met by recirculated materials, the time to restore critical services with lower material inflow, and the avoided landfill burden. Framed this way, each future shock becomes an opportunity to bend Fiji’s metabolism away from “take–make–dispose” and toward a more self-reliant, circular pathway that reduces SMR over time.

5.3 Policy Relevance: Pathways to Resilience

The findings of this thesis offer a robust, evidence-based foundation for shaping policies aimed at enhancing Fiji’s climate resilience and fostering sustainable development. By operationalizing the SMR concept, the analysis moves beyond generic calls for sustainability to identify specific leverage points within the national metabolism where interventions can be most effective. The policy implications align closely with Fiji’s existing ambitions, as articulated in its National Development Plan and National Climate Change Policy, but provide the quantitative grounding needed to prioritize and monitor action (Government of Fiji, 2024; SPREP, 2023).

1. **Strengthening Resilience through a Circular Economy:** The extremely low circularity rates highlight an urgent need to invest in waste management infrastructure and create markets for secondary materials. Key opportunities lie in developing systems for composting

organic waste to support local agriculture, and establishing facilities for recycling C&D waste, which would reduce both landfill pressure and demand for imported construction materials. Policy instruments such as advanced recovery fees, as implemented in other Pacific nations, could create sustainable financing mechanisms for these initiatives (PacWaste Plus, 2023).

2. **Increasing self-sufficiency:** The absolute reliance on imported fossil fuels is Fiji's most significant metabolic vulnerability. Accelerating the transition to renewable energy, in line with the nation's 100% renewable target for 2030, is therefore not just a climate mitigation strategy but a critical measure for enhancing energy security and economic resilience (Government of Fiji, 2023). Similarly, policies that support local food systems, from smallholder agriculture to sustainable fisheries, can help reverse the trend of declining food self-sufficiency and reduce vulnerability to global food price shocks.
3. **Breaking the Rebuild Cycle with Resilient Infrastructure:** The analysis of post-cyclone material flows features the importance of investing in resilient infrastructure. Enforcing and updating building codes to withstand higher-intensity cyclones, as advocated in Fiji's "build back better" approach, is essential to reduce the scale of material destruction in future disasters (World Bank, 2016). Furthermore, integrating nature-based solutions, such as the protection and restoration of mangrove ecosystems for coastal defense, can reduce the need for material-intensive hard infrastructure while providing co-benefits for biodiversity and livelihoods.
4. **Improving Data Governance for Adaptive Management:** A recurring theme throughout this study has been the challenge of data scarcity, particularly for waste and recycling. To effectively manage its SMR, Fiji needs to invest in robust systems for biophysical data collection and monitoring. A national, standardized ew-MFA, conducted regularly, would provide policymakers with the timely information needed to track progress, evaluate the effectiveness of interventions, and adapt strategies in response to changing conditions.

5.4 Thesis Contributions

This thesis makes several distinct contributions to both the academic literature and the practice of sustainable development in SIDS.

- **Contextual Contribution:** It provides the first multi-decadal, mass balanced ew-MFA for a Pacific SIDS from a SMR lens. This detailed, 23-year account for Fiji offers an unprecedented empirical record of a small island's metabolic trajectory, providing a valuable dataset for future comparative research and a baseline against which future progress can be measured.
- **Operationalization of SMR:** This study represents a significant step forward in the application of the SMR concept. While the foundational work of Singh et al. (2022) introduced the concept and the analysis by Martin del Campo (2023) on The Bahamas proved its utility with a single-year snapshot, this thesis is the first to fully operationalize SMR over a multi-decade time series. This longitudinal application demonstrates the concept's unique power in revealing dynamic, path-dependent risks that a static analysis cannot capture. It elevates SMR from a static diagnostic tool to a dynamic monitoring lens, capable of tracking how a nation’s vulnerability evolves in response to economic shifts, policy interventions, and climate shocks.
- **Methodological Contribution:** The research demonstrates a replicable methodology for conducting a long-term ew-MFA in a data-constrained SIDS context. The detailed data architecture, harmonization protocol, and transparent use of proxy data provide a practical guide for researchers seeking to undertake similar studies in other island nations, thereby helping to fill a critical data gap for this vulnerable group of countries.

5.5 Research Limitations and Future Directions

While this thesis breaks new ground, it is important to acknowledge its limitations, which in turn point toward valuable avenues for future research. The most significant limitation was the scarcity and fragmentation of data, particularly for material outflows. The reliance on proxy data for waste composition and the gaps in recycling statistics introduce uncertainties into the mass balance. While managed through a transparent and rigorous protocol, these data challenges highlight the need for improved national statistical capacity for biophysical accounting in SIDS. Methodologically, an ew-MFA provides a macro-level, "bird's-eye view" and cannot capture the distributional dynamics and inter-sectoral complexities within the economy.

This limitation defines the next logical step for socio-metabolic research in SIDS. Having established the overall metabolic profile of the nation, the research frontier must now move from the macroscopic to the mesoscopic, diving deeper into the internal workings of the island economy. The ew-MFA framework treats the economy as a black box, quantifying what goes in and what comes out, but not how materials are transformed and exchanged between different economic sectors. To design targeted and effective policies for a circular economy and risk reduction, it is crucial to understand these internal dynamics. For example, how are imported fossil fuels allocated between the electricity, transport, and industrial sectors? How are construction materials distributed between tourism infrastructure, residential housing, and public works? Answering these questions requires moving beyond aggregate national accounts.

The most promising methodology for this next phase of research is the development of Physical Input-Output Tables (PIOT). A PIOT is the physical counterpart to the well-established monetary input-output tables (MIOTs) used in national economic accounting (Weisz & Duchin, 2006). Instead of tracking monetary transactions between economic sectors, a PIOT tracks the flow of materials in physical units, such as tonnes. It is a comprehensive matrix that provides a detailed, mass balanced map of all the material that flows from one economic sector to another, as well as the exchanges between the economy and the natural environment (i.e., resource extraction and waste/emission outputs) (Hoekstra & van den Bergh, 2006; United Nations et al., 2014).

The structure of a PIOT is a grid where economic sectors (e.g., agriculture, construction, manufacturing, energy generation, transport) are listed as both rows and columns. Each cell within this grid represents the physical quantity of a specific material that is supplied by the sector in the row to the sector in the column. This framework allows for a complete and consistent accounting of how raw materials are transformed into intermediate goods, then into final products, and finally, how they become waste streams that may be recycled or disposed of (Hoekstra & van den Bergh, 2006; United Nations et al., 2014).

PIOTs could represent a significant methodological advancement over standard ew-MFA by combining the strengths of Material Flow Analysis with the structural detail of input-output modeling. This integration provides a much more granular and powerful analytical lens. PIOT has the potential to help in:

- Revealing Inter-Sectoral Dependencies: While an ew-MFA can show that a nation has a high dependency on imported steel, a PIOT can reveal precisely which sectors are the primary consumers of that steel (e.g., construction, automotive manufacturing, appliance production)

(Wieland et al., 2020; Hoekstra & van den Bergh, 2006; World Steel Association, 2024). This allows for a much more nuanced understanding of the economy's physical structure and its specific points of vulnerability.

- Tracing Supply Chains and Environmental Pressures: PIOTs can trace the entire physical supply chain of a product, from the extraction of raw materials to its final consumption (United Nations et al., 2014; Hoekstra & van den Bergh, 2006). This makes it possible to identify “hotspots”, the specific sectors or production stages that are responsible for the largest resource consumption or waste generation (Lenzen, 2003; Towa et al., 2020; Lutter et al., 2024). This level of detail is crucial for designing effective policies aimed at resource efficiency and pollution reduction.
- Enabling Sophisticated Circular Economy Analysis: The circular economy aims to close material loops by turning the waste from one process into a resource for another. A PIOT is a powerful tool for identifying and quantifying these opportunities for industrial symbiosis (Yeo et al., 2019; Chertow, 2000; Towa et al., 2020). By explicitly mapping waste flows (residuals) from each sector, a PIOT can show, for example, how much construction and demolition waste is generated and assess its potential for being re-used as an input for new construction materials, thereby reducing the need for virgin resource extraction (United Nations et al., 2014; Nakamura & Kondo, 2002; Salemdeeb et al., 2016; Purchase et al., 2021).
- Modeling Cascading Risks: From an SMR perspective, the greatest advantage of a PIOT is its ability to model cascading effects. A standard MFA might identify a risk, such as reliance on a single source for imported fossil fuels. A PIOT can model the systemic consequences of a disruption to that supply (Miller & Blair, 2009; Okuyama & Santos, 2014; Hoekstra & van den Bergh, 2006). It can quantify how a fuel shortage would first impact the electricity and transport sectors, and how those disruptions would then cascade through the rest of the economy, affecting everything from manufacturing output to food distribution and tourism services (Ember, 2024; Santos & Haimes, 2004; Okuyama & Santos, 2014).

By moving from the aggregate "bird's-eye view" of ew-MFA to the detailed, structural map provided by a PIOT, future research can transition from identifying the *existence* of SMRs to analyzing their “Structural Metabolic Dependencies” (SMD). This deeper understanding is the essential next step for designing robust, evidence-based policies that can effectively steer vulnerable island economies like Fiji toward a truly circular, resilient, and sustainable future.

Beyond the development of PIOTs, other important avenues of research that would benefit the discussion could be:

- Spatially Explicit MSA: Combining the stock data from this thesis with GIS mapping would allow for a spatially resolved MSA. This could identify the precise locations of critical infrastructure and building stocks, enabling a more accurate assessment of their vulnerability to specific climate hazards like SLR and cyclone storm surge, thereby providing an invaluable tool for land-use planning and prioritizing adaptation investments.
- Integration with Socio-Economic Indicators: Future studies should integrate the biophysical data from this ew-MFA with socio-economic indicators to explore the equity dimensions of SMR. This would help to answer critical questions about how the benefits of resource use and the burdens of waste and vulnerability are distributed across different income groups and communities, ensuring that the transition to a resilient society is also a just one.

A critical evolution in development discourse involves reframing island nations not as ‘Small Island Developing States’ (SIDS), a term that inherently emphasizes land scarcity and isolation, but as ‘Large Ocean States’ (LOS) (Pacific Islands Forum Secretariat, 2022; Shurety et al., 2022). This perspective powerfully reorients identity and strategic focus away from terrestrial limitations and towards the vast Exclusive Economic Zones (EEZs) and the deep cultural and economic connections islanders have with the sea. From a SMR lens, this conceptual widening of the system boundary from land to land-sea continuum is not merely academic; it represents a tangible shifting of metabolic risks. For example, seawater desalination is often promoted as a technological solution to climate-induced water stress, a key vulnerability for SIDS (Forde et al., 2024; UNESCO, 2023). However, this intervention can create a new set of metabolic dependencies: it significantly increases electricity demand, often straining already import-dependent energy grids, while introducing new environmental pressures from the disposal of high-salinity brine waste (IRENA & IEA-ETSAP, 2012; IRENA, 2020, 2024; Jones et al., 2019).

Crucially, this expanded metabolic system cannot be viewed as a simple resource frontier. As articulated by Hau‘ofa (1994), for many Islanders the ocean is a lived and connective space, a 'sea of islands' that facilitates kinship, trade, and cultural identity, rather than an empty void that separates them. This perspective demands that any land–sea metabolic accounting must move beyond purely extractive metrics and incorporate rigorous equity tests for 'blue-economy' expansion, ensuring that development aligns with cultural values and local wellbeing. Therefore, it is imperative to evaluate the distributional outcomes under various blue-growth scenarios, questioning who benefits from and who bears the costs of new marine industries to ensure that the pursuit of ocean resources leads to genuine, equitable resilience rather than new forms of metabolic risk.

In conclusion, this thesis has demonstrated that a long-term, SMR perspective is essential for understanding the complex interplay of development, resource use, and vulnerability in SIDS. For Fiji, the past two decades have been a period of profound metabolic change, leading to a heightened state of SMR. However, by revealing the specific drivers of this risk, this research also illuminates the pathways toward a more resilient and sustainable future, one built on a foundation of greater self-sufficiency, circularity, and a deep-seated commitment to aligning its development with the ecological realities of an island nation in a changing world.

References

Aishwariya, A. (2020). Orange Fiber's citrus-based cellulose yarn: A circular solution for fashion. *Textile Futures Journal, 12*(4), 45–60.

AL Circle. (2020, June 14). Bauxite mine site rehabilitation in Fiji continues. *AL Circle*. https://www.alcircle.com/news/bauxite-mine-site-rehabilitation-in-fiji-continues-57092

Altimiras-Martín, A. (2014). Analysing the structure of the economy using physical input-output tables. *Economic Systems Research, 26*(4), 463–485. https://doi.org/10.1080/09535314.2013.872379

Asian Development Bank (ADB). (2008, October). *Completion report: Fiji Ports Development Project in the Republic of the Fiji Islands* (Project No. 32525; Loan No. 1902-FIJ). https://www.adb.org/sites/default/files/project-documents/32525-fij-pcr.pdf

Asian Development Bank (ADB). (2011, December). *Performance evaluation report: Fiji Ports Development Project* (Project No. 32525; Loan No. 1902). https://www.fijiroads.org/wp-content/uploads/2024/04/Fiji-Ports-Dment-Project-ADB-Dec2011.pdf

Asian Development Bank (ADB). (2020). *Trade and maritime transport trends in the Pacific (Fiji, Papua New Guinea, Samoa, Timor-Leste, Tonga, Vanuatu).* https://www.adb.org/publications/trade-maritime-transport-trends-pacific

Asari, M., Tsuchimura, M., Sakai, S.-I., Tsukiji, M., & Sagapolutele, F. (2019). Analysis of mismanaged plastic waste in Samoa to suggest proper waste management in Pacific island countries. *Waste Management & Research, 37*(12), 1207–1216. https://doi.org/10.1177/0734242X19867391

Australian Treasury. (2011). The second international food and fuel-price shock and Forum island economies. *Economic Round-up, 3*. https://treasury.gov.au/publication/economic-roundup-issue-3-2011/economic-roundup-issue-3-2011/the-second-international-food-and-fuel-price-shock-and-forum-island-economies

Bahers, J.-B., Higuera, P., Ventura, A., & Antheaume, N. (2020). The "metal–energy–construction mineral" nexus in the island metabolism: The case of the extractive economy of New Caledonia. *Sustainability, 12*(6), 2191. https://doi.org/10.3390/su12062191

Bahers, J.-B., Singh, S. J., & Durand, M. (2022). Analyzing socio-metabolic vulnerability: Evidence from the Comoros Archipelago. *Anthropocene Science, 1*, 164–178. https://doi.org/10.1007/s44177-022-00017-1

Baldacchino, G. (2005). Editorial: Islands—Objects of representation. *Geografiska Annaler: Series B, Human Geography, 87*(4), 247–251. https://doi.org/10.1111/j.0435-3684.2005.00197.x

Bennett, N. J., Cisneros-Montemayor, A. M., Blythe, J., Silver, J. J., Singh, G., Andrews, N., … Sumaila, U. R. (2019). Towards a sustainable and equitable blue economy. *Nature Sustainability, 2*(11), 991–993. https://doi.org/10.1038/s41893-019-0404-1

Bennett, N. J., Villasante, S., Espinosa-Romero, M. J., Lopes, P. F. M., Selim, S. A., & Allison, E. H. (2022). Social sustainability and equity in the blue economy. *One Earth, 5*(9), 964–968. https://doi.org/10.1016/j.oneear.2022.08.004

Betzold, C. (2015). Adapting to climate change in small island developing states: A new era of international climate politics. *International Studies Review, 17*(4), 549–573. https://doi.org/10.1111/misr.12258

BetaKit. (2021, May 19). ALT TEX closes $1.5 million pre-seed round to commercialize sustainable polyester alternative. https://betakit.com/alt-tex-closes-1-5-million-pre-seed-round-to-commercialize-sustainable-polyester-alternative/

Binder, C. R., Athanassiadis, A., Bristow, D., Haberl, H., & Kennedy, C. (2025). Tipping points toward sustainability: The role of industrial ecology. *Journal of Industrial Ecology*, 1–12. https://doi-org.proxy.lib.uwaterloo.ca/10.1111/jiec.70000

Biswas, B. (2017, May 9). Fiji is ramping up its bauxite export capabilities despite socio-political unrest. *AL Circle*. https://www.alcircle.com/news/fiji-is-ramping-up-its-bauxite-export-capabilities-despite-socio-political-unrest-27667

Bradshaw, J., Singh, S. J., Tan, S.-Y., Fishman, T., & Pott, K. (2020). GIS-based material-stock analysis of climate vulnerabilities to the tourism industry in Antigua and Barbuda. *Sustainability, 12*(19), 8090. https://doi.org/10.3390/su12198090

Briguglio, L. (1995). Small Island Developing States and their economic vulnerabilities. *World Development, 23*(9), 1615–1632. https://doi.org/10.1016/0305-750X(95)00065-K

Cecchin, A. (2017). Material flow analysis for a sustainable resource management in island ecosystems: A case study in Santa Cruz Island (Galápagos). *Journal of Environmental Planning and Management, 60*(9), 1640–1659. https://doi.org/10.1080/09640568.2016.1246997

Chertow, M. R. (2000). Industrial symbiosis: Literature and taxonomy. *Annual Review of Energy and the Environment, 25*, 313–337. https://doi.org/10.1146/annurev.energy.25.1.313

Chertow, M. R., Graedel, T. E., Kanaoka, K. S., & Park, J. (2020). The Hawaiian Islands: Conceptualizing an industrial ecology holarchic system. *Sustainability, 12*(8), Article 8. https://doi.org/10.3390/su12083104

Circle Economy. (2025). *The Circularity Gap Report 2025*. https://www.circularity-gap.world/2025

Circular Systems. (2025). *Agraloop™: Converting banana and pineapple wastes into BioFibre threads.* https://circularsystems.com/agraloop-whitepaper

CountryEconomy. (2024). *Fiji trade balance historical data.* https://countryeconomy.com/trade/balance/fiji

Dai, T., Yue, Z., Zhang, X., & Chi, Y. (2025). A Systems Perspective on Material Stocks Research: From Quantification to Sustainability. Systems, 13(7), Article 7. https://doi.org/10.3390/systems13070587

Davies, M., & Sugden, C. (2010). *Macroeconomic impacts of energy prices in the Pacific* (PFTAC Regional Paper No. 4). Pacific Financial Technical Assistance Centre.

Dean, M. R. U. (2022). The Fiji sugar industry: Sustainability challenges and the way forward. *Sugar Tech, 24*(3), 662–678. https://doi.org/10.1007/s12355-022-01132-4

Deo, A., Chand, S. S., McIntosh, R. D., Prakash, B., Holbrook, N. J., Magee, A., Haruhiru, A., & Malsale, P. (2022). Severe tropical cyclones over southwest Pacific Islands: Economic impacts and implications for disaster risk management. *Climatic Change, 172*(3), 38. https://doi.org/10.1007/s10584-022-03391-2

Deschenes, P. J., & Chertow, M. (2004). An island approach to industrial ecology: Towards sustainability in the island context. *Journal of Environmental Planning and Management, 47*(2), 201–217. https://doi.org/10.1080/0964056042000209102

Department of Foreign Affairs and Trade (DFAT). (2021). *Pacific risk profile – Fiji.* Government of Australia.

Dietzenbacher, E., Giljum, S., Hubacek, K., & Suh, S. (2009). Physical input-output analysis and disposals to nature. In S. Suh (Ed.), *Handbook of input-output economics in industrial ecology* (pp. 123–137). Springer.

Eckelman, M. J., & Ashton, W., Arakaki, Y., Hanaki, K., Nagashima, S., & Malone-Lee, L. C. (2014). Island waste management systems: Statistics, challenges, and opportunities for applied industrial ecology. *Journal of Industrial Ecology, 18*(2), 306–317. https://doi.org/10.1111/jiec.12113

Eckelman, M. J., & Chertow, M. R. (2009). Using material flow analysis to illuminate long-term waste management solutions in O‘ahu, Hawai‘i. *Journal of Industrial Ecology, 13*(5), 758–774. https://doi.org/10.1111/j.1530-9290.2009.00159.x

Elgie, A., Singh, S. J., & Telesford, J. (2021). You can't manage what you can't measure: The potential for circularity in Grenada's waste management system. *Resources, Conservation and Recycling, 164*, 105170. https://doi.org/10.1016/j.resconrec.2020.105170

Eurostat (European Commission). (2018). *Economy-wide material flow accounts handbook: 2018 edition.* Publications Office of the European Union. https://data.europa.eu/doi/10.2785/158567

Eurostat. (2022). *Import dependency of raw materials (cei_gsr030).* https://ec.europa.eu/eurostat/cache/metadata/en/cei_gsr030_esmsip2.htm

Fischer-Kowalski, M., Krausmann, F., Giljum, S., Lutter, S., Mayer, A., Bringezu, S., … Weisz, H. (2011). Methodology and indicators of economy-wide material flow accounting. *Journal of Industrial Ecology, 15*(6), 855–876. https://doi.org/10.1111/j.1530-9290.2011.00366.x

Foolmaun, R. K., Ramjeeawon, T., & Kowlesser, P. (2011). Overview of non-hazardous solid waste in the small island state of Mauritius. *Resources, Conservation and Recycling, 55*(9–10), 974–982. https://doi.org/10.1016/j.resconrec.2011.05.002

Forde, M. S., Cashman, A., & Mitchell, K. (2024). Sustainability of water resources in Caribbean small island developing states: An overview. *Discover Sustainability, 5*(265). https://doi.org/10.1007/s43621-024-00478-x

Franzke, C. L. E., Ciullo, A., Gilmore, E. A., Matias, D. M., Nagabhatla, N., Orlov, A., Paterson, S. K., Scheffran, J., & Sillmann, J. (2022). Perspectives on tipping points in integrated models of the natural and human earth system: Cascading effects and telecoupling. *Environmental Research Letters*. https://doi.org/10.1088/1748-9326/ac42fd

Frosch, R. A., & Gallopoulos, N. E. (1989). Strategies for manufacturing. *Scientific American, 261*(3), 144–152. https://doi.org/10.1038/scientificamerican0989-144

Ghisellini, P., Cialani, C., & Ulgiati, S. (2016). A review on circular economy: The expected transition to a balanced interplay of environmental and economic systems. *Journal of Cleaner Production, 114*, 11–32. https://doi.org/10.1016/j.jclepro.2015.09.007

Government of Fiji, Ministry of Public Works, Meteorological Services and Transport, Department of Energy. (2023). *Republic of Fiji National Energy Policy 2023–2030.* Government of Fiji.

Government of Fiji, World Bank, Global Facility for Disaster Reduction and Recovery, & Partners. (2016). *Post-disaster needs assessment: Tropical Cyclone Winston, Fiji 2016.* https://www.gfdrr.org/sites/default/files/publication/Post%20Disaster%20Needs%20Assessments%20CYCLONE%20WINSTON%20Fiji%202016%20(Online%20Version).pdf

Graedel, T. E., & Allenby, B. R. (2003). *Industrial ecology* (2nd ed.). Prentice Hall.

Gravgård Pedersen, O. (1999). *Physical input-output tables for Denmark: Products and materials 1990; air emissions 1990–92.* Statistics Denmark.

Great Barrier Reef Marine Park Authority. (2024). *Outlook report 2024.* https://outlookreport.gbrmpa.gov.au/

Haas, W., Krausmann, F., Wiedenhofer, D., & Heinz, M. (2015). How circular is the global economy? An assessment of material flows, waste production, and recycling in the European Union and the world in 2005. *Journal of Industrial Ecology, 19*(5), 765–777. https://doi.org/10.1111/jiec.12244

Haberl, H., Fischer-Kowalski, M., Krausmann, F., & Winiwarter, V. (Eds.). (2016). *Social ecology: Society–nature relations across time and space.* Springer. https://doi.org/10.1007/978-3-319-33326-7

Haberl, H., Wiedenhofer, D., Erb, K.-H., Görg, C., & Krausmann, F. (2017). The material stock–flow–service nexus: A new approach for tackling the decoupling conundrum. *Sustainability, 9*(7), 1049. https://doi.org/10.3390/su9071049

Haberl, H., Wiedenhofer, D., Pauliuk, S., Krausmann, F., Müller, D. B., & Fischer-Kowalski, M. (2019). Contributions of sociometabolic research to sustainability science. *Nature Sustainability, 2*(3), 173–184. https://doi.org/10.1038/s41893-019-0225-2

Hafiz, M., Singh, S. J., Pisini, S. K., & Thammadi, S. (2024). *Islands at the brink – Country brief: Fiji* (RECOVER Working Paper 2). International Development Research Centre. https://hdl.handle.net/10625/63513

Handmer, J., & Nalau, J. (2019). Understanding loss and damage in Pacific Small Island Developing States. In R. Mechler, L. M. Bouwer, T. Schinko, S. Surminski, & J. Linnerooth-Bayer (Eds.), *Loss and damage from climate change: Concepts, methods and policy options* (pp. 365–381). Springer. https://doi.org/10.1007/978-3-319-72026-5_15

Hauʻofa, E. (1994). Our sea of islands. *The Contemporary Pacific, 6*(1), 147–161.

Hauʻofa, E. (2008). *We are the ocean: Selected works*. Honolulu: University of Hawaiʻi Press. https://doi.org/10.1515/9780824865542

Hinkel, J., Lincke, D., Vafeidis, A. T., Perrette, M., Nicholls, R. J., Tol, R. S. J., Marzeion, B., Fettweis, X., Ionescu, C., & Levermann, A. (2014). Coastal flood damage and adaptation costs under 21st century sea-level rise. *Proceedings of the National Academy of Sciences, 111*(9), 3292–3297. https://doi.org/10.1073/pnas.1222469111

Hoekstra, R., & van den Bergh, J. C. J. M. (2006). Constructing physical input–output tables for environmental modeling and accounting: Framework and illustrations. *Ecological Economics, 59*(3), 375–393.

Hubacek, K., & Giljum, S. (2003). Applying physical input–output analysis to estimate land appropriation (ecological footprints) of international trade activities. *Ecological Economics, 44*(1), 137–151. https://doi.org/10.1016/S0921-8009(02)00257-2

Intergovernmental Oceanographic Commission of UNESCO. (2024). *State of the Ocean Report 2024.* https://www.ioc.unesco.org/en/stor2024

Intergovernmental Panel on Climate Change. (2022). *Climate Change 2022: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change.* Cambridge University Press.

Intergovernmental Panel on Climate Change (IPCC). (2019). *Special report on the ocean and cryosphere in a changing climate.* https://www.ipcc.ch/srocc/

Intergovernmental Panel on Climate Change (IPCC). (2021). *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change.* Cambridge University Press.

Intergovernmental Panel on Climate Change (IPCC). (2022). Small islands (Chapter 15). In *Climate change 2022: Impacts, adaptation and vulnerability.* https://www.ipcc.ch/report/ar6/wg2/

International Energy Agency. (2024, May 27). Islands need resilient power systems more than ever: Clean energy can deliver. https://www.iea.org/commentaries/islands-need-resilient-power-systems-more-than-ever-clean-energy-can-deliver

International Monetary Fund. (2005, May 25). *Grenada: Rebuilding after Hurricane Ivan.* https://www.imf.org/en/News/Articles/2015/09/28/04/54/tr052505

International Monetary Fund. (2021). *Feeling the heat: Climate change and macroeconomic performance in the Pacific Islands* (IMF Departmental Paper No. 2021/019). https://www.imf.org/en/Publications/Departmental-Papers-Policy-Papers/Issues/2021/08/10/Feeling-the-Heat-Climate-Change-and-Macroeconomic-Performance-in-the-Pacific-Islands-462947International Renewable Energy Agency, & IEA-ETSAP. (2012). *Water desalination using renewable energy* (Technology Brief I12). IRENA.

International Renewable Energy Agency. (2015). *Renewables readiness assessment: Fiji.* https://islands.irena.org/-/media/Sids/Files/Publications/Fiji---Renewables-Readiness-Assessment-Fiji.pdf

International Renewable Energy Agency. (2020, October). Islands aim to phase out fossil fuels. https://www.irena.org/News/articles/2020/Oct/Islands-aim-to-phase-out-fossil-fuels

International Renewable Energy Agency. (2024). *Small Island Developing States at a crossroads: Towards equitable energy access in least-electrified countries.*

https://www.irena.org/Publications/2024/Mar/SIDS-at-a-Crossroads-Towards-equitable-energy-access-in-least-electrified-countries

International Renewable Energy Agency. (2024). *Tracking COP28 outcomes: Tripling renewable power and doubling energy efficiency by 2030.* https://www.irena.org/Publications/2024/Mar/Tracking-COP28-outcomes

International Trade Administration. (2022). *Trinidad and Tobago – Market overview.* U.S. Department of Commerce. https://www.trade.gov/country-commercial-guides/trinidad-and-tobago-market-overview

International Union for Conservation of Nature. (2022, July 8). Plastic pollution solutions at the forefront with the IUCN Ubuntoo community. https://iucn.org/story/202207/plastic-pollution-solutions-forefront-iucn-ubuntoo-community

Jones, E., Qadir, M., van Vliet, M. T. H., Smakhtin, V., & Kang, S.-M. (2019). The state of desalination and brine production: A global outlook. *Science of the Total Environment, 657*, 1343–1356. https://doi.org/10.1016/j.scitotenv.2018.12.076

J-PRISM II Project. (2022). *Solid waste management country profile: Fiji.* Secretariat of the Pacific Regional Environment Programme. https://www.sprep.org/j-prism-2/home

Jenkins, N. (2016, February 12). Fiji is the first country in the world to ratify the landmark Paris climate deal. *Time*. https://time.com/4225155/paris-agreement-fiji-ratification-climate-change/

Juhola, S., Filatova, T., Hochrainer-Stigler, S., Mechler, R., Scheffran, J., & Schweizer, P.-J. (2022). Social tipping points and adaptation limits in the context of systemic risk: Concepts, models and governance. *Frontiers in Climate, 4*. https://www.frontiersin.org/articles/10.3389/fclim.2022.1009234

Kelman, I. (2018). Islandness within climate change narratives of Small Island Developing States (SIDS). *Island Studies Journal, 13*(1), Article 1.

Kelman, I. (2021, May 23). *Climate change or choice? What causes disasters?* Me, Myself & Disaster. https://memyselfdisaster.com/climate-change-or-choice-what-causes-disasters/

Kim, K. E., & Bui, L. (2019). Learning from Hurricane Maria: Island ports and supply-chain resilience. *International Journal of Disaster Risk Reduction, 39*, 101244. https://doi.org/10.1016/j.ijdrr.2019.101244

Klose, A. K., Wunderling, N., Winkelmann, R., & Donges, J. F. (2021). What do we mean, 'tipping cascade'? *Environmental Research Letters, 16*, 125011. https://doi.org/10.1088/1748-9326/ac3955

Konijn, P. J. A., de Boer, S., & van Dalen, J. (1997). Input–output analysis of material flows with application to iron, steel and zinc. *Structural Change and Economic Dynamics, 8*(1), 129–153. https://doi.org/10.1016/S0954-349X(96)00063-X

Krausmann, F., Lauk, C., Haas, W., & Wiedenhofer, D. (2018). From resource extraction to outflows of wastes and emissions: The socioeconomic metabolism of the global economy, 1900–2015. *Global Environmental Change, 52*, 131–140. https://doi.org/10.1016/j.gloenvcha.2018.07.003

Krausmann, F., Richter, R., & Eisenmenger, N. (2014). Resource use in small island states: Material flows in Iceland and Trinidad and Tobago, 1961–2008. *Journal of Industrial Ecology, 18*(2), 294–305. https://doi.org/10.1111/jiec.12100

Krausmann, F., Schandl, H., Eisenmenger, N., Giljum, S., & Jackson, T. (2017). Material flow accounting: Measuring global material use for sustainable development. *Annual Review of Environment and Resources, 42*, 647–675. https://doi.org/10.1146/annurev-environ-102016-060726

Kullmann, F., Markewitz, P., Stolten, D., & Robinius, M. (2021). Combining the worlds of energy systems and material flow analysis: A review. *Energy, Sustainability and Society, 11*(1), Article 13. https://doi.org/10.1186/s13705-021-00289-2

Kumar, L., & Taylor, S. (2015). Exposure of coastal built assets in the South Pacific to climate risks. *Nature Climate Change, 5*(11), 992–996. https://doi.org/10.1038/nclimate2702

Lal, R. (2013, July 26). Ship loading tower upgrade for big chip vessels. *Fiji Sun.* https://fijisun.com.fj/2013/07/26/ship-loading-tower-upgrade-for-big-chip-vessels/

Lenzen, M. (2003). Environmentally important paths, linkages and key sectors in the Australian economy. *Structural Change and Economic Dynamics, 14*(1), 1–34. https://doi.org/10.1016/S0954-349X(02)00025-5

Lewis, J., & Kelman, I. (2025). *Development and disasters: Natural hazards and vulnerability reduction* (2nd ed.). Practical Action Publishing. https://doi.org/10.3362/9781788533966

Lutter, S., Sevenster, M., Piñero, P., & Giljum, S. (2024, February). *Technical documentation of the Sustainable Consumption and Production Hotspots Analysis Tool (SCP-HAT), Version 3.0.* Commissioned by UN Life Cycle Initiative, One Planet Network, and UN International Resource Panel.

Manglou, M., Rocher, D. L., & Bahers, J.-B. (2022). Waste colonialism and metabolic flows in island territories. *Journal of Political Ecology, 29*(1), Article 1. https://doi.org/10.2458/jpe.2836

Markolf, S. A., Chester, M. V., Eisenberg, D. A., Iwaniec, D. M., Davidson, C. I., Zimmerman, R., Miller, T. R., Ruddell, B. L., & Chang, H. (2018). Interdependent infrastructure as linked social, ecological, and technological systems (SETSs) to address lock-in and enhance resilience. *Earth's Future, 6*(12), 1638–1659. https://doi.org/10.1029/2018EF000926

Martin del Campo, A., Singh, S. J., Fishman, T., & Singh, S. (2023). Can a small island nation build resilience? The significance of resource-use patterns and socio-metabolic risks in The Bahamas. *Journal of Industrial Ecology, 27*(2), 491–507. https://doi.org/10.1111/jiec.13369

Martin del Campo, F., Singh, S. J., & Mijts, E. (2023). The resource (in)sufficiency of the Caribbean: Analyzing socio-metabolic risks (SMR) of water, energy, and food. *Frontiers in Climate, 5*. https://www.frontiersin.org/articles/10.3389/fclim.2023.1085740

Martin del Campo, F., Singh, S. J., Fishman, T., Thomas, A., & Drescher, M. (2023). The Bahamas at risk: Material stocks, sea-level rise, and the implications for development. *Journal of Industrial Ecology*, 1–19. https://doi.org/10.1111/jiec.13402

Mayer, A., Haas, W., Wiedenhofer, D., Krausmann, F., Nuss, P., & Blengini, G. A. (2019). Measuring progress towards a circular economy: A monitoring framework for economy-wide material loop closing in the EU-28. *Journal of Industrial Ecology, 23*(1), 62–76. https://doi.org/10.1111/jiec.12809

Meadows, D. H. (2008). *Thinking in systems: A primer* (D. Wright, Ed.). Earthscan.

Merschroth, S., Miatto, A., Weyand, S., Tanikawa, H., & Schebek, L. (2020). Lost material stock in buildings due to sea-level rise from global warming: The case of Fiji Islands. *Sustainability, 12*(3), 834. https://doi.org/10.3390/su12030834

Miatto, A., Schandl, H., Yamashita, N., & Fishman, T. (2025). Detailed waste flows and circularity rates reveal the limits of the circularity gap concept. *Resources, Conservation & Recycling, 219*, 108319. https://doi.org/10.1016/j.resconrec.2025.108319

Mohammadi, E., Singh, S. J., & Habib, K. (2021). Electronic waste in the Caribbean: An impending environmental disaster or an opportunity for a circular economy? *Resources, Conservation and Recycling, 164*, 105106. https://doi.org/10.1016/j.resconrec.2020.105106

Nakamura, S., & Kondo, Y. (2002). Input–output analysis of waste management. *Journal of Industrial Ecology, 6*(1), 39–63. https://doi.org/10.1162/108819802320971632

Noll, D., Lauk, C., Haas, W., Singh, S. J., Petridis, P., & Wiedenhofer, D. (2021). The sociometabolic transition of a small Greek island: Assessing stock dynamics, resource flows, and material circularity from 1929 to 2019. *Journal of Industrial Ecology*. https://doi.org/10.1111/jiec.13206

Noll, D., Wiedenhofer, D., Miatto, A., & Singh, S. J. (2019). The expansion of the built environment, waste generation and EU recycling targets on Samothraki, Greece: An island's dilemma. *Resources, Conservation and Recycling, 150*, 104405. https://doi.org/10.1016/j.resconrec.2019.104405

Noll, D., Wiedenhofer, D., Miatto, A., & Singh, S. J. (2021). The expansion of the built environment, waste generation and EU recycling targets on Samothraki, Greece: An island's dilemma. *Resources, Conservation and Recycling, 170*, 105574. https://doi.org/10.1016/j.resconrec.2021.105574

Notre Dame Global Adaptation Initiative. (2024). *Rankings.* https://gain.nd.edu/our-work/country-index/rankings/

Noy, I. (2016). Natural disasters in the Pacific Island Countries: New measurements of impacts. *Natural Hazards, 84*(1), 7–18. https://doi.org/10.1007/s11069-015-1957-6

Pacific Islands Forum Secretariat. (2022). *2050 Strategy for the Blue Pacific Continent*. https://forumsec.org/2050

PacWaste Plus. (2023). *Fiji municipal solid-waste composition report.* https://pacwasteplus.org/reports/2023-fiji-msw

Papua New Guinea Mine Watch. (2016, September 12). Fiji confirms first bauxite shipment of the year. *WordPress*. https://ramumine.wordpress.com/tag/aurum-exploration/

Pelling, M., & Uitto, J. I. (2001). Small Island Developing States: Natural disaster vulnerability and global change. *Global Environmental Change Part B: Environmental Hazards, 3*(2), 49–62. https://doi.org/10.3763/ehaz.2001.0306

Pratap, R. (2014, December 9). Fiji Minister clarifies bauxite mining site rehab works. *Fiji Broadcasting Corporation*. https://ramumine.wordpress.com/2014/12/09/fiji-minister-clarifies-bauxite-mining-site-rehab-works/

Prihardini & Zdzienicka (2021). International Monetary Fund. *The Bahamas: Selected issues paper* (IMF Country Report No. 2021/062). IMF. https://www.imf.org/en/Publications/WP/Issues/2021/03/05/Meeting-the-Sustainable-Development-Goals-in-Small-Developing-States-with-Climate-50098

Refugees International. (2021). *Cyclone Yasa: Fiji's second Category 5 storm in a year exposes deepening humanitarian needs.*

Republic of Fiji, Ministry of Economy. (2018). *Republic of Fiji National Adaptation Plan: A pathway towards climate resilience.* Government of Fiji.

Republic of the Marshall Islands (RMI). (2015). *Nationally determined contribution (NDC).* United Nations Framework Convention on Climate Change (UNFCCC). https://lpr.adb.org/sites/default/files/resource/693/marshall-islands-nationally-determined-contributions.pdf

REN21. (2023). *Transport in focus* (Module of the *Renewables 2023 Global Status Report*).

Reuters. (2024, May 24). Small islands join forces on debt relief ahead of climate talks. https://www.reuters.com/sustainability/climate-energy/small-islands-join-forces-debt-relief-ahead-climate-talks-2024-05-24/

Robinson, S. (2020). Climate change adaptation in SIDS: A systematic review of the literature pre- and post- the IPCC Fifth Assessment Report. *WIREs Climate Change, 11*(4), e653. https://doi.org/10.1002/wcc.653

Salemdeeb, R., Al-Tabbaa, A., & Reynolds, C. (2016). The UK waste input–output table: Linking waste generation to the UK economy. *Waste Management & Research, 34*(10), 1089–1094. https://doi.org/10.1177/0734242X16658545

Scheffer, M. (2010). Foreseeing tipping points. *Nature, 467*(7314), 411–412. https://doi.org/10.1038/467411a

Secretariat of the Pacific Regional Environment Programme. (2023). *Fiji national waste-audit analysis report (August 2023).* https://pacwasteplus.org/wp-content/uploads/2023/08/Fiji-National-Waste-Audit-Analysis-Report.pdf

Shah, K., & Kelman, I. (2024, April). *Institutional capacity, useability of data, and evidence-based decision-making for sustainable development in Small Island Developing States* [Working paper]. Overseas Development Institute. https://odi.org/en/publications/data-and-evidence-based-decision-making-for-sustainable-development/

Shelter Projects. (2010). *Grenada , 2004 , Hurricanes Ivan and Emily.* Shelter Case Studies. www.sheltercasestudies.org

Shurety, A. L., Bartelet, H. A., Chawla, S., & James, N. L. (2022). Insights from twenty years of comparative research in Pacific Large Ocean States. *Ecosystems and People, 18*(1), 214–231. https://doi.org/10.1080/26395916.2022.2086924

Sillmann, J., Christensen, I., Hochrainer-Stigler, S., Huang-Lachmann, J., Juhola, S., Kornhuber, K., Mahecha, M., Mechler, R., Reichstein, M., Ruane, A. C., Schweizer, P.-J., & Williams, S. (2022). *Systemic risk: Review and opportunities for research, policy and practice from the perspective of climate, environmental and disaster risk science and management*. International Science Council. https://doi.org/10.24948/2022.01

Singh, S. J. (2020). Natural hazards and complex disasters. In H. Callan (Ed.), *The International Encyclopedia of Anthropology*. Wiley. https://doi.org/10.1002/9781118924396.wbiea2399

Singh, S. J., Elgie, A., Noll, D., & Eckelman, M. J. (2023). The challenge of solid waste on small islands: Proposing a socio-metabolic research (SMR) framework. *Current Opinion in Environmental Sustainability, 62*, 101274. https://doi.org/10.1016/j.cosust.2023.101274

Singh, S. J., Fischer-Kowalski, M., & Chertow, M. (2020). Introduction: The metabolism of islands. *Sustainability, 12*(22), 9516. https://doi.org/10.3390/su12229516

Singh, S. J., Grünbühel, C. M., Schandl, H., & Schulz, N. (2001). Social metabolism and labour in a local context: Changing environmental relations on Trinket Island. *Population and Environment, 23*(1), 71–104. https://doi.org/10.1023/A:1010758419811

Singh, S. J., & Grünbühel, C. M. (2003). Environmental relations and biophysical transition: The case of Trinket Island. *Geografiska Annaler: Series B, Human Geography, 85*(4), 191–208. https://doi.org/10.1111/j.0435-3684.2003.00142.x

Singh, S. J., Huang, T., Nagabhatla, N., Schweizer, P.-J., Eckelman, M., Verschuur, J., & Soman, R. (2022). Socio-metabolic risk and tipping points on islands. *Environmental Research Letters, 17*(6), 065009. https://doi.org/10.1088/1748-9326/ac6f6c

Sundkvist, Å., Jansson, A.-M., Enefalk, Å., & Larsson, P. (1999). Energy flow analysis as a tool for developing a sustainable society, A case study of a Swedish island. *Resources, Conservation and Recycling, 25*(4), 289–299. https://doi.org/10.1016/S0921-3449(98)00070-6

Symmes, R., Fishman, T., Telesford, J. N., Singh, S. J., Tan, S.-Y., & Kroon, K. D. (2020). The weight of islands: Leveraging Grenada's material stocks to adapt to climate change. *Journal of Industrial Ecology, 24*(2), 369–382. https://doi.org/10.1111/jiec.12853

Tanikawa, H., Fishman, T., Hashimoto, S., Daigo, I., Oguchi, M., Miatto, A., … Schandl, H. (2021). A framework of indicators for associating material stocks and flows to service provisioning: Application for Japan 1990–2015. *Journal of Cleaner Production, 285*, 125450. https://doi.org/10.1016/j.jclepro.2020.125450

Taylor, S. (2021). The vulnerability of health infrastructure to the impacts of climate change and sea-level rise in small island countries in the South Pacific. *Health Services Insights, 14*, 1–11.

Thomas, A., Baptiste, A., Martyr-Koller, R., Pringle, P., & Rhiney, K. (2020). Climate change and Small Island Developing States. *Annual Review of Environment and Resources, 45*, 1–27. https://doi.org/10.1146/annurev-environ-012320-083355

Tilman, D., Hill, J., & Lehman, C. (2006). Carbon-negative biofuels from low-input high-diversity grassland biomass. *Science, 314*(5805), 1598–1600. https://doi.org/10.1126/science.1133306

Towa, E., Zeller, V., & Achten, W. M. J. (2020). Input–output models and waste management analysis: A critical review. *Journal of Cleaner Production, 249*, 119359. https://doi.org/10.1016/j.jclepro.2019.119359

UNESCO. (2023, November). *SIDS dialogues series on water: Caribbean and AIS*. https://www.unesco.org/en/articles/third-edition-unescos-global-small-island-developing-states-dialogues-series-water-caribbean-and-ais

United Nations. (2020). *Handbook on supply and use tables and input-output tables with extensions and applications.* Department of Economic and Social Affairs, Statistics Division.

United Nations Conference on Trade and Development. (2021). *The state of commodity dependence 2021.* https://unctad.org/publication/state-commodity-dependence-2021

United Nations Conference on Trade and Development. (2021). *Building resilience in Small Island Developing States.* https://unctad.org/system/files/official-document/aldc2021d1_en.pdf

United Nations Conference on Trade and Development (UNCTAD). (2024). *Strategy to support Small Island Developing States* (Document ALDC/INF/2024/D1). https://unctad.org/system/files/official-document/aldcinf2024d1_en.pdf

United Nations Conference on Trade and Development. (2024). *Economic vulnerability of small island developing states and policy responses* (UNCTAD/SIDS/2024/1). https://unctad.org/system/files/official-document/sids2024d1_en.pdf

United Nations Department of Economic and Social Affairs. (2020). *Small Island Developing States in numbers: Oceans and seas.* https://www.un.org/ohrlls/sites/www.un.org.ohrlls/files/sids_in_numbers_oceans_2020.pdf

United Nations Department of Economic and Social Affairs. (2021). *Policy Brief 13: Achieving SDG 7 in Small Island Developing States – Mid-Term Review of the Samoa Pathway.* https://sdgs.un.org/sites/default/files/2021-05/POLICY%20BRIEF%2013%20-%20ACHIEVING%20SDG%207%20IN%20SMALL%20ISLAND%20DEVELOPING%20STATES%20MID-TERM%20REVIEW%20OF%20THE%20SAMOA%20PATHWAY.pdf

United Nations Department of Economic and Social Affairs. (2023). *About Small Island Developing States (SIDS).* https://sdgs.un.org/smallislands/about-small-island-developing-states

United Nations Department of Economic and Social Affairs & United Nations Office for Disaster Risk Reduction. (2022). *Gaps, challenges and constraints in means of implementing the Sendai Framework for disaster risk reduction in Small Island Developing States.*

https://www.undrr.org/publication/small-island-developing-states-gaps-challenges-and-constraints-means-implementing-sendai

United Nations Development Programme. (2016). *Cyclone Winston Response and Recovery project in Fiji: Project report.* https://info.undp.org/docs/pdc/Documents/FJI/Project%20report%20-%20December%20%20%20%202016.pdf

United Nations Development Programme. (2017). *Small Islands, Large Oceans: Voices on the Frontlines of Climate Change* (pp. 1–10). https://www.iisd.org/system/files/2021-03/still-one-earth-SIDS.pdf

United Nations Development Programme. (2019). *Climate change adaptation in the Pacific: A situational analysis.* https://www.pacific.undp.org/content/pacific/en/home/library/crisis_prevention_and_recovery/climate-change-adaptation-in-the-pacific--a-situational-analysi.html

United Nations Development Programme. (2022). *Snapshot: Small Island Developing States (SIDS).* In *The state of climate ambition* (pp. 3–15). UNDP Climate Promise. https://climatepromise.undp.org/research-and-reports/snapshot-small-island-developing-states

United Nations Development Programme. (2024a). *Snapshot of loss and damage in SIDS under the Climate Promise.* https://www.undp.org/publications/snapshot-loss-and-damage-sids-under-climate-promise

United Nations Development Programme. (2024b). *Vulnerability, UNDP SIDS Data Platform.* https://sids.data.undp.org/vulnerability/mvi-index/bars

United Nations Development Programme (UNDP). (2024c, April 30). *Small Island Developing States are on the frontlines of climate change – here's why.* UNDP Climate Promise. https://climatepromise.undp.org/news-and-stories/small-island-developing-states-are-frontlinesclimate-change-heres-why

United Nations Economic and Social Commission for Asia and the Pacific. (2020). *The disaster riskscape across the Pacific SIDS.* https://www.unescap.org/publications/asia-pacific-disaster-report-2019

United Nations Economic and Social Commission for Asia and the Pacific. (2022). *Asia Pacific Riskscape @ 1.5°C: Subregional pathways for adaptation and resilience – Summary for* *policymakers.* https://www.unescap.org/sites/default/d8files/2022-05/Asia%20Pacific%20Disaster%20Report%202022%20for%20ESCAP%20Subregions%20Summary%20for%20Policymakers.pdf

United Nations Economic and Social Commission for Asia and the Pacific. (2023). *Asia Pacific Disaster Report 2023: Seizing the moment, redefining our future.* https://un-ggim-ap.org/sites/default/files/media/docs/Asia-Pacific%20Disaster%20Report%202023-Full%20report.pdf

United Nations Environment Programme. (2014). *Emerging issues for Small Island Developing States.* https://wedocs.unep.org/handle/20.500.11822/6890

United Nations Environment Programme. (2018). *Waste management in Pacific Island Countries and Territories.* https://www.unep.org/resources/report/waste-management-pacific-island-countries-and-territories

United Nations Environment Programme. (2023). *Adaptation Gap Report 2023: Underfinanced. Underprepared.* https://www.unep.org/resources/adaptation-gap-report-2023

United Nations Environment Programme & International Resource Panel. (2022). *Global material flows database* [Data set]. https://www.resourcepanel.org/global-material-flows-database

United Nations Environment Programme & International Resource Panel. (2022). *Global resources outlook 2022: More resource use, better resource management.* https://www.resourcepanel.org/reports/global-resources-outlook

United Nations, European Commission, Food and Agriculture Organization of the United Nations, International Monetary Fund, Organisation for Economic Co-operation and Development, & World Bank. (2014). *System of Environmental-Economic Accounting 2012, Central Framework.* United Nations.

United Nations Framework Convention on Climate Change. (2014). *Case study: Tropical Cyclone Evan – Samoa.* https://unfccc.int/sites/default/files/resource/casestudy_samoa_cyclone_evan.pdf

United Nations Framework Convention on Climate Change. (2018). *Talanoa dialogue: "Where are we?"* https://unfccc.int/sites/default/files/resource/105_Talanoa%20dialogue_Where%20Are%20We.pdf

United Nations General Assembly. (2024, July 23). *The Antigua and Barbuda Agenda for Small Island Developing States: A renewed declaration for resilient prosperity* (A/RES/78/317). https://undocs.org/en/A/RES/78/317

United Nations Office for Disaster Risk Reduction. (2019). *Disaster risk reduction in the Republic of Fiji: Status report.* https://reliefweb.int/report/fiji/disaster-risk-reduction-republic-fiji-status-report-july-2019

United Nations Office for Disaster Risk Reduction. (n.d.). *Small Island Developing States (SIDS).* https://www.undrr.org/implementing-sendai-framework/sendai-framework-action/small-island-developing-states

United Nations Office for Disaster Risk Reduction. (2023, May 27). UNDRR statement for the Fourth International Conference on Small Island Developing States: SIDS face a disaster mortality rate more than double the global average. https://www.undrr.org/news/undrr-statement-plenary-meeting-fourth-international-conference-small-island-developing-states

United Nations Office for Disaster Risk Reduction. (2024). *Snapshot of Sendai Framework monitoring (2015–2023): Target C – Disaster related economic losses.* https://www.undrr.org/implementing-sendai-framework/monitoring-sendai-framework

United Nations Office of the High Representative for the Least Developed Countries, Landlocked Developing Countries and Small Island Developing States. (2020). *Small island developing states in numbers: 2020 – oceans edition.* https://www.un.org/ohrlls/sites/www.un.org.ohrlls/files/sids_in_numbers_oceans_2020.pdf

United Nations Office for Project Services. (2024). *Infrastructure for Small Island Developing States.* https://content.unops.org/publications/Infrastructure_SIDS_EN.pdf

U.S. Energy Information Administration (EIA). (2008, July). *Short-term energy outlook: July 2008.* U.S. Department of Energy. https://www.eia.gov/outlooks/steo/archives/jul08.pdf

U.S. Energy Information Administration (EIA). (2024). *Hawaii – State energy profile overview.* https://www.eia.gov/state/analysis.php?sid=HI

U.S. Environmental Protection Agency (EPA). (2024, December 16). EPA celebrates Pacific Islands zero waste and resilience accomplishments. https://www.epa.gov/newsreleases/epa-celebrates-pacific-islands-zero-waste-and-resilience-accomplishments

U.S. Geological Survey (USGS). (2015). *The mineral industry of Fiji* (Report No. MYB3 2015 FJ). U.S. Department of the Interior. https://d9-wret.s3.us-west-2.amazonaws.com/assets/palladium/production/mineral-pubs/country/2015/myb3-2015-fj.pdf

U.S. Geological Survey (USGS). (2016). *The mineral industry of Fiji in 2015* (Area Reports: International, Asia and the Pacific). U.S. Department of the Interior. https://pubs.usgs.gov/myb/2015/myb3-2015-fj.pdf

Vousdoukas, M. I., Athanasiou, P., Giardino, A., et al. (2023). Small Island Developing States under threat by rising seas even in a 1.5 °C warming world. *Nature Sustainability, 6*, 1552–1564. https://doi.org/10.1038/s41893-023-01230-5

Wachs, L., & Singh, S. (2017, November). A physical input–output model for the food–energy–water nexus in Indiana. Paper presented at the AIChE Annual Meeting, Minneapolis, MN, United States.

Waddell, E., Naidu, V., & Hauʻofa, E. (Eds.). (1993). *A new Oceania: Rediscovering our sea of islands*. Suva: University of the South Pacific.

Weisz, H., & Duchin, F. (2006). Physical and monetary input–output analysis: What makes the difference? *Ecological Economics, 57*(3), 534–541. https://doi.org/10.1016/j.ecolecon.2005.05.016

Wieland, H., Lenzen, M., Geschke, A., Fry, J., Wiedenhofer, D., Eisenmenger, N., Schenk, J., & Giljum, S. (2020). *The PIOLab: Building global physical input–output tables in a virtual laboratory* (Ecological Economic Papers No. 36). WU Vienna University of Economics and Business.

Wisner, B., Alcántara-Ayala, I., Gaillard, J. C., Kelman, I., & Marchezini, V. (2025). *Understanding and addressing disaster risk: Who speaks? Who suffers?* Routledge. https://doi.org/10.4324/9781003292814

Wong, P. P. (2011). Small Island Developing States. *WIREs Climate Change, 2*(1), 1–6. https://doi.org/10.1002/wcc.84

World Bank. (2005). *Grenada: A nation rebuilding, An assessment of reconstruction and economic recovery one year after Hurricane Ivan.* Hazard Risk Management Unit, Latin America and the Caribbean Region.

World Bank. (2016, June 30). World Bank commits $50 million to support Fiji's long-term Cyclone Winston recovery [Press release]. https://www.worldbank.org/en/news/press-release/2016/06/30/world-bank-commits-50m-to-support-fijis-long-term-cyclone-winston-recovery

World Bank. (2016). *Tropical Cyclone Winston: Post-Disaster Needs Assessment.* https://documents.worldbank.org/en/publication/documents-reports/documentdetail/274241467986325997/tropical-cyclone-winston-post-disaster-needs-assessment

World Bank. (2017). *Climate and disaster resilience financing for Small Island Developing States.* https://documents.worldbank.org/curated/en/626571492596854843/pdf/114389-WP-v2-PUBLIC-CDRFinSIDs-20170208-webversion.pdf

World Bank. (2017). *Pacific Possible: Long-term economic opportunities and challenges for Pacific Island Countries.* https://www.worldbank.org/en/region/eap/publication/pacific-possible-long-term-economic-opportunities-and-challenges-for-pacific-island-countries

World Bank. (2017). *Cyclone Winston: Learning from Fiji's recovery.*

World Bank. (2024). *International tourism, number of arrivals – Fiji (2000–2020)* [Data set]. https://data.worldbank.org/indicator/ST.INT.ARVL?end=2020&locations=FJ&start=2000&view=chart

World Bank. (2025, July 2). *Population, total for Fiji* [Data series POPTOTFJA647NWDB]. FRED, Federal Reserve Bank of St. Louis. https://fred.stlouisfed.org/series/POPTOTFJA647NWDB

World Bank & Government of Fiji. (2017). *Making Fiji climate resilient: Climate vulnerability assessment.* https://www.gfdrr.org/sites/default/files/publication/Making%20Fiji%20Climate%20Resilient%20-%20Full%20Report_0.pdf

World Meteorological Organization (WMO). (2020). *Tropical Cyclone Harold challenges disaster and public health management.*

World Steel Association. (2024). *Steel use by sector.*

World Trade Organization. (2015). *Trade policy review: Fiji* (Report No. WT/TPR/S/330). https://www.wto.org/english/tratop_e/tpr_e/s330_e.pdf

Yeo, Z., Masi, D., Low, J. S. C., Ng, Y. T., Tan, P. S., & Barnes, S. (2019). Tools for promoting industrial symbiosis: A systematic review. *Journal of Industrial Ecology, 23*(5), 1087–1108. https://doi.org/10.1111/jiec.12846

Appendix A:

How prepared is Fiji to climate and geopolitical risks? Insights from a socio-metabolic risk (SMR) analysis.

Abstract: This appendix contains supplementary materials that support the analysis presented in this thesis. It includes detailed data tables, extended figures, and additional graphs that were generated during the research process. This information is provided for readers who wish to examine the complete empirical basis for the findings discussed in the main chapters.

Table A - 1: Complete ew-MFA Mass Balance Account of Fiji from 2000 to 2022

INPUTS	**Years ->**	**Scale: kt**																					
DE	**2000**	**2001**	**2002**	**2003**	**2004**	**2005**	**2006**	**2007**	**2008**	**2009**	**2010**	**2011**	**2012**	**2013**	**2014**	**2015**	**2016**	**2017**	**2018**	**2019**	**2020**	**2021**	**2022**
Biomass	5137.26	4081.61	4693.64	3801.11	4360.63	4203.65	4665.07	3792.61	3483.94	3454.31	2903.50	3334.15	2747.44	2892.94	3125.54	3130.24	2506.35	2850.38	2966.67	3093.84	3011.71	2691.43	2982.05
Metal Ores	0.01	0.01	0.01	0.00	0.01	0.00	0.00	0.00	0.00	0.00	0.00	50.00	500.00	600.00	640.00	250.00	58.00	60.00	60.00	0.00	0.00	0.00	0.00
Non-Metallic Minerals	452.99	471.78	551.91	580.00	603.00	688.00	658.00	675.00	658.00	625.00	513.00	515.00	495.00	533.50	538.00	552.75	565.25	593.17	595.67	560.63	490.87	495.41	470.37
Fossil/Energy Carriers	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Imports																							
Biomass	317.14	446.07	485.79	380.38	366.72	419.64	428.43	446.50	526.35	409.25	413.55	442.54	474.61	520.85	473.35	390.76	550.45	473.89	511.98	545.17	541.48	524.55	570.90
Metal Ores	111.63	37.86	146.64	163.48	60.53	75.20	159.07	130.78	35.32	60.91	46.23	40.90	49.65	55.33	227.99	86.17	98.75	104.54	101.77	81.27	75.96	63.76	74.34
Non-Metallic Minerals	56.53	97.01	106.66	59.33	58.87	48.75	119.07	122.11	79.02	87.38	77.01	86.32	62.89	120.37	332.29	221.48	285.92	306.31	212.43	230.21	164.25	144.35	303.09
Fossil/Energy Carriers	664.51	678.65	485.22	525.82	574.19	906.61	943.03	800.24	910.94	377.25	879.94	810.49	677.66	581.12	720.04	967.83	898.83	962.84	948.35	963.90	734.95	628.01	836.28
DMI																							
Biomass	5454.40	4527.67	5179.43	4181.49	4727.35	4623.29	5093.49	4239.10	4010.28	3863.56	3317.06	3776.68	3222.05	3413.79	3598.89	3521.00	3056.80	3324.26	3478.65	3639.01	3553.18	3215.98	3552.95
Metal Ores	111.63	37.86	146.64	163.49	60.54	75.20	159.08	130.78	35.32	60.91	46.23	90.91	549.65	655.33	867.99	336.17	156.76	164.54	161.77	81.27	75.96	63.77	74.34
Non-Metallic Minerals	509.52	568.79	658.57	639.33	661.87	736.75	777.07	797.11	737.02	712.38	590.01	601.32	557.89	653.87	870.29	774.23	851.17	899.48	808.10	790.84	655.12	639.76	773.47
Fossil/Energy Carriers	664.51	678.65	485.22	525.82	574.19	906.61	943.03	800.24	910.94	377.25	879.94	810.49	677.66	581.12	720.04	967.83	898.83	962.84	948.35	963.90	734.95	628.01	836.28
USE																							
DMC																							
Biomass	4461.51	3760.28	4243.79	3343.97	3954.70	3782.04	4160.63	3477.31	3355.93	3269.08	2646.86	3145.19	2492.33	2859.73	2566.58	2661.25	2379.60	2544.08	2597.41	2861.05	2738.33	2264.40	2778.91
Metal Ores	101.19	33.77	140.37	153.84	52.93	70.24	153.02	125.91	29.06	55.41	39.36	86.36	537.22	159.35	863.51	330.96	82.07	90.65	157.79	76.31	11.58	17.83	70.59
Non-Metallic Minerals	498.62	555.68	636.69	624.28	656.65	727.11	754.66	747.37	691.73	675.48	560.66	560.68	517.77	616.92	798.79	635.82	747.65	836.38	655.54	760.70	638.95	618.88	753.14
Fossil/Energy Carriers	663.61	678.24	485.17	525.47	574.00	904.48	940.67	799.33	910.60	376.38	879.10	809.71	677.52	580.88	720.01	967.81	898.73	962.64	948.10	963.77	734.25	627.90	836.15
PM																							
Biomass	4461.51	3760.28	4243.79	3343.97	3954.70	3782.04	4160.63	3477.31	3355.93	3269.08	2646.86	3145.19	2492.33	2859.86	2566.76	2661.47	2379.81	2544.32	2597.66	2861.30	2738.55	2264.61	2779.14
Metal Ores	101.19	33.77	140.37	153.84	52.93	70.24	153.02	125.91	29.06	55.41	39.36	86.36	537.22	159.36	863.52	330.98	82.09	90.67	157.81	76.33	11.60	17.84	70.60

Non-Metallic Minerals	498.62	555.69	636.69	624.28	656.66	727.11	754.67	747.37	691.74	675.48	560.67	560.68	517.77	616.93	798.80	635.83	747.66	836.39	655.55	760.72	638.96	618.89	753.15
Fossil/Energy Carriers	663.61	678.24	485.17	525.47	574.00	904.48	940.67	799.33	910.60	376.38	879.10	809.71	677.52	580.88	720.01	967.81	898.73	962.64	948.10	963.77	734.25	627.90	836.15
SM																							
Biomass	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.14	0.18	0.22	0.21	0.24	0.25	0.25	0.22	0.20	0.23
Metal Ores	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.01	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02
Non-Metallic Minerals	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01
Fossil/Energy Carriers	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
eUse																					2890.30		
Biomass	4167.95	3428.88	3823.02	2984.25	3593.44	3381.27	3787.15	3108.26	3022.01	2924.85	2131.91	2594.73	1948.92	2325.28	2037.00	2119.89	1767.73	1927.97	1981.52	2293.88	2156.05	1684.42	2217.90
Metal Ores	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Non-Metallic Minerals	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Fossil/Energy Carriers	663.61	678.24	485.17	525.47	574.00	904.48	940.67	799.33	910.60	376.38	879.10	809.71	677.52	580.88	720.01	967.81	898.73	962.64	948.10	963.77	734.25	627.90	836.15
mUse																							
Biomass	293.56	331.40	420.77	359.72	361.26	400.77	373.48	369.06	333.92	344.23	514.95	550.46	543.41	534.58	529.76	541.58	612.08	616.34	616.14	567.42	582.50	580.19	561.24
Metal Ores	101.19	33.77	140.37	153.84	52.93	70.24	153.02	125.91	29.06	55.41	39.36	86.36	537.22	159.36	863.52	330.98	82.09	90.67	157.81	76.33	11.60	17.84	70.60
Non-Metallic Minerals	498.62	555.68	636.69	624.28	656.65	727.11	754.66	747.37	691.73	675.48	560.66	560.68	517.77	616.92	798.79	635.82	747.65	836.38	655.54	760.70	638.95	618.88	753.14
Fossil/Energy Carriers	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
STOCKS																							
GAS																							
Biomass	293.56	331.40	420.77	359.72	361.26	400.77	291.09	285.04	244.62	255.42	426.60	461.93	453.30	445.94	438.76	447.92	517.87	518.48	514.06	462.50	482.23	480.60	457.05
Metal Ores	101.19	33.77	140.37	153.84	52.93	70.24	147.76	120.47	23.45	49.70	33.46	80.25	531.05	153.06	856.83	324.32	75.46	84.03	151.06	69.68	4.78	10.82	63.54
Non-Metallic Minerals	498.62	555.68	636.69	624.28	656.65	727.11	751.20	743.78	688.04	671.72	556.77	556.65	513.70	612.77	794.38	631.43	743.29	832.01	651.09	756.33	634.46	614.25	748.49
Fossil/Energy Carriers	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
NAS																							
Biomass	293.56	331.40	420.77	359.72	361.26	400.77	291.09	285.04	244.62	255.42	426.60	461.93	453.30	445.94	438.53	447.65	517.59	518.16	513.69	462.10	481.90	480.37	456.78
Metal Ores	101.19	33.77	140.37	153.84	52.93	70.24	147.76	120.47	23.45	49.70	33.46	80.25	531.05	153.06	856.68	324.15	75.28	83.82	150.81	69.42	4.55	10.67	63.36
Non-Metallic Minerals	498.62	555.68	636.69	624.28	656.65	727.11	751.20	743.78	688.04	671.72	556.77	556.65	513.70	612.77	790.91	627.45	739.06	827.21	645.56	750.35	629.47	610.79	744.41
Fossil/Energy Carriers	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
OUPUTS																							
Exports																							
Biomass	992.89	767.40	935.64	837.52	772.66	841.26	932.86	761.79	654.35	594.48	670.20	631.49	729.72	554.07	1032.31	859.75	677.19	780.18	881.24	777.96	814.86	951.57	774.03
Metal Ores	10.44	4.09	6.27	9.65	7.61	4.96	6.06	4.87	6.26	5.50	6.87	4.54	12.43	495.98	4.48	5.21	74.69	73.89	3.97	4.96	64.38	45.94	3.75
Non-Metallic Minerals	10.90	13.11	21.88	15.05	5.22	9.65	22.41	49.75	45.29	36.90	29.35	40.64	40.12	36.95	71.50	138.41	103.53	63.10	152.56	30.14	16.17	20.88	20.33
Fossil/Energy Carriers	0.91	0.41	0.04	0.36	0.18	2.13	2.37	0.91	0.35	0.87	0.84	0.79	0.14	0.24	0.03	0.01	0.10	0.20	0.25	0.13	0.70	0.11	0.12
Throughput																							
Biomass	0.00	0.00	0.00	0.00	0.00	0.00	82.39	84.02	89.30	88.81	88.35	88.54	90.11	88.64	91.01	93.66	94.22	97.86	102.08	104.92	100.27	99.58	104.19

Metal Ores	0.00	0.00	0.00	0.00	0.00	0.00	5.26	5.44	5.61	5.71	5.91	6.11	6.18	6.30	6.69	6.66	6.62	6.64	6.75	6.64	6.82	7.02	7.06
Non-Metallic Minerals	0.00	0.00	0.00	0.00	0.00	0.00	3.46	3.58	3.69	3.76	3.89	4.03	4.07	4.15	4.41	4.38	4.36	4.37	4.45	4.38	4.49	4.62	4.65
Fossil/Energy Carriers	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
C&D																							
Biomass	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.23	0.27	0.28	0.32	0.37	0.40	0.33	0.23	0.27
Metal Ores	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.15	0.18	0.19	0.21	0.25	0.27	0.22	0.15	0.18
Non-Metallic Minerals	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	3.47	3.98	4.22	4.80	5.53	5.98	5.00	3.47	4.08
Fossil/Energy Carriers	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Int/Out																					3007.43		
Biomass	4167.95	3428.88	3823.02	2984.25	3593.44	3381.27	3869.54	3192.27	3111.31	3013.67	2220.26	2683.27	2039.04	2413.93	2128.23	2213.82	1862.23	2026.16	2083.97	2399.20	2256.65	1784.23	2322.36
Metal Ores	0.00	0.00	0.00	0.00	0.00	0.00	5.26	5.44	5.61	5.71	5.91	6.11	6.18	6.30	6.85	6.83	6.81	6.85	7.00	6.91	7.04	7.17	7.24
Non-Metallic Minerals	0.00	0.00	0.00	0.00	0.00	0.00	3.46	3.58	3.69	3.76	3.89	4.03	4.07	4.15	7.88	8.37	8.58	9.17	9.98	10.36	9.49	8.09	8.73
Fossil/Energy Carriers	663.61	678.24	485.17	525.47	574.00	904.48	940.67	799.33	910.60	376.38	879.10	809.71	677.52	580.88	720.01	967.81	898.73	962.64	948.10	963.77	734.25	627.90	836.15
EoL																							
Biomass	648.75	671.13	686.84	755.39	861.81	774.80	915.63	941.05	946.58	655.93	746.31	961.95	1166.09	848.01	895.28	1122.41	752.66	1560.52	1600.52	1520.61	1174.17	1255.80	1964.45
Metal Ores	0.00	0.00	0.00	0.00	0.00	0.00	5.26	5.44	5.61	5.71	5.91	6.11	6.18	6.30	6.85	6.83	6.81	6.85	7.00	6.91	7.04	7.17	7.24
Non-Metallic Minerals	0.00	0.00	0.00	0.00	0.00	0.00	3.46	3.58	3.69	3.76	3.89	4.03	4.07	4.15	7.88	8.37	8.58	9.17	9.98	10.36	9.49	8.09	8.73
Fossil/Energy Carriers	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
DPOe																							
Biomass	3519.20	2757.75	3136.18	2228.86	2731.63	2606.47	2953.92	2251.22	2164.73	2357.73	1473.95	1721.32	872.94	1565.91	1232.95	1091.41	1109.57	465.63	483.45	878.59	1082.48	528.43	357.91
Metal Ores	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Non-Metallic Minerals	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Fossil/Energy Carriers	663.61	678.24	485.17	525.47	574.00	904.48	940.67	799.33	910.60	376.38	879.10	809.71	677.52	580.88	720.01	967.81	898.73	962.64	948.10	963.77	734.25	627.90	836.15
DPOw																							
Biomass	648.75	671.13	686.84	755.39	861.81	774.80	915.63	941.05	946.58	655.93	746.31	961.95	1166.09	847.88	895.11	1122.19	752.45	1560.29	1600.26	1520.35	1173.95	1255.60	1964.22
Metal Ores	0.00	0.00	0.00	0.00	0.00	0.00	5.26	5.44	5.61	5.71	5.91	6.11	6.18	6.29	6.83	6.82	6.79	6.83	6.98	6.89	7.03	7.16	7.23
Non-Metallic Minerals	0.00	0.00	0.00	0.00	0.00	0.00	3.46	3.58	3.69	3.76	3.89	4.03	4.07	4.14	7.87	8.36	8.57	9.16	9.97	10.34	9.48	8.08	8.72
Fossil/Energy Carriers	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
DPO																							
Biomass	4167.95	3428.88	3823.02	2984.25	3593.44	3381.27	3869.54	3192.27	3111.31	3013.67	2220.26	2683.27	2039.04	2413.79	2128.06	2213.60	1862.02	2025.92	2083.72	2398.95	2256.43	1784.03	2322.13
Metal Ores	0.00	0.00	0.00	0.00	0.00	0.00	5.26	5.44	5.61	5.71	5.91	6.11	6.18	6.29	6.83	6.82	6.79	6.83	6.98	6.89	7.03	7.16	7.23
Non-Metallic Minerals	0.00	0.00	0.00	0.00	0.00	0.00	3.46	3.58	3.69	3.76	3.89	4.03	4.07	4.14	7.87	8.36	8.57	9.16	9.97	10.34	9.48	8.08	8.72
Fossil/Energy Carriers	663.61	678.24	485.17	525.47	574.00	904.48	940.67	799.33	910.60	376.38	879.10	809.71	677.52	580.88	720.01	967.81	898.73	962.64	948.10	963.77	734.25	627.90	836.15

Table A – 2: Biomass Circularity (%)

Scale: %

Circularity indicators	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022
ISCr	0.00	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01
OSCr	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01

Table A – 4: Metal Ores Circularity (%)

Circularity indicators	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022
ISCr	0.01	0.00	0.00	0.02	0.02	0.01	0.02	0.14	0.09	0.02
OSCr	0.16	0.19	0.24	0.23	0.26	0.27	0.27	0.23	0.21	0.24

Table A – 3: Non-Metallic Minerals Circularity (%)

Circularity indicators	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022
ISCr	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
OSCr	0.16	0.11	0.13	0.12	0.13	0.12	0.12	0.11	0.12	0.13

Table A – 4: Fossil Fuels/Energy Carriers Circularity (%)

Circularity indicators	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022
INCr	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00
ONCr	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00

Table A – 5: Construction Waste Data (Source: Fiji Bureau of Statistics)

Year	Private dwellings		Other		Total 000 sq m	Construction Waste (Kt)
	new building 000 sq m	addition 000 sq m	new building 000 sq m	addition 000 sq m		
2014	26	10	42	14	92	3.86
2015	25	9	45	11	90	4.43
2016	26	8	42	11	87	4.69
2017	31	13	54	11	109	5.34
2018	37	16	75	13	141	6.14
2019	38	13	63	15	129	6.64
2020	34	13	54	13	114	5.55
2021	38	9	42	12	101	3.85
2022	31	16	48	14	109	4.53

Table A – 6: Import Dependence Ratio (2000 to 2022)

Import Dependence Ratio %				
Year	**Biomass %**	**Metal Ores %**	**Non-Metallic Minerals %**	**Fossil/Energy Carriers %**
2000	5.81	100.00	11.09	100.00
2001	9.85	99.98	17.06	100.00
2002	9.38	100.00	16.20	100.00
2003	9.10	100.00	9.28	100.00
2004	7.76	99.99	8.89	100.00
2005	9.08	99.99	6.62	100.00
2006	8.41	100.00	15.32	100.00
2007	10.53	100.00	15.32	100.00
2008	13.12	100.00	10.72	100.00

2009	10.59	100.00	12.27	100.00
2010	12.47	100.00	13.05	100.00
2011	11.72	45.00	14.35	100.00
2012	14.73	9.03	11.27	100.00
2013	15.26	8.44	18.41	100.00
2014	13.15	26.27	38.18	100.00
2015	11.10	25.63	28.61	100.00
2016	18.01	63.00	33.59	100.00
2017	14.26	63.53	34.05	100.00
2018	14.72	62.91	26.29	100.00
2019	14.98	100.00	29.11	100.00
2020	15.24	100.00	25.07	100.00
2021	16.31	100.00	22.56	100.00
2022	16.07	100.00	39.19	100.00

Table A – 7: Fiji's Municipal Solid Waste (Source: Fiji Bureau of Statistics)

Material	**Year**	**Total (Kt)**	**Recycled (Kt)**
Solid Waste	2006	150.63	Data NA
Solid Waste	2007	153.60	Data NA
Solid Waste	2008	163.26	Data NA
Solid Waste	2009	162.36	Data NA
Solid Waste	2010	161.51	Data NA

Solid Waste	2011	161.86	Data NA
Solid Waste	2012	164.74	Data NA
Solid Waste	2013	162.05	0.25
Solid Waste	2014	166.37	0.32
Solid Waste	2015	171.23	0.40
Solid Waste	2016	172.24	0.38
Solid Waste	2017	178.90	0.43
Solid Waste	2018	186.61	0.46
Solid Waste	2019	191.81	0.46
Solid Waste	2020	183.30	0.40
Solid Waste	2021	182.05	0.37
Solid Waste	2022	190.47	0.42

Table A – 8: Construction Waste Data (Source: Fiji Bureau of Statistics)

Year	Private dwellings		Other		Total 000 sq m	Construction Waste (Kt)
	new building 000 sq m	addition 000 sq m	new building 000 sq m	addition 000 sq m		
2014	26	10	42	14	92	3.86
2015	25	9	45	11	90	4.43
2016	26	8	42	11	87	4.69
2017	31	13	54	11	109	5.34
2018	37	16	75	13	141	6.14
2019	38	13	63	15	129	6.64
2020	34	13	54	13	114	5.55
2021	38	9	42	12	101	3.85
2022	31	16	48	14	109	4.53

Table A – 9: Biomass DE disaggregation by Crops

DE (Crops) (Kt)									
Year	Cereals	Crop Residues	Fruits	Oil-bearing Crops	Other Crops	Pulses	Roots & Tubers	Sugar Crops	Vegetables
2000	14.18	43.18	19.09	184.28	4.30	0.78	80.22	3786.00	18.21
2001	14.90	36.92	20.77	186.82	2.01	1.01	72.17	2805.00	18.12
2002	13.52	49.63	19.20	184.62	4.14	0.70	92.31	3423.00	20.93
2003	16.55	43.47	20.51	139.78	3.87	0.30	92.80	2610.00	21.14
2004	14.43	48.64	22.16	175.09	4.09	0.17	136.27	3001.00	22.49
2005	15.95	47.60	20.32	199.08	4.18	0.15	154.47	2789.00	23.94
2006	13.70	52.41	21.55	198.94	3.73	0.19	137.28	3226.00	28.35
2007	15.21	39.22	24.54	197.87	3.57	0.09	131.18	2478.00	28.64
2008	12.23	36.77	28.43	25.93	6.22	0.09	142.10	2321.00	33.97
2009	12.19	32.83	19.48	245.39	3.40	0.68	117.46	2247.00	32.70
2010	9.78	27.73	20.78	17.32	5.75	1.84	124.87	1780.00	20.30
2011	11.99	33.49	23.11	16.19	5.44	2.95	153.80	2095.00	30.36
2012	4.90	24.48	16.80	27.94	10.00	0.61	195.65	1547.00	15.28
2013	7.12	25.51	26.24	38.87	10.30	2.52	224.25	1610.00	34.10
2014	7.84	28.03	35.17	36.56	10.05	3.57	158.77	1832.00	30.27
2015	7.43	28.07	33.32	40.18	13.13	2.89	153.31	1845.00	29.81
2016	9.54	21.72	27.69	26.24	14.48	1.70	117.39	1387.00	26.67
2017	10.07	24.65	29.75	24.93	17.06	1.78	125.56	1631.00	33.20
2018	8.28	25.44	31.53	25.53	20.74	1.82	144.58	1696.00	33.98
2019	7.17	28.34	35.07	26.21	21.58	2.25	150.32	1806.00	37.84
2020	9.94	30.29	40.77	23.98	25.06	2.72	148.88	1729.00	55.34
2021	11.83	24.86	48.57	22.66	28.12	1.81	165.97	1417.00	57.48
2022	14.70	28.76	48.45	22.17	27.64	1.90	179.02	1639.00	66.16

Table A – 10: Biomass DE disaggregation by Crops

DE (Kt)					
Year	**Aquatic**	**Crops**	**Livestock**	**Processed**	**Wood**
2000	49.36	4150.24	77.40	544.66	315.60
2001	50.03	3157.72	78.14	464.04	331.68
2002	41.53	3808.03	80.39	495.02	268.67
2003	37.63	2948.42	63.47	444.04	307.55
2004	50.19	3424.32	75.19	464.19	346.73
2005	47.95	3254.69	82.93	447.54	370.54
2006	50.35	3682.14	84.85	501.57	346.15
2007	48.08	2918.32	85.92	413.59	326.71
2008	47.48	2606.75	86.25	414.61	328.85
2009	47.06	2711.14	36.63	330.63	328.85
2010	42.71	2008.37	44.05	283.64	524.73
2011	47.55	2372.32	52.88	311.66	549.73
2012	47.47	1842.66	47.90	259.68	549.73
2013	43.01	1978.91	44.59	276.70	549.73
2014	44.39	2142.27	47.43	341.72	549.73
2015	41.95	2153.14	49.68	335.74	549.73
2016	45.01	1632.44	38.41	240.75	549.73
2017	47.75	1898.00	64.69	290.22	549.73
2018	43.03	1987.91	66.14	319.86	549.73
2019	42.00	2114.78	64.74	322.58	549.73
2020	37.92	2065.96	53.51	304.59	549.73
2021	33.22	1778.30	55.58	274.60	549.73
2022	32.84	2027.79	74.29	297.40	549.73

Table A – 11: IMP of Non-Metallic Minerals (Sub Category)

IMP of Non-Metallic Minerals (Sub Category) (Kt)			
Year	**Other Non-metallic minerals**	**Products**	**Chemical Fertilizers**
2000	7.51	14.83	34.09
2001	10.78	45.75	40.42
2002	15.42	44.78	46.04

2003	9.04	24.33	25.75
2004	6.51	4.60	47.77
2005	14.83	4.49	29.43
2006	28.77	58.21	32.09
2007	8.18	84.72	29.21
2008	11.67	30.74	36.61
2009	3.75	55.05	28.58
2010	7.13	57.04	12.83
2011	6.12	30.16	23.63
2012	6.44	32.48	23.97
2013	7.55	86.89	25.93
2014	21.52	292.65	18.12
2015	9.82	177.89	33.77
2016	8.92	252.81	24.20
2017	11.17	265.79	29.36
2018	23.03	165.51	23.89
2019	6.54	197.36	26.31
2020	7.57	122.61	34.07
2021	12.66	112.27	19.43
2022	15.99	263.12	23.98

Table A – 12: DE of Precious Metals (Gold & Silver)

DE of Precious Metals (Gold & Silver) (t)			
Year	**Precious metals**	**Gold ore**	**Silver (refined)**
2000	5.27	3.81	1.46
2001	5.82	3.88	1.93
2002	5.65	3.74	1.90
2003	4.78	3.53	1.25
2004	5.58	4.05	1.52
2005	4.22	2.81	1.42
2006	2.46	1.96	0.49
2007	0.84	0.84	0.00
2008	1.31	1.04	0.27
2009	1.41	1.10	0.31
2010	2.18	1.86	0.33
2011	1.85	1.43	0.42

2012	1.65	1.31	0.34
2013	1.57	1.11	0.46
2014	1.45	1.09	0.36
2015	1.53	1.18	0.35
2016	1.72	1.37	0.35
2017	1.78	1.43	0.35
2018	1.69	1.28	0.41
2019	1.80	1.11	0.69
2020	1.57	1.09	0.48
2021	1.73	1.11	0.62
2022	1.01	0.53	0.48

Table A – 12: IMP of Fossil Fuels/Energy Carriers by Sub Categories

IMP of Fossil Fuels/Energy Carriers (Sub Categories) (Kt)			
Year	**Liquid/Gas**	**Solid**	**Refined Petroleum**
2000	24.03	0.13	639.69
2001	22.54	0.17	629.03
2002	12.20	16.41	456.35
2003	12.79	16.62	495.51
2004	13.65	7.30	552.81
2005	12.31	0.09	893.76
2006	13.74	8.89	920.10
2007	18.18	4.12	777.78
2008	17.20	8.39	885.10
2009	16.45	6.05	354.58
2010	20.33	4.50	854.92
2011	18.20	7.29	784.67
2012	19.30	12.49	645.73
2013	20.84	14.19	545.68
2014	26.91	11.25	681.02
2015	26.51	6.13	934.38
2016	29.09	11.38	857.76
2017	30.36	5.33	925.89
2018	33.65	18.09	896.23
2019	34.04	8.55	920.86
2020	24.32	2.17	708.27

2021	27.79	0.99	599.00
2022	31.03	5.58	799.53

Table A – 13: Climate Disaster Frequency by Year (Data from EMDAT: https://www.emdat.be/)

Climate Disasters			
Year	Storm/Cyclones	Flood	Drought
2000	0	1	0
2001	1	0	0
2002	0	0	0
2003	1	0	0
2004	1	1	0
2005	0	0	0
2006	1	1	0
2007	2	2	0
2008	1	0	0
2009	1	1	0
2010	1	0	0
2011	0	0	0
2012	1	2	0
2013	0	0	0
2014	0	0	0
2015	0	0	1
2016	2	0	0
2017	0	0	0
2018	2	0	0
2019	1	0	0
2020	3	0	0
2021	1	0	0
2022	1	0	0

Table A – 14: Data for Sankey Diagram.

INPUTS	**Years ->**	**Scale: kt**			
DE	**2000**	**2010**	**2013**	**2016**	**2022**
Biomass	5137.26	2903.50	2892.94	2506.35	2982.05
Metal Ores	0.01	0.00	600.00	58.00	0.00
Non-Metallic Minerals	452.99	513.00	533.50	565.25	470.37
Fossil/Energy Carriers	0.00	0.00	0.00	0.00	0.00
Imports					
Biomass	317.14	413.55	520.85	550.45	570.90
Metal Ores	111.63	46.23	55.33	98.75	74.34
Non-Metallic Minerals	56.53	77.01	120.37	285.92	303.09
Fossil/Energy Carriers	664.51	879.94	581.12	898.83	836.28
DMI					
Biomass	5454.40	3317.06	3413.79	3056.80	3552.95
Metal Ores	111.63	46.23	655.33	156.76	74.34
Non-Metallic Minerals	509.52	590.01	653.87	851.17	773.47
Fossil/Energy Carriers	664.51	879.94	581.12	898.83	836.28
USE					
DMC					
Biomass	4461.51	2646.86	2859.73	2379.60	2778.91
Metal Ores	101.19	39.36	159.35	82.07	70.59
Non-Metallic Minerals	498.62	560.66	616.92	747.65	753.14
Fossil/Energy Carriers	663.61	879.10	580.88	898.73	836.15
PM					
Biomass	4461.51	2646.86	2859.86	2379.81	2779.14
Metal Ores	101.19	39.36	159.36	82.09	70.60
Non-Metallic Minerals	498.62	560.67	616.93	747.66	753.15
Fossil/Energy Carriers	663.61	879.10	580.88	898.73	836.15

SM					
Biomass	0.00	0.00	0.14	0.21	0.23
Metal Ores	0.00	0.00	0.01	0.02	0.02
Non-Metallic Minerals	0.00	0.00	0.01	0.01	0.01
Fossil/Energy Carriers	0.00	0.00	0.00	0.00	0.00
eUse					
Biomass	4167.95	2131.91	2325.28	1767.73	2217.90
Metal Ores	0.00	0.00	0.00	0.00	0.00
Non-Metallic Minerals	0.00	0.00	0.00	0.00	0.00
Fossil/Energy Carriers	663.61	879.10	580.88	898.73	836.15
mUse					
Biomass	293.56	514.95	534.58	612.08	561.24
Metal Ores	101.19	39.36	159.36	82.09	70.60
Non-Metallic Minerals	498.62	560.66	616.92	747.65	753.14
Fossil/Energy Carriers	0.00	0.00	0.00	0.00	0.00
STOCKS					
GAS					
Biomass	293.56	426.60	445.94	517.87	457.05
Metal Ores	101.19	33.46	153.06	75.46	63.54
Non-Metallic Minerals	498.62	556.77	612.77	743.29	748.49
Fossil/Energy Carriers	0.00	0.00	0.00	0.00	0.00
NAS					
Biomass	293.56	426.60	445.94	517.59	456.78
Metal Ores	101.19	33.46	153.06	75.28	63.36
Non-Metallic Minerals	498.62	556.77	612.77	739.06	744.41
Fossil/Energy Carriers	0.00	0.00	0.00	0.00	0.00
OUPUTS					
Exports					

Biomass	992.89	670.20	554.07	677.19	774.03
Metal Ores	10.44	6.87	495.98	74.69	3.75
Non-Metallic Minerals	10.90	29.35	36.95	103.53	20.33
Fossil/Energy Carriers	0.91	0.84	0.24	0.10	0.12
Throughput					
Biomass	0.00	88.35	88.64	94.22	104.19
Metal Ores	0.00	5.91	6.30	6.62	7.06
Non-Metallic Minerals	0.00	3.89	4.15	4.36	4.65
Fossil/Energy Carriers	0.00	0.00	0.00	0.00	0.00
C&D					
Biomass	0.00	0.00	0.00	0.28	0.27
Metal Ores	0.00	0.00	0.00	0.19	0.18
Non-Metallic Minerals	0.00	0.00	0.00	4.22	4.08
Fossil/Energy Carriers	0.00	0.00	0.00	0.00	0.00
Int/Out					
Biomass	4167.95	2220.26	2413.93	1862.23	2322.36
Metal Ores	0.00	5.91	6.30	6.81	7.24
Non-Metallic Minerals	0.00	3.89	4.15	8.58	8.73
Fossil/Energy Carriers	663.61	879.10	580.88	898.73	836.15
EoL					
Biomass	648.75	746.31	848.01	752.66	1964.45
Metal Ores	0.00	5.91	6.30	6.81	7.24
Non-Metallic Minerals	0.00	3.89	4.15	8.58	8.73
Fossil/Energy Carriers	0.00	0.00	0.00	0.00	0.00
DPOe					
Biomass	3519.20	1473.95	1565.91	1109.57	357.91
Metal Ores	0.00	0.00	0.00	0.00	0.00
Non-Metallic Minerals	0.00	0.00	0.00	0.00	0.00
Fossil/Energy Carriers	663.61	879.10	580.88	898.73	836.15

DPOw					
Biomass	648.75	746.31	847.88	752.45	1964.22
Metal Ores	0.00	5.91	6.29	6.79	7.23
Non-Metallic Minerals	0.00	3.89	4.14	8.57	8.72
Fossil/Energy Carriers	0.00	0.00	0.00	0.00	0.00
DPO					
Biomass	4167.95	2220.26	2413.79	1862.02	2322.13
Metal Ores	0.00	5.91	6.29	6.79	7.23
Non-Metallic Minerals	0.00	3.89	4.14	8.57	8.72
Fossil/Energy Carriers	663.61	879.10	580.88	898.73	836.15

Figure A-1: DPO (Emissions + wastes) 2013 to 2022

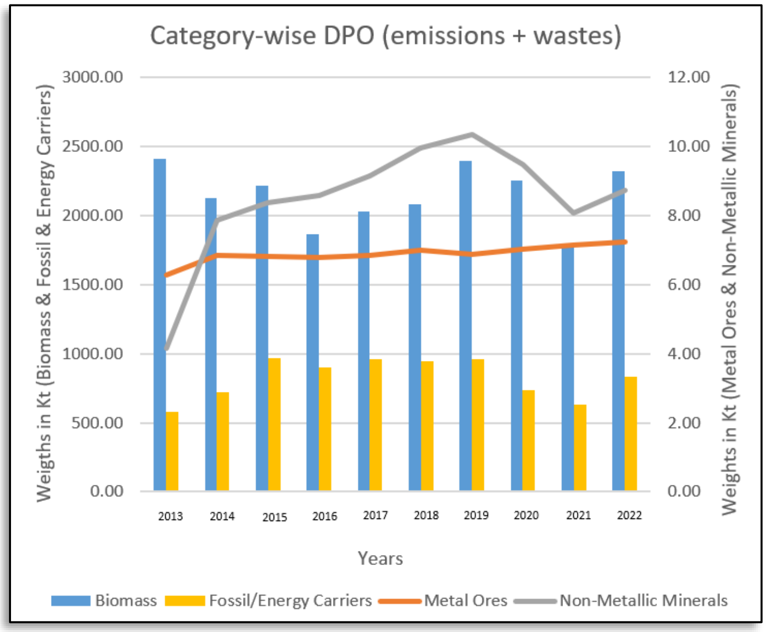


Figure A-2: Construction & Demolition Wastes (2013 to 2022)

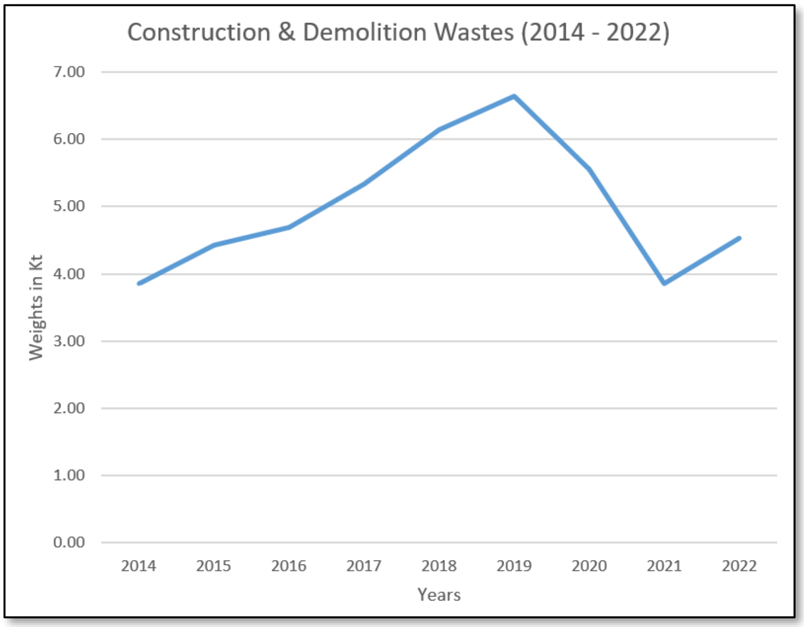


Figure A-3: Biomass DMC (2000 to 2022)

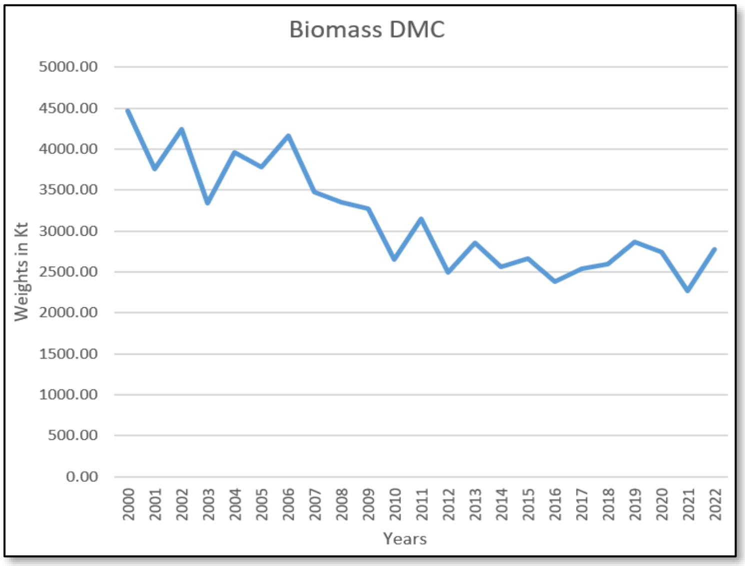


Figure A-4: Biomass Exports (2000 to 2022)

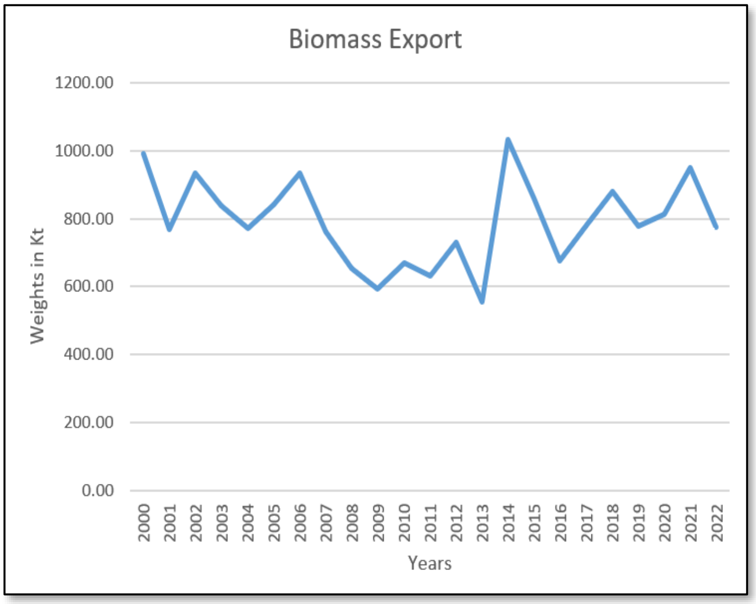


Figure A-5: Metal Ores Export (2000 to 2022)

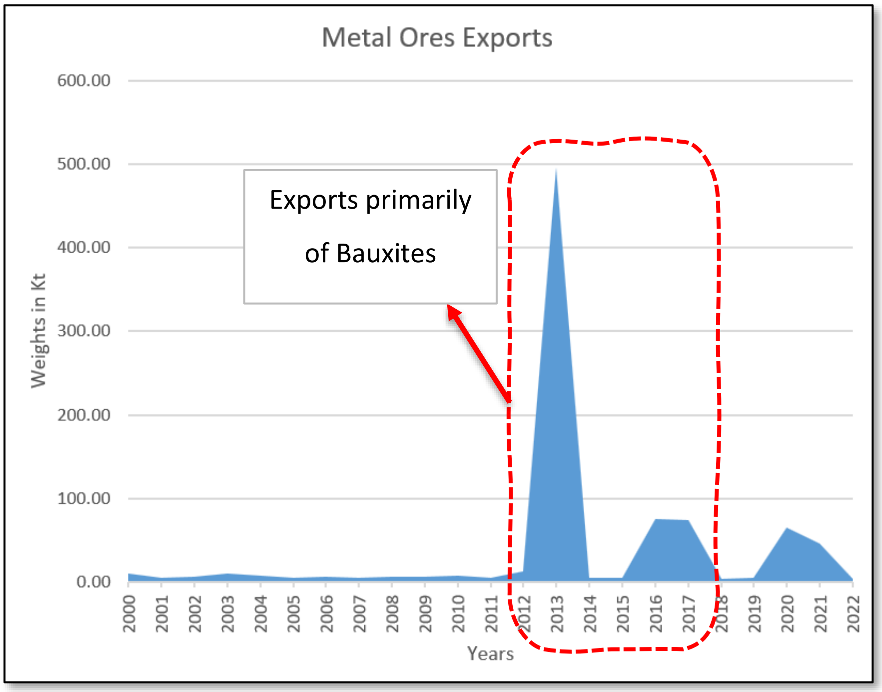


Figure A-6: Fossil Fuels DMC (2000 to 2022)

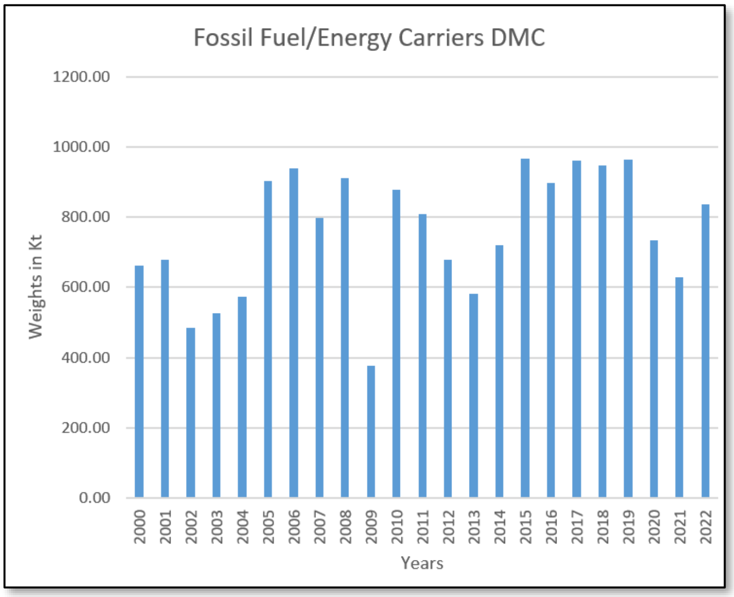


Figure A-7: Types of Climate Disasters in Fiji (2000 to 2022)

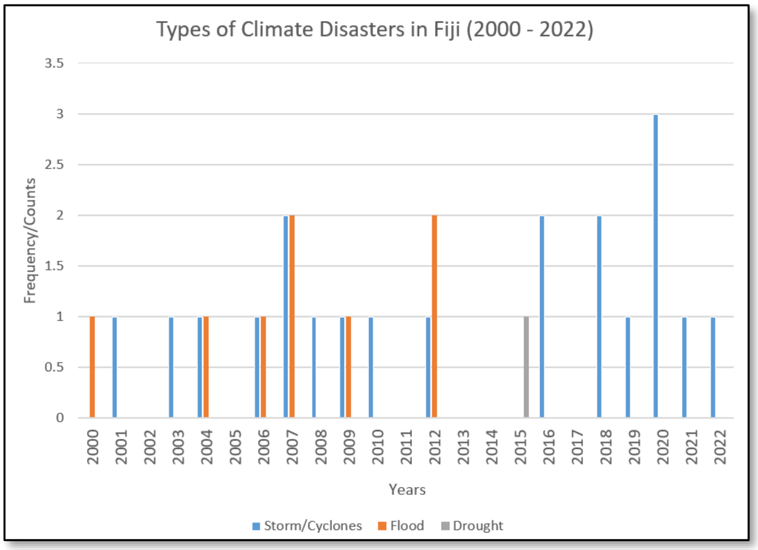


Figure A-8: Net Addition to Stock (NAS) (2000 to 2022)

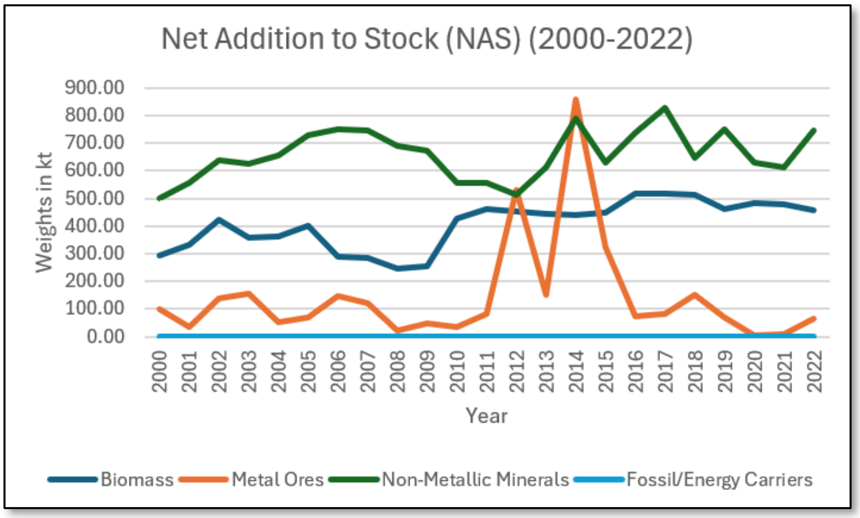
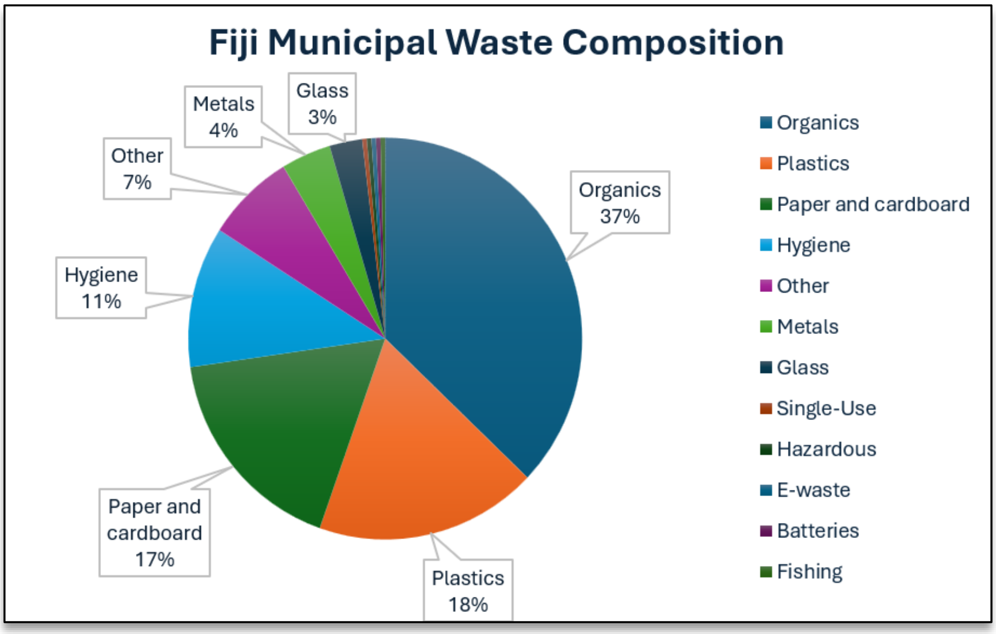


Figure A-9: Fiji Municipal Waste Composition (SPREP, 2023).



Glossary

System	A **system** is “an interconnected set of elements that is coherently organized in a way that achieves something”. It consists of three kinds of things: elements, interconnections, and a function or purpose. Systems can be self-organizing, self-repairing, and resilient, often changing and adapting over time while maintaining their integrity. (Meadows, 2008)
Risk	**Risk** is the potential for adverse consequences for human or ecological systems, recognizing the diversity of values and objectives associated with such systems. In the context of climate change, risk results from the interaction of vulnerability (of the affected system), its exposure over time to hazards, and the likelihood of occurrence of hazard (IPCC, 2022). A simplified mnemonic often used is Risk = Hazard × Exposure × Vulnerability. This highlights that reducing vulnerability can lower risk even when hazards remain (Lewis & Kelman, 2025; Wisner et al., 2025)
Systemic risk	**Systemic risks** describe the likelihood and impact of cascading events in an increasingly interconnected and interdependent world. It is characterized by the possibility of sudden, unexpected change and the potential for impacts to spread within and across systems and sectors (Sillmann et al., 2022).
Cascading Risk	**Cascading risk** is defined as a process by which an initial risk event triggers a sequence of secondary events in connected systems, leading to increasing impacts that can be disproportionate to the original event. These cascades occur due to interdependence between physical, ecological, and socio-economic systems, where failure or disruption in one component propagates across others (Klose et al., 2021).
Socio-metabolic risk	**Socio-metabolic risks** are a sub-set of systemic risks associated with the availability of critical resources, the integrity of material circulation, and the (in)equitable distribution of derived products and societal services in a socio-ecological system (Singh et al., 2020, 2022)
Tipping point	A **tipping point** is a critical threshold where small perturbations can trigger a large, abrupt shift to an alternative state, with characteristic critical slowing down near that threshold (Scheffer, 2010)
Resilience	**Resilience** is defined as the capacity of social, economic, and environmental systems to cope with a hazardous event, trend, or disturbance; respond or reorganize to maintain essential function, identity, and structure; and retain capacity for adaptation, learning, and transformation (IPCC, 2022).
Vulnerability	**Vulnerability** is defined as the propensity or predisposition to be adversely affected and encompasses a variety of concepts and elements, including sensitivity or susceptibility to harm and lack of capacity to cope and adapt (IPCC, 2022).