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ORIGINAL ARTICLE

Analyzing Socio-Metabolic Vulnerability: Evidence from the Comoros Archipelago

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Abstract
Small island developing states are often characterized as vulnerable owing to their unique geographies of smallness and remoteness, resource insecurity, and more recently from the impacts of climate change. These vulnerabilities are often manifested in resource insecurity, significant imports, poor waste management, and the inability to develop economies of scale. In effect, sustaining small islands in an era of global environmental change is a task both scholars and policy makers are increasingly grappling with. Can small islands be sustainable? This research examines the social metabolism of an island system, and introduces the concept of "socio-metabolic vulnerability". As such, this research provides novel insights into the linkages between patterns of resource-use, systemic risks and vulnerability. Results from a local material and energy flow analysis (local-MEFA) for the island of Ndzuwani (Comoros) suggest a very low level of resource-use but at the same time heavy reliance on critical imports that cover vast distances, that are vulnerable to price and climate shocks. Informal activities in resource extraction play an important role in lending both vulnerability and resilience to Ndzuwani. This study adds to the scarce body of literature that argues that small island economies would need to leverage resource-use patterns to build system resilience, along with bold policies and institutions that support material circularity, engage communities and fosters frugal innovation.

Keywords Socio-metabolic vulnerability · Island metabolism · Socio-metabolic research, Small Islands Developing States (SIDS) · Ndzuwani Island · Comoros archipelago · Material and energy flow analysis

1 Introduction

1.1 Vulnerabilities Associated with Island Economies

Islands are sites of compound events and multiple vulnerabilities (Pelling and Uitto 2001; UNEP 2019). They suffer disproportionally from the effects of climate change such as sea-level rise, frequent and intense hurricanes, increased flooding, droughts, and water stress (Kelman 2010). Limited resources and waste absorption capacity, isolation from markets, and heavy reliance on imports to meet basic needs such as food and energy characterize island systems (Baldacchino 2006). Shocks such as hurricanes or pandemics result in the abrupt breakdown of supplies and reveal the vulnerability of island economies (Baldacchino and Bertram 2009).

According to the new Universal Vulnerability Index (UVI) of the Commonwealth (2021),[1] more than 20 years after the research of Briguglio on the economic vulnerabilities of islands (Briguglio 1995), the Small Islands Developing States (SIDS) still have the lead as the most vulnerable territories. Building on the Economic and Environmental Vulnerability Index (EVI), the Multidimensional Vulnerability Index (MVI) highlights the acute and multidimensional vulnerability of SIDS by drawing on lessons learned from the COVID-19 pandemic. This MVI has been applied

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[1] Available on https://thecommonwealth.org/sites/default/files/inline/Universal%20Vulnerability%20Index%20Report.pdf .

for 144 nations with a focus on six sectors (ecosystem services, food, human habitat, health, infrastructure and water), demonstrating the Caribbean countries are among the most vulnerable nations in the world (Edmonds et al. 2020).

This research investigates the social metabolism of Comoros archipelago situated in the Mozambique Channel between Madagascar and the Swahili Coast in East Africa. It makes a theoretical contribution by introducing the concept of "socio-metabolic vulnerability", where "vulnerability" is defined as "the propensity or predisposition to be adversely affected" (IPCC 2014). The vulnerability analysis is a function of exposure, environmental effects, and recovery (also termed resilience or adaptive capacity) (Turvey 2007; De Lange et al. 2010). Several frameworks for vulnerability assessment exist (Birkmann 2006), such as the school of the double structure of vulnerability (Bohle 2001), the conceptual frameworks of the disaster risk community (Bollin et al. 2003) or the analytical framework for vulnerability assessment in the global environmental change community (Turner et al. 2003).

Of these frameworks and indexes, none really consider resource-use dynamics as part of vulnerability analysis. Materials and energy flows are critical for the survival and wellbeing of any socio-economic system. By introducing the notion of socio-metabolic vulnerability, we examine the extraction, production, and circulation of resources within the system, and by way of trade, and how socio-spatial inequality is reproduced at both the local and global scale (Schaffartzik et al. 2019). Analysis of these vulnerabilities "includes several dimensions: impacts, exposure, sensitivity, capacity to adapt, and actual responses" (Romero Lankao and Qin 2011). A territory may thus be considered "vulnerable from a socio-metabolic perspective" due to the potential threats to its resource supplies, socioeconomic ways of functioning, and waste and emissions management (Singh et al. 2020).

Scholars are beginning to study islands from a socio-metabolic perspective, a field of research that systematically analyzes material stocks and flows associated with societal production and consumption. Socio-metabolic research (SMR) "links the study of socioeconomic processes with biophysical processes and thus plays a pivotal role in understanding society-nature interactions. It includes a broad range of systems science approaches for measuring, analysing and modelling of biophysical stocks and flows as well as the services they provide to society" (Haberl et al. 2019). Therefore, SMR offers crucial insights to develop strategies to reconfigure and reduce societies' use of natural resources that is compatible with ecological boundaries, while also providing essential services to reach social thresholds (Singh et al. 2020). Understanding "island metabolism" (Singh et al. 2020) and associated vulnerabilities is crucial for island economies to move towards more sustainable resource-use configurations, increase self-reliance, and resilience to impacts of climate change. The objective of this research is to examine socio-metabolic vulnerability, defined as the propensity of the socio-economic system to be negatively affected by trends and patterns of social metabolism. We hypothesize that reconfiguring and restructuring of resource use patterns can be an effective adaptation strategy and build system resilience. In doing so, we focus on critical flows that lend Comoros its socio-metabolic vulnerability, mainly construction materials, biomass, wood, and waste, and identify key drivers and actors that influence the social metabolism of the archipelago. We ask: What are the trends and patterns of materials and energy flows in a given socio-economic system? What is driving those flows? What are the impacts of resource use across geographical areas? What types of risks and vulnerabilities are associated with these flows?

1.2 Island Metabolism: A Scientific Archipelago

Islands have "methodological utility" (Chertow et al. 2020). With relatively well-defined boundaries, naturally and socially, they can be "real-world laboratories" (Schäpke et al. 2018)—an approach that is gaining momentum in addressing complex societal problems. In this respect, islands with clearly delineated boundaries are excellent geographies for socio-metabolic (SMR) research, that is, tracking flows of matter and energy in and out of an economic system. An early MFA was for Trinket Island (India) (Singh et al. 2001; Singh and Grünbühel 2003), the same case later compared to the rise in material and energy consumption caused by excessive aid following the 2004 Asian tsunami (Singh and Haas 2016; Fetzel et al. 2018). Other notable "flow" studies on islands are Cuba (Eisenhut 2009), Iceland, Trinidad and Tobago (Krausmann et al. 2014), Malta (Conrad and Cassar 2014), the Philippines (Martinico-Perez et al. 2018), Hawaii (Chertow et al. 2020), New Caledonia (Bahers et al. 2020), and more recently, an investigation of long-term biomass flows in the Caribbean (Rahman et al. 2022).

Some island SMR have focused only on problematic flows, in particular waste and energy. With limited land area, and the high cost of exporting waste elsewhere has exacerbated sustainability challenges on islands (Eckelman et al. 2014; Mohee et al. 2015; UNEP 2019). Some archipelagos are known for their difficulties in managing waste, such as Samoa, whose open landfill has more than reached its capacity (Brown 2015), Nauru, for its mining waste and phosphate-polluted water (Gowdy and McDaniel 1999), and Corfu, where 4000 tonnes of waste which is left behind by tourists each year (Skordilis 2004). Notable waste studies on islands using SMR include aluminum flows on Fiji (Bahers 2011), e-waste in five Caribbean countries (Mohammadi et al. 2021), solid waste in Grenada (Elgie et al. 2021), plastic waste in Trinidad and Tobago

(Shah et al. 2019), construction waste on Samothraki Island (Noll et al. 2019), and disaster waste on St. Martin (Popescu et al. 2020). Few studies focus only energy flows on islands, which is also a problematic issue. Cecchin (Cecchin 2016) assesses local policies on the consumption of fossil fuels and on agricultural production on the Galapagos Islands. Lenzen (Lenzen 2008; Lenzen et al. 2014) includes material flow in a case study of Norfolk Island businesses and an energy flow study determining the energy consumption for Cocos (Keeling) Islands. The social metabolism of the Balearics argues for a shift towards more resilient low-carbon islands due to the increase in the use and demand of imported fossil fuels (Ginard-Bosch and Ramos-Martín 2016).

Studies with a focus on material "stocks" are rare, and only recently scholars have started to pay attention to islands using Material Stock Analysis (MSA), a method to quantify materials that remain in use for longer than a year, such as buildings, infrastructure, machineries, electronics and all other durable goods (Augiseau and Barles 2017). The spatial distribution of stocks, such as type of materials, how much, and where they are located are of crucial importance for island sustainability. As stocks provide critical societal services to society, insights into stock dynamics can play an important role in building system resilience from impacts of climate change, such as sea-level rise and hurricanes. Tanikawa et al. (2014) estimated the loss in material stocks following the earthquake and tsunami in Japan. Merschroth et al. (Merschroth et al. 2020) estimated the loss in stocks in Fiji due to sea-level rise and global warming. Symmes et al. (Symmes et al. 2019) conducted the first spatially explicit material *stock-flow* analysis in the Caribbean, focusing on Grenada's metabolism of construction materials, their distribution across the different sectors of the economy, and the potential impacts from sea-level rise. (Bradshaw et al. 2020) explores the first material *stock-service* relationship for any island (Antigua and Barbuda) with consequences for island sustainability under sea-level rise scenarios.

Overall, however, since the seminal works by Singh et al. (2001), Deschenes and Chertow (2004), Eckelman and Chertow (2009), research on islands from a SMR perspective has been inadequate. Recognizing the urgency of small islands to transition to more sustainable modes of production and consumption, the International Society for Industrial Ecology (ISIE) has recently founded a special section called "Island Industrial Ecology". Further impetus to this area of research has been given by a collection of papers in a special issue "The Metabolism of Islands" (Singh et al. 2020).

2 Methodology: The Material Flow Analysis (MFA) of Ndzuwani Island

2.1 The Study Area of Ndzuwani Island in the Comoros

The Union of the Comoros (or Comoros) is a Small Island Developing State (SIDS) facing a number of issues that drive vulnerability, and societal efforts to adapt to it (Altschuler and Brownlee 2016; Magnan and Duvat 2020; Piggott-McKellar et al. 2020). With 846,281 inhabitants in 2020 and an average per capita GDP of 1445 USD/cap/yr, it has one of the lowest nominal GDPs and is classified by the UN as the least developed country. Also, the Gini coefficient (the measurement of inequality) and HDI (Human development index) are very low, respectively the 141st and the 160th in the world according to the World Bank and the United Nations Development Program (Belghith et al. 2018). Comoros has numerous structural defects in the fields of health, education, infrastructure, transport, and tourism, partly due to a lack of public and private investment (Lenzen 2015). As Taglioni (2008) notes, "history and geography have conspired to place this archipelago on the margins of political and economic development and global flows". This transpires in high levels of poverty and infant mortality, low literacy, and limited life expectancy. Despite this, there is little criminality and peace reigns in the streets of Mutsamudu, the capital city.

The volcanic archipelago of the Comoros lies in the Mozambique Channel between Madagascar and the Swahili Coast in East Africa. The archipelago is composed of four islands, Ndzuwani, Ngazidja, Mwali and, Mayotte (the latter is still a municipality of France). Ndzuwani is an island with a very mountainous topography, limiting its habitability. Its capital, Mutsamudu, is the only cargo port on the island. In 2017 Ndzuwani had a population of 327,382 inhabitants (according to a UN estimate). It covers an area of only 424km^2, making it the island with the highest population density in the Comoros (772 inhabitants per km^2). According to a recent research on deforestation (Boussougou et al. 2015), the woodland represents 65% of the land use, the agricultural land 30% and the building zones 2%. It is also the poorest island in the archipelago, engendering migratory flows towards Mayotte, belonging to France.

The political situation in the Comoros seemed to have calmed down until reforms to the revolving presidency and to the length of periods of office seriously destabilized its internal and external politics in 2018, resulting in the army stepping in. Furthermore, relations with Mayotte continue to be very tense due to problems relating to migration and the close family ties between inhabitants of

Mayotte and the Comoros. The Comoros also have a trade deficit with Mayotte and colonial ties with France remain strong. Research has also shown that the population of Mayotte is far less vulnerable to climate change (Wu-Tiu-Yen 2015) and to natural catastrophes (Legoff 2011) than that of Ndzuwani.

Agriculture is the largest economic sector on the Comoros (accounting for about 40% of GDP), comprising both traditional subsistence agriculture (Robineau 1966) and cash crops for export, such as vanilla, ylang-ylang, and cloves, controlled by local communities with a trading history (Blanchy 2015). Thus, most of the population is rural (about 70%), but with a population shift towards the towns on the coast (Gérard 2009).

2.2 Conducting a MFA: A Case in "Local Studies"

This research follows the MFA research tradition (Baccini and Brunner 1991; Hendriks et al. 2000) with a local approach. It seeks to "understand the ways by which the 'local' is altered by global processes through interventions such as subsidies, markets, legal frameworks, creation of infrastructure" (Singh and Haas 2016). Local MFA becomes necessary in data-poor environments, and, therefore, secondary data collection is complemented by fieldwork that brings researchers in direct contact with actors and stakeholders. A local MFA also provides valuable insights into system dynamics through narratives provided by the stakeholders, thus allowing to interpret quantitative data within a certain socio-cultural context. Analyzing the social metabolism of a local system highlights problematic flows that may the propensity to negatively affect the system as a whole, and generate cascade effects throughout the system. In this respect, an MFA is intended to provide a range of experiences of how local environments are shaped, contested and rendered vulnerable.

Data for MFA, secondary data on the physical flows entering and leaving the territory was compiled to the extent possible using national and international sources. Embedded in the *System of Environmental Economic Accounting* (SEEA) framework, MFA offers a consistent compilation of all resources entering the socioeconomic system, the changes in biophysical stocks within the system, and outflows to the environment (such as wastes and emissions), as well as exports to other socioeconomic systems (Eurostat 2018). Standard headline indicators (Eurostat 2018) were used in this study, mainly Domestic Material Input (DMI) which is a sum of Imports and Domestic Extraction (DE), and Domestic Material Consumption (DMC), which is DMI – Exports. The flows accounted for, and derived indicators are consistent with the main categories of EUROSTAT (2018). These are construction materials (cement, lime or plaster), biomass (such as food and crops), fossils fuels (petroleum products, coal), metals (including manufactured appliances and metallurgical products, household equipment, cars, electronic products). On the output side, Domestic Processed Outputs (DPO) quantify solid waste, emissions and dissipative uses. Solid waste includes municipal, commercial and construction waste. The Net Addition to Stocks (NAS) corresponds to the accumulation of material in the economy per year, such as construction minerals in buildings and durable goods (Eurostat 2018).

Data collection was a combination of secondary sources research as well as two field visits, one in February 2018, and the more extended one between March and June 2018. Secondary sources research soon revealed one important challenge: the lack of a full and consolidated database. International studies of socio-economic metabolism generally use national and international statistics (Krausmann et al. 2009; Fischer-Kowalski et al. 2011a). In our case, the available statistics did not cover all flows, especially local extraction (biomass and minerals production) and domestic processed outputs (or wastes). The main database used in MFA for mining data is the U.S. Geological Survey (USGS) (Krausmann et al. 2014; Duro et al. 2018; Wiedenhofer et al. 2019), but the latest issue (USGS 2010) did not mention any local production of material in Comoros, what the field survey later invalidated.

To fill these significant data gaps that drive material flows (such as quarries), a brief field trip of three weeks was undertaken in February 2018. Field observation showed that there are two authorized quarries producing about 80% of the minerals mined on the island (sand of various grain size, gravel, and pebbles). Other data limitations were overcome by a workshop over two days with local actors to refine and reconstruct missing data for the MFA. Forty political, economic, and non-governmental organizations were invited to this workshop, who also participated in surveys to identify, assess and interpret the important flows. These were from, for example, the Comoros institutions (customs and port), Ndzuwani institutions (the economic and the environmental director for the Ndzuwani Governorate, and local ministers in charge of the environment, the economy, and urban development), the local actors (elected officials), local and environmental NGOs (Ouani vert, Commission Mutsamudu Propre, and Sac Marie), and international NGOs (Initiative Développement (ID), Naipenda Comores, and Gevalor). During the workshop, the participants drew up a map of the material and energy flows that are imported, produced, exported and discharged on the island.

Statements by those local actors helped develop a better understanding of the visible and less visible flows circulating on the island. We also had the opportunity to meet and build a relationship with a customs official from Comoros. Data on imports and exports were gathered from the port of Mutsamudu in Ndzuwani, which is the only point of entry

Fig. 1 Photos of **a** extracting sand in a river (Source: Perez 2018) and **b** depositing of burnt waste along Mutsamudu beach next to a sign forbidding this placed there by local inhabitants (Source: Bahers 2018)

of goods to the island. Customs data provided a rather accurate picture of flows entering or leaving the territory. This methodological stance is innovative in the field of territorial metabolism studies, which tend to be guided by national or international sources, as mentioned earlier. The map of flows, their characteristics, and their transformations, that was elaborated by local actors during the first field visit, and the workshop formed the basis of the 4-month field visit between March and June 2018 (Perez 2018).

In the first field visit, it became clear that informal activities generated a significant amount of material flows within the system. The objective of the second field visit was, therefore, to observe, quantify and assess the material flows induced by informal economic activities, such as sand extraction, waste, or the production of ylang-ylang essential oil. For that, we conducted 20 interviews with key actors in the area of agriculture, the production of essential oil, forestry, fishing, the collection of waste on beaches, sand extraction, quarrying, and in the recovery of construction waste, scrap metal and other discarded materials from landfills. Interviews also involved understanding the end uses of recovered waste to make products such as plastic bags, tablecloths textiles, and plastic carpets. Interviews were semi-structured, open ended, and were conducted in Comorian and translated into French by a local collaborator. Opening questions were of general nature, for example, how they work, the goods (biomass, construction materials, manufactured products) and quantities they produce and from which source, or the waste they collect, and where they are sold. When possible, questions surrounding their working conditions, the social, political and environmental implications of their activities in the island economy were also asked. That enabled us to understand the political economy of metabolic links and emphasize the metabolic relationships and resultant antagonisms (Demaria and Schindler 2016; Martinez-Alier et al. 2016a). Practices and activities were also documented through photos (almost 250) during the field visits (cf. Fig. 1). An overview of data sources and steps of study taken is presented in Table 1.

3 Results

3.1 Indicators from MFA

Figure 2 summarizes the results of the MFA obtained for the island of Ndzuwani. In 2016, the DMI for the island was 483 kt (which is the sum of imports and domestic extraction). Imports in relation to DMI were only 27% or 130 kt (or 0.4 t/cap), contrary to what one might have thought intuitively. Imports were mostly of construction minerals (cement, lime or plaster) and biomass (such as food and crops), which represented 51 and 52 kt respectively in 2016 (or 80% of all imports (cf. Figs. 2 and 3). Fossil fuel imports were very small with 19 kt (or 0.06 t/cap). Metal imports have the smallest share with 8 kt. It has to be noted that 61% of metals imports are manufactured products. Domestic extraction had the larger share in DMI with 353 kt or 1.1 t/cap, with biomass, especially food from subsistence farming (cereals and vegetables) being 182 kt (or 0.5 t/cap) and wood 87 kt (or 0.26 t/cap).

The total Domestic Material Consumption (DMC)—which is DMI minus Exports—was 480 kt or 1.5 t/cap in 2016. This DMC is very low, and actually Ndzuwani has a very low metabolic rate as compared to other researched islands so far (Table 2). Moreover, according to the International Resource Panel, the Union of Comoros appears to have one of the lowest metabolic rates (DMC: 1.7/cap) in the world (Fischer-Kowalski et al. 2011b), which makes it a very specific and relevant territory. The share of biomass is the most significant with 48% of total DMC, followed by construction minerals (28%) and fossil fuels (22%). Metals (such as manufactured appliances and metallurgical products) represent a very small share in consumption, which

Table 1 Source and steps of study for the material flow analysis

Data	Source	Steps of study
DOMESTIC EXTRACTION		
- Biomass (and food)	FAO for Comoros	Secondary sources
- Construction minerals	Interviews with local stakeholders, Interviews with informal actors, field observation	First field trip and second field trip
IMPORTS		
- Biomass (and food)	Customs data/interviews with port authority	First field trip
- Construction minerals	Customs data/interviews with port authority	First field trip
- Fossil fuels	Customs data/interviews with port authority	First field trip
- Metals (and manufactured products)	Customs data/interviews with port authority	First field trip
EXPORTS		
- Biomass	Customs data/interviews with port authority	First field trip
DPO		
- Emissions to air	FAO for Comoros/estimation from fossil fuel consumption	Secondary sources
- Waste disposal	Interviews with local stakeholders/Interviews with informal actors, field observation	First field trip and second field trip
- Dissipative use	FAO for Comoros/Interviews with local stakeholders	Secondary sources and first field trip
- Recycling	Interviews with local stakeholders/Interviews with informal actors, field observation	First field trip and second field trip

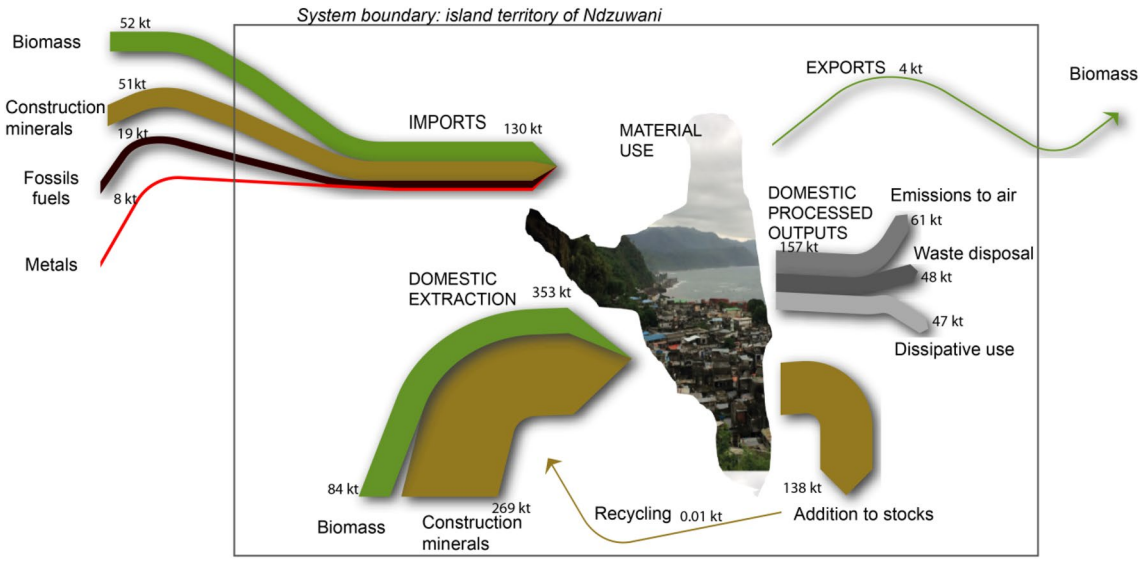

Fig. 2 Material flows (in kilotons) for the island of Ndzuwani in 2016

also explains the lack of durable goods equipment (household equipment, cars, electronic products) of inhabitants. In this, the annual net addition to stocks (NAS), that is to say the materials that remain in the territory, represents about 138 kt/year, so 0.42 t/cap. It consists mainly of construction minerals and a few imported durable products.

The DPO of 0.5 t/cap consists of solid waste, including construction materials (30%), dissipative uses (30%) from agricultural waste, and atmospheric emissions (40%) from the combustion of fossil fuels, wood, and from the decomposition of organic matter. It should be noted that on Ndzuwani, unlike other resource-exporting countries, little waste results from the extraction and manufacture of exported products. However, the wastewater from the production of essential oils is significant (Tongnuanchan and Benjakul 2014). Finally, recycling is not very significant compared to the production of island waste.

Comparing Ndzuwani's metabolism with other islands (Table 2), we find the former's use of materials is very low (Singh et al. 2001; Krausmann et al. 2014; Martinico-Perez

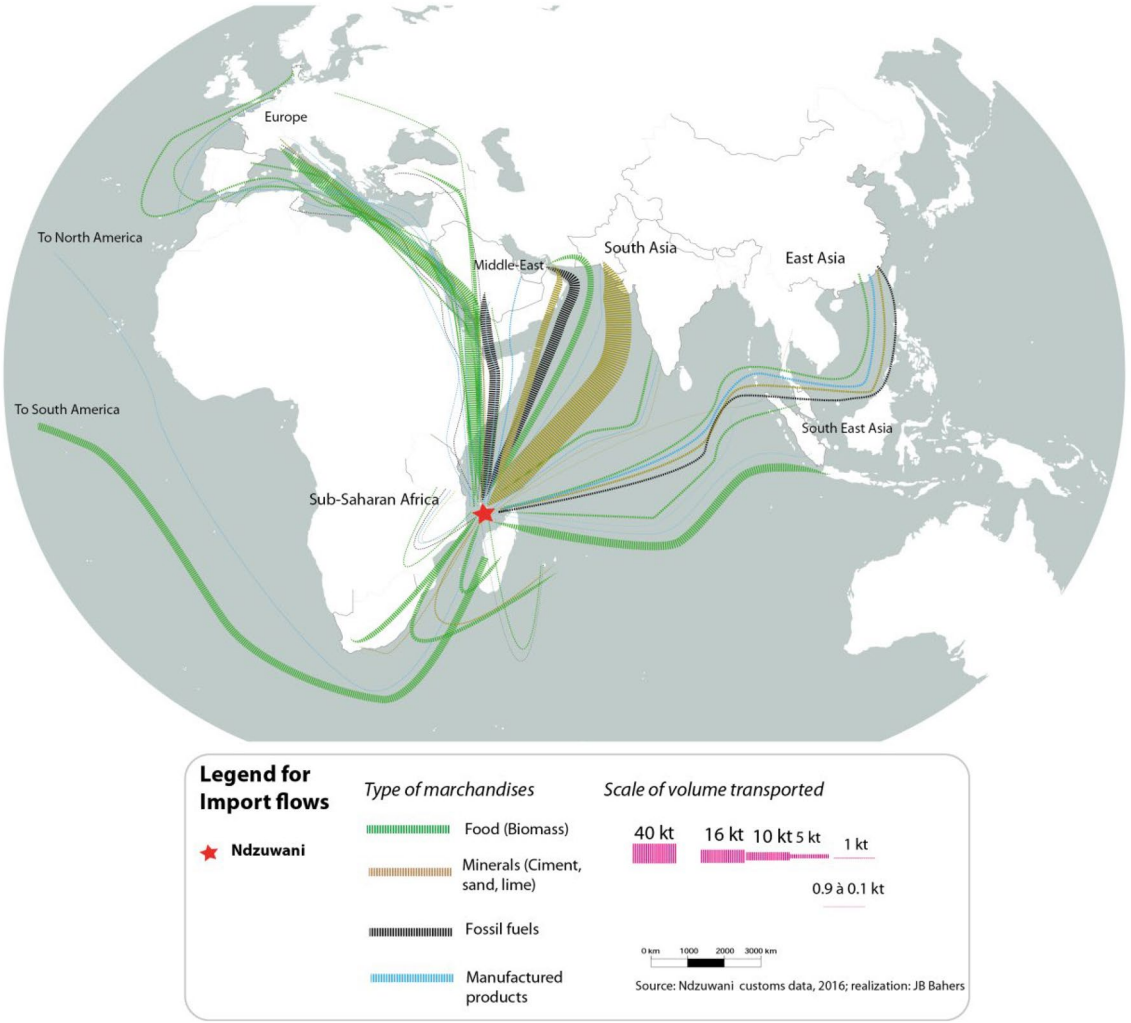

Fig. 3 Import flows from foreign countries (Note: The thickness of arrows corresponds to the volumes imported by foreign countries). Source: Customs data, 2016; realization: Bahers)

Table 2 Comparison of MFA indicators with others island metabolisms

t/cap/yr	DE	Imports	Exports	DPO	DMC	Source
Ndzuwani (2018)	1.1	0.4	0.01	0.5	1.5	
Martinique (2015)	7.8	5.5	2.4	7	10.9	CEREMA (2019)
New Caledonia (2016)	36.3	14.3	21.7	13.9	29.0	Bahers et al. (2020)
Trinidad and Tobago (2008)	34.7	8.8	26.2	NA	17.4	Krausmann et al. (2014)
Iceland (2008)	14.0	15.1	6.1	NA	23.0	Krausmann et al. (2014)
Philippines (2014)	6.0	1.2	1.5	NA	5.9	Martinico-Perez et al. (2018)
Trinket (2000)	5.8	0.4	2.4	NA	3.8	Singh et al. (2001)

t/cap/yr tons per capita per year mentioned closed to the countries, *DE* Domestic extraction, *DPO* Domestic Processed Output, *DMC* Domestic Material Consumption; see Sect. 4 for explanations of these indicators

et al. 2018; CEREMA 2019; Bahers et al. 2020). For example, the DMC of Ndzuwani is 1.5 t/cap/yr, quite low as compared to the Philippines (6 t/cap), Trinidad Tobago (17 t/cap), and New Caledonia (29 t/cap). All three are extractive economies where the industry is heavily slanted towards exporting local resources (metal ores for the Philippines, oil for Trinidad and Nickel for New Caledonia), with resultant high levels of energy use and production of waste. Equally,

the amount of goods imported to Ndzuwani, at 0.4t per capita, is far lower than the 5.5 t per capita in Martinique, the 8.8 t per capita in Trinidad and Tobago or the 15.1 t per capita in Iceland. The Domestic Process Output (DPO) is also very low in comparison to other islands. Ndzuwani is close to the metabolic profile of Trinket, even if the Domestic Extraction (DE) is much more important in Trinket (5.8 t/cap), in particular the minerals.

3.2 Spatial Distribution of Resources Imports

Figure 3 shows the spatial distribution of Ndzuwani imports, demonstrating a complex supply chain for sustaining a remote small island. The thickness of the arrows is proportional to the quantity of flow per country. Regional imports come from Mayotte, Madagascar, La Reunion, Tanzania, and we can also include South Africa that is 3000 km away. These regional imports account for only 7% of the total but are very varied. For a low-income country, Ndzuwani is, therefore, well integrated into the circuits of the global flow of goods. The biomass (in green) comes from thirty-six different countries, and many European countries. This mainly comprised of rice, sodas and meat products, especially a large amount of chicken wings from France. Indeed, these are products of very low quality, often discarded in France, and, therefore, cheap. However, chicken wings are popular on the islands and thrive as part of the French colonial heritage. Construction minerals (in brown) are mainly composed of cement, sand, lime and plaster. Pakistan is the first partner in these materials, followed by the United Arab Emirates and China. Manufactured products (in black), which are imported in relatively small quantities (10 kg/cap/year), come from Asian countries such as China and India, and the Middle East (United Arab Emirates and Saudi Arabia).

3.3 Socio-metabolic Vulnerabilities

This section highlights examples of socio-metabolic vulnerabilities as revealed by the MFA. These socio-metabolic vulnerabilities are both related to inflows (imports and domestic extraction) and outflows (i.e. waste and emissions) of island metabolism.

3.3.1 Biomass Metabolism and Food Insecurity

In 2017, the MFA shows that subsistence crops amount to 0.5 t per capita, directly consumed by producers. Yet this is insufficient and has to be supplemented by imported foodstuffs. A quarter of food comes from outside (cf. Fig. 2), that is mostly low-quality protein as there are a lot of meat products. Moreover, the economic value of imported foodstuffs has quadrupled since 2005 (FAO 2018) It is, therefore, becoming very expensive to import food, which is one of the indicators of declining food security, according to the FAO.

The food production has increased between 2006 and 2016 (up 65%) by expanding agricultural land for a population that has also increased by 30%. Yet, imports have grown to an even greater extent, by about 77% (FAO 2018). Thus, even with increased local production, local food makes up a decreasing share of domestic consumption, meaning the island is not on the path to food security. Indeed, the inhabitants also consume more food, and while malnutrition is decreasing, obesity is increasing due to the consumption of cheap low quality proteins, fats, sweet beverages, and other processed foods. Obesity among adults has increased from 4.1% of the share of the population in 2000 to 7.8% in 2016 (FAO 2018).

3.3.2 Extraction of Sand and Ecological Consequences

The spatial distribution of MFA demonstrates that large physical and financial volumes of sand, cement, lime, and plaster are imported (mainly from Pakistan, amounting to 40 kt in 2016, and to a lesser extent from China and the United Arab Emirates—see the minerals brown arrows in Fig. 2). This might seem surprising, but "sand is rarer than one thinks" (Peduzzi 2014), so these bulk materials cross oceans despite their relatively low economic value per ton, making them very expensive to transport. This is due to the booming trade in construction material, created by increasing coastal urbanization. The size of urban areas doubled between 1995 and 2014 (Boussougou et al. 2015). In Ndzuwani, these imports result from the shortage of domestic resources.

In recent years quarries have been opened on Ndzuwani, leading to a drop in imports of sand and gravel (Customs data, 2016). Yet interviews with those involved showed that these domestically produced materials are too expensive for many households. At the same time, the informal extraction of sand on the coast and rivers continues to be popular when possible and accounted for about 20% of building material extraction on the island in 2016. Furthermore, this practice is very labor intensive (cf. Fig. 4) and poorly paid: "I extract a quantity of thirty buckets per day. When I reach about $4m^3$, about a month's work, I sell the sand for FRC50,000 [about €100]" (interview with worker extracting sand from the river at Ouani, 2018). It is also a disaster for the island's landscape because the coasts are progressively disappearing and undergoing major erosion as a result of this practice (Sinane et al. 2011). Furthermore, it endangers the road infrastructure along the coasts which sometimes collapse due to the receding beaches (cf. Fig. 4).

However, interviews indicate that the building sector generates very little waste, unlike in northern countries, for most of it is reused on site, due simply to lack of accessible

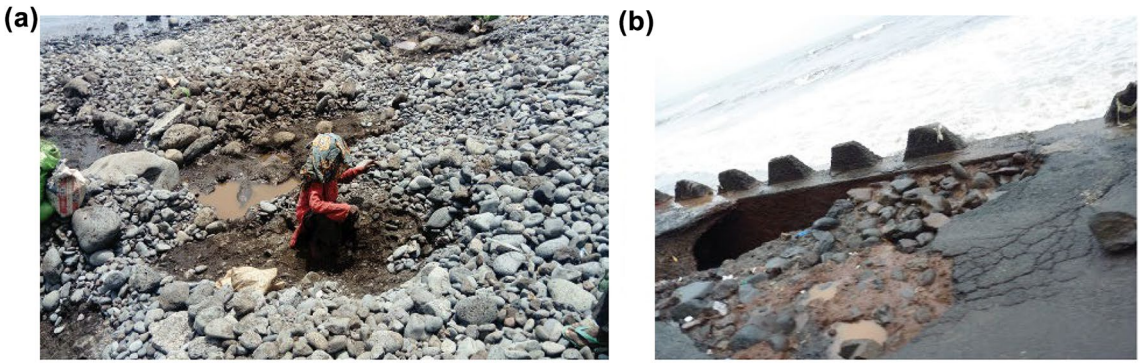

Fig. 4 Photos of **a** informal worker collecting sand on the coast (Source: Perez 2018) and a collapsed road at Mutsamudu (Source: Bahers 2018)

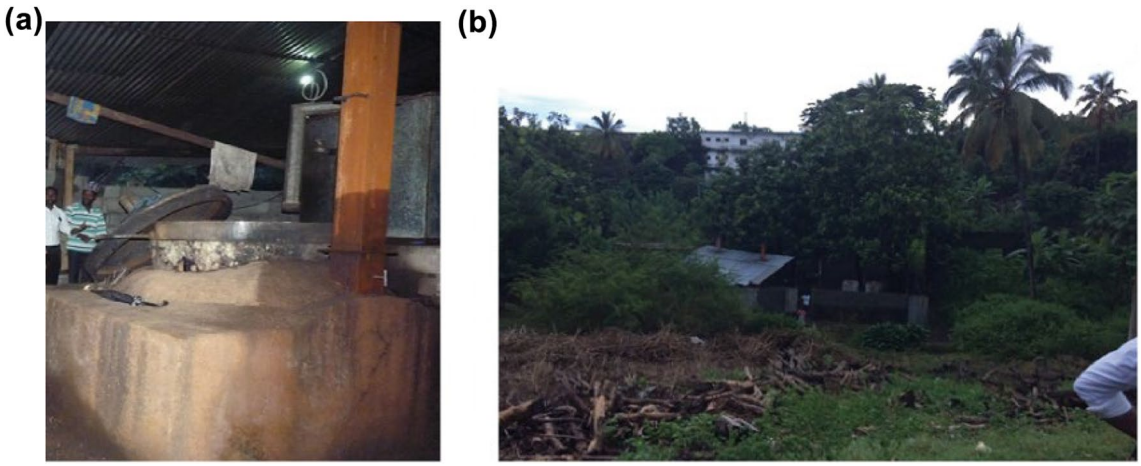

Fig. 5 Photos of **a** Ylang-ylang still (Source: Bahers 2018) and **b** Distillation site with store of cut wood (Source: Durand 2018)

raw materials: "the building sector is highly informal, and as the population cannot pay for new materials they reuse building waste and even make community contributions to fund the building of roads and mosques in their neighborhood or village" (interview with an inhabitant building his house, 2018). Secondary materials are thus fully reintegrated into local production cycles, giving rise to different forms of collective organization and informal activities. In this way, informal actors can be important levers for optimizing the management of flows on the island of Ndzuwani.

3.3.3 Deforestation for Ylang-Ylang Oil Production

The third vulnerability relates to large-scale deforestation related to producing the ylang-ylang essential oil. The distillation of ylang-ylang used for perfumery is a flagship product of the island's economy, employing roughly 15% of the working population (interview with NGO official, 2018). There are about 270 distillation operations per year on the island, producing 3 L of oil per distillation (cf. Fig. 5). However, this process consumes large qualities of river water, ultimately drying them up, and similarly large quantities of timber, being one of the main causes of deforestation in Ndzuwani. About 1 ton of timber is consumed per distillation (cf. Fig. 5), and "most of the time they get a logger to select and cut the tree, but don't replant afterwards" (interview with NGO official, 2018). The wood is cut from natural forest and from agroforestry whose main species is *Eucalyptus robusta*, a colony plantation. The area of deteriorated forest is reported to have doubled between 1995 and 2014, from 8.3 to 15.3% of the land use (Boussougou et al. 2015) with logging of timber being as high as 260 kg per capita in 2016. This weakens the economic viability of the essential oil production sector, which is based on deforestation and, therefore, about increasing loss of forest, that leads to less domestic wood resources over time.

Fig. 6 Photos of **a** Lack of supervision of the "controlled" Domoni landfill (Source: Bahers 2018) and **b** protests to the siting of a dump in Ouani (Source: Bahers 2018)

3.3.4 Conflicts Relating to "New" Urban Waste Flows

As shown in the MFA in Fig. 2, roughly 48 kt of household waste was produced in 2016, that is about 150 kg per capita. This is very low in comparison to high-income countries such as France (530 kg/cap) or the United States (725 kg/cap) (OECD 2013). Urban waste is not externalized on Ndzuwani, unlike European or North American territories which export several categories of waste. Even if the quantity of waste is very low, these externalities are mainly processed under conditions that increase the island's fragility. It is in Ndzuwani a clearly visible negative externality, which could paradoxically induce more transparent and controlled management by these territories. Still, the lack of facilities to collect and process waste is a stumbling block in its management. Indeed, some of the waste is thrown into rivers or on the seashore, sometimes after being burnt alongside beaches such as in the urbanized Mutsamudu bay, which is the main city of Ndzuwani (cf. Fig. 3). The rest goes to landfill or more accurately is placed in illegal dumps, some of which are very large, dotted around rural areas. Field observations show a significant part of this urban waste is comprised of plastic objects not previously found there. A very big issue is plastic flip-flops "bought very cheaply from China and lasting no more than two weeks" (interview with an economic development officer, 2018). It is particularly difficult to combat the obsolescence of this object, which is another stigma of "cheap things" (Patel and Moore 2017). This also represents a beginning shift from reuse and repair towards a throw-away society.

Since 2014, the need to "govern municipal waste" (Bulkeley et al. 2005) has led the local authorities to try to sort out this situation by selecting controlled landfill sites, even if the municipal waste is still not collected. However, this political decision soon sparked social conflict on the island (cf. Fig. 6). These protests about dumps do not differ much from those in other countries, mainly involving residents who rightly fear the landfill may "overspill" (cf. Fig. 6) and are worried about the systematic traffic of trucks transporting dangerous material. Thus the first plan for a dump had to be abandoned in the face of resistance from the inhabitants of Ouani, the fifth main city of Ndzuwani very close to Mutsamudu, who organized protests against the project as soon as the government decree was issued in 2014. Protesters argued there were risks of increased numbers of mosquitoes and flies in the vicinity of the cities. Interviews indicated that for the inhabitants of Ouani it was also a matter of not becoming a "garbage town" (interview with an economic development officer, 2018) receiving waste from all over the island.

The second project for an official landfill site closed to Domoni, the second city of the island started in 2014 with the support of European institutions and of a French NGO which conducted communication and awareness campaigns with inhabitants" (interview with an economic development officer, 2018). However, the site is not yet operational due to lack of oversight and the fact that it was soon "too full" (see Fig. 6). Waste collection was halted in 2018 because waste could no longer be stored in the dump due to lack of space, and was spilling out across the access road and nearby stream. Waste collectors and residents protested, and managed to get the dump closed. It is currently abandoned, and no steps are envisaged to correct the situation or control the dump, for its waste cannot be burnt as a nearby village which might receive all the smoke.

4 Discussion: Four Socio-Metabolic Vulnerabilities

Our research showed that by combining MFA and in situ observations of the territorial context, we can reveal several socio-metabolic vulnerabilities of significance for the economy and environment on the island.

The first concerns the food security related to the biomass flow circulation. Thus, even with increased local production, local food makes up a decreasing share of domestic consumption, meaning the island is not on the path to self-sufficiency. Food security is one of the main issues for SIDS that determines their vulnerability and resilience (Allen 2015). According to Lowitt et al. (Lowitt et al. 2015): "Global and regional economic and environmental change processes […] can have very serious implications for household food and nutrition security, potentially affecting the sustainability of fishing and farming systems and the health of the island populations that depend on them for food, nutrition and livelihoods" (p. 1296). The intersection of metabolic and economic aspects is, therefore, directly connected to the consequences for food security.

The second socio-metabolic vulnerability reveals the social and environmental consequences of sand extraction on island metabolism. The booming trade in construction material is created by increasing coastal urbanization in Ndzuwani. The size of urban areas doubled between 1995 and 2014 (Boussougou et al. 2015), following a similar trajectory as in other African towns (Crush and Battersby 2016). Despite the public authorities repeatedly legislating against informal material extraction, this practice continues. Such activities result in unreliable buildings less able to resist climate hazards (particularly floods and cyclones) because of the poor quality of sand extracted. Critical analysis of the island metabolism brings out this socio-metabolic vulnerability, in a picture combining high-impact environmental materiality, social constraints on labor, and defective infrastructure.

The third socio-metabolic vulnerability highlights the economic relationship between a resource (wood) and the export of goods (ylang-ylang essential oil). The circuits of various flows come together for ylang-ylang distillation, producing territorial vulnerability (threats to island forestry), material vulnerability (voluminous consumption of wood and river water), and social vulnerability (with a sector of precarious employment depending on these exports). Furthermore, there is fierce global competition even in this niche capitalist market, leading to a race towards production and yields that are at odds with the island's capacity. Additionally, these products are exported unprocessed, limiting their added value. Exports continue to increase in volume (up about 30% from 2016 to 2017), accompanied by an increase in their sale price from which local producers benefit little.

Nevertheless, Ndzuwani remains dependent on global commodity markets, since the local industry has insufficient capacity to influence prices given the structure of the capitalist market, primarily driven by external demand. Analysis of the balance of forces between the island and its export territories goes to the heart of its socio-metabolic vulnerability. It highlights the tension between the economic need to export goods, the strong increase in demand from importing countries (particularly Chinese companies), and the need to commit large volumes of island resources, driving deforestation. In the long term, these dependencies significantly add to the island's environmental, social, and economic fragilities. This situation is symptomatic of other island economies driven by export-oriented extractivism (Krausmann et al. 2014; Schaffartzik et al. 2016; Bahers et al. 2020).

The last socio-metabolic vulnerability that our study reveals regards urban waste flows. Waste generation and its management lend another vulnerability to the island, where environmental consequences (the illegal dumping of waste destroying coastal areas) are inextricably linked to material flows (induced by short-lived cheap products), socio-political resistance (conflicts and protests against waste infrastructure), and historical processes (with the shift towards a throw-away society). This situation of waste on Ndzuwani can be framed as an "environmental justice" issue (Walker 2012; Fragkou et al. 2014; Martinez-Alier et al. 2016b; Griffin et al. 2017) that analyzes metabolic conflicts related to the unequal distribution of cost and benefits of environmental goods and services in space and time.

Finally, the concept of "socio-metabolic vulnerability" complements research in political-industrial ecology (Newell and Cousins 2015; Pincetl and Newell 2017), which "provides the framework necessary to assess the quantities of resource flows, to track them across space and time, and to decipher intertwined social and environmental dynamics that both reveal internal urban inequities and link the city to the distant areas from which these flows originate" (Pincetl and Newell 2017, 382). A growing number of scholars within industrial ecology are increasingly focusing on the political dimensions of resource flows, an approach that is being referred to as "political-industrial ecology", "which entails an importing of method and an exporting of spatial sensitivity and critical political economy" (Newell and Cousins 2015, 271). Its ambition is to combine methods from environmental assessment and political ecology to provide a social and economic critique of the flows of materials that travel between territories and produce environmental impacts at multiple scales (Cousins and Newell

2015; Goldstein and Newell 2020). Few empirical studies have been carried out so far. An important achievement of this research is precisely to engage a discussion with the PIE field to move towards a socio-metabolic analysis of island metabolism.

Within this context of Ndzuwani's metabolism, we also find numerous examples of adaptation and resilience building. Many local and international NGOs are implementing in situ solutions based on vernacular practice to close the material loop and reduce dependency on external flows. Such initiatives include recycled bags made from recuperated fabric and paper, ovens to optimize the combustion of wood, rugs made from the remains of plastic sandals (of which very large numbers are to be found in the illegal dumps along the coast), cooking pots made from aluminum cans, compressed cardboard pellets for burning as fuel, and tablecloths made from used textiles by groups of women. These solutions, though modest in terms of volume, show that there are "socio-ecological alternatives" (Ernstson and Swyngedouw 2018) from "local voices" (Kelman 2010). Certain communities also organize coastal cleanups every weekend, without waiting for the state to step in.

Furthermore, the government of the Union of the Comoros and the municipality of Ndzuwani are involved in a transition towards an integrated economy of resources (particularly forestry) and more sustainable waste management. New legislations are constantly being put in place, though implementation challenges remain, to make local authorities responsible for collecting and processing waste, introducing quotas to cap logging, and setting up a land registry to develop the territory and its irrigation infrastructure.

Finally, informal economic activity is not the cause of vulnerability. On the contrary, it is sometimes the informal sector which can reduce certain aspects of socio-metabolic vulnerability (Kaviti Musango et al. 2020; Kovacic et al. 2020). The presence of informal actors may be one of the main levers for optimizing the management of flows on the island of Ndzuwani. We have observed, for example, that the reuse of building waste by informal actors is important and effective.

5 Conclusion: Resisting Island Vulnerabilities

Materials and energy do not always flow on their own. They are deliberately organized by society in culturally and historically prescribed ways that shape a society's socio-metabolic vulnerability. Given the links between a material's life-cycle, its spatial trajectory, and its socio-economic consequences, approaches need to be combined. By linking the materiality of social metabolism with political ecology relations (Ernstson and Swyngedouw 2018), as in the case of Ndzuwani, we find greater explanatory power to unpack the complex relationships between the drivers of material flows, decision-making institutions, and the resultant metabolic traps and vulnerabilities: this is the interest of the concept of socio-metabolic vulnerability. This study adds to the scarce body of literature that argues that small island economies would need to leverage resource-use patterns to build system resilience, along with bold policies and institutions that support material circularity, engage communities and fosters frugal innovation.

The case of Ndzuwani is crucial for understanding island sustainability in general. It suggests that island vulnerability is not a given because of their smallness or remoteness, a position held by Briguglio and colleagues (Briguglio 1995, 2014). Such a fatalist view of islands is challenged by a number of island scholars, among them Armstrong and Read (Armstrong and Read 2002, 2006), Baldacchino (Baldacchino 2006, 2008), Baldacchino and Bertram (Baldacchino and Bertram 2009). This research supports the latter position, but with some caution. While islands have unique characteristics owing to their geographies, but when combined with a global historical political economy, vulnerabilities can be reproduced, as is evident from the Ndzuwani case, but also in the cases of Hawaii, Puerto Rico and Singapore (Chertow et al. 2013). As such, a territorial island metabolism approach combined with historical and political context, as well as the analysis of formal and informal actors can lend power to understand island vulnerability. One can argue that the informal economy on Ndzuwani plays a significant role in maintaining lower levels of resource use. As such, "local studies" allow to identify efforts and opportunities for adaptation and resilience-building across space and time, efforts that are likely to be overlooked at high resolution. The research provides novel insights into the linkages between patterns of resource-use, systemic risks and vulnerability. Moving away from a linear metabolism (characterized by a one-way flow of materials) that does not benefit marginalized communities, to an equitable circular metabolism (e.g., by localizing resource supply, as well as closing material cycles) can be an important sustainability strategy for small island economies. To this end, while appropriate policies and institutions are relevant, the role of communities and frugal innovation equally need to be recognized in building resilient island systems, and, therefore, resist vulnerability.

Data availability The datasets generated during and/or analysed during the current study are available from the corresponding author on reasonable request.

Declarations

Conflict of interest The authors declare no conflict of interest.

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