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Socio-metabolic risk and tipping points on islands

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Abstract

Small Island Developing States (SIDS) face enormous sustainability challenges such as heavy reliance on imports to meet basic needs, tenuous resource availability, coastal squeeze, and reduced waste absorption capacity. At the same time, the adverse effects of global environmental change such as global warming, extreme events, and outbreaks of pandemics significantly hinder SIDS' progress towards sustainable development. This paper makes a conceptual contribution by framing the vulnerability of small islands from the perspective of socio-metabolic risk (SMR). SMR is defined as 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. We argue that specific configurations and combinations of material stocks and flows on islands and their 'resistance to change' contribute to the system's proliferation of SMR. For better or for worse, these influence the system's ability to consistently and effectively deliver societal services necessary for survival. By positioning SMR as a subset of systemic risk, the paper illustrates SMRs and tipping points on small islands using insights from three sectors: water, waste, and infrastructure. We also identify effective leverage points and adaptation strategies for building system resilience on small islands. In conclusion, our synthesis suggests that governing SMR on SIDS would mean governing socio-metabolic flows to avoid potential disruptions in the circulation of critical resources and the maintenance of vital infrastructures and services while inducing interventions towards positive social tipping dynamics. Such interventions will need strategies to reconfigure resource-use patterns and associated services that are sustainable and socially equitable.

1. Introduction

Small Island Developing States (SIDS) face immense sustainability challenges from resource scarcity, water insecurity, reduced waste absorption capacity, and isolation from global markets. They rely heavily on imports for meeting their basic needs such as food, energy, manufactures, and materials for developing infrastructures, often up to 80%–90% of their requirements (Deschenes and Chertow 2004, FAO 2016, Dorodnykh 2018, Singh *et al* 2021). Global warming exacerbates existing challenges, disproportionally affecting SIDS through sea-level rise (SLR) and extreme events, such as hurricanes, flooding, droughts, and water stress (Nurse *et al* 2014, UN-OHRLLS 2015, Ourbak and Magnan 2018).

The ability for small island economies to withstand shocks such as climate-induced extreme events or pandemics is limited. When they do occur, losses tend to be uneven relative to their economy. Infrastructure damage from hazards can result in the loss of societal services and the breakdown of critical food, water, and energy supplies. Restoring services in the aftermath comes with large material and fiscal requirements. The adverse effects of climate change on SIDS as hindering progress towards sustainable development are repeatedly recognized by the international community (IMF 2021, Sachs 2021), with SIDS being consistently ranked high on various vulnerability indices (Atkins *et al* 2000, Commonwealth Secretariat 2021, UNDP 2021).

In this paper, we elaborate on the notion of socio-metabolic risk (SMR), a concept already introduced elsewhere (Singh *et al* 2020) but not discussed deeply. While systemic risk is associated with cascading impacts that spread within and across systems and sectors via the movements of people, goods, capital and information within and across boundaries (Sillmann *et al* 2022, p 4), SMR is '*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*'. We propose thinking of SMR as a subset of the concept of systemic risk to further hone and operationalize the latter. Using SIDS as a scope, we argue that framing SIDS' vulnerability from an SMR perspective can help identify leverage points and adaptation strategies.

Based on several years of socio-metabolic research, this paper is a conceptual contribution to illustrate SMR and tipping points on islands using three sectoral examples: water, waste, and infrastructure. We recognize that several aspects raised in this paper are covered elsewhere in more depth in disciplinary publications and journals, e.g. water (Kumar 2015, Dadson *et al* 2017, Krueger *et al* 2019), waste (Tisserant *et al* 2017, Menegaki and Damigos 2018, Luhar and Luhar 2019, Payne *et al* 2019), and infrastructure (Zio 2016, Lam *et al* 2017, Thacker *et al* 2019). Instead, we highlight the systemic nature of risk toward addressing multiple aspects in tandem. The final section offers perspectives on the governance of SMRs to mitigate potential disruptions in the circulation of critical resources and vital services they provide.

2. SMR as a subset of systemic risk

The Organization for Economic Co-operation and Development introduced the category of 'systemic risk' to account for risks that threaten society's essential systems, such as infrastructure, health care, and telecommunications (OECD 2003). Systemic risk evolves especially in tightly coupled dynamic systems, such as SIDS, following non-linear cause-effect patterns that often come with tipping points. A key feature of systemic risk is are that they cause cascading impacts that spread within systems and across systems (Sillmann *et al* 2022). These impacts may lead to devastating consequences and potentially system collapse. However, despite this potential for catastrophe, systemic risk often meets with less public attention than would be required for effective risk management and follow-through (Renn *et al* 2020, Schweizer 2021).

SMR, as a subset of systemic risk, focuses on the pattern and problematic circulations of resources within socio-ecological systems. SMR is concerned primarily with the availability, integrity, and circulation of critical resources, for example, materials, energy, and water, necessary for societal wellbeing in a socio-ecological system. Disturbances, such as climate-induced extreme events, invasion or warfare, geopolitical and financial crises, or decline of local resource supplies by overexploitation, lead to cascading dysfunction and eventual breakdown of the biophysical basis of social systems.

SMR takes reference from the concept of *social metabolism*. Analogous to biological metabolism, a society (deliberately) draws material and energy flows from the natural environment, and by way of trade, for their sustenance and reproduction, a process that has been termed *social metabolism* (Molina and Toledo 2014, Fischer-Kowalski and Weisz 2016). Some of these flows end up as waste rather quickly (for example, food waste, packaging, paper), while the rest become net additions to 'material stocks' or 'stocks' that remain in the system for longer than a year (for example, the built infrastructure, machines, furniture, and durable products). Social metabolism is a human-centric process that begins with the human appropriation of materials and energy from nature and circulates to be consumed and excreted back to nature (figure 1).

With economic growth and subsequent long-term societal development, the demand for essential services (such as housing, transport, sanitation, health, and education) provided by the built infrastructure is stimulated, requiring the accumulation of massive long-term physical stocks. The growth, maintenance, and use of these stocks require the mobilization of material and energy flows, either from domestic sources or through imports from other societies. The larger the stocks and the demand for services, the greater the flows required to maintain and reproduce these stocks. Haberl *et al* (2017) termed this systemic interdependence and feedback loops as the material stock-flow-service nexus.

It is not only the size of material flows but also the quality of materials in the mix that lends society its metabolic profile. For instance, a significant share of imports by small island states comprises non-renewables, such as metals, minerals, and fossil fuels, often relying on long and complex supply chains likely to be disrupted by small perturbations. Thus, specific resource-use patterns will embody and exhibit varying degrees of SMR. Established social processes, path-dependent behavior, and resistance to change may further contribute to the system's proliferation of SMR. All this together, over time, may influence the system's ability to consistently and effectively maintain its social metabolism and provide critical societal services necessary for survival (Singh *et al* 2020).

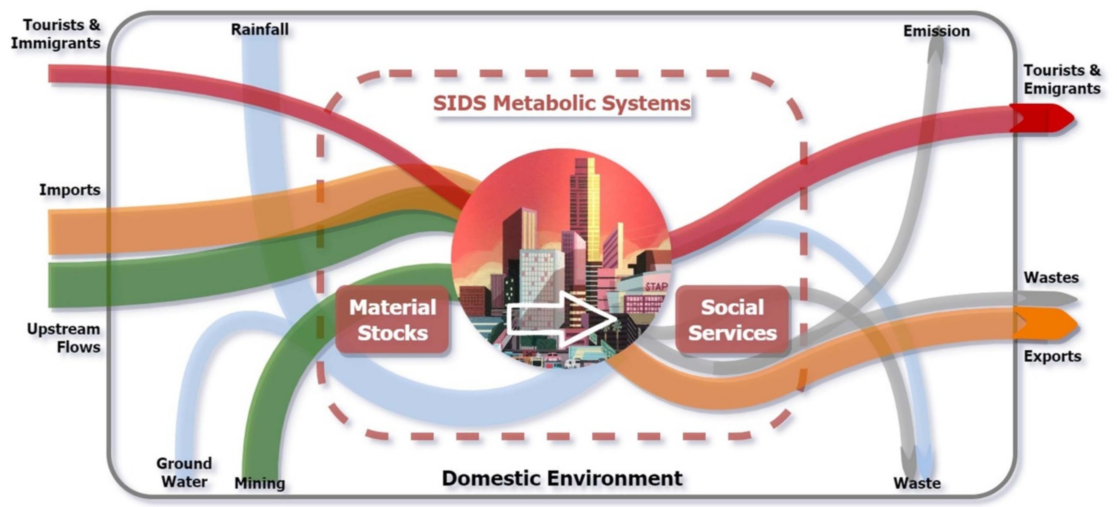

Figure 1. Specific combinations of material stocks and flows, which are used, consumed and/or controlled by humans for their purposes, contribute to the system's proliferation of risk. Reproduced from Singh *et al* (2020). CC BY 4.0. The city icon in the figure is taken from the open source Clipart: https://openclipart.org/detail/277648/la-fixed. Reproduced from OPENCLIPART. CC0 1.0.

Modern societies rely on facilities, assets, and systems interconnected with national or global infrastructure networks. Critical resources such as food, water, and energy are transformed and circulated to provide utilities and services vital to societal development (DHS 2008). Each critical resource is linked in varying degrees to extraction, transportation, communications, information technology, and other industrial sectors. We argue that the unfolding of systemic risks starts from a problematic socio-metabolism of a society. Such problematic circulations lead to internal functional disorders and accumulate dynamic pressures. Sequentially, the functional disorders and dynamic pressures manifest as symptoms or warning signs, i.e. crises or accidents, and jointly determine the system's conditions at the time (Blaikie *et al* 2003). Depending on the coping actions to restore socio-metabolic circulations, outcomes of catastrophic events may eventually impact the system's long-term sustainable development, creating additional underlying sources of vulnerability. That, in turn, deteriorates the system's metabolic processes and amplifies risk in the next cycle, thus 'trapping' the system into an unsustainable metabolic state.

As size-constrained socio-ecological systems, SIDS respond to constant social and environmental changes, striving to sustain and develop. Even a small event can lead to severe, multifaceted consequences. In consequence, their socio-metabolic conditions fluctuate. Over time, the systems may reach a 'tipping point' defined as '[a] *level of change in system properties beyond which a system reorgani[z]es, often in a non-linear manner, and does not return to the initial state even if the drivers of the change are abated*' (IPCC 2019, p 699). While tipping points can be both desired and undesired, leading to either negative or positive consequences (Franzke *et al* 2022), a socio-metabolic collapse (SMC) is essentially an adverse system outcome. SMC is characterized by the failure of the society's ability to organize its own social metabolism without external aid, and to govern its recovery by interfering with its cultural, economic, and political regulation. Thus, an SMC refers only to the breakdown of society's social metabolism. However, negative tipping points in any part of the system can trap and push for a system-wide metabolic collapse. In other words, if a system reaches a tipping point in one of the key variables, such as labor power, this may cascade and force its entire social metabolism into collapse.

Negative tipping points, and eventual SMC, can be reached due to ecological factors (e.g. overuse exploitation of natural resources and land-use changes), climate impacts (e.g. disruptions from extreme weather events), economic arrangements (e.g. reliance on a single export such as tourism), or social or institutional phenomenon (e.g. outmigration due to lack of services or jobs), or a combination of all of the above (Petridis and Fischer-Kowalski 2016). Tipping points on small islands can be rapid, such as disruptions from hurricanes, or slow, such as the gradual depletion of resources, rapid urban expansion, migration, or SLR.

Analyzing a society's metabolic profile, structure and processes, and the risks that pose in space and time requires conceptual clarity and knowledge of appropriate methods, e.g. material and energy flow analysis, material stock analysis, and geospatial analysis. Table 1 offers an overview of SMR as a subset of systemic risks and positions the two with respect to their focus, system boundaries, sources

Table 1. Articulating socio-metabolic risk as a subset of systemic risks (after Scheffer 2010, Schweizer 2021, Renn *et al* 2020) and metabolic risks (after Huang 2010, Singh *et al* 2020).

	Systemic risk	Socio-metabolic risk (SMR)
Definition of risk	Hazards and threats that endanger the functionality of systems of critical importance for society cause transboundary and cascading impacts in time and space	Disturbances from problematic socio-metabolic circulation lead to cascading dysfunction and eventually a socio-metabolic collapse (SMC).
Boundary conditions	As systemic risks have no clear boundaries concerning scope, time, and space, uncertainty exists about which other systems are affected. Research needs to address which of these potentially affected systems must be included or excluded.	SMR sets boundary conditions by focusing on the biophysical dimension of systemic risks associated with the availability of critical resources and integrity of material circulation for equitable distribution of derived products and services in socio-ecological systems.
Sources of uncertainty	• Uncertain occurrence and outcome severity of events or accidents • Non-linear development • Occurrence of tipping points • Human behavior and intentional action	• Limited knowledge of underlying socio-metabolic structures that may generate problematic resource flows • Latent patterns of institutional and organizational behaviors
Major properties	Systemic risks are: • transboundary or cross-sectoral in the scope of their consequences. • highly interconnected leading to complex causal structures and system dynamics • non-linear in their cause–effect relationships often associated with tipping points. • stochastic in their effect structure, and • tend to be socially attenuated rather than amplified	SMRs are associated with: • specific combinations of material stocks and flows, and path dependencies of social processes. • systemic risks and cascading effects caused by patterns of resource use. • materialized 'systemic risks' in terms of supply-and-demand of resources vital to the system's socio-metabolism. • the 'risk of change' that arises from the changing socio-metabolic state of a complex dynamic system.
Strategies to risk governance	• Characterizing risk by hazard, exposure, impact, and vulnerability. • To mitigate consequences and societal impacts. • To enhance resilience and sustainability • Managing the variability of and vulnerability to surprise events • To recognize the complex structure of systemic risks and design early warning systems from weak signals.	• Identifying risk from problematic socio-metabolic circulations. • To restore dynamic balance and sustain the socio-metabolic circulation. • Managing the circulation integrity and availability of critical resources. • Managing social processes for equitable distribution of cost and benefits of resource stocks, flows, and associated services.

of uncertainty, major properties and strategies for risk governance.

3. SMR and tipping points on islands

Given their size and the tight socioeconomic and environment coupling, small islands can reach tipping points very rapidly, and recovery can be prolonged or none. Even small and insignificant individual events on small islands can set in motion a series of cascading impacts. Tipping points can trigger the system on an entirely different operational and functional paradigm. When the system crosses a certain threshold beyond the point of no return, stability and sustainability, balance and flux dynamics, and cascading effects are multiple and diverse. Reaching such tipping points will impact demographics, and the availability, circulation integrity, and distribution of key resources as food, water, and energy. We argue that understanding the behavioral patterns of resources is the key to increasing our ability to balance the systemic risk of change (Huang 2010) and build resilience in systems. Let us note some context with particular reference to SIDS.

- Disturbance of fragile ecosystem services due to coastal squeeze, concentrated tourist activity, and growth in long-term material stocks can negatively tip local people's environmental quality and needs, such as air and water quality, water recharge, nutrient balance, and other environmental flows. Polman *et al* (2016) illustrate this phenomenon concerning St. Eustatius in the Caribbean, making a point that efforts at restoring degraded ecosystem services and their provisioning in an inclusive approach are a challenging task for SIDS; often such interventions do not garner enough community support.

- Recurrent droughts and loss of top soil due to flash floods can negatively impact the local food production system, tip people's livelihood, displace them, or trigger them to migrate for the search of economic stability and income generation. In such settings in small islands with limited economic development, socio-economic impacts could be intense. Iese *et al* (2021) explained this multifaceted impact using the El Niño induced drought from 2015 to 2016 in the pacific region that affected essential services and sectors such as water supply, health, tourism, and agriculture.
- Policies incentivizing cheap food imports not only destroys local food production, and experience supply disruptions during shocks, but also tip the system into moderate or severe food insecurity (Mohammadi *et al* 2022, Rahman *et al* 2022). Carribean, for example, imports 83% of its total food requirements (Dorodnykh 2018), with 67.5% of the population facing food insecurity, in contrast to the global average of 27.6% (FAO 2021).
- Conflict for limited and competing land, water, and other natural resources can destabilize the socio-economic landscape of the state/community. For example, White *et al* (2004) focusing on small island nations in the Pacific highlights how limited land areas severely restricts surface water storages and water availability. Water management problems have in turn exacerbated challenges related to land tenure and conflict between urban societies and subsistence communities. Duvat *et al* (2021) warns that Western Pacific will experience the highest risk and increased island destabilization by 2050 due to water stress that will cascade into food, infrastructure and economic insecurity.

Projected to experience multiple interrelated risks at 1.5 °C of global warming (IPCC 2018), SIDS are also referred to as 'canaries in the climate change coal mine' (Hanna and McIver 2014). The IPCC (2018) reports with high-to-medium confidence about the long term risks of 1.5 °C of global warming on SIDS, with severe impacts on populations, livelihoods, infrastructure, marine ecosystem, and critical sectors and resources such as water, that will limit adaptation opportunities as well (Mechler and Schinko 2016, Mechler *et al* 2018). Enhanced understanding of what might constitute tipping points in the context of SIDS that lend to their vulnerability, therefore, remains crucial. Below we discuss examples from three sectors and the SMR they experience, with potential to reach tipping points sooner or later. We will also offer examples of existing and potential levers that mitigate metabolic risks.

3.1. Water management

Most SIDS often have limited resources for freshwater provisioning systems as structural features like geography, hydrogeology, climate pattern influences water availability patterns. In addition, anthropogenic interventions, impacts of climate change on precipitation patterns, lack of groundwater protection legislation are factors that act as barriers for aquifer recharge and to maintain the sustainability of water stock. UNESCO-IHP (2016) reported 71% of SIDS are at risk of water shortage, a figure that goes up to 91% in SIDS with low altitude. The increase in impermeable surfaces from building up long-term stocks on the islands to expand tourism facilities along the coastline or habitation for growing population can be at the cost of conversion of natural landscapes and coastal ecosystems and biodiversity (Gheuens *et al* 2019, Bradshaw *et al* 2020). Impact of climate change and events such as floods can both, directly and indirectly, affect hydrogeology, cause sedimentation of freshwater sources, deteriorate water quality, and damage both hard and soft assets on the island and often disrupt the water management systems since floodwaters flow rapidly without allowing recharge of aquifers.

Based on the assessment of 43 small island developing states distributed worldwide, Holding *et al* (2016) projected per capita decrease in aquifer recharge capacity by >50% in 31 islands from climate change impacts. While water stocks are diminishing, the water demand in islands nations is escalating due to pressure from growing population and economic expansion. The dependence of many islands states economies on tourism and fulfilling the water demand of a large number of tourists (Hernández-Delgado *et al* 2012) is becoming crucial in managing the water management demand-supply dynamics. Approximately 44 million tourists visited SIDS in 2019 and often water footprint of these floating populations is not accounted for in planning and designing water and wastewater systems (Hampton and Jeyacheya 2020, UNWTO 2020). The 'water disparity index' reflects on the water use by tourists, noting that the number far exceed that of the local population by a factor as high as 8.3–8.6 in Fiji and Sri Lanka (Becken 2014).

To provide a broad context to the behavioral patterns of water stock, we refer to explanation by Taylor and Rising (2021) on how resource/land use dynamics and influence of drivers/pressures such as water availability and how a variety of divergent land use pathways affect the system resilience, and resource demands of a growing population. Further, by the non-linear interactions between SLR and wave dynamics in low-lying atolls, Storlazzi *et al* (2018) predict that by mid-21st century, these islands will fail to recover their freshwater aquifers between overwash events. As a consequence, it will become necessary for the low-lying island states to abandon and relocate causing unavoidable geopolitical issues.

The set of crises act independently or in tandem to trigger a tipping point in the space-time continuum and, in some instances, to disrupt the inflow-outflow metabolic flux of the fragile island's systems. For instance, Tuvalu, an island archipelago in the Pacific is the first among the countries that noted displacement of its population due to a myriad of factors, including water and climate crisis such as heavy rains floodings due to tropical cyclones (Farbotko and Lazrus 2012). A study by United Nations University noted that three quarter of household surveyed in Tuvalu reported that they had been impacted by natural hazards between 2005 and 2015, with droughts and flash floods being the most common causes (Milan *et al* 2016). The islands depends on rainwater for provisioning needs, and the impact of hydro-climatic variability that is creating water stress (dry conditions/droughts) is rendering inhabitants vulnerable, often tipping points are breached, for instance, the drought of 2011 left around 15% of its population without water access (Gheuens *et al* 2019).

Another important dimension in water management is the risk of/from groundwater pollution, and seawater intrusion and salinization affecting the metabolic flux of the surface and sub-surface water systems. Examining this phenomenon Gibson *et al* (2020) documented that in 73% of the surveyed (42) islands water stocks face the risk of high metabolic fluxes and tipping points. Overall, for SIDS the spillover impacts of water and climate crisis such as soil pollution, biodiversity degradation and disruption of ecosystem services, alongside the loss of livelihood and income opportunities for the communities who depend on coastal biodiversity for income can lead to cascading risk for socioeconomic systems as well as pose mental, economic and financial strain to the islanders (*ibid*).

Leverage points to reduce SMR in the water sector would entail capturing inflows and increasing water stocks from rainwater harvesting. For example, Grenadine islands in the Caribbean significantly improved water availability through the use of household drums and communal cisterns. Their per capita water use in some households correspond to the levels subscribed in developed countries. These self-financed projects with local capacity (involving people with construction know-how) of stakeholders demonstrated potential for wide scale diffusion (Peters 2014). To offset the increasing demand and diminishing water stocks, the Maldives adopted desalination and other adaptive mechanisms after the 2004 Asian Tsunami, and the local Government provided every household with a rainwater tank (Gheuens *et al* 2019).

In response to the severe drought of 1994–1995, Barbados initiated a desalination plant construction, and the Barbados Water Authority on boarded universal metering and the gradual removal of public standpipes. Similarly, due to impacts of drought in 2009–2010, Antigua and Barbuda, Bahamas, and the Cayman Islands now obtain a significant portion of their potable water supplies from desalination plants, >14 islands throughout the Caribbean use desalination as a water supply source (Cashman 2013). However, the operational efficiency of desalination units (cost of operation and maintenance) is affected by electricity supply and global fuel prices fluctuation, making it an expensive option and possibly lead to metabolic breakdown when metabolic fluxes are disrupted. To explain the point of system response and tipping points, on Marshall Islands (Oceania region) wherein the water supply from groundwater and desalination is often affected by power outages cascades into land ownership issues, and lack of water conservation strategies. This presents an example of challenges while implementing specific strategies/solutions to mitigate sectoral metabolic risks (UNEP 2011).

Boosting groundwater protection legislation could help to tackle some cascading SMR's. The assessment by Jaleel *et al* (2020) of 45 islands across Maldives points that groundwater wells and septic tanks maintenance, smart agricultural practices, infrastructure interventions like distance between the septic tank and the groundwater well as better stormwater/rainwater management can help improve groundwater recharge and quality. Another area of intervention is capturing the outflow. Using examples from Micronesia, Rouse (2015) points to the environmentally sustainable methods for domestic wastewater and sewage sludge treatment. The study shows that these interventions are part of centralized wastewater primary treatment systems with communal septic tanks installed in health centers and schools (removal of suspended solids). Part of treated wastewater and solid waste is directed to farming systems for use as fertilizer. Cost effective and innovative mechanisms to retrofit and enhance the effectiveness of the wastewater treatment system offer potential for plugging the circularity and sustainability goals aligning with the SMR governance pathways and guiding principles.

3.2. Solid waste management

Just as island metabolisms are supported by inflows of water, energy, food, and coastal infrastructure (and associated materials), they must also have ability to treat and dispose of the various wastes that are the outflows of their economy. Different approaches are required for the management of biological wastes such as wastewater, food, paper, and green waste, as well as abiotic wastes such as plastics, metals, construction and demolition debris, and hazardous materials. Materials imported to support tourism are left behind when tourists leave, causing some islands to have very high waste generation rates per capita.

The most obvious barrier to effective waste management on islands is geographical: small islands typically have few suitable sites for treatment and disposal facilities. There is competition for land that is flat, well-drained, and easily accessible. As a result, landfills are often built in ecologically sensitive areas such as wetlands that populations have traditionally avoided due to flooding risk or vector-borne diseases, such as malaria. The use of open-air dumps or burning rather than sanitary landfills can further compound the risk to local ecosystems and water quality.

Another barrier is also related to size: waste flows on small islands can lack the economies of scale needed for conventional facilities such as incinerators or recycling centers to be financially sustainable. Several small islands are known for their difficulties when it comes to waste management and their cascade effects like social conflicts and out-migration (Bahers *et al* 2022, Manglou *et al* 2022). While some materials can be readily processed locally, such as food and green waste for composting, SIDS typically do not have the industrial capacity to reprocess all of the myriad recyclable materials of modern society, and so are reliant on exporting some portion. If on-island or off-island treatment cannot cover costs, then managers may be forced to landfill those materials instead, putting even more pressure on existing sites (Eckelman *et al* 2014, Mohee *et al* 2015, Camilleri-Fenech *et al* 2018, Millette *et al* 2019, Elgie *et al* 2021, Mohammadi *et al* 2021).

Social, economic, and physical barriers to implementing safe and sustainable waste management practices on islands can hinder planning and investment and can lead to a lack of adaptive capacity. One such possibility is that an island loses the ability to manage its own waste and instead relies on neighboring islands or the mainland for this service. In some cases, this works well, as island groups can pool wastes (both recyclable and otherwise) to achieve economies of scale and promote local processing businesses. Else it presents a major risk in case shipping is disrupted, contracts are not renewed, or costs increase, leaving islands with no viable options in the short term (Noll *et al* 2019, Elgie *et al* 2021). Another potential tipping point is environmental, when waste management systems are overwhelmed by natural hazards such as hurricanes or flooding, leading to long-term pollution that harms sensitive ecosystems such as coral reefs and mangroves and can severely impact tourism (Lavers *et al* 2021, Mohammadi *et al* 2021). Or, in the aftermath of an event, SIDS may lack the capacity to dispose of debris on-island as well as the ability to export it, hindering redevelopment efforts (Popescu *et al* 2020).

On the positive side, effective waste management policies and practices can reduce metabolic risks. The most obvious approach is to increase circularity through adaptive reuse and local recycling, especially for critical materials such as water. Singapore has been a leader in local reuse of treated wastewater, such that 'reclaimed water' now fulfills 40% of total demand. Green infrastructure approaches that promote stormwater detention and infiltration can reduce pressures on water infrastructure during extreme events and reduce sediment loading that negatively impacts coral reefs. In Hawai'i, recovery and reuse of used building materials, including concrete that can be crushed and reused in civil engineering works, prolongs the life of on-island quarries, avoids importation of heavy, low value minerals, and frees up space in disposal sites (Eckelman and Chertow 2009, Chertow *et al* 2013).

3.3. Infrastructure—a specific example of seaports

Seaports are essential critical infrastructure for small island economies and have key dependencies with the material stocks and flows of SIDS. SIDS' imports constitute 60%–100% of national GDP. Hence, ports, facilitating the majority of these material flows are critical for the national economies. Recent research, for instance, highlights that on average, every US$ 1000 increase in a country's final demand for goods results in an 18 dollar increase in maritime imports, although this number is 1.6 times higher for SIDS, and can be up to 80 USD for some islands. Most islands have only one importing port that handles most trade and are served by a few liner services given the high transportation costs ('sea locked'), making them reliant on efficiency of these services.

The SIDS' reliance on maritime imports means that ports are essential for facilitating growth in materials stocks and flows. In fact, seaports are important materials stocks themselves, as noted by (Noll *et al* 2019) for the Greek island of Samothraki (∼30% of material stock). In addition, ports can have significant feedback loops, as port enlargements allow further expansion of materials stock (through enhanced capacity or being able to handle certain type of goods (e.g. heavy lifting, forty-foot equivalent unit containers). The dependencies and feedbacks between ports and the rest of island material stocks and flows is becoming increasingly important as the risks to ports associated with extreme weather events and natural hazards is expected to rise due to climate change impacts and extreme events (Becker *et al* 2018).

First, ports are often vulnerable to the impacts of climate change. For instance, a recent study shows that every year 1%–2% of maritime trade in SIDS can be disrupted due to natural hazards, imposing a heavy financial burden on top of the direct damages to port infrastructure (Verschuur *et al* 2021b). Such disruptions can have wider economic repercussions. For instance, Hurricanes Irma and Maria closed Puerto Rico ports for 11 days, with major losses in terms of imported fuels, resulting in widespread energy outages (Preston *et al* 2016). Climate change will inevitably worsen this situation. Port infrastructure is often heavily exposed and at risk to an increase in SLR, as was demonstrated for the islands of Grenada (1 m SLR) (Symmes *et al* 2020), Antigua and Barbuda (2 m SLR) (Bradshaw *et al* 2020) and St. Lucia (1 m SLR) (Adshead *et al* 2020).

Second, given that widespread disaster impacts often require substantial new supply of materials, disruptions to ports can prevent effective reconstruction. After Hurricane Irma in 2017, the port of Sint Maarten was heavily damaged, resulting in difficulties to the emergency response and a long reconstruction time. The hurricane also damaged multiple cruise ports, closing them for several weeks, causing massive financial loss to the island's service industry. Third, the adaptation of seaports to SLR can have large implications for materials stocks needs. Although not yet quantified for the SIDS, a study showed that adapting the 100 largest ports in the United States to 2 m of SLR would require 700 million m^3 of fill material (Becker *et al* 2017).

Fourth, given the tourism dependency, limited maritime transport connectivity and small number of trading partners of SIDS, they are highly exposed to systemic risks in the economic, trade and maritime transport networks. During COVID-19, a significant drop in maritime trade was recorded in SIDS, with a larger drop in countries that are highly dependent on tourism (Verschuur *et al* 2021a). Overall, failing to adapt to the risks posed by climate change can result in the exceedance of tipping points, as continuous disruptions can isolate the islands off from valuable income streams (e.g. tourism), essential food and energy resources, and place a burden on government's balance sheets and decrease foreign investments, thereby negatively impacting economic development.

In case of SIDS addressing such metabolic risks is challenging, but not impossible. Besides reducing reliance on imports and localizing requirements as much as possible (e.g. food, energy and construction materials), integration of adaptation strategies in the port, maritime transport and economic systems also hold promise. Both stocks and flows need to be considered. Specific sectoral adjustments could include:

(a) making small island port suitable for year-round operations by improving, often outdated, infrastructure. For instance, the Asian Development Bank (ADB) has proposed various projects in the Pacific region to adapt Pacific ports, such as upgrading the wharf in Alotau port (Papua New Guinea) and upgrading the port of Apia (Samoa) by rehabilitating the breakwater, upgrading land-side infrastructure and replacing existing tugboats (ADB 2020).
(b) importing substitution of trade that if disrupted can have large knock-on effects on island economies, such as refined fuels, as another resilience strategy. Most SIDS have a vast potential for renewable energy alternatives (*ibid*), in particular solar energy, which can help provide energy to households and firms during and after port disruptions.
(c) since ports provide the lifeline of emergency reliefs after disasters occur, emergency strategies need to be in place in case some ports are out of service. This could include an analysis of the ability of smaller ports to compensate for the loss of larger ports (Rozenberg *et al* 2021). Importantly, the port's disaster preparedness plan to need to aligned with the national emergency strategy.

4. The way forward: managing SMR and orienting towards positive tipping points through inclusive risk governance

To manage SMR and avoid metabolic collapse, mechanisms and strategies to reconfigure resource-use patterns and associated services that are sustainable and socially equitable are crucial. As discussed in the previous section, some of the strategies include resource-localization where possible, shortening supply chains, increase resource circularity rates by closing material cycles, and optimizing spatial planning that promotes multifunctional infrastructure use and align to nature-based solutions guidelines. Strategies will also need to consider the distribution of costs and benefits (beyond just monetary) of specific resource-use configuration across different segments and sectors of the society. Certain material flows or infrastructure development may benefit one group over the other, or negatively impact another. Take for example, metabolic flows that support tourism can generate large amount of solid waste and wastewater that will likely end up in poorer neighborhoods, and in turn cause health burdens for people and communities living in vulnerable settings. Or certain types of coastal development and sea ports intervention that benefit some groups can result in loss of livelihoods for communities depending on coastal and marine ecosystems.

In order to achieve this goal, risk governance in SIDS must embrace societal goals with the boundaries set by metabolic flows. Thus, governance of SMR must merge aspects of risk analysis and governance (Schweizer 2021) and apply governance principles to the identification, assessment, management and communication of risks (IRGC 2005, Aven and Renn 2019). Governance of SMR needs to analyze the interdependencies between risks as well as institutional structures and socio-political processes that guide collective activities, partnerships and collaborations when dealing with risk issues (Klinke and Renn 2019). Therefore, governance of SMR also benefits from analyses of institutional settings, regulatory regimes, actor networks, and social perceptions of risk.

Furthermore, governance of SMR needs to be inclusive to ensure an equitable sharing of cost and benefit of metabolic stocks, flows and related societal services. In this sense, SMR is not only biophysical, but can cascade into irreversible hotspots of social conflicts, crime, and resistance movements (Martinez-Alier *et al* 2016) thereby, undermining the security, wellbeing and sustainability of a society as a whole. Thus, particular attention should be paid to the inclusion of evidence and multiple criteria in decision-and policymaking while valuing experiential, indigenous and local value and knowledge systems (Bidwell and Schweizer 2021). This approach is based on the assumption that all stakeholders can make important contributions to the process of SMR governance and that mutual communication and exchange of ideas, assessments and evaluations can help improve the final decisions, rather than impeding the process or compromising the quality of scientific input and the legitimacy of legal requirements (Renn and Schweizer 2009, Schweizer and Bovet 2016, 2020). Inclusion will also assist an adaptive approach towards governance which is especially relevant for responding to societal demands in a timely manner before a negative tipping point will be reached that leads to metabolic collapse.

Governing SMR and tipping points on SIDS would mean governing metabolic flows so that potential disruptions in the circulation of critical resource can be avoided, or interventions towards 'positive social tipping dynamics' can be induced (Otto *et al* 2020). For SIDS, engineering those positive tipping points for SMR relies on anticipating societal demands and trajectories as well as their interdependencies with material stocks and flows. Policies in this context are based on envisioning potential future trajectories and value judgments about their social and ecological implications. Furthermore, the inclusion of stakeholders and the public insights provides orientation for policies targeted towards positive tipping points (Franzke *et al* 2022). In that context, known experiences reflecting water, energy, food security and infrastructure dimensions needs to be reoriented towards interdisciplinary and cross-sectoral cooperation, and the engagement of scientists, regulators and other stakeholders must be steered to foster effective risk governance.

The competition over scarce resources on SIDS, such as land and water, serves as a case in point how an inclusive approach to risk governance can assist mitigating SMC, although empirical research will need to provide evidence. Quantification of SMR using spatially explicit material stock and flow analysis is a first step to provide evidence on problematic resource-use patterns and possible scenarios. The modeling outputs are then assessed in a transdisciplinary and inclusive approach that takes societal concerns into account which leads to evidence-informed decisions about tradeoffs, e.g. whether to reduce tourism in favor of land preservation. It should be noted that stakeholder inclusion and public engagement in risk governance are no panacea that will automatically result in equally distributed costs and benefits of SMR on SIDS. Yet, inclusive risk governance can assist finding pareto-superior outcomes and pathways towards positive social tipping dynamics. On the basis of this conceptual contribution, we hope to stimulate future empirical work in SIDS.

Data availability statement

No new data were created or analyzed in this study.

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