Can a small island nation build resilience? The significance of resource-use patterns and socio-metabolic risks in The Bahamas

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RESEARCH ARTICLE

Can a small island nation build resilience?

The significance of resource-use patterns and socio-metabolic risks in The Bahamas

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Abstract

Resource-use patterns may entail systemic risks and cascade effects, which consequently inhibit the ability to deliver socioeconomic services. Identifying resource-use patterns exhibiting systemic risks and reshaping their combinations is a potential lever in realizing the transition to a sustainable, resilient, and resource-secure system. Using an island context to assess the quantity and composition of resource throughput enables a more comprehensive analysis of these risks. This article presents the first mass-balance account of socio-metabolic flows for The Bahamas in 2018, to identify socio-metabolic risks and cascading effects. Socio-metabolic risks are systemic risks related to critical resource availability, material circulation integrity, and (in)equities in cost and benefit distributions. We utilize the economy-wide material flow accounting framework to map the material flow patterns across the economy. In 2018, annual direct material input was estimated at 9.4 t/cap/yr, of which 60% were imports. High masses of waste (1.4 t/cap/yr) remained unrecovered due to the lack of recycling. Total domestic extraction (DE) were dominated by non-metallic minerals with more than 80%, while marine biomass makes up barely 1% of total DE. Due to its linear, undiversified metabolism, and heavy imports dependency, the system is susceptible to socio-metabolic risks and cascading effects including low levels of self-sufficiency, high vulnerability to shocks, commodity price fluctuations, threats to sensitive ecosystems, health impacts, and economic losses, among others. A holistic resource management strategy and nature-based solutions that consider the trade-offs and synergies between different resource-use patterns are critical when exploring potential plans for metabolic risk reduction.

KEYWORDS
circular economy, island industrial ecology, island sustainability, material flow analysis, socio-metabolic research, socio-metabolic risk

1 | INTRODUCTION

The unprecedented growth in the use of resources has caused global material extraction to quadruple since the 1970s, from around 22 billion tonnes to 100 billion tonnes in 2020, with projections reaching around 180 billion tonnes by 2050 (Circle Economy, 2020; Krausmann et al., 2018; UNEP, 2016; UNEP & IRP, 2017). Meanwhile, the circularity rates of materials re-entering the economy at the end of their lifecycle remain low, slightly declining from 9.1% in 2018 to 8.6% in 2020 (Circle Economy, 2020). Similarly, global energy use almost tripled from 224 EJ in 1971 to 624 EJ in

2019 and is estimated to hit 879 EJ by 2050 (British Petroleum, 2021; Schandl et al., 2016; Smil, 2017; World Energy Council, 2013). While these resource-use dynamics may have brought about an improvement in global material standards of living, it has come at the cost of destabilizing the Earth system on which we depend (IPCC, 2018; Rockström et al., 2021; Steffen & Morgan, 2021; Steffen et al., 2015; UNEP & IRP, 2017; Wiedmann et al., 2020).

The situation becomes even more critical in concentrated geographic settings like small island developing states (SIDS). SIDS are often characterized by sustainability challenges like limited resource bases, reduced waste absorption capacity, geographic dispersion, natural and built environment that is progressively been caught between rising sea levels and already limited available inland areas (coastal squeeze), and geographic isolation from markets which impacts connectivity and the ability to mobilize people and resources (Deschenes & Chertow, 2004; UNCTAD, 2021). SIDS often rely on imports for up to 80–90% of their basic needs (Bradshaw et al., 2020; Dorodnykh, 2017; FAO, 2019; IRENA, 2014; Symmes et al., 2019) and consistently rank high on various vulnerability indices like the World Risk Report (Aleksandrova et al., 2021), The Commonwealth Universal Vulnerability Index (The Commonwealth Secretariat, 2021), and the Commonwealth Vulnerability Index for Developing Countries (Atkins et al., 2000). For many SIDS, social and economic impacts have combined with the adverse effects of environmental impacts such as climate change and sea level rise, resulting in compounding shocks, which often amplify pre-existing vulnerability levels and sustainability challenges (IMF, 2021; Sachs et al., 2021; Thomas et al., 2020).

A major gap in the island socio-metabolic research (SMR) literature is investigations of the risks embedded in the metabolic profiles of island socioeconomic systems. Socio-metabolic risks are systemic risks related to critical resource availability, material circulation integrity, and (in)equities in cost and benefit distributions. Specific resource-use patterns exhibit potentials for systemic risks and cascade effects, which in turn inhibit progress toward greater resource security, self-reliance, and the system's ability to deliver necessary societal services (Singh et al. 2020, 2022). Socio-metabolic risk is to islands as circulatory health problems are to humans—both constrain the entity's ability to withstand significant shocks and changes. Mitigating socio-metabolic risk is crucial for small islands to withstand climate impacts and avoid cascading dysfunction of environmental, economic, and social systems.

Examples of this in small islands include St. Eustatius in the Caribbean, where soil erosion caused by goats grazing and marine resource extraction (e.g., fishing for conch) both impact the marine ecosystem, which is a prime source for tourism in the island (Polman et al., 2016); Nauru in the Pacific Ocean showed signs of exploitation of a single key resource (phosphate mining), which in turn had devastating environmental consequences (McDaniel & Gowdy, 2000; Pollock, 2014); and in Bonaire in the Caribbean, tourism-related coastal development and high import dependency of basic needs (e.g., water, energy, and food) is pressuring island resilience through habitat loss, waste generation, and high import costs (Slijkerman & van der Geest, 2019). Resource-use patterns can contribute to global environmental change but also determine their own vulnerability or resilience to those changes. Societies could adapt to climate change, build system resilience and achieve an improved standard of living at the lowest environmental costs by identifying and reconfiguring resource-use patterns that exhibit potential systemic risks (Singh et al., 2022).

Previous research has demonstrated the value of material flow analysis (MFA) as an innovative means of measuring levels of socioeconomic metabolism in the context of small islands. Most SMR focuses on inflows (Bahers et al., 2022; Chertow et al., 2020; Eisenhut, 2009; Krausmann et al., 2014; Rahman et al., 2022; Singh et al., 2001), very few on biophysical stocks (Bradshaw et al., 2020; Noll et al., 2019; Symmes et al., 20190) and outflows (Eckelman et al., 2014; Elgie et al., 2021; Mohammadi et al., 2021), however only one uses a mass-balanced approach to explore the potential for a "circular economy" in an island context (Noll et al., 2021).

Our research focuses on identifying socio-metabolic risks and cascading effects for the Caribbean SIDS of The Bahamas. The Bahamas has identified some immediate challenges it needs to address: a slowdown in social progress; governance arrangements that do not support a modern Bahamas; a highly vulnerable built and natural environment; and a highly vulnerable, undiversified, and underperforming economy (Government of The Bahamas, 2016). This has led the country to develop strategies that prioritize human well-being, natural resource exploitation, climate change, and sustainable resource-use to catalyze sustainable economic development and risk minimization (Bahamas Development Bank, 2018; Climate Ambition Alliance, 2019; Government of The Bahamas, 2015, 2016; WHO, 2021). The country, with its narrow resource base, large imports requirements, heavy dependence on tourism, extensive areas of flatland, and high concentration of coastal inhabitants (Bahamas Department of Statistics, 2017; Lutter et al., 2018; The Bahamas Natural Resources Foundation, 2021; WHO, 2021), serves as a great opportunity to explore the linkages between dynamics of resource-use and associated systemic risks.

We present here the first mass-balance account of socio-metabolic flows aimed at investigating the systemic risks and cascading effects embedded in the metabolic profile of an island's socioeconomic system. By means of measuring the mass and composition of materials that flow through the economy we determine the metabolic scale and circularity rates within The Bahamas socioeconomic system, which serve to identify potential metabolic and systemic risks as well as opportunities to develop and implement risk mitigation and adaptation strategies. We conducted a mass-balance study of The Bahamas for the year 2018 by applying the economy-wide material flow analysis (ew-MFA) framework. Our study is motivated by the following questions: (1) What characterized the metabolic profile of The Bahamas in 2018? (2) What are the inherent socio-metabolic risks and cascading effects associated with the country's resource-use patterns? (3) What are potential options for reconfiguring the country's resource-use patterns and build resilience? Thus, our analysis further expands the literature on islands SMR, by innovatively incorporating both MFA and circularity principles in the account of socio-metabolic flows to provide a broader view of potential socio-metabolic risks and cascading effects for a Caribbean SIDS. We identify and compare The Bahamas' metabolic profile to other island socioeconomic systems and investigate

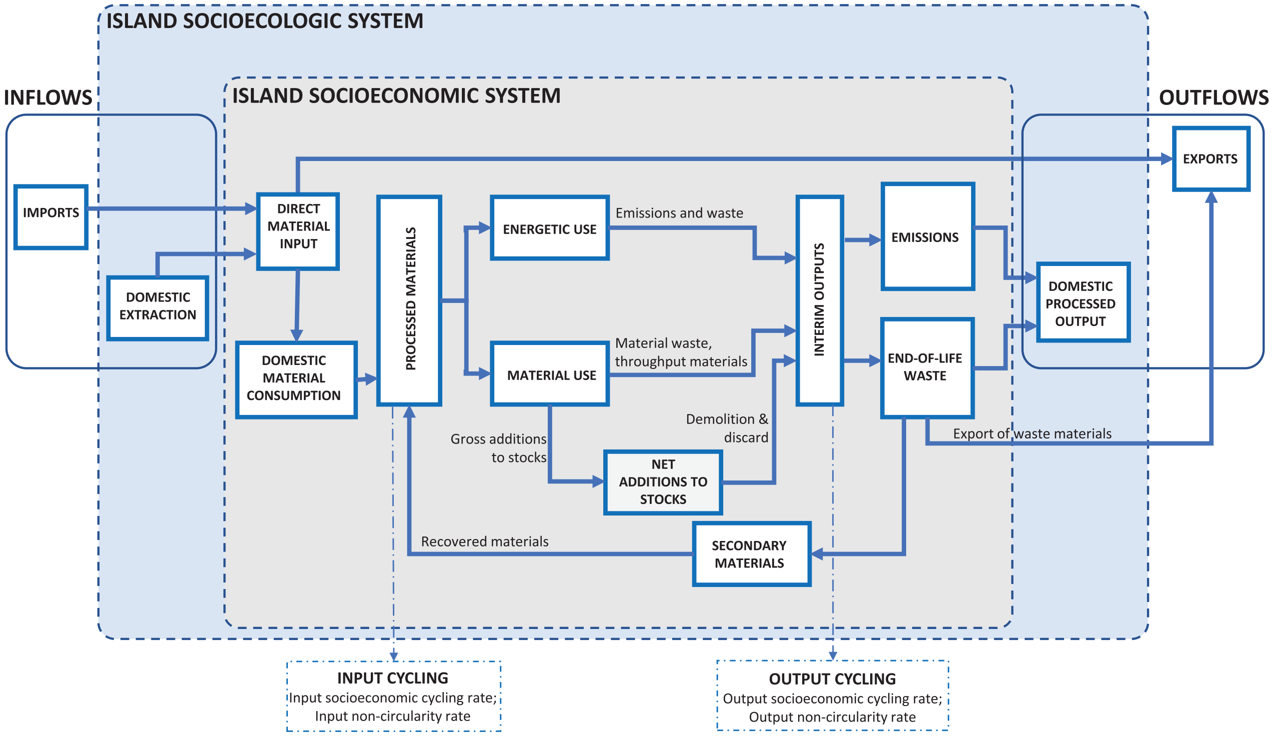

FIGURE 1 General framework for the ew-MFA in The Bahamas. Adapted from Haas et al. (2020) and Mayer et al. (2019)

TABLE 1 Main material categories and materials considered in the study

Main material categories	Materials included
Fossil fuels	Mineral fuels, mineral oils and products of their distillation, petroleum gases and other gaseous hydrocarbons, coal, spirits for motors, aviation turbine fuel, kerosene oil, diesel, fuel oil, base oil, and others
Biomass	Crops, crop residues, wood, wild catch, and other biomass
Metals	Iron, copper, nickel, lead, zinc, tin, precious metals, aluminum, uranium and thorium, other non-ferrous metals, and other miscellaneous products mainly composed of metals
Non-metallic minerals	Sand/gravel, salt, limestone, clays, gypsum, chalk and dolomite, slate, fertilizers, and other non-metallic minerals
Other	Materials not assigned to the previous four material categories, or which are not elsewhere specified (e.g., furniture, vehicles, machinery, clothing, and other miscellaneous products)

Source: Adapted from European Commission (2018).

the interdependence between the dynamics of resource-use and associated systemic risks. We further provide empirical insights to define future strategies for metabolic and systemic risks reduction in The Bahamas, advising to plan for resilience, and to implement monitoring approaches that fully incorporate and maximize the local capacity to help in the transition toward a sustainable, resilient, and resource-secure system.

2 | METHODOLOGICAL FRAMEWORK

The system boundary of our ew-MFA is consistent with the geographical boundary of The Bahamas. The study adopted the most recent ew-MFA accounting guidelines from EUROSTAT (European Commission, 2018), complemented by the circularity accounting frameworks proposed by Mayer et al. (2019) and Haas et al. (2020). Figure 1 shows the general framework used for the ew-MFA.

We consider all inflows and outflows for the year 2018 across all four main aggregated material flow categories as established by the guidelines from EUROSTAT (European Commission, 2018), namely: fossil fuels, biomass, metal ores, and non-metallic minerals. We include a fifth category of “other” complex goods and their materials that are not clearly attributed to any of the other four categories in the official statistics (e.g., miscellaneous furniture, boilers, vehicles, electrical machinery, and clothing). Table 1 provides an overview of the materials included in each material category. Using data on trade and domestic production, waste masses, waste composition, and recycling, we mapped and traced the material flows in the socioeconomic system. Information on in situ material and energy use, waste, and recycling efforts was obtained to understand the resource flow status and circularity rates in The Bahamas. Fully detailed descriptions of the used data, their sources, and processing can be found in Section 2.2 and in the Supporting Information.

2.1 | Scale and circularity indicators for the biophysical monitoring of the economy

We calculated a series of indicators for material input and output across all material categories to measure the metabolic scale and circularity rates, as well as to identify potential socio-metabolic risks. Scale indicators measure physical accounts and balances of mass flows, resource-use, stocks, and waste and emissions outputs in mass, which serve to plan for resource efficiency and conservation as well as sustainable resource management. Similarly, circularity indicators measure rates of flows related to the recovery of materials into the economy. In a circular economy, energy provisioning depends on renewable sources and moves away from fossil fuels. Additionally, the recovery and utilization of waste materials is a key element in the development of a robust circular economy. As such, circularity indicators at both system input and output level may contribute to a more general vision of material flows as these can serve as proxies to investigate the pressures and socio-metabolic risks associated with resource-use patterns. Table 2 shows an overview of these indicators.

2.2 | Economy-wide MFA: Data review and sources

2.2.1 | Scale indicators

Data on masses of domestic extraction (DE) from official Bahamian statistics were insufficient. As such, DE flows were captured through different data sources. The Energy Information Administration (EIA, 2021) provides data on fossil fuel production, consumption, and trade. The FAOSTAT statistical database (FAO, 2021a, 2021b) was the main data source for the biomass category. The UN IRP Global Material Flows Database (UNEP & IRP, 2022) was referred to for non-metallic minerals and the British Geology Survey (Brown et al., 2021) for metals and non-metallic minerals. Table S1 in Supporting Information S1 provides an overview of the databases utilized to account for all DE. Please note that this and other tables and figures mentioned in the article can be found in the Supporting Information.

Import and export flows include traded goods made of primary and processed materials. Although the country releases quarterly and yearly reports on foreign trade, these only contain the top 25 commodities ranged by value ($) instead of mass (weight) (Government of The Bahamas, 2022). Therefore, we accounted only for those goods reported in the official international trade statistics platform of the United Nations (United Nations Statistics Division, 2018) and enumerated using clear mass units. These were disaggregated using the Harmonized System (HS) 2012 for classifying goods using six-digit codes. Table S2 in Supporting Information S1 shows information for the main data sources for imports and exports.

Processed materials (PM) are used either for energy (eUse) or for their material properties (mUse). PM are calculated including data on waste recycling efforts in The Bahamas. The share of PM utilized for energy use (eUse) includes all flows utilized for provisioning energy for technical applications as well as for livestock and humans (feed and food). Technical applications include fossil fuels and biomass for combustion (wood fuel and coal). Food and feed include goods of animal and vegetal origin as well as processed foods. Material use (mUse) was calculated as the difference in mass between PM and eUse.

Masses and composition of solid waste from official Bahamian statistics were not available. As such, the most recent estimates (2016) from the World Bank Group on municipal solid waste (MSW) generation rates for The Bahamas as well as of MSW composition in Latin America and the Caribbean (LAC) region (Kaza et al., 2018, p. 54) were taken for this analysis. Calculations on MSW masses and composition for The Bahamas can be seen in Table S3 in Supporting Information S1. The shares of total solid waste streams (MSW and demolition and discard [D&D]) in The Bahamas were taken from estimates from the InterAmerican Development Bank (IDB, 2018, p. 53).

Regional or country-specific characterization of D&D for The Bahamas is non-existent. As the building code of The Bahamas is based generally on the South Florida Building Code (Ministry of Works & Utilities, 2003), we assume that D&D waste composition mentioned in the US EPA report "Construction and Demolition Debris Generation in the United States," (U.S. Environmental Protection Agency, 2016, p. 18) was also applicable in our case study. Calculations on total D&D types, shares, and masses for The Bahamas can be seen in Table S4 in Supporting Information S1.

Estimates on recycled materials from official Bahamian statistics were limited. Recycling, if any, is managed mainly through non-profit organizations in the country, and the data collection and reporting on masses and composition is usually not publicly available. To account for this, major efforts were undertaken to contact recycling non-profit organizations such as WasteNot Bahamas Limited, Cans for Kids Bahamas, and Bahamas Waste Limited. Reported masses of recycled materials are shown in Table S7 in Supporting Information S1.

Interim outputs (IntOut) includes emissions and waste from eUse, mUse, and D&D. The eUse component of IntOut comprised emissions and ashes from fuel combustion for both biomass and fossil fuels, along with biomass food waste obtained from total MSW (Table S3 in Supporting

TABLE 2 Overview of the scale and circularity indicators and their definitions for the biophysical monitoring of the economy

Scale [Kt/yr]	Indicators	Description
	Material input indicators	
	Domestic extraction (DE)	All materials extracted from the domestic environment
	Imports	Inputs of goods originating from outside the national economy
	Direct material inputs (DMI) = DE + Imports	Input of materials into the national economy originating from the domestic environment and the rest of the world
	Material use indicators	
	Domestic material consumption (DMC) = DMI – Exports	Total amount of materials that are directly used in a national economy
	Processed materials (PM) = DMC + SM	All materials processed domestically
	Secondary materials (SM)	Includes materials recovered from end-of-life waste which are reintroduced into the domestic economy
	Energetic use (eUse)	Share of PM that provide energy for technical applications as well as for livestock and human metabolism (feed and food)
	Material use (mUse)	Share of PM that is used for its material properties
	Material stocks indicators	
	Gross additions to stocks (GAS)	All materials going into material stocks (lifetime greater than 1 year)
	Net additions to stock (NAS) = GAS – Demolition and discard	Net amount of material added to the stocks per year
	Material output indicators	
	Exports	Outputs of goods and materials to other economies
	Demolition and discard (D&D)	Quantity of materials removed from material stocks after their service lifetime
	Interim outputs (IntOut)	Includes all materials that are accounted as an output from the socioeconomic system before divided into emissions and end-of-life waste
	Domestic processed outputs (DPO)	All materials that are released back into the environment as a result of consumption and production processes
	Emissions	The part of the DPO corresponding to emissions, whether from combustion processes or metabolic processes of livestock and humans
	End-of-life (EoL) waste	The part of the DPO corresponding to solid materials that can no longer be cycled back to the economic system as secondary materials and have reached the end of their service lifetimes
Circularity [%]	***Input circularity indicators***	
	Input socioeconomic cycling rate (ISCr) = (Secondary materials ÷ PM) × 100	Share of secondary materials reintroduced through socioeconomic processes into the economic system
	Input non-circularity rate (INCr) = (Fossil energy carriers ÷ PM) × 100	Fossil energy carriers as share of PM
	Output circularity indicators	
	Output socioeconomic cycling rate (OSCr) = (Secondary materials ÷ IntOut) × 100	Share of secondary materials present in IntOut
	Output non-circularity rate (ONCr) = (Fossil energy carriers ÷ IntOut) × 100	Fossil energy carriers as share of IntOut

Sources: European Commission (2018); Haas et al. (2020); Hotta & Visvanathan (2014); Jacobi et al. (2018); Mayer et al. (2019).

Information S1). The mUse component includes all other material waste from MSW except for food waste. Waste from gross addition to stocks (GAS) considers the total mass of D&D (Table S4 in Supporting Information S1).

GAS was calculated as the difference between mUse and material waste from MSW not including biomass from food waste. The difference between GAS and D&D equals the net addition to stocks (NAS).

End-of-life (EoL) waste considered total D&D, total MSW, ashes from fossil fuel and biomass combustion, and livestock excrement resulting from metabolization of biomass feed. Ash masses were based on typical post-combustion ash content per fuel type (Table S5 in Supporting Information S1). Excrements were estimated by considering the number of livestock animals and by applying coefficients of manure generation per livestock (Table S6 in Supporting Information S1).

Masses of emissions resulting from fossil fuels and from biomass were estimated using the principles of mass balance. The former was estimated as the difference between the total mass of eUse and the total mass of fossil fuel ashes from combustion, while the latter was estimated as the difference between the total masses of biomass share in IntOut (ashes from combustion, biomass waste, and excrement) and the total mass of biomass share from EoL waste. The sum of emissions and EoL waste equals domestic processed output (DPO).

The rest of the indicators were calculated using the principles of mass balance through a combination of data on DE, imports, exports, MSW, D&D, and recycling masses, among others (see Table 2).

2.2.2 | Circularity indicators

Both the input non-circularity rate (INCr) and the output non-circularity rate (ONCr) quantify the fossil energy carriers' share in PM and IntOut, respectively. In the case of the socioeconomic cycling rate (ISCr) and output socioeconomic cycling rate (OSCr), these measure the share of secondary materials in the system input and output, respectively (Haas et al., 2020; Mayer et al., 2019). These indicators were calculated through data on recycling masses by category (secondary materials) and fossil energy masses, divided by the masses of PM or IntOut.

2.2.3 | General considerations

This study relied primarily on international data sources like the UN IRP Global Material Flows Database, the World Mineral Production report from the British Geology Survey, the FAO, and the UN Comtrade database. A combination with available national statistics (Government of The Bahamas, 2019) as well as by contacting local government officials and non-governmental organizations (NGOs) allowed us to cross-check, verify, and improve datasets where possible. A semi-quantitative assessment of data quality based on an adapted "pedigree matrix" (Allesch & Rechberger, 2018) is presented in Table S8 in Supporting Information S1. The main indicators of DE, imports, and exports and their derived indicators exhibit a good data quality as these stems directly from established international statistical data sources. The lack of good waste data (due to assumptions and limited data availability) affects the ability to effectively assess masses and composition of outflows. Major efforts were undertaken to verify the various data sources and find the most accurate and up-to-date information available. Most of these data sources have been compiled and processed from sources believed to be reliable, however, it is advised that these should be considered with a degree of caution due to global inconsistencies in definitions, data collection methodologies, and completeness. The reader is referred to consult the detailed data compilation methodologies for the different indicators utilized in this study as indicated in Supporting Information S1.

In the results section, you will note that part of the imported flows simply pass through the economy, first being imported and then re-exported. In this case, The Bahamas is exposed to the Rotterdam effect as it serves as a middle point in the transit of flows of goods to other economies. However, separately accounting for these throughflows that simply pass through the economy, and for all material categories, posed a significant challenge as this disaggregated information was not explicitly reflected in the consulted international data sources for The Bahamas. Accordingly, we did not make a distinction between these throughflows and accounted for the total material flows imported and exported regardless of origin or destination.

3 | RESULTS

3.1 | Scale indicators

Figure 2 shows the ew-MFA Sankey diagram for The Bahamas for 2018. An extended version of these indicators with mass flows by main categories and sub-categories can be seen in Table S9 in Supporting Information S3.

In 2018, the Bahamian economy resembled that of a linear socio-metabolic profile with material flows mainly directed to final consumption and high waste generation that remained unrecovered. The country showed a high reliance on external sources for energy carriers and manufactured goods due to the lack of domestic supply. The country's extractive resource patterns are focused on a few key natural resources, while the economy's

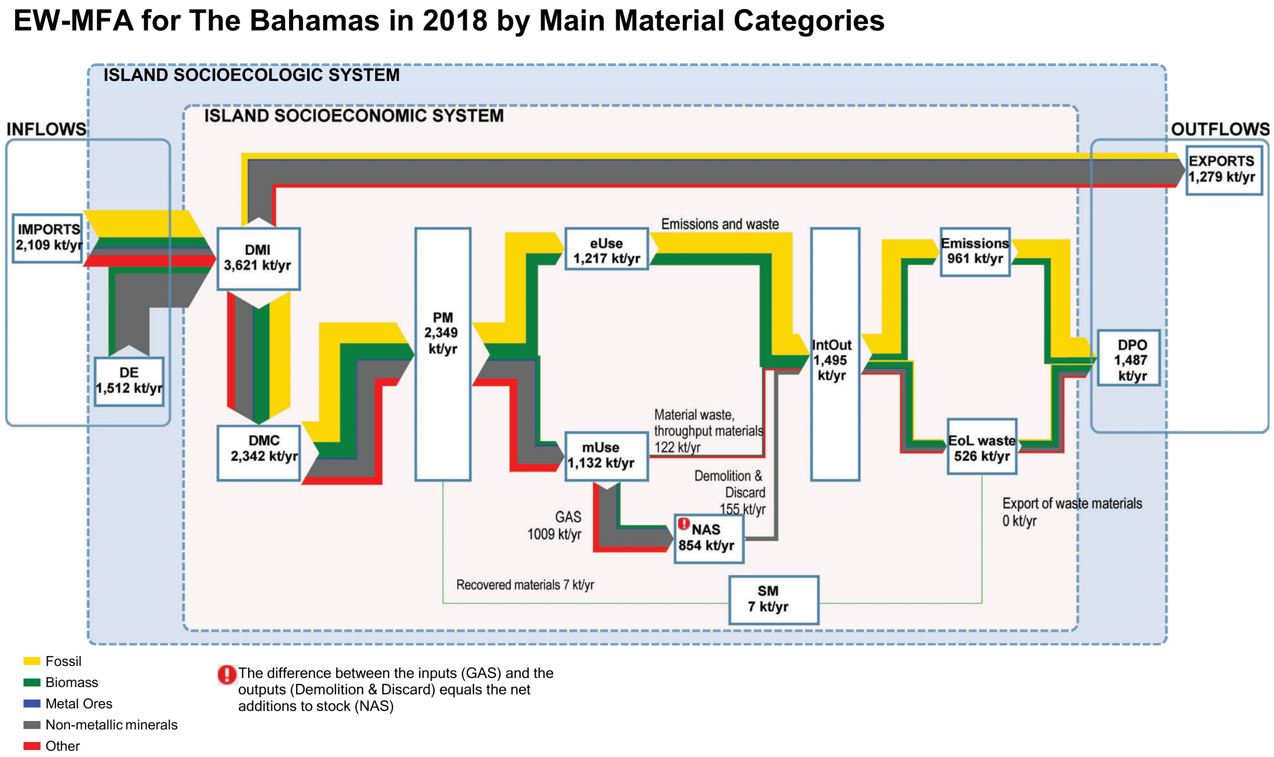

FIGURE 2 Estimated ew-MFA for The Bahamas during the year 2018. Units in kilo tonnes per year [kt/yr]. *Source*: Current study. Abbreviations: DMI, direct material inputs; DE, domestic extraction; DMC, domestic material consumption; DPO, domestic processed outputs; EoL, end-of-life waste; eUse, energy use; GAS, gross additions to stocks, IntOut, interim outputs; mUse, material use; NAS, net additions to stocks; PM, processed materials; SM, secondary materials

exports are mainly based on domestically extracted non-metallic minerals. Materials that are released back into the environment as emissions and waste (DPO) represent almost two thirds of the total resource consumption (DMC).

Direct material input (DMI) was estimated at 3620 kt/yr of which 60% were imports. As the population in 2018 was around 385,600 habitants (Worldometer, 2022), per capita values of DMI are close to 9.4 t/cap/yr. Total DE was estimated at 1500 kt/yr or 3.9 t/cap/yr. Non-metallic minerals represented more than 80% of the total DE (Figure S1a in Supporting Information S2). Of this, 70% was salt and 30% was aggregate materials (sand and gravel). For DE, the total biomass was estimated at 250 kt/yr or 0.7 t/cap/yr. Of this, around two thirds were utilized for food or feed, while less than one third was directed to either energy use or construction processes (industrial timber and fuelwood). Marine biomass extraction amounted to only 11 kt/yr, less than 5% of the total biomass DE. Imports were estimated at 2100 kt/yr or 5.5 t/cap/yr. Half of total imports were fossil fuels, which were directed toward energy use or exports (Figures 1a and 1b in Supporting Information S2).

Total processed materials (PM) were estimated at 2350 kt/yr or 6.1 t/cap/yr. Of this, PM was divided almost equally between eUse and mUse. For eUse, around 60% comprises imported fossil fuels while the rest comes from biomass. For mUse, the largest flow is from non-metallic minerals, which represent almost 60% of the total mUse. Furthermore, 90% of the total mUse was used for building up stocks (GAS), comprising mainly commodities such as cement, aggregates, furniture, and miscellaneous products.

Total exports and DPO were estimated at 1300 kt/yr (3.3 t/cap/yr) and 1500 kt/yr (3.9 t/cap/yr), respectively. Exports were heavily influenced by non-metallic minerals, particularly salt (around 850 kt/yr), which represents around two thirds of total exports. Minimal masses of biomass exports (1% of the total) were focused on marine products, timber, and fuelwood. High masses of waste (530 kt/yr or 1.4 t/cap/yr) remained unrecovered due to virtually no recycling (1%), while exports of waste materials were negligible. DPO flows were dominated by fossil fuels, which represent around half of the total DPO, and by biomass flows, which represent around one third of the total DPO. Moreover, emissions and EoL waste represent two thirds and one third of the total DPO, respectively (Figure 1c in Supporting Information S2).

3.2 | Circularity indicators

Complementing the understanding of socio-metabolic risks in the island context, this section presents circularity indicators calculated in this study (see Table 3).

TABLE 3 Overview of circularity indicators in The Bahamas for 2018

Indicator	Circularity [%]
Input socioeconomic cycling rate (ISCr)	
Fossil products	0
Biomass	1.1
Metals	0
Non-metallic minerals	0
Other	0.1
Total	**0.2**
Output socioeconomic cycling rate (OSCr)	
Fossil products	0
Biomass	1.4
Metals	0
Non-metallic minerals	0
Other	0.2
Total	**0.3**
Input non-circularity rate (INCr)	**32.9**
Output non-circularity rate (ONCr)	**51.6**

The input and output socioeconomic cycling rates, as well as non-circularity rates, clearly indicate low material circularity and a high dependence on fossil fuels for energy needs in The Bahamas. With 2350 kt/yr of PM utilized in the island system, and recycling of only 7 kt/yr (see Table S7 in Supporting Information S1), the total ISCr in 2018 results in 0.2%. OSCr shows a slightly higher average value at 0.3%. Our analysis shows that biomass is the material category with the highest ISCr at 1.1% and OSCr at 1.4%, as green (biomass) waste is the predominant material recycled (6.4 kt/yr). In 2018, there was no reported recycling of fossil products or minerals. The INCr indicates that 33% of the total mass of PM is comprised of fossil energy carriers. Similarly, the ONCr indicates that 52% of the total mass of IntOut is composed of fossil energy carriers. In the Bahamian context, major obstacles to increase circularity include: the low levels of recycled materials, the physical growth of the economy as in-use stocks (NAS), and the relatively high shares of fossil energy carriers in PM.

4 | DISCUSSION

4.1 | Resource-use patterns in The Bahamas compared to other island territories

Overall, island territories exhibit a limited and unequal distribution of natural resource bases, growing trends in resource demand, rapid urbanization, heavy dependence on imports that causes elevated costs of basic supplies, poor connectivity and high costs of crossing open sea, which function as stressors over the supply of essential resources. Together with other complex social, economic, structural, and climate pressures that further exacerbate their exposure to shocks (UN-OHRLLS, 2022), the overall resource security and sustainability of island territories are under threat. Proper management and monitoring of the biophysical characteristics of national economies (e.g., through MFA and circularity indicators) are key to foster their sustainable and resilient development. By comparing island territories (e.g., based on their characteristics of production, trade, and resource-use patterns), one gains a better understanding of varying patterns of metabolic profiles, embedded socio-metabolic risks, and opportunities for mitigating those risks by reconfiguring trajectories of resource-use within their own contexts.

Table 4 shows a comparison between different input, output, and use indicators for various island territories and regions around the world, normalized per capita to enable comparison. These island cases exhibit varying combinations of resource extraction, waste, trade, and use. Characteristics such as the main economic activity, infrastructure (e.g., fishing fleet, harbors, mines, pipes for fuels transportation), and natural resource bases influence their metabolic profiles. The Bahamas can be viewed as a tourism-driven economy with a limited resource base and low manufacturing capacity. With no fossil fuel reserves and limited renewable-energy generation capacity, the energy carriers extracted from the domestic environment comprise low amounts of biomass fuelwood. This makes the country almost 100% dependent on imports of fuels for its energy needs. In comparison, Trinidad and Tobago—an industrial Caribbean country with an adequate resource base and infrastructure dedicated to fossil fuel extraction and processing—is not dependent on fuel imports.

TABLE 4 Comparison of per-capita MFA indicators, numbers in [tonnes/cap/yr]

Island territory	Year	DE	Import	Export	DMI	DMC	Main DMC contributor	Sources
The Bahamas	2018	5.5	3.9	3.3	9.4	6.1	Fossil fuel, Non-metallic minerals	Present study
Samothraki	2018	13.8	5.0	2.3	18.8	16.5	Biomass	Noll et al. (2021)
Iceland	2008	14	15.1	6.1	29.1	23	Biomass, Non-metallic minerals	Krausmann et al. (2014)
Trinket Island	2000	N.D.	N.D.	2.4	6.2	3.8	Biomass, Non-metallic minerals	Singh et al. (2001)
Trinidad and Tobago	2008	34.7	8.8	26.2	17.3	17.4	Fossil fuels	Krausmann et al. (2014)
Oahu Hawaii	2005	3.7	16.6	6.7	20.3	13.6	Fossil fuels	Eckelman & Chertow (2009)
New Caledonia	2016	N.D.	10.6	N.D.	N.D.	29.3	Non-metallic minerals	Bahers et al. (2020)
Santa Cruz (Galapagos)	2012	16.3	4.4	0.1	20.7	20.8	Non-metallic minerals	Cecchin (2017)
Japan	2015	4.6	6.13	1.4	10.7	9.3	Non-metallic minerals	Tanikawa et al. (2021)
Global average	2019	12.5	1.9	1.8	14.4	12.4	Non-metallic minerals	UNEP and IRP (2022)
Europe average	2019	16.4	7.9	5.8	24.3	18.5	Non-metallic minerals	UNEP and IRP (2022)
LAC average	2019	16.9	1.2	2.3	18.1	15.8	Biomass	UNEP and IRP (2022)

Abbreviations: DE, domestic extraction; DMC, domestic material consumption; DMI, direct material input; LAC, Latin America and the Caribbean; N.D., no data.

The Bahamas' DE mainly comprises non-metallic minerals (salt, sand/gravel). Virtually all salt extraction (around 850 kt/yr) is exported, while close to 100% of sand and gravel extraction (360 kt/yr) is directed toward building and maintaining building stocks. Likewise, the islands of New Caledonia and Santa Cruz also exhibit a DE focused on minerals; however, slight differences are seen in the end uses in these islands. New Caledonia is one of the largest nickel producers in the world, as such the country is a supply base for other economies, with export flows of this resource (Bahers et al., 2020). On the other hand, Santa Cruz extracts large amounts of volcanic rocks that end up being used for the local construction of stocks and concrete block production (Cecchin, 2017).

In The Bahamas, although the exclusive economic zone (EEZ) of the country is many times larger than its land area (45:1 ratio) (Sea Around Us, 2016), marine biomass DE represents less than 1% of total DE and just around 5% of total biomass DE. With a fishing fleet characterized as small scale (FAO, & Government of The Bahamas, 2016) and dedicated to catching a few targeted species, The Bahamas' exploitation of marine resources is low compared to other islands. Contrastingly, Iceland, with a lower EEZ-to-land area ratio (7:1), has a marine biomass DE of 30% of total DE and 60% of total biomass DE (Krausmann et al., 2014). The development of its fishing fleet infrastructure has enabled Iceland to exploit that particular resource.

A similarity seen across many islands is the high masses of waste generation, especially in Caribbean SIDS. Most of this ends up in (uncontrolled) disposal sites where it takes up space and generates greenhouse gases from decomposing (biomass), which contributes to global warming and produces residues that may pollute underground water, among other issues. The Bahamas shows higher levels of MSW generation (1.85 kg/cap/day) than the global (0.74 kg/cap/day) and LAC region (0.99 kg/cap/day) averages during 2016, and is one of the highest waste generators among the Caribbean SIDS (Kaza et al., 2018) (see Figure S3 in Supporting Information S2). A common characteristic of island territories is the high share of organic waste in MSW (Kaza et al., 2018), the lack of sanitary landfills to properly dispose of waste (IDB, 2016, p. 23), and the low masses of waste materials recycled (Mohee et al., 2015). This could be associated with limited policies and funding to promote waste management, a lack of understanding of material waste composition, limited studies on waste characterization and recycling opportunities, and limited infrastructure to process waste that arrives at disposal sites (Global Environment Facility, 2019; Mohee et al., 2015). Although the government, environmental activists, local NGOs, and other initiatives have made efforts to curb waste and pollution, the total masses of waste generation are still relatively high.

4.2 | Do current patterns of resource use in The Bahamas constitute a socio-metabolic risk?

As the analysis of indicators shows, the case of The Bahamas displays specific patterns of resource use that might place the country at socio-metabolic risks. By improving the understanding of such risks and their aftereffects, the island system can continue to provide critical societal services consistently and effectively in the long run. Table 5 briefly shows the condition of the case study, emphasizing the potential risks associated

TABLE 5 Metabolic patterns, associated risks, the current situation in The Bahamas, potential cascading effects and mitigation strategies

Metabolic pattern	Socio-metabolic risks	Observed evidence	Cascading effects	Potential risk mitigation strategies
High fuel imports and consumption	Energy price fluctuations	Fuel prices have been steadily increasing over the past years.	Impact on cost of electricity and other goods/services; continued emissions of greenhouse gases contribute to climate change hazards.	Increase energy efficiency and self-sufficiency through energy generation via clean technologies (wind, solar, ocean, etc.).
	Oil spills and runoffs	Equinor oil spill (5 million gallons spilled over Grand Bahama's pine forest after Hurricane Dorian in 2019) (Save the Bays & Waterkeeper Alliance, 2019).	Damage to pine forest and wetland ecosystems; water table pollution; power generation shortages; specialized labor required to clean up and restart plants.	Strengthen oil spill prevention, control, and mitigation programs. Hasten the transition to cleaner energy technologies.
High extraction of minerals	Erosion, loss of coastal shoreline, impacts on local ecosystems	Past mining of sand at Ocean Cay left the island in a poor state, with extensive damage to the ecosystem.	Loss of habitat for species offshore and onshore; change in water flows; economic losses from tourism abandonment; economic losses from fisheries; loss of ecosystem services such as protection from extreme sea levels, leading to greater exposure to climate change hazards.	Design, apply, and evaluate management strategies aimed at the sustainable exploitation and utilization of resources. Application of restoration programs for local ecosystems (e.g., through nature-based solutions).
High utilization of materials for construction	Higher maintenance requirements	Nassau and Freeport contain more than 80% of the population, and Nassau's urban growth has reached the extent of the island.	Increase in use of resources from building construction, maintenance and operation; noise, traffic, pedestrian congestion; hotspots of pollution; health issues.	Optimize development planning and existing infrastructure by redesigning and upgrading stocks through the adoption of alternative construction materials (e.g., ecofriendly materials).
	Higher exposure to natural hazards in areas prone to erosion and flooding	Infrastructure at risk from the negative effects of climate change (e.g., flooding and storms).	Interruption of critical services; costly debts from the reconstruction of infrastructure (e.g., roads, ports).	Implement strategies that combine the use of natural, vegetated, hard, and engineered coastal defense structures that can reduce the need for additional materials, lower overall infrastructure expenditure and increase resilience.
	Increase in logistics complexity	The archipelagic nature of The Bahamas and its dense urban centers make it difficult to transport resources in a timely and efficient manner.	Untimely deliveries causing services/businesses to suffer; potential loss of lives when facing external shocks; food insecurity.	Identifying and mapping critical buildings, transport nodes, and networks to prevent and adapt to potential logistics issues.
Undiversified utilization of marine resources	Overexploitation of targeted species	Spiny lobster/queen conch harvest has suffered from unsustainable fishing practices.	Threats to the balance of fragile ecosystems, food security, and local livelihoods.	Enforce a monitoring framework to collect and maintain data on marine resources in the country, including research on potentials for sustainable exploitation of marine species.
	Increased dependency on non-renewable energy sources	Limited ocean/offshore (wind/solar/ocean currents/other) renewable energy capacity installed.	Continued risk of environmental pollution and greenhouse emissions; increased foreign dependency.	Further support the national energy policy to promote and apply a comprehensive program of efficiency improvement and energy diversification in the country.

(Continues)

TABLE 5 (Continued)

Metabolic pattern	Socio-metabolic risks	Observed evidence	Cascading effects	Potential risk mitigation strategies
High masses of waste	Uncontrolled management, no space for proper processing, landfill leachate, and fires	There have been recurring landfill fires over the past years (Bahamas Information Services, 2017; PAHO, 2017); currently, only three sanitary landfills (main islands) and six open non-sanitary landfills and dumpsites exist.	Pollution of the water table, gas emissions, health impacts in the surrounding community, impacts in the tourism industry.	Implement and strengthen solid waste management plans and strategies (technical and operational), as well as proper waste disposal infrastructure and maintenance. Waste characterization studies may be an opportunity to explore waste-to-energy alternatives.

with the levels of inflows and outflows and resource use as well as observed evidence of those risks, some of the potential cascading effects and suggested mitigation strategies.

Overall, fossil fuel prices have been steadily increasing over the past years, directly impacting the costs of goods and services. In addition, the growing population, shifting consumption patterns, and increasing urbanization, among others, have escalated the demand for mineral resources mainly used for construction. The accumulation of these materials for building stocks, in turn, influences the need for more resources for their maintenance. While these mineral resources are indeed necessary, extractive practices could be environmentally damaging to sensitive ecosystems. Coupled to the country's socioeconomic and physical exposure to disasters, future affectations on infrastructure and critical services represent an existential threat (UNISDR, 2015).

Although the Bahamian EEZ territory covers a vast ocean area, there is an undiversified utilization of marine resources. This untapped potential for exploitation, however, should consider the predicted consequences of using or not using the resource. Diversification of fish stocks DE (e.g., through aquaculture, or emerging fisheries such as the deep-sea ones) could reduce the pressure on currently targeted species to significantly improve the overall fisheries stocks' health. Additionally, this could alleviate imports dependency and increase the competitiveness of the country in the international scenario. Similarly, investments in ocean-based renewable energies (e.g., near-shore and off-shore wind turbines, ocean thermal energy conversion) can improve the energy self-sufficiency of the country, thus reducing foreign dependency on fossil fuels.

The country generates high masses of waste and has minimal levels of circularity. The most pressing issue is the disposal of waste, which continues to be dumped in open or uncontrolled dumpsites as opposed to properly designed sanitary landfills. Combined with insufficient infrastructure and gaps in technical and operational procedures, the country is exposed to health and public safety risks such as recurrent fires and environmental litter, which also negatively impact the tourism industry.

4.3 | How can The Bahamas reduce its socio-metabolic risks?

Given the specific metabolic profile of The Bahamas, a holistic resource management strategy and nature-based solutions (NBS)—which consider the trade-offs and synergies between different resource-use patterns—are critical when exploring directions for reducing risks (Failler, 2020; Gerritsen et al., 2021; Wüstemann et al., 2017). The current energy crisis triggered by the war in Ukraine at the beginning of 2022 and interruption of global supply chains since the beginning of the Covid 19 pandemic lays bare socio-metabolic risks associated with import dependencies, especially for SIDS. Strategies should include features and monitoring approaches that fully incorporate and maximize the local capacity for resilience and mitigation at both the environmental and socioeconomic levels.

Like many island nations, The Bahamas is almost 100% reliant on imported fossil fuels. It is imperative to find ways to accelerate the energy transition and increase energy efficiency in the country. The Bahamas shows excellent conditions to benefit from a combination of modern and efficient renewable-energy technologies due to the elevated cost of fossil fuels, its size, and the potential of renewable energy. Estimations from the National Renewable Energy Laboratory set the potentials of wind and solar renewable energies at 200 and 60 MW, respectively (NREL, 2015). Given the current generation capacity of around 536 MW based on fossil fuels (NREL, 2015), renewable energy could reduce the dependency on imported energy carriers by almost 50%, thus reducing the associated socio-metabolic risks and providing direct economic advantages.

Infrastructure development requires construction materials. Non-metallic minerals (sand/gravel) are key materials utilized for this expansion, particularly for the construction of buildings and roads. However, commercial exploitation of these resources may lead to severe environmental and economic issues such as erosion, flooding, and coastal hazards, among others. Options to reduce these potential risks include optimizing or even reducing existing infrastructure by redesigning and upgrading stocks through the adoption of alternative, sustainable construction materials. By incorporating ecofriendly materials (e.g., bamboo), The Bahamas could transform its built environment, facilitate material circularity, create green jobs, improve tourism amenities, and overall health and quality of life through reduced emissions. In addition, the repurposing of waste materials could reduce overall raw material consumption and waste pollution streams as in the case of the utilization of plastic waste in the roads on the Honduras island of Utila in the Caribbean (Pelliccia, 2018). In parallel, studies on current rates of production and consumption of minerals with mapping of mining areas are critical to correctly evaluate the environmental and economic impacts. With this, it would be possible to design management strategies aimed at the sustainable exploitation and utilization of resources.

In regard to the low material circularity rates in The Bahamas, the adoption of a circular economy can be viewed as an opportunity to enhance resource efficiency and reduce waste streams. One of the first steps to achieve this transition should be focused on understanding the waste streams and designing strategies to collect, transport, separate, and reuse them. Based on our results, as food losses represent around half of the total MSW in The Bahamas, a potential "high-return, low-risk" item could be the proper management of this outflow. Investment in infrastructure and proper management of supply chains at the production, storage, operation, and distribution levels may reduce food waste in the country (Ewing-Chow, 2019). Moreover, the organic fraction of the waste stream could be used as input to produce an array of safe and valuable products such as fertilizer (green waste compost), soil substrate, energy carrier (biogas), and more.

Highly dense urban centers in low-lying flatlands with close proximity to the coastline may cause an array of environmental, health, and infrastructure issues, including inland flooding, erosion, coastal hazards, and pollution that are increasing with strengthening climate change. Conventional approaches to combat these threats include hard engineered structures such as sea walls and breakwaters. However, these man-made structures further perpetuate the dependency on non-metallic mineral imports for their construction. Nature-based coastal defense structures such as coastal wetlands, coral reefs, and salt marshes have the potential to help reduce metabolic risk by means of reducing wave heights and can be several times cheaper than artificial submerged breakwaters (Narayan et al., 2016). Coastal wetlands also can serve as a nursery habitat for fish, a home for other marine species, and a natural filter for pollutants (Lee et al., 2014). Coastal wetlands have the potential to grow with climate change-driven sea level rise and expand in area. However, this is only possible if enough inland accommodation space is given to coastal wetlands (e.g., through elevation management of the coastal topography, or through a process of "managed retreat" in which wetlands can form as inundation occurs) and these areas are protected such as with upland nature reserves (Bridges et al., 2021; Hein et al., 2021; Schuerch et al., 2018; Zhu et al., 2010). However, these approaches have to be considered cautiously so they do not heighten the existing dependency on material imports and do not add to the current coastal squeeze effect.

The dependency of The Bahamas on imported food and fuel could possibly be lessened with introduction of forest management adopted to dryland forests. Fall et al. (2021) conducted pollen analysis of the Bahama's sediment record and found that the current pine forests are not native but were introduced about 1000 years ago by Amerindian settlers. The original forest cover consisted of local hardwood and palm species that were more hurricane resilient than the current pine species. Most of The Bahamas is covered by a tropical savannah climate and characterized by karst geology, suggesting that forest management approaches specialized to semi-arid regions would be required. These approaches might serve to produce a limited supply of local fuel wood, regenerate soil, and reduce soil erosion. Acknowledging typical soil moisture and nutrient limitations of karst ecosystems (Zhang et al., 2022), opportunities could be explored to combine native tree species reforestation with agro-forestry approaches to include modest pastures for small livestock or intercropping of suitable crop species (Bayala et al., 2022; Keesstra et al., 2018).

5 | CONCLUSIONS

This is the first study to apply an ew-MFA mass balance to assess the biophysical economy of a small island nation to identify socio-metabolic risks. We have characterized The Bahamas' distinctive metabolic profile and identified associated risks through assessment of its socioeconomic metabolism in regard to resource-use, waste generation, and material circularity. Our study offers insights on the potentials that reconfiguring the flows of material input, output, and circularity may offer to articulate adaptation strategies aimed at bringing functionality, stability, and resource security, while minimizing socio-metabolic risks and build resilience in the system. In addition, our study clearly demonstrates that resource management is integral to properly managing systemic risks, especially in SIDS. Inadequate resource management could adversely impact primary economic sectors (e.g., tourism), resource self-sufficiency, resilience, human and ecosystems health, and quality of life, among others.

This study provides insights into the potentials of using the ew-MFA framework to identify socio-metabolic risks. Mitigating socio-metabolic risk is crucial for small islands to withstand climate impacts and avoid cascading dysfunction of environmental, economic, and social systems. Simultaneously, it enables a much-needed estimation of the biophysical dimension of the economy in terms of flows of materials in the island context. As most of the data sources utilized in this study are freely available, the proposed framework can be easily replicated in many other territories with relatively low time and resource investments, especially for other SIDS and developing countries. However, care must be taken to ensure the quality and completeness of the data to reduce uncertainties as the particularities of data collection for each case study may represent a challenge. The ew-MFA mass-balance analysis thus calls for improvements in overall data quality, including the development of proper input and output statistics, in addition to waste composition and materials cycling data.

Moreover, as the ew-MFA and circularity indicators are more focused on the monitoring of the biophysical dimension of the economy, there is the need to expand the analysis to other components of the economy like the social and cultural dimensions (e.g., governance, consumer habits, and preferences). These play a key role in shaping the resource-use dynamics and in the adoption of strategies that could minimize socio-metabolic risks. These improvements would allow for a more holistic understanding of not only metabolic scales, rates of circularity, and end-uses of materials in the system, but also of the cultural and institutional drivers and barriers influencing over the resource-use dynamics. Future work should include robust strategies that analyze, identify, and quantify the social, economic, and environmental trade-offs and synergies of reconfiguring resource-use patterns. This would consequently lay the foundation for a better understanding and prioritization of potential socio-metabolic risks and cascading effects to build resource security and system resilience.

SIDS must continue exploring and developing an enabling environment to progress toward greater resource security and resilience. For The Bahamas, an untapped potential exists in the ocean that is "at hand's reach" (CARICOM, 2017; CCREEE, 2019; Failler, 2020; IRENA, 2016). Currently, efforts dedicated to truly broadening these possibilities have focused on outlining and pursuing a development pathway aligned with the blue economy, which is inclusive of the assets, goods, and services that the ocean may offer, and embedded with the concepts of the circular economy (Bahamas Development Bank, 2018; Government of The Bahamas, 2016; IDB Group, 2021). However, these efforts have just recently been implemented. Moreover, climate change impacts the already insufficient ocean infrastructure (Government of The Bahamas, 2021; Kemp, 2019), while challenges such as governance and monitoring deficiencies still remain (Bethel et al., 2021; IDB, 2022; Sustainable Islands Platform, 2019). Notwithstanding, designing a strategy through a blue economy vision could thereby assist in minimizing or reducing socio-metabolic risks and building resilience by employing reconfigured resource-use patterns.

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CONFLICT OF INTEREST

The authors declare no conflict of interest.

DATA AVAILABILITY STATEMENT

Most of the data supporting the findings of this study are openly available in Comtrade database at https://comtrade.un.org/data, and in the FAO-STAT database at https://www.fao.org/faostat/en/#data/. All other data supporting the findings of this study are available within the article and its Supporting Information files or are available from the corresponding author upon request.

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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

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