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The resource (in)sufficiency of the Caribbean: analyzing socio-metabolic risks (SMR) of water, energy, and food

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Introduction: Socio-metabolic risks (SMRs) are systemic risks associated with the availability of critical resources, the integrity of material circulation, and the distribution of their costs and benefits in a socio-ecological system. For resource-stressed systems like small island nations, understanding trade-offs and synergies between critical resources is not only crucial, but urgent. Climate change is already putting small islands at high risk through more frequent and intense extreme weather events, changing precipitation patterns, and threats of inundation with future sea-level rise.

Methods: This study compares the shifting resource-baseline for 14 Caribbean island nations for the year 2000 and 2017. We analyze water, energy, and food (WEF) and their nexus through the lens of SMRs, using indicators related to their availability, access, consumption, and self-sufficiency.

Results: Our findings point to the decreasing availability of all three resources within the Caribbean region. Meanwhile, between 2000 and 2017, consumption levels have increased by 20% with respect to water (from 230 to 275 m^3/cap/yr) and primary energy (from 89 to 110 GJ/cap/yr), and 5% for food (from 2,570 to 2,700 kcal/cap/day). While universal access to these resources increased in the population, food and energy self-sufficiency of the region has declined.

Discussion: Current patterns of resource-use, combined with maladaptive practices, and climate insensitive development—such as coastal squeeze, centralized energy systems, and trade policies—magnify islands' vulnerability. Disturbances, such as climate-induced extreme events, environmental changes, financial crises, or overexploitation of local resources, could lead to cascading dysfunction and eventual breakdown of the biophysical basis of island systems. This research is a first attempt at operationalizing the concept of SMRs, and offers a deeper understanding of risk-related resource dynamics on small islands, and highlights the urgency for policy response.

KEYWORDS

socio-metabolic risks, WEF-nexus, climate change adaptation, resource security, Caribbean SIDS

1. Introduction

The concept of risk is defined as the possibility or chance of potential consequences and the severity of these arising from some action or event (e.g., human-induced, natural event, or a combination of both) (Renn et al., 2011; IPCC, 2012). Individual risks describe how an event perturbs a single component in a system, while systemic risks capture the potential to inflict immediate and long-term changes on the system—including the potential cascade effect to other systems on which our society depends, especially for those living in vulnerable conditions (OECD, 2003; Sillmann et al., 2022). Socio-metabolic risks (SMRs) could then be described as a subset of systemic risks associated with the availability of critical resources, the integrity of material circulation, and the distribution of their costs and benefits in a socio-ecological system (Singh et al., 2022). In the context of this study, the term has a negative connotation as it emphasizes the potential negative consequences of unsustainable resource dynamics.

The impact on vital resource systems can jeopardize the quantity, quality, and accessibility of natural resources, as well as the sectors reliant on them. In some instances where high SMRs exist, the system's ability to organize its own social metabolism is severely compromised, thus potentially leading to the system's socio-metabolic collapse (Singh et al., 2020, 2022). A socio-metabolic collapse is usually characterized by crossing a threshold or tipping point, defined as a point at which the number of small changes or incidents (on the social metabolism's organization) over a period of time reaches a level where a further small change has a sudden and very great effect on a system (Oxford University Press, 2022) that is oftentimes irreversible. Reaching this threshold or tipping point can be due to biophysical (e.g., overexploitation of natural resources), social phenomena (e.g., resource-insensitive models of development), or a combination of both (Petridis and Fischer-Kowalski, 2016).

The international community is tasked with solving a set of intricate and interdependent issues directly linked to the management of critical resources such as water, energy, and food (UN General Assembly, 2015; De Amorim et al., 2018). Climate variability, and complex social, economic and structural changes (e.g., population growth, rapid urbanization, resource scarcity and increase in consumption, among others) are putting increasing pressure on these resources (UNIDO, 2010; Endo et al., 2015; Spiegelberg et al., 2017; IRP, 2021), which can impact on overall global resource security, resilience and the exposure to risk.

The water-energy-food (WEF) nexus seeks to understand the (inter)dependency, synergies, conflicts and trade-offs between water, energy, and food and the way these resources are shaped by our global resource system (FAO, 2014; De Laurentiis et al., 2016; Simpson and Jewitt, 2019; Future Earth, 2022). Moreover, the nexus explores the extent to which the water, energy and food objectives from the UN Sustainable Development Goals (SDGs) 2, 6, and 7 can be simultaneously achieved (Ferroukhi et al., 2015; Mohtar, 2016). Given the intricate WEF interactions, many complex issues have confronted communities at all scales with an increasing number of challenges that affect progress toward the SDGs and that directly impact on resource security and resilience, especially for Small Island Developing States (SIDS).

SIDS are often characterized by their narrow resource base, small size, remoteness, high dependence on imports, and their vulnerability to extreme weather events and external shocks, among others (Deschenes and Chertow, 2004; UNCTAD, 2021). Impacts from climate change are already being experienced by most SIDS, hampering the efforts to transition into a more sustainable future (Thomas et al., 2020; IMF, 2021; Sachs et al., 2021). SIDS are at a very high risk of anthropogenic groundwater pollution (UNESCO-IHP and UNEP, 2017; UN, 2022), and most are already experiencing freshwater stress due to increasing demand and decreasing supply (IPCC, 2018; Gheuens et al., 2019). Average energy rates are higher than in other regions (IRENA, 2019) and they depend on imported fossil fuels for up to 90% of their energy needs (UNEP, 2014). Similarly, SIDS are primarily net food-importing countries with low domestic food production, which makes them highly vulnerable to price fluctuations and availability, thus impacting on food security (UN-OHRLLS, 2013; Dorodnykh, 2017; FAO, 2019, 2020b, 2021b).

The decoupling of island economies from their natural environment is characteristic of SIDS, and their reconnection is a precondition for island sustainable development (Chertow et al., 2013). For SIDS, a combination of distinct resource-use patterns, demographics, maladaptive and climate-insensitive models of development, and the adverse effects of climate change have led to compounding shocks and weak coping and adaptive capacities to face systemic risks, which often amplify pre-existing system's vulnerability levels and sustainability challenges, and reduces its resilience to shocks and changes (Singh et al., 2020, 2022; Thomas et al., 2020; IMF, 2021; Sachs et al., 2021). These dynamics should also be understood through the amplification of risks due to the compounding effects of multiple hazards happening simultaneously or sequentially that trigger cascade effects and affect other components of the system, which puts development needs in jeopardy (Klose et al., 2021; Franzke et al., 2022). Natural hazards like flooding can compromise access to clean freshwater resources, leading to disruptions in agriculture and food production; hurricanes can damage to energy infrastructure, leading to fuel shortages and impacting on the ability to power essential services like hospitals and emergency response systems; a drought followed by a heatwave could cause crops to wither and die, leading to food shortages and price spikes that increase food insecurity, affecting the ability of people to access essential nutrients (Zhang et al., 2018; OECD, 2021; Rentschler et al., 2022). Thus, water, energy, and food can be regarded as interdependent and essential resources in need of a sustainable management approach that maximizes resource-security, improves the linkages within the nexus, and reduces inherent systemic risks.

This study compares the shifting resource-baseline for 14 Caribbean SIDS during the years 2000 and 2017. It analyzes three critical resources: water, energy, and food (WEF) and their nexus, focusing on the dimensions of availability, access, consumption, and self-sufficiency. We discuss these findings through the lens of SMRs. We adopt a combined quantitative and qualitative approach to (a) analyze the WEF-nexus in the Caribbean region with regards to the four dimensions, and to (b) identify and interpret potential socio-metabolic risks associated with WEF-nexus dynamics. Our study is motivated by the question: Do the trends on these critical resources constitute potential socio-metabolic risks in Caribbean SIDS? This original research offers the first attempt at operationalizing the concept of SMRs. It further expands the WEF-nexus literature and aims at providing baseline data for policy and other stakeholders to better understand the resource dynamics, resource availability and security, as well as identify potential barriers and openings for positive transformative change in Caribbean SIDS.

The remainder of this article is organized as follows. Section 2 provides a brief review of the origins, evolution, and state-of-the-art research on the WEF-nexus. Section 3 outlines the methods, data sources and indicators utilized for analyzing the WEF. In Section 4, we present our results in the form of spider-grams for each resource across the four dimensions, followed by a discussion on socio-metabolic risks in Section 5. The final section offers a meta-reflection on the key findings of this study.

2. Brief overview of the emergence and current state of the water-energy-food nexus

There is no clear consensus on the precise origins of the WEF-nexus concept. Some scholars may argue that it first appeared on *The Limits to Growth* report, stating the "varied but interdependent components-economic, political, natural, and social-that make up the global system in which we all live" (Meadows et al., 1972, p. 9). Similarly, *The Report of the World Commission on Environment and Development* of 1987 stated that sustainable development and natural resources "are connected and cannot be treated in isolation one from another" (Brundtland, 1987, p. 18), suggesting the need of "nexus thinking". Newell et al. (2019) presented a 40-year literature review of WEF-nexus where they highlight academic publications on the (partial) nexus approach from as early as in 1988. A review by Endo et al. (2017) reveals that a large number of nexus-related conferences, initiatives and projects have been held since the early 80's. More prominently, the WEF-nexus concept has gained momentum both in policy and academia in the past decade. Several authors (Biggs et al., 2015; Endo et al., 2017; Albrecht et al., 2018; Simpson and Jewitt, 2019) agree that one of the key events that marked in earnest the recognition of the WEF-nexus was the Bonn 2011 Nexus Conference *The Water Energy and Food Security Nexus–Solutions for the Green Economy* (Hoff, 2011). In addition, the 2011 report of the World Economic Forum titled *Water Security–The Water-Food-Energy Climate Nexus* was pivotal in bringing the concept under the global spotlight (The World Economic Forum, 2011). Subsequently, the number of academic publications on the WEF-nexus more than doubled between 2011 and 2016 (Newell et al., 2019).

According to Pahl-Wostl (2017), the focus of WEF-nexus publications in the first 4 years immediately after the Bonn 2011 conference was closely related to resource *security*, and widely promoted in policy and development circles (Simpson and Jewitt, 2019). In addition, several clusters of research have been identified by Endo et al. (2017) and Newell et al. (2019). According to their classification, these clusters range from partial nexuses such as energy-food, energy-biofuels, water-food, and water-energy to a more integrated WEF nexus-based approach, with some clusters exploring even newer concepts such as the urban WEF-nexus or climate-related nexuses. The WEF-nexus concept has also broadened its scope to emphasize the interconnectedness and interdependencies of other resources with the goal to achieve sustainable management of natural resources more generally. The nexus approach has also lent its power to advance conceptual frameworks aimed at understanding problem framing or for promoting cross-sectoral collaboration (Bazilian et al., 2011; Keskinen et al., 2016; De Amorim et al., 2018). Increasingly, the WEF-nexus concept has been mainstreamed in development practice and policy, and also being used at the project planning level with uptake by public and private sectors (FAO, 2018).

The analysis of the WEF-nexus has also covered an umbrella of different tools, scales and approaches to evaluate the nexus (Albrecht et al., 2018). Tools include Integrated Assessment Models (Howells et al., 2013), Material Flow Analysis (Walker et al., 2014), Life Cycle Analysis (Mohtar and Daher, 2014), or Sankey Diagrams (Mukuve and Fenner, 2015), among others. Spatial and temporal scales include Asia-Pacific region (Asian Development Bank, 2013; UN-ESCAP, 2013; Taniguchi et al., 2017), Europe (Adamovic et al., 2019), and Latin America and the Caribbean (LAC) (Mahlknecht et al., 2020), while others have investigated more specific case-studies on the water-energy-food accounting, such as in Egypt (El-gafy, 2017), and Southern Africa (Nhamo et al., 2018). Other groups of scholars have analyzed a partial nexus, or a nexus coupled with emphasis on other aspects such as with ecosystems, land, or climate change (Hoff et al., 2013; Ferroukhi et al., 2015; UNECE, 2015). Yet, only a few studies have adopted the nexus approach to address resource challenges in the island context (see Table 1).

With respect to the Caribbean, Mahlknecht et al. (2020) performed one of the first WEF-nexus studies, examining the baseline and trends of these essential resources. However, this study was done in combination with Latin America which restricts a fuller understanding of WEF dynamics specifically for Caribbean SIDS. The most complete study to date on the WEF-nexus for Caribbean SIDS was performed by Winters et al. (2022), in which an evaluation of sustainability under current conditions was performed. However, the approach used in their study provided only a partial view of the WEF-nexus and prevented a more thorough understanding of the resource-use dynamics, particularly the associated risks from such trends.

To effectively address the complexity of the WEF-nexus, it is essential to develop a nexus methodology that can systematically highlight the trade-offs and synergies between water, energy, and food resources in a socio-ecological system. The implementation of such approach would benefit from a combination of qualitative and quantitative methods and tools from natural and social sciences. Our study stands out for its attempt to fill both the methodological and data gaps in the current understanding of the WEF-nexus in Caribbean SIDS. Additionally, our proposed approach is the first attempt at operationalizing the concept of socio-metabolic risks, making it a unique contribution to the field. By including social and natural science methods and tools with a socio-metabolic risk perspective, the approach provides a more holistic understanding of the interdependent resource-use dynamics and the associated risks, ultimately contributing to the sustainable management of these essential resources in the Caribbean region and benefiting policymakers and researchers.

3. Methods

Fourteen Caribbean SIDS formed the basis of our analysis. The island territories analyzed together represent more than 90% of the Caribbean's total population as well as land area, a diversity of landscapes, climatic conditions, island sizes, governance structures, and levels of economic and human development (see Table 2).

TABLE 1 Overview of water-energy-food nexus studies on island territories across the world.

Island territory	Scope of the nexus	Source
Orkney Island (Scotland)	**Water-energy:** Potential for energy generation from tidal power	UN Sustainable Water and Energy Solutions Network (2020)
Mauritius	**Water-energy:** Potential of water desalination through solar energy	UN Sustainable Water and Energy Solutions Network (2020)
Canary Islands	**Water-energy:** Potential of water desalination through solar energy	UN Sustainable Water and Energy Solutions Network (2020)
Mauritius	**Water-energy-food:** Potential of biofuel generation from sugarcane	Giampietro et al. (2013)
14 Pacific Island Countries	**Energy-food:** Connections between bioenergy and food security	Chapman (2009)
Crete, Greece	**Energy-food:** Connections between agriculture and renewable energies	Vourdoubas (2020)
Small Island Developing States	**Water-food:** Freshwater for food and nutrition security	FAO and Vrije Universiteit Amsterdam (2020)
St. Eustatius	**Water-energy-food:** Analysis of resource shortages caused by extreme weather events	Daw and Stout (2019)
Bonaire	**Water-energy-food:** Introductory factsheet of potential nexus interventions	van der Geest and Slijkerman (2019)
Trinidad & Tobago, Dominican Republic, Jamaica, Haiti, Cuba	**Water-Energy-Food:** Planetary boundaries (including indicators for WEF) within the "safe and just space" framework	Jia (2019)
LAC	**Water-energy-food:** Challenges and opportunities for resource security	Bellfield (2015)
LAC	**Water-energy-food:** Role of green infrastructure in achieving WEF security in the region	IDB (2019)
The Bahamas	**Water-energy-food:** Options for resource security	Beatty (2015)
LAC	**Water-energy-food:** Baseline and trends of these essential resources in the region	Mahlknecht et al. (2020)
10 Caribbean SIDS	**Water-energy-food:** Evaluation of WEF sustainability under current conditions	Winters et al. (2022)

LAC stands for Latin America and the Caribbean.

TABLE 2 Comparative table among countries, showing different biophysical and socioeconomic attributes.

Countries	Population 2017	Land area km^2	GDP Per capita 2017	HDI 2018	Ease of doing business index 2019
1. Antigua and Barbuda	95,400	440	15,820	0.776	113
2. Aruba	105,400	180	25,630	0.908	N/A
3. Barbados	286,200	430	16,300	0.814	128
4. Cuba	11,340,000	103,800	8,540	0.778	N/A
5. Dominica	71,500	750	6,950	0.724	111
6. Dominican Republic	10.510,000	48,300	7,200	0.745	115
7. Grenada	110,900	340	10,200	0.763	146
8. Haiti	10,980,000	27,600	770	0.510	179
9. Jamaica	2,921,000	10,800	5,100	0.726	71
10. St.Kitts and Nevis	52,000	260	19,100	0.777	139
11. St. Lucia	181,000	610	9,600	0.745	93
12. St. Vincent and the Grenadines	110,000	390	7,150	0.738	130
13. The Bahamas	382,000	10,100	31,900	0.805	119
14. Trinidad & Tobago	1,384,000	5,100	16,000	0.799	105

Sources: The World Bank (2022d,g,i), Villeret (2022), and Worldometer (2022). HDI stands for Human Development Index. Ease of doing business was based on a rank among 190 countries.

Please note that the Supporting Material provides underlying data in tabular form utilized to elaborate Figures 2–4 of this study.

To evaluate the WEF nexus and operationalize the concept of SMRs for the 14 Caribbean SIDS, the study adopts a combined quantitative and qualitative approach. For the quantitative part, key attributes for water, energy, and food are measured in two points in time, the years 2000 and 2017. We proposed four resource dimensions, namely: a) **availability**, b) **access**, c) **consumption,** and d) **self-sufficiency,** which were evaluated and compared with respect to each of the resources. These dimensions are mostly based on the SDGs 2–Zero Hunger, SDG 6–Clean Water and Sanitation, and SDG 7–Affordable and Clean Energy.

- *Availability* is the estimated amount of "exploitable" resources per capita that is potentially available to the population of a country in a given year and that is based on the island's domestic resource-base.
- *Access* is the percentage of the population in a country that can utilize the benefits of a particular resource for their basic needs.
- *Consumption* is the estimated amount of resources consumed per capita each year, and is a measure of affluence.
- *Self-sufficiency* measures the capacity of a country to meet their resource needs through locally available resources.

These four dimensions attempt to encompass most of the characteristics of the dynamics of resource-use in the island context. Availability highlights the abundance or lack thereof of a particular resource. Access and Self-sufficiency build on the physical, social, economic, and political circumstances of the system, and reveals deficiencies and strengths in the supply chain. Consumption describes knowledge and habits of the quality and quantity of the resource consumed: assuming that sufficient resources are available and accessible, the population decides the type of resource to acquire and consume.

The qualitative part of this analysis is performed through an assessment of the quantitative part of the WEF dimensions in which we interpret the associated potential SMRs as well as opportunities to develop and implement risk mitigation and adaptation strategies in the system. Instead of focusing on definitive thresholds, a directionality approach is used to identify whether the system is at an increasing risk of being locked into a pattern of resource use that could potentially lead to collapse. This was done in such a way due to not existing an established definitive index, scale, or threshold specifically for evaluating SMRs. Additionally, when internal and external pressures are included such as governance or climate change, we could further identify those elements that exacerbate or alleviate SMRs. Figure 1 shows a conceptual figure utilized to operationalize the concept of SMRs.

Results are visualized using spider-grams, a technique that enables the identification of the different variations in performance of all resources involved with respect to a specific dimension. To aid comparison, the performance on resource **access** and **self-sufficiency** was measured both in percentages (from 0 to 100%). For resource **availability** and **consumption,** the performance was visualized through a single range scale going from zero to the maximum estimated value between the 2 years analyzed**.** Average numbers for the 14 case studies analyzed are also included in the spider-grams for each dimension. Table 3 below provides further details on data sources, description of dimensions, and calculations for the analysis.

3.1. Features considered for the WEF-nexus and the operationalization of socio-metabolic risks

This study relied primarily on international data sources like FAO AQUASTAT database for water, FAO Food Balance Sheets database for food, and a variety of international platforms and institutions that compile information on the energy sector such as the U.S. Energy Information Administration, IRENA, NREL, and others. Due to limitations in data availability and the methodological approach applied in this study, the analysis focused on the years 2000 and 2017. Historical baseline data was not fully available at the required level of detail to analyze all four proposed dimensions for water, energy, and food and thus prohibited a more in-depth time-series assessment. To complement our results, we reviewed baseline data for other time points and identified general trends using international data sources and national statistics where possible. These data sources have been compiled and processed from sources believed to be reliable, however it is advised that our results should be considered with a degree of caution due to inconsistencies in definitions, data collection methodologies, and completeness.

3.1.1. Water

For water availability, we accounted for all available internal renewable water resources (surface water and ground water). We did not consider water that was desalinized for utilization of the island, as this is drawn from outside the island's boundary (therefore an "import") and is not regulated by the island's internal hydrology. For water access, "basic sanitation" refers to facilities that are not shared with other households and include flush/pour flush toilets connected to piped sewer systems, septic tanks or pit latrines, or pit latrines with slabs (including ventilated pit latrines), or composting toilets (The World Bank, 2022f). "Basic drinking water" refers to "water coming from an improved source, provided collection time is not more than 30 min for a round trip. Improved water sources include piped water, boreholes or tube-wells, protected dug wells, protected springs, and packaged or delivered water" (The World Bank, 2022f).

3.1.2. Energy

For energy availability, we accounted for fossil fuel reserves (oil and natural gas), and potentials of renewable energy. Energy sources for total primary energy consumption include coal, natural gas, petroleum and other liquids, and nuclear. Renewable energy potentials include wind, solar, hydro, biomass, and geothermal energy. Energy access refers to the percentage of population in each country that have relatively simple, stable access to electricity and related services. It can also

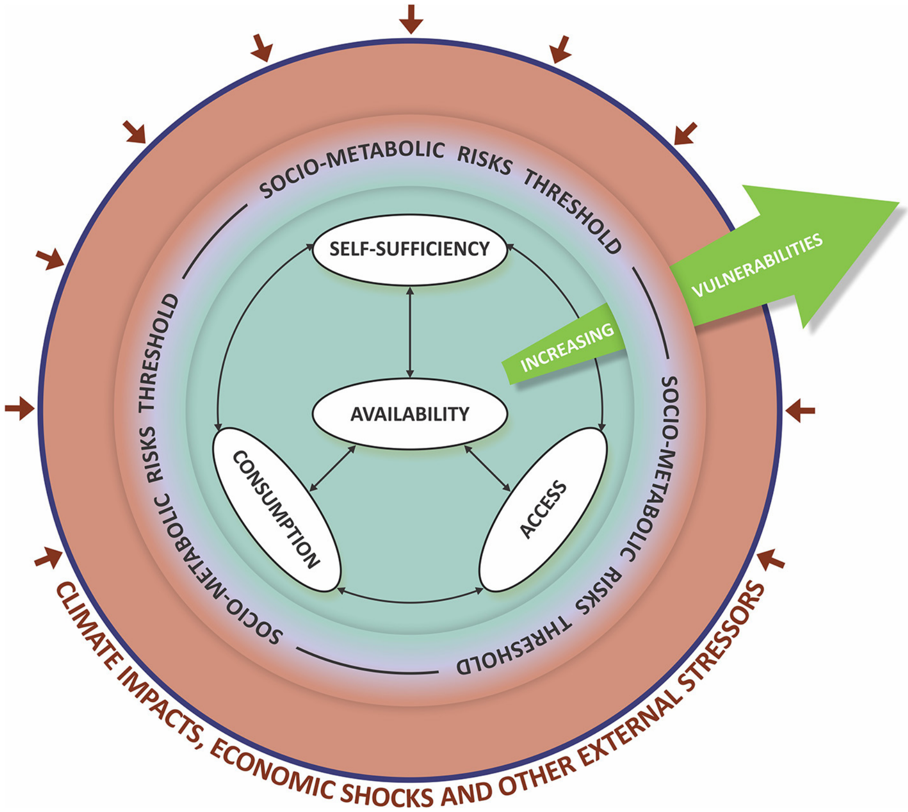

FIGURE 1
Conceptual figure utilized to operationalize the concept of socio-metabolic risks. Certain combination of resource-use dynamics could entail socio-metabolic risks, which could lead to weak coping and adaptive capacities to face systemic risks. At the same time, a better understanding of these resource-use dynamics and socio-metabolic risks could enhance resource performance across all the dimensions through identifying potential barriers and openings for positive transformative change.

be seen as the "electrification rate". Energy self-sufficiency accounts only for locally extracted primary energy resources (fossil, biomass), as well as for installed capacity of renewable energy generation.

3.1.3. Food

Food availability accounts for all food (inclusive of primary crop harvest, marine catch, main livestock products and processed foodstuff) reaching the consumer at households and outside home (e.g., restaurants, etc.) for residents only. Residents include refugees and long-term guest workers and exclude tourists or temporary visitors. This dimension corresponds to the "Food Supply Quantity" indicator from FAO–Food Balance Sheets and is essentially the food available for consumption measured in kg/cap/yr. The "Prevalence of undernourishment" was utilized to account for Food Access. It expresses the probability that an individual consumes an insufficient amount of daily calories for an active and healthy life and it is an indicator of lack of food access. Food consumption refers to the estimated energy content from foodstuffs available for consumption, measured in caloric value (kcal/cap/day). This indicator can be useful to determine if the food availability is of sufficient energy content to meet the resident's needs. Food self-sufficiency accounts for the country's capacity to meet its own food needs from domestic food production.

4. Results

On average, the availability of locally exploitable resources for the case studies analyzed showed a decreasing trend between 2000 and 2017. Simultaneously, there is not only an increase in the universal access of WEF by island citizens but growing affluence and industrial development has also led to higher levels of resource consumption and lower self-sufficiency, especially for energy (at 14%) and food (at 70%). Water consumption and primary energy consumption both increased 20%, while food consumption slightly increased 5%.

4.1. Water performance

Between 2000 and 2017, the Caribbean SIDS did not show a significant change in the available (or potentially exploitable) water resources per capita as it went from 1,900 m^3/cap/yr to 1,700 m^3/cap/yr. Water access showed small improvements in the region, going from 83 to 89%. Water consumption per capita slightly increased from 230 m^3/cap/yr to 275 m^3/cap/yr. There

TABLE 3 Description, calculations, and sources of the different dimensions utilized to analyze the water, energy, and food.

	Dimensions	Description	Calculations	Sources
Water	**Availability** [m^3/cap/yr]	Amount of "exploitable" water per capita that is potentially available to the population	(Total Renewable Surface Water plus Total Renewable Ground Water) divided by population	FAO, 2022b; The World Bank, 2022j
	Access [%]	Average percentage of the population having basic drinking water and sanitation services	Directly obtained from source	FAO, 2022c
	Consumption [m^3/cap/yr]	Amount of consumed water per capita per year	(Fresh water withdrawals plus desalinized water) divided by population	FAO, 2022c
	Self-sufficiency [%]	Share percentage of total water consumed that is domestically harvested, or from within the national boundary	100% minus Water Dependency Ratio measured in percentage	FAO, 2022c
Energy	**Availability** [GJ/cap/yr]	Amount of primary energy per capita that is potentially available to the population	(Non-renewable energy plus renewable energy) divided by population	IRENA, 2012; Herbert, 2013; NREL, 2015j; Ochs et al., 2015; CARICOM, 2018b; EIA, 2022a; Energypedia, 2022
	Access [%]	Percentage of population in each country that have relatively simple, stable access to electricity	Directly obtained from source	The World Bank, 2022b
	Consumption [GJ/cap/yr]	Amount of consumed energy per capita per year	Total primary energy consumption divided by population	EIA, 2022a
	Self-sufficiency [%]	Share of total energy consumption satisfied from locally extracted primary energy resources	Directly obtained from source	EIA, 2022a
Food	**Availability** [kg/cap/yr]	Amount of available food per capita	Directly obtained from source	FAO, 2021a
	Access [%]	Proportion of the population at or above the minimum level of dietary energy consumption based on the 3-year average prevalence of undernourishment.	100% minus prevalence of undernourishment measured	FAO et al., 2015; FAO, 2022b
	Consumption [kcal/cap/day]	Refers to the quantities of food available for human consumption at the retail level by the country's resident population (apparent consumption)	Directly obtained from source	FAO, 2021a
	Self-sufficiency [%]	Share of food coming exclusively from local production	Total food availability divided by total locally produced food	FAO, 2021a

was no change in the region's water self-sufficiency levels, staying close to 90%. The results of our methodology are comparable with the results of the WEF study in Caribbean SIDS presented by Winters et al. (2022) for water availability, access, and consumption. Nonetheless, slight variations remain due to completeness of the data, indicator definitions, and differences in data compilation methodologies. Figure 2 shows the water spider-grams of the 14 Caribbean SIDS across all four dimensions during the years 2000 and 2017.

For availability, Antigua & Barbuda, Barbados, and St. Kitts and Nevis show values of <700 m^3/cap/yr for both 2000 and 2017, with Aruba having values close to 0 m^3. In comparison, other countries show more than four times this water availability. Jamaica in 2000 exhibits water resources of around 4,000 m^3/cap/yr, followed closely by Cuba and Trinidad & Tobago, with values of around 3,400 and 3,000 m^3/cap/yr respectively. In 2017, Jamaica and Trinidad & Tobago reduced their availability by around 9%, moving to 3,700 m^3/cap/yr and 2,800 m^3/cap/yr respectively.

Water access increased from 83% in 2000, to 89% in 2017. Improvements in water access was seen across all countries. Haiti and Cuba, which have the lowest access scores in the region, increased their water access from 36 to 50% for Haiti, and from 63 to 70% for Cuba.

Water consumption per capita for Caribbean SIDS in the year 2000 was close to 230 m^3/cap/yr, increasing 20% in 2017 to 275 m^3/cap/yr, showing an overall rising trend of total water use. The highest water consumptions per capita for Caribbean SIDS were for Cuba and Dominican Republic, with 470 and 570 m^3/cap/yr respectively in 2000. Consumption increased by 30% for Cuba (to 610 m^3/cap/yr) and by 20% for Dominican Republic (to 680 m^3/cap/yr) in 2017. St. Vincent and the Grenadines, and The Bahamas present the lowest values for both periods, with 93 and 94 m^3/cap/yr respectively for the year 2000, and 77 and 92 m^3/cap/yr respectively for the year 2017.

On average, we found no change in the region's water self-sufficiency. Most countries are 100% water self-sufficient, except for Haiti, which has around 90% water self-sufficiency, and Aruba with values close to 0%. Aruba lacks enough surface water and ground water to satisfy their needs. This country partially overcomes that challenge through desalination of sea water.

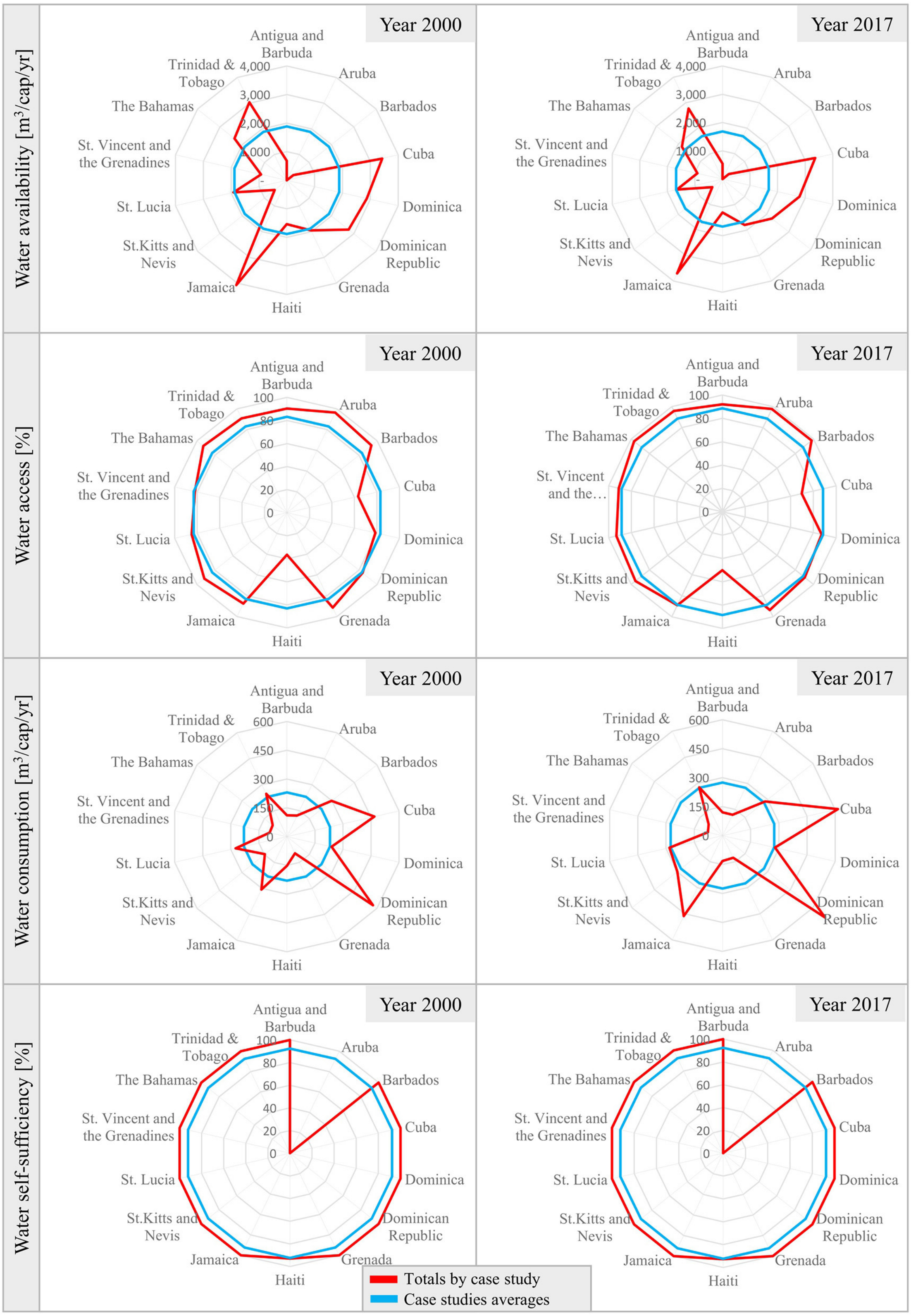

FIGURE 2
Caribbean SIDS water spider-gram for the years 2000 and 2017.

4.2. Energy performance

Between 2000 and 2017, Caribbean SIDS remained constant in the average availability of energy resources (210 GJ/cap/yr in 2000 and 160 GJ/cap/yr in 2017), however there are great disparities between countries as changes mainly depend on fossil fuel reserves. Significant improvements in energy access in the region took place, advancing from 85 to 96%. Average energy consumption per capita increased from 89 GJ/cap/yr to 110 GJ/cap/yr. Overall, energy self-sufficiency in the region remains low at only 14%. Our results are in a similar range when cross-checked with independent studies that include an analysis on energy access and energy self-sufficiency in Caribbean SIDS (Surroop et al., 2018; OECD et al., 2021). Figure 3 shows the energy spider-grams of the 14 Caribbean SIDS across all four dimensions during the years 2000 and 2017.

Throughout the region, we found huge disparities among individual countries in terms of energy availability. The only 3 countries in this study with proven fossil fuel reserves are Trinidad & Tobago, Barbados, and Cuba (EIA, 2022b). In 2017, the countries that continue having fossil fuel reserves are Trinidad & Tobago and Cuba, however the reserves from Barbados significantly diminished (EIA, 2022d). The country with the highest renewable energy potential is St. Kitts and Nevis, followed by St. Vincent and the Grenadines, Dominica, and Antigua & Barbuda. This renewable potential comes mainly from geothermal energy (for St. Kitts and Nevis, Dominica, and St. Vincent and the Grenadines), and Wind (for Antigua & Barbuda) (IRENA, 2012; Herbert, 2013; NREL, 2015b,c,d,e,f,g,h, 2020; Ochs et al., 2015; CARICOM, 2018a).

Trinidad & Tobago's available energy per capita (mainly from fossil fuels) is the highest from Caribbean SIDS for both years, with a value of around 34,000 GJ/cap/yr in 2000 and around 13,000 GJ/cap/yr in 2017. The country with the second highest availability is St. Kitts and Nevis with 960 GJ/cap/yr and 810 GJ/cap/yr for 2000 and 2017 respectively. Cuba ranks third with 560 GJ/cap/yr in 2000, and 320 GJ/cap/yr in 2017.

Without accounting for Trinidad & Tobago, the average value of energy availability per capita in the year 2000 was 210 GJ/cap/yr, while in the year 2017 was of 160 GJ/cap/yr. The lowest values of exploitable energy are for Dominican Republic and Haiti with less than 5 GJ/cap/yr for both years. In 2000 and 2017, the exploitable energy potential for 6 out of 14 countries was below 50 GJ/cap/yr. Barbados dropped 70% from 280 GJ/cap/yr to around 80 GJ/cap/yr. The remaining countries were over 130 GJ/cap/yr in both years.

Energy access for the year 2000 was 85% on average, and increasing to 96% in 2017. Antigua & Barbuda, Barbados and The Bahamas showed 100% energy access for both years, while countries such as St. Vincent and the Grenadines, Trinidad & Tobago, and Dominica show a 26, 20, and 19% increase in energy access respectively between the years 2000 and 2017. In the year 2017, Aruba, Cuba, Dominica, Dominican Republic, Jamaica, St. Kitts and Nevis, St. Vincent and the Grenadines, and Trinidad & Tobago reached 100% energy access. Haiti's score was the lowest for both years, with 34 and 44% for the years 2000 and 2017 respectively, with huge variation in access between rural and urban populations.

Among Caribbean SIDS, Trinidad & Tobago has the highest energy consumption per capita for both years, almost doubling from 370 GJ/cap/yr to 690 GJ/cap/yr in 2000 and 2017 respectively, which is more than 4 times the regional average of 89 GJ/cap/yr in 2000 and 110 GJ/cap/yr in 2017. The Bahamas and Aruba ranked second (200 GJ/cap/yr) and third (180 GJ/cap/yr) in 2000. The rest of the countries were below the 100 GJ/cap/yr in both years. Noticeably, Haiti exhibits consumptions of <5 GJ/cap/yr for both years.

On average, we found no change in the region's energy self-sufficiency, remaining low at only 14%. Trinidad & Tobago was the only country with 100% energy self-sufficiency during both years. Cuba ranks second, at 35% in 2000 and increasing to 41% in 2017. The rest of the countries fall below the 20% of energy self-sufficiency for both years. Antigua & Barbuda, Aruba, Grenada, St-Kitts and Nevis, St. Lucia, and The Bahamas had 0% self-sufficiency in 2000, and virtually no progress was made up to 2017. The most effort in self-sufficiency was seen on Aruba, which increased from 0% in 2000 to 8% in 2017.

4.3. Food performance

Average food availability remained constant at around 650 kg/cap/yr, but with high variations between countries. Considerable improvements in sufficient food access were observed, increasing from 81% in 2000 to 88% in 2017. Moderate change in food consumption per capita was observed as consumption changed from 2,570 kcal/cap/day in 2000 to 2,700 kcal/cap/day in 2017. Overall, food self-sufficiency dropped from 78% in 2000 to 67% in 2017. For food availability and self-sufficiency, the results of our methodology during 2000 and 2017 are in line with the results of the study on biomass flows accounting performed by Rahman et al. (2022) when considering primary crop harvest, marine catch, and main livestock products. A study by the Caribbean Public Health Agency (2017) on food consumption (in kcal/cap/day) in the Caribbean also validates our findings. Figure 4 shows the food spider-grams of the 14 Caribbean SIDS across all four dimensions during the years 2000 and 2017. Food statistics for Aruba were unavailable and have been left out of the visualizations. Nonetheless, a report from The World Bank highlights that food self-sufficiency in Aruba is extremely low, whereas food availability and access are high (Boyer et al., 2020).

We could observe slight differences among individual countries in terms of food availability. Dominica showed the highest levels at above 1,000 kg/cap/yr during both years, while Haiti showed the lowest levels at 380 kg/cap/yr and 420 kg/cap/yr for 2000 and 2017 respectively. Dominican Republic had a drastic increase in food availability (close to 60%) going from 500 kg/cap/yr to 790 kg/cap/yr. Contrastingly, The Bahamas dropped significantly (close to 30%), from 900 kg/cap/yr to 640 kg/cap/yr. A decline in food availability of almost 30% was also observed in St. Lucia, going from 720 kg/cap/yr to 560 kg/cap/yr.

Reported sufficient food access of more than 80% was seen in 9 out of 13 countries in 2000, while for 2017 these increased to 12 out of 13 countries (no data was available for Aruba). The countries with the highest access were Barbados, Cuba, and Dominica with values above 94% in both years. The country that showed the

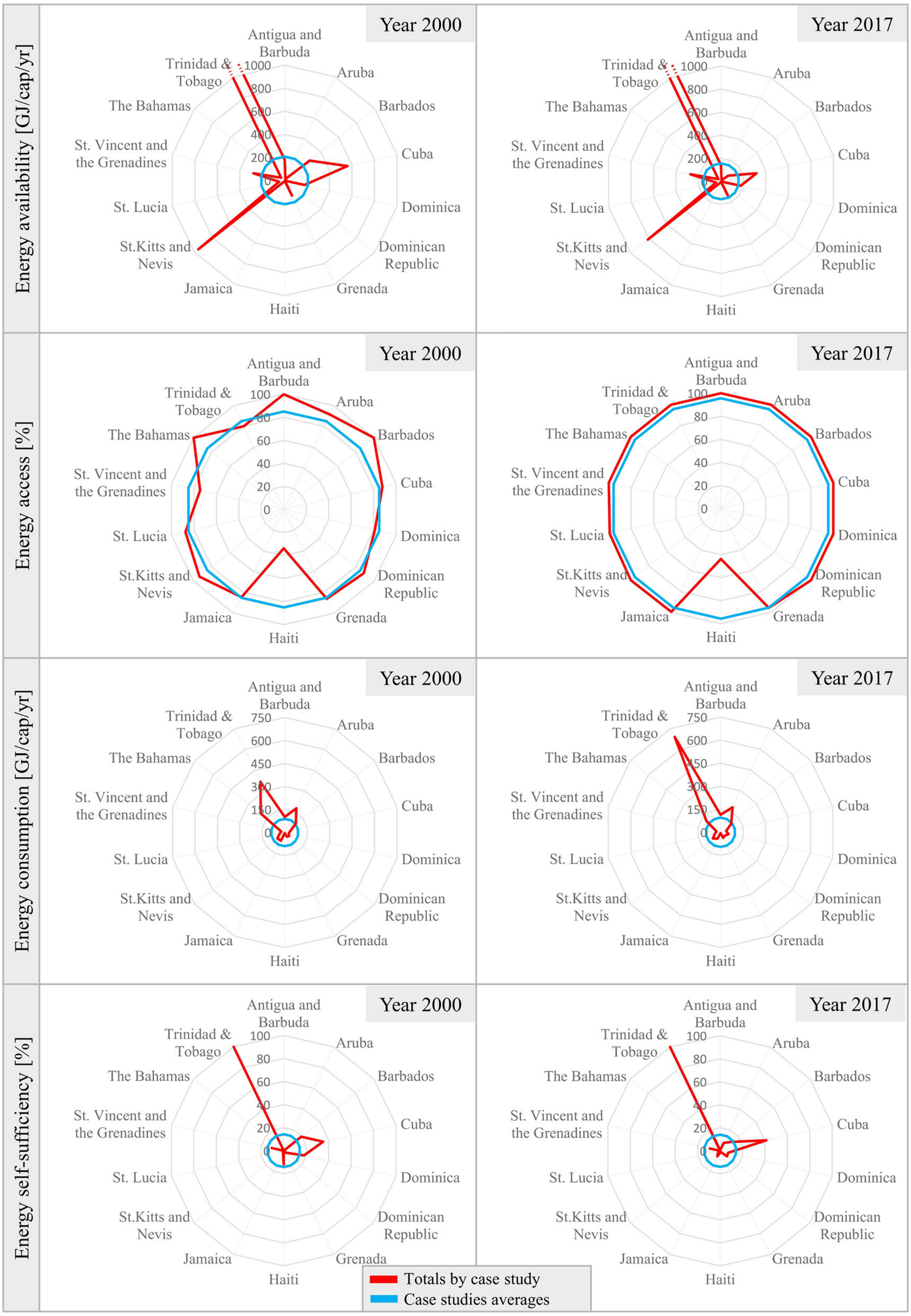

FIGURE 3
Caribbean SIDS energy spider-gram for the years 2000 and 2017. Note that, as Trinidad & Tobago exhibits a contrasting difference as compared to the rest of Caribbean SIDS for energy availability, we set its maximum "boundary" to 1,000 GJ/cap/yr to better visualize the rest of the countries.

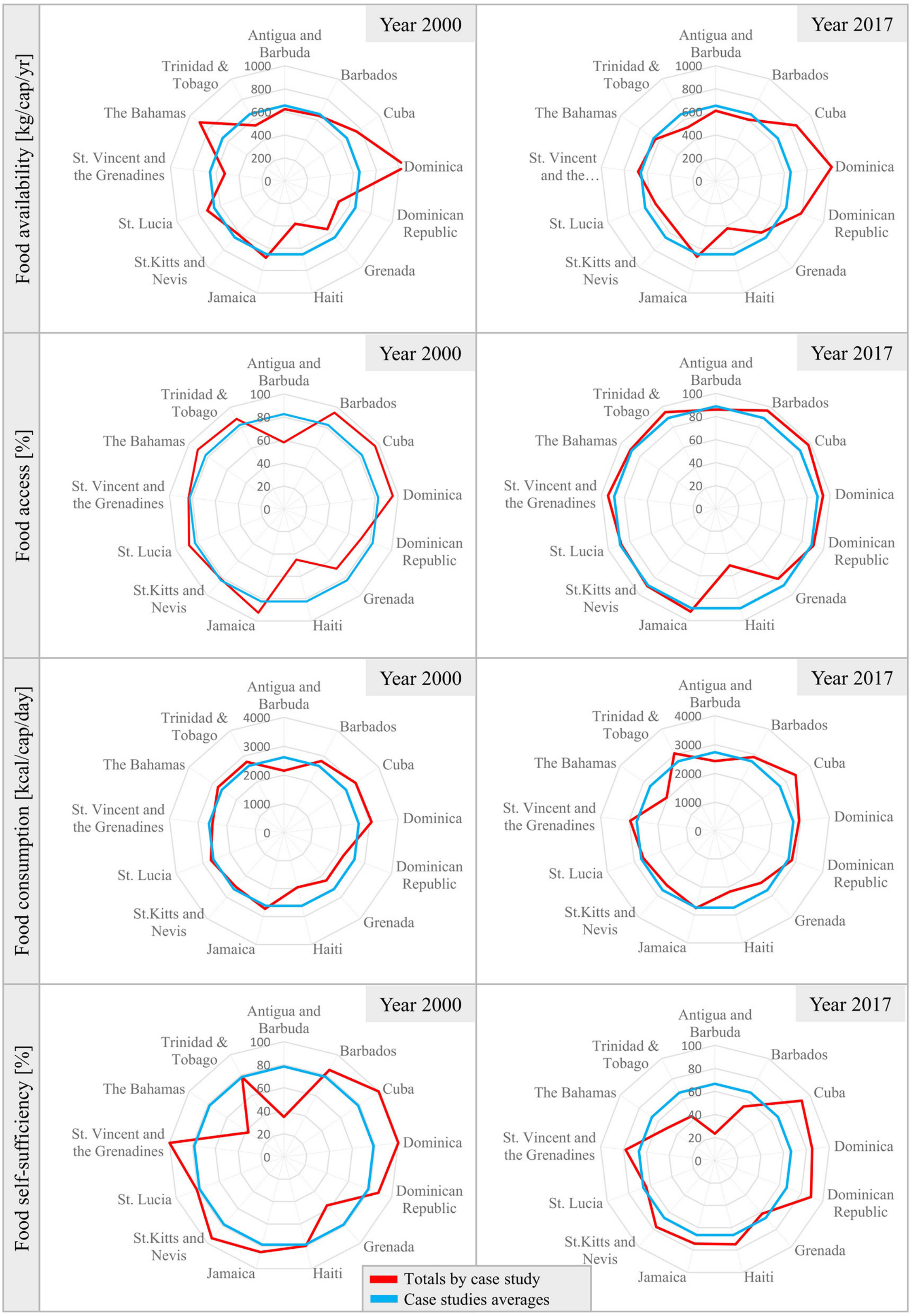

FIGURE 4
Caribbean SIDS food spider-gram for the years 2000 and 2017. Note that food statistics for Aruba were unavailable and as such Aruba was not included in the food analysis.

highest increase in food access was Antigua & Barbuda, with 58% in 2000, and that increased to 86% in 2017. For both years, Haiti had the lowest food access, with 45 and 51% in 2000 and 2017 respectively.

In 2000, the highest food consumption per capita was seen in Cuba and Dominica, both at around 3,000 kcal/cap/day. In the same year, Haiti had the lowest score, with around 2,000 kcal/cap/day that increased 10% to 2,200 kcal/cap/day in 2017. In 2017, Cuba overtook Dominica as the highest food consumer with 3,400 kcal/cap/day, followed closely by Trinidad & Tobago, St. Vincent and the Grenadines, and Dominica at around 3,000 kcal/cap/day. Between 2000 and 2017, nine countries had an increasing trend in their food consumption per capita, with the maximum increase being for Dominican Republic (30% more), from 2,200 to 2,900 kcal/cap/day. On the other hand, The Bahamas showed the highest decline in their consumption per capita in the same period (35% less), going from 2,800 to 2,000 kcal/cap/day.

Food self-sufficiency in the region showed a steep decline between 2000 and 2017, from 78 to 67%, also with significant variations between countries. Cuba and St. Vincent and the Grenadines have the highest self-sufficiency in the region in 2000, at 100%. Countries with the lowest self-sufficiency in 2000 were Antigua & Barbuda and The Bahamas, both at levels below 40%. The rest of the countries are above the 50% self-sufficiency. In 2017, the food self-sufficiency for Antigua & Barbuda declined to 23%, followed by St. Kitts and Nevis at 77%. The rest of the countries were all above 50% food self-sufficiency. The country with the highest increase in self-sufficiency was The Bahamas, going from 37% in 2000 to 50% in 2017. The countries that showed the highest decrease in self-sufficiency were Trinidad & Tobago (from 78 to 44%), Barbados (from 85 to 53%), and St. Vincent and the Grenadines (from 100 to 78%).

5. Discussion

Singh et al. (2022, p. 7) define socio-metabolic risks as the "systemic risk associated with the availability of critical resources, the integrity of material circulation, and the (in)equitable distribution of derived products and societal services in a socio-ecological system". In this sense, specific resource dynamics can entail SMRs and cascade effects, which in turn inhibit progress toward greater resource security, self-reliance, and the system's ability to continue delivering societal services necessary for survival (Singh et al., 2022). In the island context, their distinct characteristics of economic model, small size, remoteness, biogeography, limited resource-bases and more, could present a scenario where socio-metabolic risks can occur. From our analysis, we can observe that Caribbean SIDS exhibit distinct WEF dynamics conductive of varying degrees of SMRs.

In the following sub-sections, we will discuss each resource and potential SMRs at the level of the region. However, we need to consider variations, shifting baselines, and context when it comes to country-level planning. Table 4 offers an overview of the observed SMRs for each resource and across all four dimensions analyzed.

5.1. Water and socio-metabolic risks

Water resources in Caribbean SIDS are limited as these exhibit special vulnerabilities to anthropogenic and natural pressures. From our case studies analyzed, Antigua & Barbuda, Aruba, Barbados, St. Kitts & Nevis, and St. Vincent and the Grenadines are already below the thresholds of *water scarcity* levels of 1,000 m^3/cap/yr established by the UN-Water organization (UN-Water TF-IMR, 2009). In fact, our results show that Aruba, Barbados, and St. Kitts & Nevis are currently experiencing *extreme water scarcity* levels, with <500 m^3/cap/yr available (UN-Water TF-IMR, 2009). The threat of water scarcity is increased in islands such as Grenada, Jamaica, St. Lucia, and Trinidad & Tobago due to various factors such as pollution, saltwater intrusion, and others. This is particularly acute for low-lying islands like Barbados and The Bahamas (UNESCO-IHP and UNEP, 2017). For Caribbean SIDS, the risk of water scarcity and water crisis increases as demand steadily becomes larger than supply (Holding et al., 2016). FAO (2022b), reports a declining trend in renewable water resources per capita since the 1960's, alongside an increasing trend in freshwater withdrawals since the 1990's. The concentration of population and industries in dense urban areas and the growing tourism develops into higher water demand and in changes in surface water and groundwater quality. This increasing risk is partially caused by the conversion of catchment areas for urban development zones or for agriculture, by fresh-saline water interface migration, chemical pollution, and improper sewage disposal, among others. Moreover, during natural hazards, the already limited freshwater resources are often contaminated by seawater, and pollutants intrusion, which in turn further jeopardize water security and health (UNESCO-IHP and UNEP, 2017; UNESCO and UN-Water, 2020; Dubrie et al., 2022). We can already observe evidence of this in Jamaica, Trinidad & Tobago, Antigua & Barbuda, Barbados, and Aruba (Kelman and West, 2009; Cashman, 2014).

The impacts of climate change can have severe consequences in resource security, especially with projections of 2 degrees Celsius warming above preindustrial levels by 2030 (Karnauskas et al., 2018; Drakes et al., 2020). Large variability of rainwater and temperature has been observed in Caribbean SIDS: a rise in temperature exceeding 0.5°C has been registered since 1900 (Ghebreyesus and Espinosa, 2001) and projections in total annual rainfall by 2100 relative to 1961–1990 range from −50 to +30% (Marrero and Mattei, 2007). This situation is conducive of a major shift in frequency and intensity of extreme weather events such as droughts and heat waves which, combined with sea-level rise, will also cause higher incidences of flooding in coastal zones of SIDS, with increased saltwater intrusion into surface and groundwater aquifers (Lincoln, 2017). Being in a situation of water scarcity could then exacerbate inequalities within countries, especially for the poorest populations (e.g., Dominican Republic, Haiti, St. Lucia) (WHO and UNICEF, 2021). Insufficient access to clean water resources increases people's vulnerabilities, which in turn contributes to health problems and lower employment rates, as well as social unrest, and increased household and government expenditures, among others (UN, 2021; ECLAC, 2022).

Droughts caused by declines in precipitation during the wet season are likely to increase in frequency and severity by the

TABLE 4 Overview of some associated WEF socio-metabolic risks with respect to the dimensions of availability, access, consumption, and self-sufficiency in Caribbean SIDS.

<table>
<tr><th rowspan="2">Dimension</th><th colspan="4">Associated SMRs</th></tr>
<tr><th>Availability</th><th>Access</th><th>Consumption</th><th>Self-sufficiency</th></tr>
<tr><td>Water</td><td>Declining levels of water availability:
• water shortages
• lower recharge capacity through changes in hydrology
• water stocks contamination through saline water intrusion and other pollutants</td><td>Unequal access between social groups:
• water insecurity
• social unrest
• decline in local food production
• increased household and government expenditures</td><td>Quantity and quality of the resource is compromised:
• exhaustion of water stocks
• political and socio-economic instability
• ecosystems damage
• impacts on human health</td><td>Demand larger than supply:
• water scarcity and water crisis
• impacts on local economy
• decline in local food production</td></tr>
<tr><td>Energy</td><td>Damages during transport and extreme weather events:
• oil spills and runoffs
• shortages due to disruption on supply
• degradation of marine and coastal ecosystems
• impact on local development and economy</td><td>Frequent energy provisioning disruptions:
• quality and stability of the supply (blackouts)
• impacts on health, agriculture, drinking water, sanitation, and food
• increased energy consumption</td><td>Deficiencies of affordable and clean energy supply:
• increased consumption
• transmission and distribution losses
• elevated energy tariffs
• pressure on grid and risk of destabilizing it
• impacts on health and national energy security</td><td>Fossil-fuel dependent economies:
• imports dependency is perpetuated
• increased exposure to external shocks
• delays in recovery responses in case of disasters</td></tr>
<tr><td>Food</td><td>Low resource productivity and competing land uses:
• decline in arable land (<0.06 ha/cap)
• decline in locally sourced food (<20%)
• increased import dependency and food bills</td><td>Deficiencies in food security:
• prevalence of undernourishment
• impairing of human development
• intergenerational cycle of malnutrition and poverty</td><td>Shift from healthier diets to nutritionally inferior diets:
• higher levels of non-communicable diseases such as stunting, wasting or anemia
• low work productivity
• poor school performance
• loss of healthy life</td><td>Deficiencies in the agri-food supply chain:
• decline in domestic foodstuff production
• higher food losses
• increased food insecurity
• increased foodborne hazards and diseases outbreaks</td></tr>
</table>

The terms *scarcity*, *shortage* and *stress* are commonly used interchangeably. *Scarcity* refers to an imbalance of supply and demand under prevailing institutional arrangements and/or prices. Similarly *shortage* is used to describe a state where levels for supply do not meet the minimum levels necessary for basic needs. *Stress* would be the symptomatic consequence of scarcity (Kummu et al., 2016).

end of the 21st century (IPCC, 2015). The harsh 2009–2010 and 2014–2016 Caribbean-wide drought events resulted in significant impacts across multiple sectors, including decline of hydropower generation, reduction of crop yields, increases in food prices, riots, increase in diseases proliferation, livestock losses and human fatalities (Cashman, 2014; Trotman et al., 2021; EM-DAT and CRED, 2022). Derived from this, progress has been made among Caribbean SIDS to adapt desalination technologies as a source of supply in preparation for future water scarcity. Aruba is almost 100% reliant on this technology to satisfy the water demand, while the installed capacity for Antigua & Barbuda reaches almost 60% of its total demand. Nonetheless, desalination is characterized as having high operation and maintenance costs which oftentimes is affected by disruptions in the supply chain as these depend from a great deal of (usually imported) energy for its operation (UN, 2018b). Resource allocation to ensure sufficient levels of clean water and sanitation among the population should be prioritized, thus care should be taken as plans have to accommodate for the current and future resource-bases of the territory (UNWTO, 2014).

Overall, there are some SMRs that were identified during this analysis: vulnerability to water shortages and extreme weather events, ecosystem degradation, threats to local food production and access inequality, among others. Solutions to mitigate these will require actions aligned to SDG 6 and that encompasses strategies that strengthen the reliability and availability of water supplies needed to meet economic, environmental, and social development (e.g., waste management practices to ensure the protection of water quality, wastewater reuse and recycling, or incentives for eco-friendly practices). This in turn will also aid in human health and wellness, food production, energy generation, manufacturing of goods, as well as sustained biodiversity (Nagabhatla et al., 2019; IWRA, 2023).

5.2. Energy and socio-metabolic risks

With a very limited renewable energy generation capacity, the energy resource-base of Caribbean SIDS is largely dependent on fossil fuels for over 80% of their primary energy supply (ECLAC, 2016; UNESCO, 2017). Available fossil fuel reserves for Trinidad & Tobago, Barbados, and Cuba are declining due to accelerated exploitation, especially for Barbados (EIA, 2022d). Investments in new oil exploration zones (e.g., on and offshore the coasts of The Bahamas, Jamaica, and Dominican Republic) have not yielded positive results as fossil fuel sources were not quantifiable or easily accessible (Geo ExPro, 2019; Vyawahare, 2021). The distribution of these fossil fuels within the region is managed through large vessels passing between the islands, oftentimes resulting in high risks for spills that threaten the entire Caribbean ecosystem, in addition to the threat of a decrease in tourism due to closure of recreational areas. Major oil spills and beach pollution have already been reported in major tourist destinations such as Trinidad & Tobago, The Bahamas, Barbados, Grenada, Dominica, and St.

Lucia, among others (Save the Bays and Waterkeeper Alliance, 2019; UNEP, 2022). The negative effects of these harmful chemicals are diverse, however one of the most concerning ones is the impact on marine and coastal ecosystems, potentially causing genetic mutations that could endanger species reproduction and the ability to maintain healthy ecosystems, thus leading to long-term ecosystem collapse (Degnarain, 2020). Moreover, while access to clean fuels and technologies for cooking and heating has shown improvement over the past years, there are still deficiencies. As of 2017, nearly 20% of the population in Caribbean SIDS still utilize traditionally low-efficient technologies and lower quality fuels like biomass from agricultural products, charcoal, dung, and fuelwood. Strikingly, this proportion has remained persistently high at over 90% for Haiti since the year 2000 (The World Bank, 2022a; WHO, 2022b). This situation leads to high levels of household and ambient air pollution, with mortality rates per 100,000 inhabitants of 180 in Haiti compared to 20 in The Bahamas, and 39 in LAC (The World Bank, 2022h).

Overall, the energy sector plays a critical role in the provisioning of essential services as these require energy for everyday activities, including recovery in case of disasters. Energy provisioning systems, including those of buildings, infrastructures, and machinery, are key to transform flows of energy and materials into useful services. Among Caribbean SIDS, these systems vary between countries and are oftentimes subject to the negative impacts of climate change. Coupled with their socioeconomic and physical exposure to disasters, future affectations on infrastructure, disruptions in supply and changes in consumption present an existential threat that may lead to dangerous and unpredictable SMRs and potentially to system collapse (UNISDR, 2015; Singh et al., 2022). When disasters strike, the quality and stability of the electrical supply is also affected, impacting households and industries in general (e.g., electrical outages), thus, shocking most socioeconomic sectors and delaying recovery responses (Flores and Peralta, 2019; Erlick, 2021). The passage of Hurricane Matthew in 2016, and Irma and Maria in 2017 caused extensive damages to critical infrastructure, including the electrical power sector. The interruption of the electricity supply heavily impacted on water and food security, as well as on other essential sectors across the Caribbean SIDS (ACTED, 2016; OCHA and UNCT-Cuba, 2016; BBC News, 2017; UNDP, 2017; UN, 2018a). In The Bahamas, Matthew damaged close to 50% of the electrical power sector, causing electrical outages that lasted for more than 1 week, and that affected more than 100,000 consumers and impacting over the provisioning of drinking water, sanitation, food, and health (ECLAC, 2020).

On average, the Caribbean SIDS analyzed are above the minimum energy consumption threshold of 1,000 kWh/cap/yr, or 3.6 GJ/cap/yr (Moss et al., 2020), which includes both household and non-household electricity consumption. This can be an enabler of development aspirations for employment, higher incomes, prosperity, and economic transformation. However, it is important to consider the context in which the energy sector and society function. Evidence suggests that Caribbean SIDS continue to rely heavily on fossil fuels, indicating a potentially risky energy strategy. There is a concern that this reliance on non-renewable energy sources could lead to severe metabolic risks and cascading effects, ultimately resulting in a metabolic trap. Energy consumption in Caribbean SIDS has been on the rise since the early 1980's, and currently, it surpasses the global average of 80 GJ/cap/yr (EIA, 2022d). This can be partially attributable to changes in living standards and significant energy system losses. Estimated average electricity transmission and distribution losses for our selected Caribbean SIDS case studies are at around 30% (IDB, 2013; NREL, 2015a,c,d,e,f,g,h, 2020), with countries such as Haiti, St. Kitts and Nevis, and St. Vincent and the Grenadines reaching more than 60% in losses (IDB, 2013; NREL, 2015e). By comparison, the Energy Information Administration reports average transmission and distribution losses of 5% for the United States (EIA, 2022c). Moreover, Caribbean SIDS have electricity tariffs higher than the global average of US$0.14/kWh (Smith, 2020). Prices range from US$0.44/kWh for Grenada (NREL, 2015d) and US$0.39/kWh for Antigua & Barbuda and Haiti (NREL, 2015a,e), to US$0.26/kWh for Dominican Republic (Escalante, 2019) and US$0.04/kWh for Trinidad & Tobago (NREL, 2015i). As electricity tariffs rates increase, so are the access inequalities among the population. Energy theft through illegal connections to the grid could then ensue, which are currently one of the main causes of non-technical electricity system losses in Caribbean SIDS (Ochs et al., 2015; ECLAC, 2016). A feedback-loop could be created as energy theft imposes elevated costs to ratepayers and in turn increases electricity tariffs. The high fossil fuels dependency, large energy losses due to theft, increasing consumption patterns, threats to supply disruptions and fossil fuel price volatility put at risk the national energy security and other critical sectors in many Caribbean SIDS.

Coupled with a limited domestic energy generation capacity, elevated and growing rates of energy consumption, and high electricity tariffs, several Caribbean SIDS also experience an unstable supply of energy with recurrent power outages, further threatening energy security. According to the System Average Interruption Duration Index (SAIDI), power outages in Caribbean SIDS reach above 7 h/year, which place them at levels above the global average of 3 h/year (The World Bank, 2022e; WEB Aruba, 2022). The interruption of the energy supply can negatively impact telecommunications, water supply and sanitation, food security, health, and household expenditures, among others (Jimenez et al., 2016; Hull-Jackson and Adesiyun, 2019; Mcintosh, 2020; Weiss et al., 2021). As future power outages are certain to recur, fuel supply disruptions are also a permanent feature, and the adverse effects of climate change will likely amplify pre-existing vulnerability levels in the region. Strengthening structural, financial, and social resilience is key to reducing risks and vulnerabilities in the system and to hasten recovery responses in case of disasters.

There are plentiful renewable resources that Caribbean SIDS could exploit (IRENA, 2012; Herbert, 2013; NREL, 2015b,c,d,e,f,g,h, 2020; Ochs et al., 2015; CARICOM, 2018a). In Antigua & Barbuda for example, estimations from the National Renewable Energy Laboratory set the potentials of renewable energy generation at more than 400 MW (NREL, 2015a). Given the (fossil fuel-based) installed capacity (in 2015) of around 120 MW (ibid), renewable energy could surpass that capacity by more than 100%, thus reducing the dependency on imported energy carriers while minimizing the associated SMRs and providing direct economic advantages. Similar contexts can be observed in Dominica, Grenada, and Saint Kitts & Nevis (NREL, 2015c,d,h). The diversification of the energy mix offers an opportunity to mitigate SMRs by reducing price volatility and the potential for supply disruptions, resulting in more energy self-sufficiency and in a resilient and stable energy supply in the long run. In addition, if Caribbean SIDS become energy self-sufficient, then surplus clean energy could also assist nearby island nations in meeting their renewable energy targets. Nonetheless, financial, infrastructural and organizational challenges hinder progress to achieve such transition (ECLAC, 2015; Harrison and Popke, 2018).

The deployment of affordable and clean energy (aligned to SDG 7) is considered an effective tool to raise productivity and competitiveness, energy security, energy access, and self-sufficiency, and to address the negative SMRs of the high-dependence of fossil fuels (e.g., impacts on local health, emissions, degradation of ecosystems) in an integrated way. Benefits are also achieved through increased diversification of the power supply (e.g., ocean-based energy generation) and improved energy access, which lowers the risk of a single resource having an adverse impact on the national energy security (OHRLLS, 2019). Moreover, synergistic effects can be achieved through the utilization of clean energy for water desalination technologies, thus, reducing the associated costs of operation and maintenance while at the same time increasing water supply and food productivity.

5.3. Food and socio-metabolic risks

In Caribbean SIDS, the tourism sector is a major driver for resources use as they represent the most tourism-dependent region globally (Ford and Dorodnykh, 2016; WTTC, 2022). During 2019, the values of travel & tourism contribution to GDP were above 80% for Antigua & Barbuda, and 60% for Aruba and St. Lucia (WTTC, 2022). In the region, tourist arrivals have increased close to 15% between 2010 and 2014 with numbers close to 80% for Haiti, 30% for Aruba, and 25% for Dominican Republic (UNWTO, 2015). However, accounting for the rapid globalization of traded goods, changes in consumer habits, climate change and the growth of the tourism industry, the transmission of foodborne hazards and diseases within and between Caribbean SIDS and abroad could also increase (Guerra et al., 2016; Clarke and Roopnarine, 2022). A large majority of Caribbean SIDS have adopted international standards on quality control for laboratory testing and calibration, but only few have been actually accredited by an official body (Guevara et al., 2014). With limited resources available, the regional monitoring systems of the agrifood chains are likely to be deficient. Studies indicate outbreaks and infections from foodborne pathogens in island populations as well as in tourists visiting islands such as Antigua & Barbuda, Barbados, Cuba, the Dominican Republic, Jamaica, and Haiti (Kendall et al., 2012; Tighe et al., 2012; Mughini-Gras et al., 2014; Gray et al., 2015). Island governments thus need to prioritize food safety systems in all stages of production, processing, storage, distribution and trade that assess the incidence and prevalence of pathogens linked to foodstuffs (FAO and WHO, 2005; FAO et al., 2021). By doing so, the incidences of cases could be minimized, saving lives and avoiding the economic burden from costly medical bills (Scharff, 2012; Guerra et al., 2016; Lee, 2017).

Food security is heavily dependent on sustainable, resilient, inclusive, and efficient systems of production and consumption (FAO, 2017). Nonetheless, in Caribbean SIDS, the access to affordable foods that support healthy dietary patterns not only at a single point in time but also across the lifespan and possibly for future generations remains a pressing issue. Healthy diets are driven by preferences, but also by prices as these foodstuff are mostly imported (Massa, 2021). Between 2000 and 2017, food inflation has shown a steady increase in Caribbean SIDS, with an average increase of almost 6%. Notably, Dominica, the Dominican Republic, Haiti, Jamaica, and Trinidad & Tobago have experienced inflation rates of more than 10% (FAO, 2022a). Today, close to 50% of the population in Caribbean SIDS are unable to afford a healthy diet due to elevated costs or unavailability (FAO et al., 2021). This situation is strongly linked to the prevalence of severe levels of food insecurity as these have been climbing slowly, now affecting 37.6% of the Caribbean SIDS population compared to the LAC averages of 11.3% and global averages of 10.5%. Moreover, although some progress has been made, the prevalence of undernourishment in the Caribbean region is currently almost double the global average of 9% (FAO et al., 2021).

Deficiencies in food security and nutrition are an outcome of several complex internal and external factors (e.g., island geography, governance deficiencies, institutional constraints, environmental and economic vulnerabilities) which can result in severe consequences on the overall wellbeing of the population (Massa, 2021; Mohammadi et al., 2022). Food insecurity and malnutrition impact social and economic progress and materializes among the population as physical growth and mental development deficits, morbidity, increased risk of death, poor school performance, and low work productivity among others, which in the long run could impair human development and even trap the population in an intergenerational cycle of malnutrition, poverty and health issues (Ruel, 2013; ECLAC, 2017). According to FAO's estimates (FAO, 2022b), the *Minimum Dietary Energy Requirements* for the analyzed case studies ranged from 1,700 to 1,900 kcal/cap/day between 2000 and 2017. Despite all countries exceeding these minimum thresholds, it's important to note that meeting minimum energy requirements does not necessarily indicate a healthy or nutritionally adequate diet. For Caribbean SIDS, we can observe a shift toward an increased dependency on food imports of non-traditional, lower quality diets, with lower intake of vegetables and fruits, an increased intake of food from meat and especially of nutritionally inferior processed foods with high caloric content (FAO, 2021a, 2022b). This shift away from local, often healthier foods has led to the loss of a healthier and productive life (UN, 2010; FAO, 2017). The human potential that is lost due to poor health and the burden of disease is measured through the Disability-Adjusted Life Years (DALY) indicator, which equals to one lost year of healthy life because of either premature death or disease or disability (Roser et al., 2021; WHO, 2022a). In the Caribbean SIDS, the percentage of total DALYs resulting from non-communicable diseases (NCDs) increased from 67 to 74% between 2000 and 2017, compared to a global average of 60% in 2017 (IHME, 2022). We also observe a rising trend in total DALYs attributed to NCDs, with Haiti and Dominican Republic showing values over 40% higher in 2017 compared to 2000. Furthermore, more than 40% of these DALYs fall into only 3 categories: cancers, diabetes & kidney diseases, and cardiovascular diseases (ibid), which are the leading cause of death and disability among Caribbean SIDS (CARICOM, 2016; CARPHA, 2021).

Food self-sufficiency in Caribbean SIDS is declining, as domestic food production is insufficient to meet the demand. With a narrow agricultural resource-base, the per capita arable land in Caribbean SIDS is around 0.06 ha/cap, three times less than that of the least developed countries (LDCs) and developing countries (The World Bank, 2022c). This can be partially explained by the absence of an adequate accessible volume of water for irrigation and changes in land-use in favor of urbanization. Moreover, the combined effects of structural policy adjustments, climate variability and extremes like storms, droughts, excessive rains, and loss of top soil due to flash floods are also a significant factor in food production decline, which can cascade into negative effects on food prices, value chains, water supplies and livelihoods, and overall food security (FAO et al., 2018, 2021; FAO, 2020a; Rahman et al., 2022; Singh et al., 2022). In monetary terms, Caribbean SIDS import more than 80% of their domestic food supply needs (Dorodnykh, 2017), while deficiencies in the agri-food supply chain have contributed to food losses of more than 50% of supply (Kaza et al., 2018). Considering their heavy food imports dependency and elevated food losses, these countries are also exposed to high foodstuff bills that in the long run will further put at risk their resource-security levels (WFP, 2022). Moreover, disruptions in the global supply chain (e.g., due to the war in Ukraine at the beginning of 2022) and price volatility have sharply affected commodity prices in the Caribbean, especially for foodstuffs (Ewing-Chow, 2019; The World Bank, 2022k). A shift toward food self-sufficiency in small islands as a food security and resilience strategy would then require an approach that is intersectional, flexible, adaptive and that is supported by an effective regulatory and institutional framework that allow for context-specific implementations (Dorodnykh, 2017; Mohammadi et al., 2022; Rahman et al., 2022).

To address the identified SMRs of obesity and related diseases while at the same time achieving SDG 2 of food security and nutrition will require coordinating efforts from different stakeholders at both the local, and international level. Benefits are achieved through promoting inclusive policies as well as social protection programmes for the most vulnerable groups, and that support locally manufactured foods (e.g., by improving the local food supply chain and reducing overall prices) in favor of traditional healthier foods. Nature-positive production and supply models (e.g., system-based conservation agriculture, river basin management, bio-inputs, integrated soil fertility management, soil and water conservation and nutrient recycling) are also important to improve market conditions and to increase food security while at the same time increase resource-security (e.g., through prevention of soil degradation, water and energy consumption, etc.), which can also have important benefits in terms of both food productivity and sustainability (Hodson et al., 2021; Massa, 2021).

6. Conclusions

This research offers a first attempt at operationalizing the concept of SMRs. By means of characterizing the shifting baseline of 14 Caribbean SIDS with respect to water, energy, and food, and the dimensions of resource availability, access, consumption, and self-sufficiency, we have identified potential SMRs in need of addressing. Our study expands knowledge on socio-metabolic research and the WEF-nexus at country-and regional level for Caribbean SIDS, and provides baseline data for policy and other stakeholders to better understand critical resource dynamics. In addition, our study offers a general overview of the potentials that our methodology may offer in identifying SMRs.

Our study demonstrates an urgent need for an integrated approach to manage critical resources like water, energy and food in resource-stressed contexts like Caribbean SIDS. Maximizing resource-security, minimizing trade-offs, and improving the linkages between critical resources may offer synergistic solutions that can be leveraged to mitigate inherent risks. Understanding the overall dynamics of critical resources to identify, manage and mitigate SMRs is crucial for SIDS. By doing so, we could design a strategy to build resilience, adapt to, anticipate, resist, and recover from climate change impacts and shocks, and to avoid cascading dysfunction of environmental, economic, and social systems.

Meanwhile, as Caribbean SIDS share common technical, institutional and regulatory barriers and vulnerabilities, they also vary greatly in terms of their resource-bases, population, economic development, infrastructure, health, and more. Regional average figures tend to mask these variations across individual countries, as such, we also need to consider trends and context when it comes to country-level planning. Along with regional cooperation, interventions must consider the wide range of realities within the region to properly identify potential barriers and openings for positive transformative change.

Notably, by analyzing SMRs within the overall resource dynamics could be key to achieve the global UN Sustainable Development Goals 2, 6, and 7 with greater confidence and certainty. One must recognize the existing and potential impacts of SMRs arising from alterations to human and natural systems in SIDS, including increases in droughts, floods, and some other types of extreme weather; sea level rise; and biodiversity loss; and also the trends of resource-use, including low food production and high processed foods imports and consumption, water quantity and quality challenges, and high dependence of fossil fuels, etc. Making stakeholders aware of these risks is key to inform and enable them to employ and implement sustainable and efficient solutions and practices that could aid in minimizing SMRs and that generate synergistic effects in the long run (FAO, 2018).

Our methodology can be replicated and transferred to other regions that share similar resource-use challenges. Through appropriate calibration, our approach can be customized to fit different contexts. By standardizing our approach, we aim to promote the development of a consistent and comparable knowledge base, which can benefit decision-makers, researchers, and practitioners working toward sustainable management practices in various regions. The potential transferability of our approach adds value as it can provide useful insights and solutions to resource management challenges beyond the Caribbean SIDS.

While acknowledging the limitations of the methodology and datasets used, our analysis still provides valuable insights on the state of the systems under study (locally and regionally), especially in identifying emerging risks and trends, as well as potential solutions to mitigate them. To address these limitations, future analysis can benefit from the inclusion of additional data points to enable a time-series assessment. This would generate more granular results in the analysis by further capturing the complexity and nuances of changes over time, thus providing more accurate representations for each country's profiles.

Regarding our methodology, we employ a combined quantitative and qualitative approach that assesses the directionality of SMRs in the availability, access, consumption and self-sufficiency dimensions, rather than focusing on thresholds. The understanding of metrics related to resource-use dynamics is constantly evolving due to the complexity of these and the degree of uncertainty involved. Although establishing boundaries can be useful in certain cases, it is unclear if they apply to SMRs as these may not be subject to "hard" thresholds. In such complex dynamic systems, these thresholds could be scientifically questionable and politically used to delay early action, potentially pushing the system to its limits. Yet, we recognize that an enhanced quantitative analysis would improve the study's reliability and comparability that can also be aligned with established global risk reports. Thus, future work should explore the potentials of developing a coherent measurement framework specifically for evaluating SMRs that enables stakeholders to understand the relationships between the metrics and the metrics themselves. This framework could also aid in understanding, communicating and promptly implementing the most effective ways to achieve SMRs minimization strategies' goals and objectives.

Future research should also look beyond our proposed dimensions of availability, access, consumption, and self-sufficiency, and include others like the social and political *(un)acceptability* of SMRs and mitigation strategies. For SMRs mitigation strategies to be better evaluated, these need to analyze the costs and benefits, while considering the socio-economic context in which these will be applied, together with the needs, issues, and concerns of the stakeholders involved. As few studies attempt to understand and/or incorporate the perceptions and preferences by small island communities and peoples in terms of acceptability of risks and mitigation strategies, the inclusion of this dimension would be valuable to consider. Moreover, by aligning these solutions with the values, needs, preferences and expectations of the society and searching for socially acceptable and desirable futures can help bridge the gap between research and implementation of strategies to minimize risks (Stephanides et al., 2019).

Data availability statement

Publicly available datasets were analyzed in this study. This data can be found here: FAO AQUASTAT database at https://www.fao.org/aquastat/en/, the FAOSTAT database at https://www.fao.org/faostat/en/#data/, and in the U.S. Energy Information Administration database at https://www.eia.gov/international/data/world. All other data supporting the findings of this study are available within the article and its Supplementary material or are available from the corresponding author upon request.

Author contributions

FM contributed to the conceptualization, methodology, visualization, formal analysis, review, and editing of this study. SS contributed to the conceptualization, methodology, review, and editing of this study. EM contributed to the review and editing of this study. All authors contributed to the article and approved the submitted version.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

The handling editor P-JS declared a past co-authorship with the author SS.

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Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fclim.2023.1085740/full#supplementary-material

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