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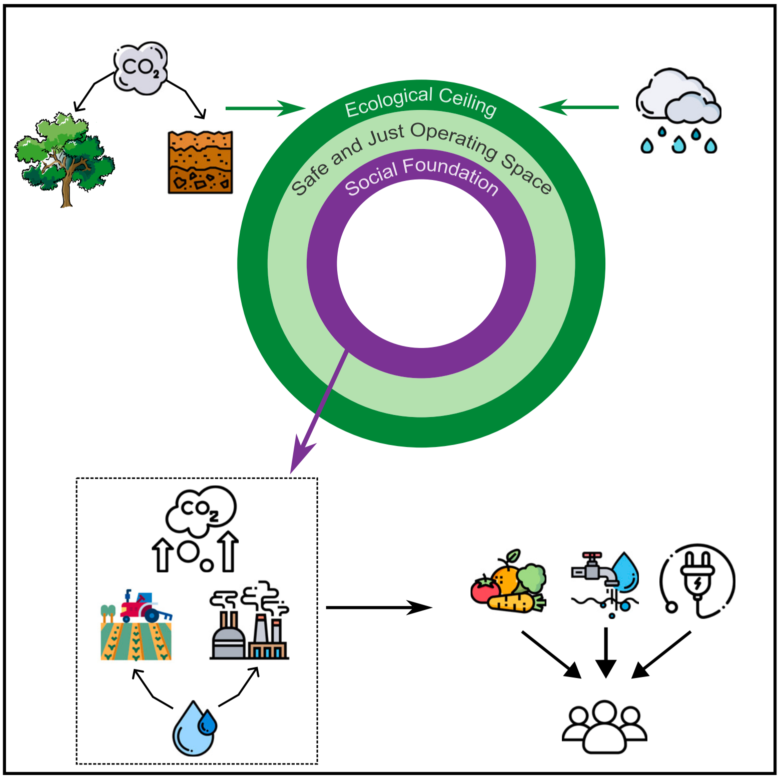
Possible but rare: Safe and just satisfaction of national human needs in terms of ecosystem services

Graphical abstract



Highlights

- We use a biophysical approach to find the safe and just operating space
- Ecosystem services can link the ecological and social dimensions of sustainability
- Only 6% of the countries can be safe and just simultaneously
- Most countries need to change their food and energy production practices

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In brief

Securing basic food, energy, and water resources for everyone without compromising natural ecosystems is a critical challenge for humanity to achieve sustainability. We develop a framework with biophysical models and data to find whether nations across the world can meet their basic needs in a safe and just manner. The framework can allow the identification of opportunities for enabling a sustainable and equitable future through changes in technologies, policies, diets, and the restoration of ecosystems.

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Possible but rare: Safe and just satisfaction of national human needs in terms of ecosystem services

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SCIENCE FOR SOCIETY Approaches for securing food, energy, and water resources cause environmental impacts due to greenhouse gas emissions and water consumption. To be socially just, nations need to secure resources to meet their basic needs. To be environmentally safe, meeting these needs should not result in exceeding the capacity of the nation's ecosystems to supply goods and services. We present a framework based on biophysical models and data to determine these requirements. We apply this approach at the country level to determine whether 178 nations can meet their needs in a safe and just manner. We find that many lack this ability, particularly for carbon sequestration. Our analysis can allow the identification of technologies and policies that can help nations transition toward meeting their food, energy, and water needs in a safe and just manner.

SUMMARY

Providing adequate food, energy, and water to everyone without exceeding nature's carrying capacity is a formidable challenge facing humanity. For this, we need to know whether each nation's needs are being met in an environmentally safe and socially just manner. Here, we develop a biophysical approach for such quantification in terms of ecosystem goods and services. For each nation, we quantify the minimum greenhouse gas emissions and water consumption to meet basic needs, the actual demand of these flows, and their ecosystems' capacities to provide these services. We find that 67% of nations are operating within their safe and just space for water provisioning but only 9% are doing so for carbon sequestration and 6% for both. A safe and just space does not exist for 37% for carbon sequestration and 10% for water provisioning. Our framework can guide technology, policy, and trade decisions for meeting basic needs in a safe and just manner.

INTRODUCTION

Meeting food, energy, and water needs is essential for sustaining human lives, but it must be conducted in a manner that respects nature's capacity and meets basic human needs. Environmental sustainability requires that the pressure on ecosystems imposed by human activities does not exceed their ability to provide essential contributions to people.[1] The framework of planetary boundaries (PB)[2] has introduced the concept of a "safe operating space," which identifies the "ecological ceiling" that human activities need to operate within to reduce the risk of irreversible global change. This framework has been extended to include social sustainability by setting a lower limit or "social foundation" that must be surpassed to meet basic demands and avoid critical human deprivation.[3] The space between the ecological ceiling and social foundation is referred to as the "safe and just operating space" (SJS) for humanity.

The PB and SJS frameworks have been used in many studies on environmental footprints,[4,5] absolute environmental sustainability,[6] and life cycle assessment.[7] In addition, efforts to translate these frameworks to subglobal scales have relied on downscaling the ecological limits to regions[8,9] and individual countries[10–12] and on comparison across countries.[13,14] However, the downscaling approach has its challenges, including the subjectiveness and significant differences in results based on the sharing principle used.[15–18] Other works have focused on understanding and modeling the complex relationships between environmental and social objectives[19,20] and the impact of achieving the United Nations Sustainable Development Goals (SDGs) within the PB framework.[21,22]

However, due to the complexity of the social dimension, these studies do not integrate or identify clear connections between the ecological and social objectives but focus on them separately. For example, the ecological ceiling may be for carbon dioxide and phosphorus emissions, but the social foundation may be for employment and access to energy, with no quantitative or causal relation between them. It is evident that nature and society are interconnected. Many efforts qualitatively demonstrate the relation between social and environmental dimensions[1,23] or describe the relation using empirical models.[13] However, to date, no work has explored the relation using biophysical models and the safe and just space is not represented in common physical units.

We advance beyond previous frameworks by quantifying the relationship between the ecological and social dimensions using biophysical models and data. By aligning the two objectives, we identify the SJS in terms of ecosystem goods and services (ESs) and represent the ecological ceiling and social foundation in a common unit for various ESs. Using biophysical models provides a thorough, systematic, and general approach for quantifying the effect of various scenarios on meeting basic food, energy, and water needs in a safe and just manner and guides technology and policy decisions toward such a future. In addition, we illustrate the redefined framework to determine the SJS for 178 nations across the world using the most recent supply and demand data for the water provisioning and carbon sequestration ESs. The proposed framework is general and may be used to determine the SJS in terms of other ESs as well.

Instead of using all the environmental and social indicators suggested by the SJS framework,[3] we focus on access to food, energy, and water resources, which are connected to ESs and are biophysically quantifiable. We define the social foundation based on the minimum consumption of food, energy, and water to meet the basic needs of a specific population. We follow the definition of basic needs and minimum threshold values of access to food, energy, and water resources identified by the United Nations (UN) and the World Health Organization (WHO).[24–28] This information is converted into the minimum demand or social foundation for water provisioning and carbon sequestration ESs by using information about the resources to meet food, energy, and water requirements in terms of water consumption and greenhouse gas (GHG) emissions required in the selected country.

Understanding the food-energy-water nexus has been a popular topic of research. It studies the competing interest and interlinkages between the resource systems.[29–31] However, this work does not focus on understanding food-energy-water flows. Instead, it uses information from these systems to study the impact of providing essential food, energy, and water resources in an environmentally safe and socially just manner.

This research identifies each nation's ability to be safe and just for meeting food, energy, and water needs in terms of carbon sequestration and water provisioning ecosystem services. It also identifies the potential conflicts in meeting those needs for everyone in the selected country while operating within nature's capacity. We also identify where improvements such as ecological restoration or technology transitions to renewable sources are most needed. The resulting insight can improve social and ecological conditions, identify hotspots and trade-offs, manage supply chains, and guide decision-making processes and policies. The proposed framework and underlying data account only for direct flows in each nation, resulting in a production-based approach. However, they can be the basis for quantifying the SJS associated with the life cycle of consumption, global trade, and supply and demand networks.

RESULTS

Determining the national safe and just space

For a country to be self-sufficient in ensuring access to food, energy, and water resources for all of its population, it needs to rely on various local ecosystems. To operationalize the SJS framework, we identify the following elements for the i-th ES and j-th country: the ecological supply ($S_{i,j}$), the current total demand from all economic activities ($D_{i,j}$), and the minimum demand to meet food, energy, and water needs ($D_{i,j}^{min}$). The following requirements must be satisfied to operate within the SJS:

$$\text{safe requirement} : S_{i,j} \geq D_{i,j} \qquad \text{(Equation 1)}$$

$$\text{just requirement} : D_{i,j} \geq D_{i,j}^{min} \qquad \text{(Equation 2)}$$

The "safe" requirement constrains the current demand to be within the ecological capacity to avoid degradation of ESs below critical thresholds. For the "just" requirement, the current demand must exceed the minimum demand required to meet food, energy, and water needs to avoid any social deprivation.

We focus on the impact of meeting the basic needs on water provisioning and carbon sequestration ESs by calculating the safe and just requirements at a country scale. To highlight the differences across the world, we group the 178 countries analyzed in this study into six regions: East Asia and Pacific, Europe and Central Asia, South Asia, Americas and Caribbean, Middle East and North Africa, and Sub-Saharan Africa. Please see the supplemental information (Note S2; Tables S1 and S2) for a list of the included and excluded countries in this study.

The SJS is bounded by the ES supply ($S_{i,j}$) and the minimum demand ($D_{i,j}^{min}$) to secure the required resources to meet the basic needs from that specific ESs. The combination of these thresholds and the total current demand ($D_{i,j}$) introduces six possible scenarios for the SJS, as shown in Figure 1. For a country to have an SJS, its supply must exceed the minimum demand threshold:

$$S_{i,j} > D_{i,j}^{min} \qquad \text{(Equation 3)}$$

This is the situation in scenarios a, b, and c in Figure 1. The size of the SJS, which is the light green region in these three scenarios, suggests more resilient operating conditions for an ecologically safe and socially just country. In turn, countries with small SJSs have limited operating spaces to avoid violating either the ecological safety or social justice requirements. However, for many countries, having a large SJS does not mean they

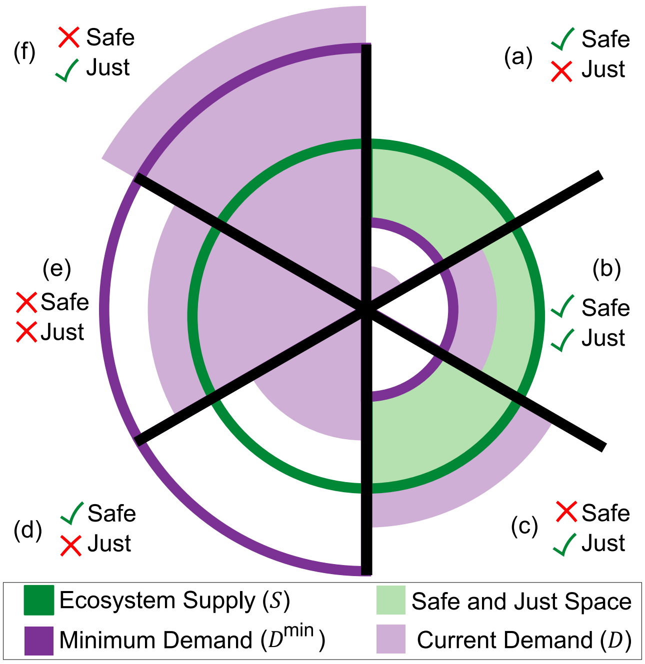

Figure 1. Possible scenarios for the SJS

The scenarios are determined by the current level of demand and the ecological and social thresholds. The SJS exists for scenarios a, b, and c, but only scenario b operates in the SJS. For scenarios d, e, and f, the SJS does not exist because the social foundation (minimum demand) exceeds the available ecosystem supply. Countries that belong to these scenarios cannot meet the safe and just requirements simultaneously.

are currently meeting the safe and just requirements. Among scenarios a, b, and c, only scenario b is safe and just since the current demand, $D_{i,j}$, is such that it satisfies both Equation 1 and 2. Scenario a satisfies only Equation 1, making it safe but not just. Scenario c satisfies only Equation 2, making it just but not safe.

Notably, social and ecological thresholds can overlap as a result of the trade-offs between the objectives of human development and environmental conservation.[32] This happens when the condition of Equation 3 is not satisfied. For example, there are countries where the ESs needed for meeting basic food, energy, and water needs exceed their local ES supply. As a result, these countries cannot simultaneously meet the safe and just requirements, and an SJS does not exist. Moreover, these countries can also fail to meet the just requirement (scenario d), the safe requirement (scenario f), or both (scenario e).

Assessment results of the carbon sequestration ES

Emissions of GHGs are inevitable with the current technologies used around the world to produce food and electricity. Therefore, the fuel sources used to generate electricity and the different types of crops a country produces play a significant role in defining the just requirements and, consequently, the SJS. The total supply of the carbon sequestration ES of a country is calculated as the sum of its forest and soil sequestration capacities.

Table 1 and Figures 2, 3, and S3 depict the current conditions of the carbon sequestration ES for meeting the safe and just requirements for the 178 countries considered in this study. They show that in terms of this ES, the safe and just space exists for 112 countries (63%) (scenarios a, b, and c). However, only 16 countries (9%) currently meet the safe and just requirements (scenario b). These include Sweden and Gabon, owing to their high carbon sequestration capacity compared with their emissions.

The requirement for social justice is satisfied by 175 countries (98%) (scenarios b, c, and f), which means that their GHG emissions exceed the minimum emissions required to secure their population's food, energy, and water resources using current approaches. Most of the countries in the Middle East, North Africa, and Sub-Saharan Africa cannot meet the safe and just requirements simultaneously (scenarios e and f) due to an insufficient supply of the carbon sequestration ES caused by a lack of vegetation cover and soil carbon sequestration. However, even many countries with the potential for good vegetation cover cannot meet the safe and just requirements simultaneously due to their high demand levels resulting in large GHG emissions and minimum demand requirements (GHG emissions to maintain the social foundation with current technologies). For example, the United Kingdom shares the same scenario as Saudi Arabia where the SJS does not exist, and both minimum and current demands exceed their local ES supply (scenario f). Despite their comparable demand levels, the apparent difference in ES supply levels indicates that the actions required to reach their SJSs may have to be significantly different. Both countries require critical changes in their approaches for producing energy and food to reduce the minimum demand threshold within their ecosystem supply. However, as we can see from Figures 3 and S3, the minimum demand threshold for the United Kingdom exceeds its supply by a small amount compared with the gap in these metrics for Saudi Arabia. Hence, in addition to the previous changes, Saudi Arabia must implement methods to improve and restore local ecosystems to increase its carbon sequestration capacity. On the other hand, Somalia, Yemen, and Djibouti meet neither the safe nor the just requirements (scenario e). They need to increase ecological capacity and social consumption. The United States and Canada have an ample and similar sequestration supply, but the current emissions in the United States for meeting its food, energy, and water needs exceed its supply, while in Canada, it does not. Efforts toward net-zero GHG emissions are likely to help the United States in moving from scenario c to b.

Figures 3 and S3 show the significant differences between regions and countries regarding their ecological capacities, demand levels to meet basic food, energy, and water needs, and total current emissions. All values are normalized by the ES supply for each country. We can see that most countries in East Asia and the Pacific, Europe and Central Asia, the Americas, and Caribbean regions have an SJS, indicated by the presence of a green region, but their current emissions levels exceed their carbon sequestration capacities. In contrast, the just requirement for most countries in South Asia, the Middle East, North Africa, and Sub-Saharan Africa exceeds their local ES supplies; hence, an SJS does not exist in these countries, as indicated by the absence of a green region.

Table 1. Performance of countries in terms of scenarios for meeting requirements of a safe and just space based on carbon sequestration and water provisioning ecosystem services

Scenario	Safe requirement ($S \geq D$)	Just requirement ($D \geq D^{min}$)	SJS exist ($S \geq D^{min}$)	Carbon sequestration (%)	Water provisioning (%)
a	✓	X	✓	0 (0)	37 (21)
b	✓	✓	✓	16 (9)	119 (67)
c	X	✓	✓	96 (54)	4 (2)
d	✓	X	X	0 (0)	2 (1)
e	X	X	X	3 (2)	10 (6)
f	X	✓	X	63 (35)	6 (3)

The total number of countries considered is 178.

While the results for most countries provide a disturbing outlook, there is a glimmer of hope in terms of operating within the SJS. The results show that most nations can secure the required resource of the social foundation at much lower demand than the current levels, such as Paraguay, Norway, and New Zealand, as demonstrated by their sizable green SJS in Figure 3. This indicates that these countries can operate within the SJS by reducing their demand without requiring fundamental changes. Adopting more renewable energy sources and plant-based diets could help reduce current demand and the social thresholds, resulting in a larger SJS. Moreover, ecosystem rehabilitation, restoration, and protection will help increase nature's ability to supply ESs, yielding a similar outcome. These results show the available operational space and help identify the actions necessary to meet the safe and just requirements. In addition, our results confirm the importance of meeting global goals such as nature-positive decisions[33] and net-zero emissions.[34]

Assessment results of the water provisioning ES

The results for the water provisioning ES summarized in Table 1 and Figure S4 show that an SJS exists in 160 countries (90%), but only 119 (67%) are currently meeting both requirements. However, the just requirement is currently not met in 49 countries (28%) (scenarios a, d, and e) (for more details, please see Data S1, Note S6, and Figure S4).

In Figure 4, we can see that most countries meet both the safe and just requirements (scenario b). Only a few countries, mainly in the Middle East and North Africa, do not have SJSs and cannot meet the safe or just requirements simultaneously (scenarios d, e, and f), which is expected for arid countries. Moreover, low-income countries, such as Angola and Somalia, are not meeting the just requirement due to a lack of development. Meeting the just requirement by increasing the current level of demand might bring Angola to the SJS but not Somalia, as the minimum demand exceeds its ES supply.

In Figure 5, we show the different utilization levels of the SJS of each country. The current level of demand differs widely between countries and regions. The minimum demand needed to secure the required resource of food, energy, and water varies based on the food and electricity generation practices in a country. For example, in Europe and Central Asia, Turkmenistan and Uzbekistan are the only countries where an SJS does not exist due to their current practice of growing water-intensive crops.

DISCUSSION

The approach presented in this work determines the SJS by connecting the safe and just requirements in terms of biophysical models of ecosystem services. Application to assess the carbon sequestration and water provisioning ESs across all nations confirms the unsustainable utilization of carbon sequestration ESs across the world. Countries emit significantly more than their national ecosystem capacity for carbon sequestration. For the water provisioning ES, the global condition is better: most countries operate within their SJS, but there is a noticeable tendency to operate close to supply limits.

The results bolster the findings in the literature about the relation of environmental degradation with human development.[35] Furthermore, our results confirm the distribution disparities that motivated the concept of Doughnut economics and the global ecological conditions highlighted in the PB framework regarding freshwater use being within the safe operating space compared with the water provisioning ES presented in this work. Moreover, the carbon sequestration ES condition aligns with the overshooting of the safe PB of climate change.

Utilizing the concept of ESs in this research allows us to identify a physical connection between ecological limits and the demand that economic activities in each nation directly place on their local ESs to meet basic human needs. Despite the ability of ESs to satisfy the just requirement, some people do not have access to these services, which brings attention to a critical distribution issue. This work does not account for inequalities in resource distribution and wealth. Instead, it estimates the potential for a country at an aggregate level to operate within its ecological boundaries and be self-sufficient by utilizing ESs to meet food, energy, and water demands.

Our results do not suggest that the impact of a country only occurs within its borders. There is a sufficient amount of literature on the consumption-based impact of countries due to globalization and trades such as virtual water[36] and embodied carbon.[37] However, the impact on ecosystems occurs where the goods and services are produced. Hence, this research provides new insights into the production-based impact of meeting basic needs at the national level on local ESs. Moreover, the approach can be implemented to assess the impact of ESs and identify SJSs at global, regional, and local scales. In addition, more ESs, such as water and air quality regulation, need to be included in the assessment to determine the full impact of meeting basic human needs.

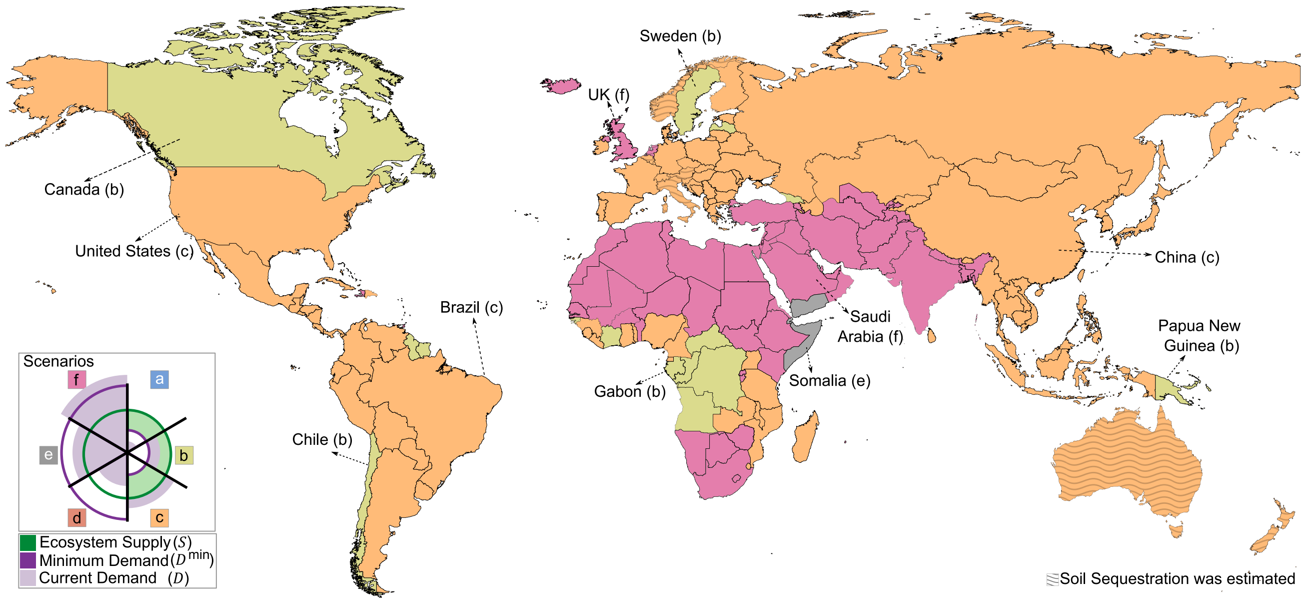

Figure 2. National performance relative to the safe and just requirements for the carbon sequestration ES

Countries that belong to scenario b meet both requirements for being safe and just, while countries in scenario e meet neither. The safe and just operating space does not exist for countries in scenarios d, e, and f, and they cannot meet both requirements simultaneously since the minimum demand exceeds the maximum supply of ES.

Quantifying nations' emissions with respect to their sequestration capacity reveals that most countries are operating in an unsustainable manner. For performance details for each country, please see Data S1. Our biophysical approach for determining each nation's ecological capacity overcomes the subjectiveness of allocating or downscaling PBs and the potential disincentives for ecosystem restoration.[17,18] The SJS defined in this research confirms that low- and lower-middle-income countries with high ecological supply have a range of operating conditions under which to develop and improve the wellbeing of their population. In contrast, high-income countries with high emissions levels must reduce their current demand levels. Countries where the safe and just requirements cannot be met simultaneously require more critical transformations to achieve SJSs. This includes restoring local ecosystems to increase ES supply and adopting environmentally friendlier technologies to reduce the minimum demand to levels below the supply of relevant ESs. Reliance on global trade and cooperation is critical and can also help ensure access to resources for everyone.

Based on our findings, two action plans may help move nations closer to having SJSs. First, food and energy production practices need to change drastically; for example, a global and regional transition away from water-intensive crops, such as sugarcane in Pakistan and livestock production in Sudan, are essential for reducing water demand. In addition, a shift to cleaner energy sources and renewables is necessary for countries to reduce their GHG emissions, for example moving away from coal in India and Kazakhstan and high per-capita consumption in the United States and the European Union. Second, rehabilitation and restoration of local ecosystems are essential for ensuring a continuous flow of goods and services. This framework can be used for policy design, for example to reduce emissions from the agriculture sector resulting from land and soil management and other practices to ensure sustainable operations within the sequestration capacity.

This work provides a positive outlook for a sustainable future by showing that the SJS does exist for most nations. However, it requires major transitional changes in operations to move toward the SJS. It also emphasizes the importance of global cooperation for the cases where the SJS does not exist due to a lack of ESs. In addition to reducing the environmental impact of human activities worldwide, it is crucial to ensure that these reductions will not prevent societies from securing basic food, energy, and water needs and levels of wellbeing. To address this dilemma, ecological and social objectives need to be connected and met simultaneously, as shown in this research.

EXPERIMENTAL PROCEDURES

Resource availability

Lead contact

Further information and requests for resources and reagents should be directed to and will be fulfilled by the lead contact, Bhavik R. Bakshi (bakshi.2@osu.edu).

Materials availability

This study did not generate new unique materials.

Data and code availability

All the source data used in this paper are derived from the cited references or databases. The consolidated dataset supporting the findings of this study is provided in Data S1 and deposited to Zenodo: https://doi.org/10.5281/zenodo.7722816. Any additional information required for reanalyzing the data reported in this article is available from the lead contact upon request.

Methods

To define the SJS, we do not directly use the indicators proposed by the PB and the Doughnut economics frameworks.[2,3] Our approach defines the

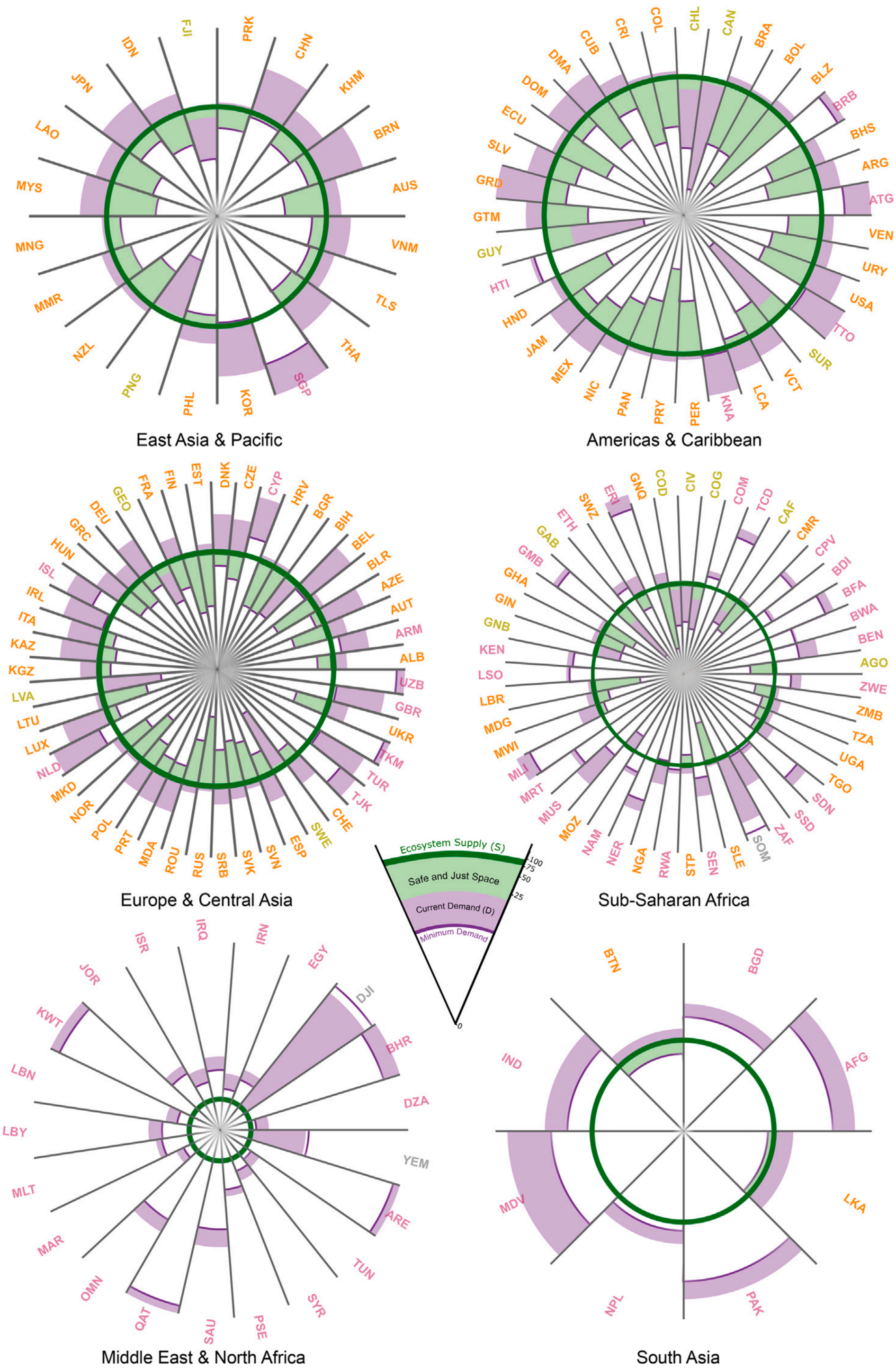

Figure 3. National performance relative to the SJS for the carbon sequestration ES

The donut plots show the extent of overshooting the ecological boundary (dark green) or the shortfall from the social foundation (dark purple) based on the current levels of demand (light purple) for all 178 countries in this study. The size of the SJS (light green) is different for each country. Operating within the SJS is ideal, and the size represents the different conditions where a country can meet the safe and just requirements. However, fundamental changes to lower the minimum demand and increase the supply are required for countries that do not have an SJS. The colors used for country names represent the same categories as used in Figure 2. The parameters are normalized by the supply and plotted on a log scale for legibility (see Table S1 for full country names).

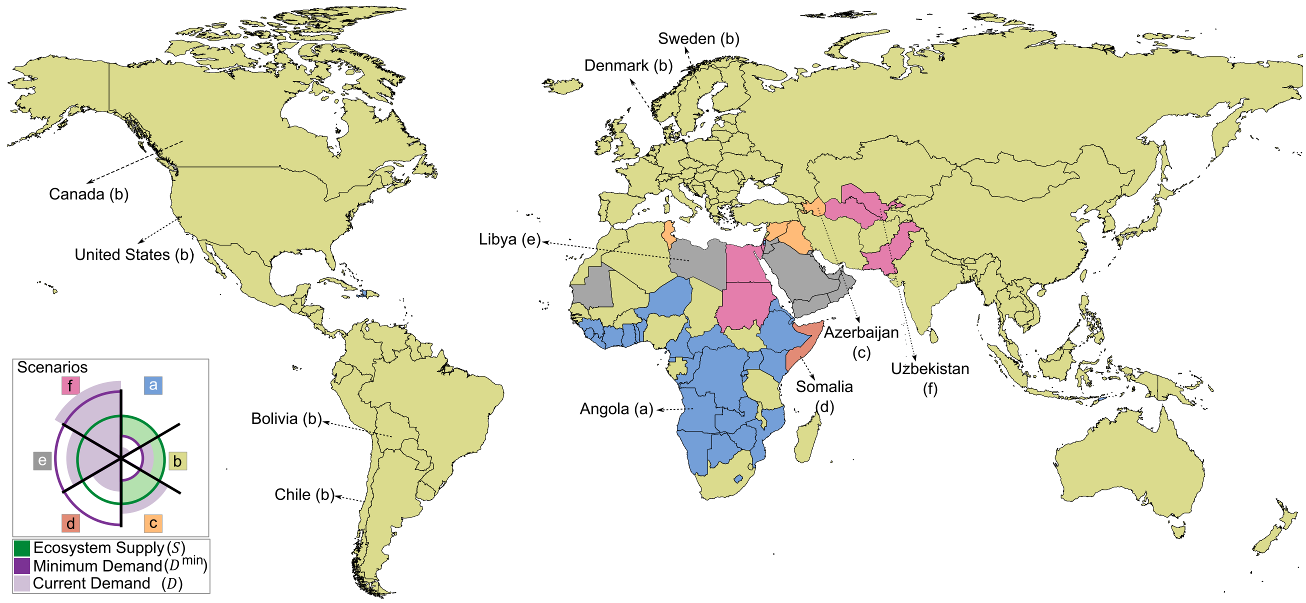

Figure 4. National performance relative to the safe and just requirements for the water provisioning ES

Most countries are operating within their SJS (scenario b), except the water-scarce countries, which is expected. Most African countries have high supply, but they do not meet the just requirements due to lack of development (scenarios a, d, and e). The colors and categories are used as per Figure 2.

ecological ceiling using the capacity of an ecosystem to provide goods and services as the ecological indicators. For the social foundation, we focus on the quantifiable social indicators that can be connected to ESs through biophysical models, thus bridging the limits to define the SJS in physical units.

To analyze the impact of human activities on local ESs, we calculate country-specific supply and demand for water provisioning and carbon sequestration ESs. Subsequently, we calculate the minimum demand for ESs that is necessary for meeting food, energy, and water needs for the entire population within a nation. This provides the social foundation in terms of carbon sequestration and water provisioning ESs. For determining the ecological ceiling, we use biophysical models and data to determine the capacity of a nation's ESs and establish a physical connection to calculate the social requirement that ensures access to food, energy, and water.

Ecological ceiling

We identify the ecological ceiling in terms of the supply of ES $(S_{i,j})$, which can vary based on the type of service provided. For example, the supply of provisioning ESs is defined based on the maximum service flows obtained from that ecosystem *i* within a country *j*, such as water flow. For regulating ESs, the supply is defined as the capacity of the ecological system to provide the service by the relevant biophysical activities. For example, for the climate regulation ES, the supply is the capacity to sequester carbon dioxide and other GHGs.

We quantify the supply of the water provisioning (*W*) ES by the capacity of the ecosystem to provide water ($S_{W,j}$). This refers to the flow of renewable resources such as river flows and rainfall within a country using data from the Food and Agriculture Organization (FAO).[26]

The sequestration of atmospheric carbon dioxide is a prominent issue and essential for addressing climate change. Carbon is stored in diverse ways in nature, including in soil, oceans, and vegetation. In this work, we define the supply of the carbon sequestration service (*C*) as sequestration in forests ($S_{C,j}^{forest}$) and soil ($S_{C,j}^{soil}$). We utilize the global map for forest sequestration capacity published by the Global Forest Watch Project[38] and the soil organic carbon sequestration map published by the FAO[39] to calculate the sequestration capacity for each country. The two maps use ecological models to show the change in soil carbon content and carbon flux in forests for a period of 20 years. We extract the data for each country using the geographic information system ArcGIS. Then, we calculate the annual sequestration rate to use as the ecological supply of ESs:

$$S_{C,j} = S_{C,j}^{forest} + S_{C,j}^{soil} \quad \text{(Equation 4)}$$

We also account for GHG emissions from forests and the loss of soil organic carbon due to agricultural practices but as a part of the total demand.

Some countries were not included in the soil sequestration dataset for several reasons, as reported by the data sources. These countries are Australia, Austria, Belgium, Dominica, Italy, the Maldives, the Netherlands, New Zealand, Norway, Saint Lucia, and Saint Vincent and the Grenadines. We estimated these countries' soil carbon sequestration capacities based on their land cover types and the global average soil sequestration amount.

Social foundation

We identify the social foundation as the minimum demand to meet people's basic needs ($D_{i,j}^{min}$) from the selected ESs. In this work, we focus on the minimum availability of carbon sequestration and water provisioning ESs. This definition aligns with the UN SDGs of providing access to food (SDG2), water (SDG6), and energy (SDG7) for everyone. Meeting these demands requires more than just goods from ecosystems; the negative impacts from agricultural activities and electricity generation require other ESs, such as air and water quality regulation services. The UN[25] and WHO[24] define the minimum water threshold for basic activities ($T_{basic,j}$) such as drinking, cooking, and sanitation as 0.1 m^3/day/capita. The FAO[26] defines the minimum amount of food in terms of caloric intake ($T_{cal,j}$) based on age, sex, and physical activity, and this amount differs relative to a community's cultural and geographical location, with a range of 1,650–2,100 kcal/day/capita. The International Energy Agency (IEA) and the UN use a threshold ($T_{e,j}$) of 1,250 kWh/year/household to define access to energy.[27,28]

Hence, we formulate the social foundation by physically quantifying the demand ($D_{i,j}^{min}$) for all goods and services from the different ESs necessary to meet the basic needs of the entire population (P_j) in the study area. Then, the demands are added to form the lower limit of the SJS (an illustration of the method is provided in Note S1 and Figure S1).

The minimum water needed for basic activities for the entire population in a country may be calculated as

$$W_{basic,j} = P_j \, T_{basic,j} \quad \text{(Equation 5)}$$

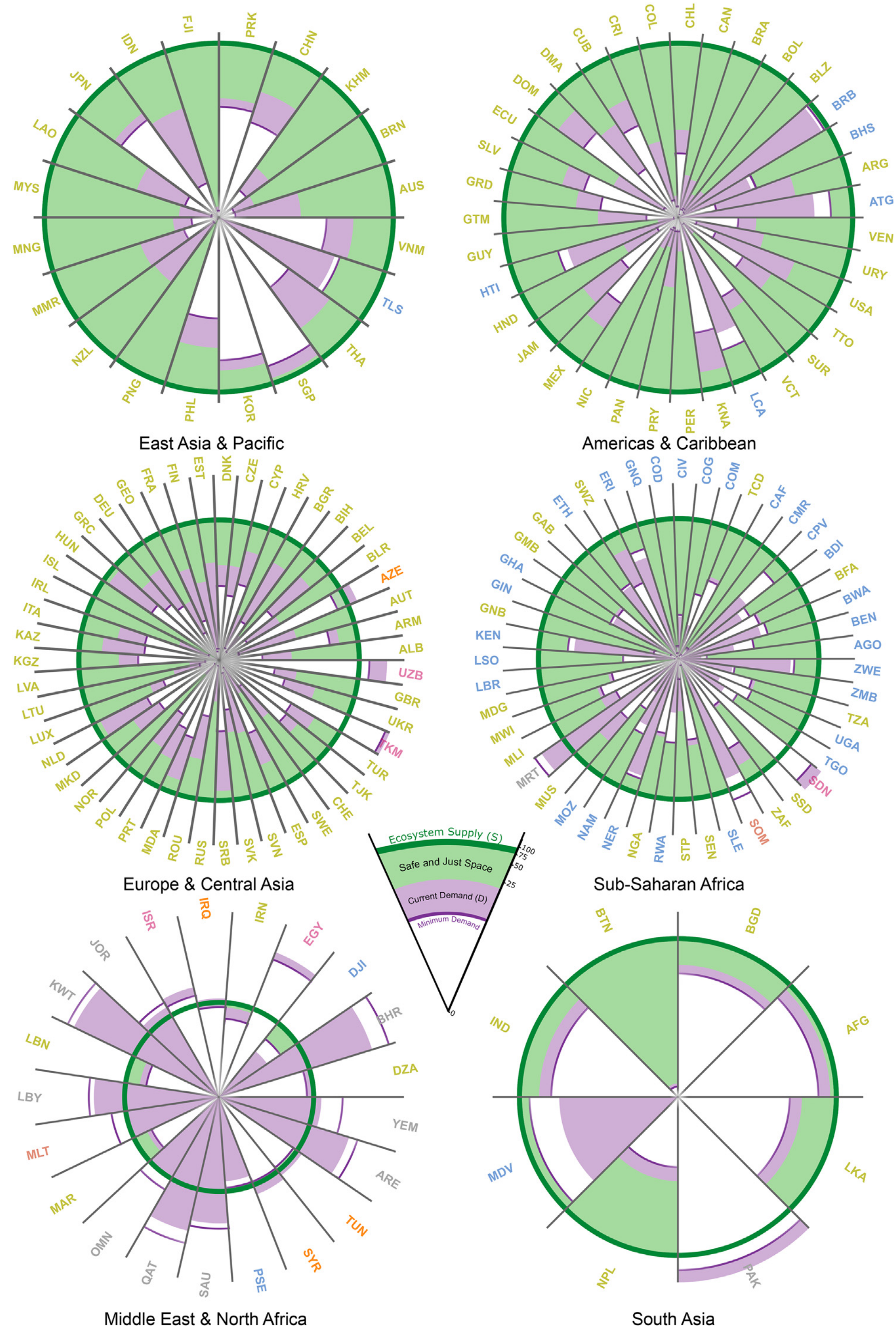

Figure 5. National performance relative to the SJS for the water provisioning ES

The donut plots show the extent of overshoot beyond the ecosystem supply or the extent of shortfall from the minimum demand thresholds for the water provisioning ES. Countries are grouped and colored as per Figure 3. The parameters are normalized by the supply and plotted on a log scale for legibility (see Table S1 for full country names).

To grow food and meet the basic caloric intake threshold, water is needed in most parts of the world. Since this analysis is based on current practices, we calculate the water intensity ($I^W_{f,j}$) per calorie for each country based on the water withdrawal of the agricultural sector and the total calories produced. Then, we use this to calculate the water needed for food production to meet the social threshold as

$$W_{f,j} = I^W_{f,j} P_j T_{cal,j} \quad \text{. (Equation 6)}$$

Electricity is also needed for cooking, heating, and shelter and requires a significant amount of water in its generation process. Water intensity ($I^{W}_{e,j}$) varies significantly based on the fuel source and technology used. Although data for actual water intensity are available for some countries, they are missing for most. Therefore, we use data on the latest energy mix (m_j)[27] to calculate the water intensity for comparison. We use the following equation to calculate the water needed for electricity generation to satisfy the energy threshold.

$$W_{e,j} = P_j\, T_{e,j} \sum \left(m_j\ I^{W}_{e,j} \right) \quad \text{(Equation 7)}$$

Then, the minimum demand to meet food, energy, and water needs from the water provisioning ES ($D^{min}_{W,j}$) is calculated as

$$D^{min}_{W,j} = W_{basic,j} + W_{f,j} + W_{e,j} \quad \text{. (Equation 8)}$$

Food production and electricity generation are the leading sectors of GHG emissions. We use a similar approach to calculate the GHG intensities ($I^{C}_{e,j}$, $I^{C}_{f,j}$) and the necessary emissions to meet the energy and caloric intake thresholds and calculate the minimum demand ($D^{min}_{C,j}$) as follows:

$$D^{min}_{C,j} = C_{f,j} + C_{e,j} \quad \text{, (Equation 9)}$$

where

$$C_{f,j} = I^{C}_{f,j}\, P_j\, T_{cal,j} \quad \text{, and (Equation 10)}$$

$$C_{e,j} = P_j\, T_{e,j} \sum \left(m_j\, I^{C}_{e,j} \right) \quad \text{. (Equation 11)}$$

Current levels of demand

After defining the SJS, we use the current demand ($D_{i,j}$) for water and carbon sequestration from all sectors within a country to assess the operating conditions with respect to the safe and just requirements. Different scenarios can emerge from the relative relation of ecological boundaries, social foundation, and current demand as illustrated in Figure 1 (see also Notes S3 and S4).

Most activities in our daily life require water use, such as irrigation for agricultural activities or electricity generation for industrial activities. We quantify the total freshwater withdrawal demand from all activities, including water from desalination plants ($D_{W,j}$). The amount withdrawn can exceed the supply in cases where there is a high dependency on desalination processes or withdrawal from nonrenewable aquifers.

Humans are already emitting more CO_2 than the capacity of the ecosystems has to sequester it at an alarming rate. This is one of the main drivers of GHG reduction initiatives and net-zero commitments. Energy generation, such as for electricity, heat, and transportation, is the leading source of CO_2 emissions globally.[40] The total demand for carbon sequestration ES is derived from all these sectors, in addition to deforestation, agricultural practices, and land-use change ($D_{C,j}$). An illustrative example highlighting the full methodology is shown in Note S7.

SUPPLEMENTAL INFORMATION

Supplemental information can be found online at https://doi.org/10.1016/j.oneear.2023.03.008.

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AUTHOR CONTRIBUTIONS

Y.M.A. and B.R.B. designed research; Y.M.A. performed research and analyzed data; B.R.B. supervised the research; and Y.M.A. and B.R.B. wrote the paper.

DECLARATION OF INTERESTS

The authors declare no competing interests.

INCLUSION AND DIVERSITY

We support inclusive, diverse, and equitable conduct of research.

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