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Fanxin Meng and Danqi Liao contributed equally to this work.

Key Points:

- A consumption-based integrated framework for subnational environmental sustainability management within planetary boundaries was developed
- All Chinese provinces overconsumed Nitrogen, Phosphorus, and Carbon dioxide-intensive products
- Henan, Shandong, Shanghai, and Jiangsu were identified as priorities for absolute environmental sustainability management

Supporting Information:

Supporting Information may be found in the online version of this article.

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A Consumption-Based Integrated Framework for Subnational Absolute Environmental Sustainability Management

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Abstract As human consumption expands, four environmental footprints (EFs) exceed the planetary boundaries (PBs) at the global scale. Managing absolute environmental sustainability (AES) based on PBs and EFs at the subnational level is crucial for policy insights. However, a consumption-based AES management framework still needs to be developed. A framework, including five nexus environmental pressures embodied in the supply chain, was developed and tested in our study across China's 30 provinces to address this knowledge gap. The framework involved three steps: (a) assessing AES for five environmental pressures, (b) measuring environmental surplus and overshoot and composition of EFs, and (c) identifying priority areas for AES management. The results showed that only some provinces are sustainable for three impact-oriented indicators, especially those with larger populations. Moreover, the embodied environmental pressure mainly flows from the Northwest to Southeast China. For two resource-oriented indicators, over 74% of provinces are absolutely sustainable. From a nexus perspective, Shandong and Shanghai are identified as priorities for AES management due to their low IESI values of 0.32, 0.33, and 0.40, respectively, which means the worst performance. To improve their IESI, Shanghai needs to control the consumption of blue water-intensive products, while Shandong and Henan should consume fewer CO_2 emissions and N- and P-loss-intensive products. This framework can clarify subnational responsibilities of environmental overshoots, guide sustainable development, and be widely used at the subnational level in countries worldwide.

Plain Language Summary Earth's ecosystem has a limited ability to provide natural resources and accept pollutants. Absolute environmental sustainability (AES) assumes that irreversible impacts will occur once human needs surpass this capacity, emphasizing the need for policymaking based on the current situation. As a crucial policy-related entity, subnational regions urge AES management. Here, we focus not only on assessing AES of five environmental pressures (including carbon dioxide (CO_2) emission, freshwater use, Nitrogen (N) loss, Phosphorus (P) loss, and land use) embodied in supply chains but also on identifying the priorities of AES management among 30 Chinese provinces. We found that the CO_2, N, and P driven by final demands have transgressed the absolute limits in all provinces, especially with larger populations. They mainly consume products from Northwest China. More than 74% of the provinces are within the freshwater and land use boundaries. Shanghai, Shandong, and Henan are identified as priorities of AESA management because of their lousy performance from a nexus perspective. They should be responsible for consumption. Applying this framework globally at the subnational scale is crucial for consumption-based AES management and global environmental preservation.

1. Introduction

The Earth has a finite biophysical carrying capacity for natural resource provision and pollutant absorption (Arrow et al., 1995; Daily & Ehrlich, 1994). Keeping global human appropriation of natural capital (Hoekstra, 2009) below the carrying capacity (Goodland & Daly, 1996) and revisiting limits for environmental sustainability assessment (ESA) attract attention from the academic community (Chen et al., 2021; Price, 1999). Absolute environmental sustainability assessment (AESA) utilizes the absolute environmental limits as the

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carrying capacity (Bjørn et al., 2016; Ryberg et al., 2020) and is connected with UN Sustainable Development Goals (SDGs) (United Nations, 2015) to inform decision makers.

Planetary boundaries (PBs) (Rockström et al., 2009) define a safe operating space for humanity by setting absolute limits for nine critical Earth system processes, beyond which the ecosystem would face irreversible environmental problems (Steffen et al., 2015). It is allocated to the analyzed activity (Oosterhoff et al., 2023) and compared with the current level of environmental pressure embodied in comprehensive supply chains (Yang et al., 2022), namely consumption-based environmental footprints (CEFs), in AESA. Recent studies have shown that the global CEFs are expanding rapidly (Hoekstra & Wiedmann, 2014), with four transgressing the PBs (Li et al., 2021).

The PBs and CEFs framework (Fang et al., 2015a, 2015b) has been widely used at global and national scales (Fanning et al., 2022; Hickel et al., 2022; Li et al., 2019; O'Neill et al., 2018; Zhang & Zhu, 2022). It can quantify the absolute environmental sustainability (AES) and allocate the responsibility for consumption-based ecological breakdown (Rockström et al., 2021; Wiedmann & Lenzen, 2018). Previous studies quantified the countries' responsibility for climate (Hickel, 2020) and ecological (Hickel et al., 2022) breakdown by calculating the national contribution of global cumulative carbon dioxide emission and material use overshoot. They conclude that high-income countries are the main contributors to ecological breakdown. To further measure the performance of high-income countries, some studies focus on a single developed country, such as Sweden (Nykvist, 2013), Denmark (Bjørn et al., 2018), Switzerland (Dao et al., 2018), and New Zealand (Chandrakumar et al., 2020), and found that a large portion of their allocated PBs has been exceeded by their CEFs, with external footprints often larger than internal footprints, indicating the need for these countries to take more responsibility for external environmental problems. For example, Dao et al. (2018) downscaled six national boundaries for Switzerland based on population. They found that four (climate change, ocean acidification, biodiversity loss, and nitrogen loss) have already been exceeded as Switzerland relies on the rest of the world (RoW) for its consumption. It also shows that though some footprints remain within their planetary boundaries at the global scale, they have already exceeded or approached downscaled boundaries in Switzerland. It means that downscaled analysis is vital for a country to achieve AES.

Subnational regions have a significant role in cross-scale decision-making and environmental management (Wilting et al., 2021; Xu et al., 2022). Evaluating their AES is the key to identifying hotspot regions of a country (Xu et al., 2020). Li et al. (2020) developed two consumption-based PB indicators to assess the exceedance and surplus of water. They discovered that all analyzed Chinese provinces and cities exceed the downscaled freshwater PB, which is different from the situation at the global scale. Specifically, two aspects are needed to consider. First, we should assess if each environmental footprint has exceeded its boundary at the subnational scale. Second, we need to analyze multiple footprints comprehensively, as a single footprint cannot reflect the complexity of the entire environmental issues within the supply chain (Fang et al., 2014). Fanning and O'Neill (2016) developed a biophysical framework that translates planetary boundaries (carbon emission, nitrogen, phosphorus, fresh water, and biocapacity) into national and subnational levels of Spain and Canada and links them to consumption to prioritize which environmental pressures need to decline based on the extent of overshoots. Hu et al. (2020) examined the sustainability of the Chinese food system by conducting AESE for four pressures. They used scenario analysis considering the adjustment of the food system to observe the change of these pressures and identify management strategies for the food system. Considering seven environmental pressures, Hachaichi and Baouni (2020) developed a PBs-EFs framework for 62 large cities in the Middle East and North Africa (MENA) region to link the growing economies to global environmental sustainability issues. These studies have contributed to the practice and application of managing absolute environmental sustainability (AES) by considering the AES of multiple environmental pressures. However, they lack an overall picture of AES management that includes AES assessment and measurement of overshoot and surplus for responsibility clarification and the use of integrated indicators (Wu et al., 2021) to rank subnational regions based on their comprehensive performance of the environment.

To address this knowledge gap, we construct a consumption-based AES (CAES) management framework based on the PBs and CEFs at the subnational scale. We have incorporated the metacoupling analysis (Liu, 2023; Wiedmann & Allen, 2021) and the nexus thinking (Meng et al., 2023; Wang et al., 2022) in our framework, which provides a flow-based perspective. It helps measure the intracoupled (local), pericoupled (transferring through imports from other subnational regions), and telecoupled (transferring through imports from other countries)

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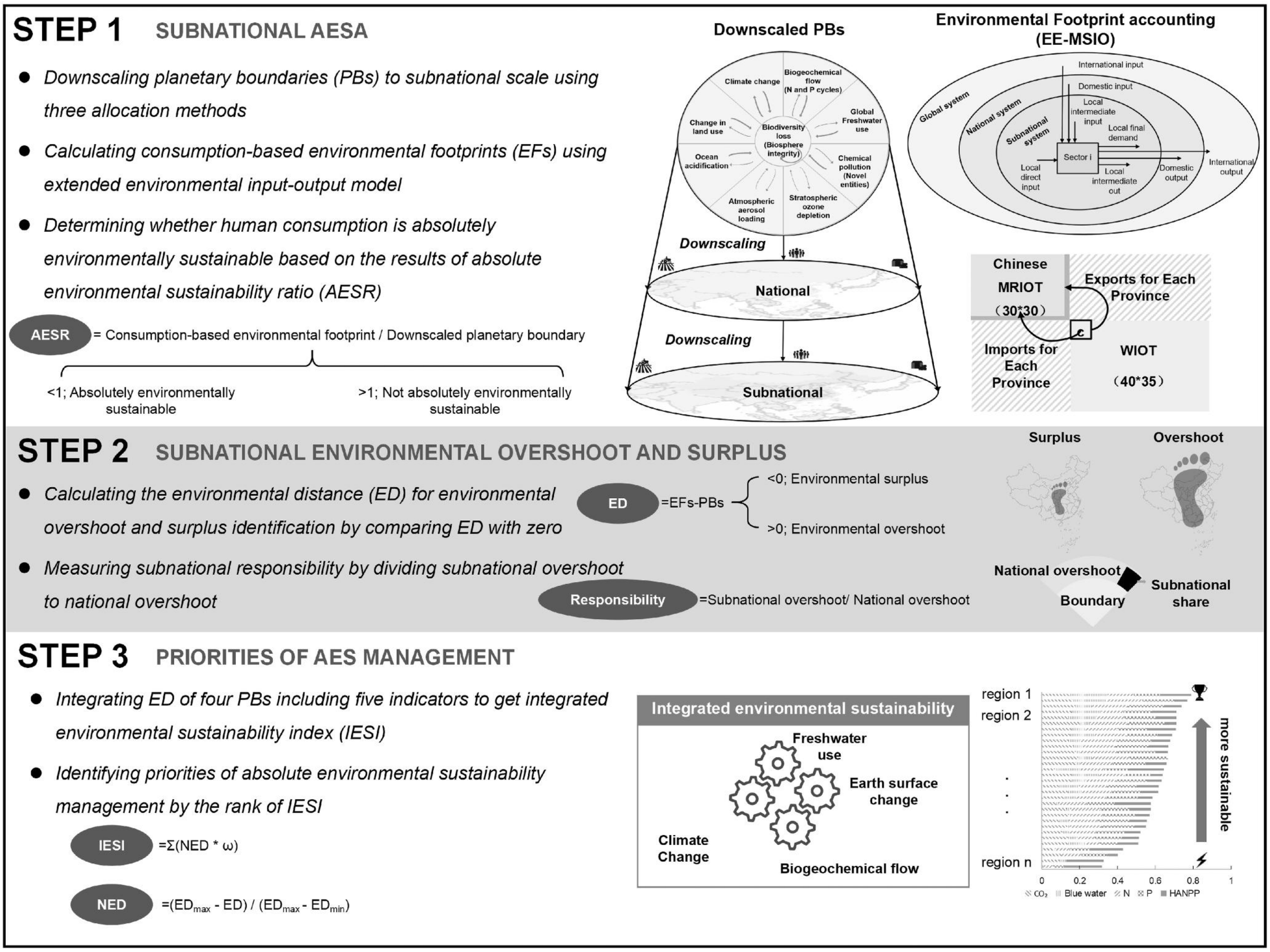

Figure 1. Subnational consumption-based absolute environmental sustainability management framework.

environmental pressure. It has been conducted to analyze metacoupling environmental pressures of subnational regions in terms of individual environmental elements (Li et al., 2023; Xu, et al., 2019b) and multiple environmental elements (Xu et al., 2022; Xu, et al., 2019a), which can be well-connected with our CAES management framework. Then, 30 provinces of China were chosen to evaluate the CAES of each environmental control variable, measure the overshoots and surpluses, and identify priorities for AES management among subnational regions. The paper is organized as follows: (a) an introduction of calculating methods and data sources, (b) the application of a subnational consumption-based absolute environmental sustainability framework in China's 30 provinces, and (c) discussions based on results.

2. Methods

2.1. Subnational Consumption-Based Absolute Environmental Sustainability Management Framework

We constructed a subnational consumption-based absolute environmental sustainability management framework based on PBs and EFs (as shown in Figure 1) to determine whether human consumption is absolutely environmentally sustainable, to clarify the responsibility for environmental overshoot, and to identify the priorities in environmental sustainability management.

In the first step, we calculated the EFs, downscaled the boundaries, and divided downscaled PBs by EFs to get the indicator Absolute Environmental Sustainability Ratio (AESR) of each environmental pressure.

In the second step, we constructed a metric environmental distance (ED) by subtracting downscaled PBs from EFs to calculate the environmental surplus and overshoot of each province and quantify the responsibility of overshoot through the contribution of each province to national environmental overshoots. Moreover, we used the metacoupling analysis to help explain the composition of overshoots by considering the intracoupled pressure, pericoupled pressure, telecoupled pressure.

In the third step, we standardized the ED using an extreme values method and combined them with equal weights to obtain the integrated environmental sustainability index (IESI), which was ranked to identify the priority of environmental sustainability management from a nexus perspective.

Specifically, five parts are considered in this section. (a) The environmental pressures along the supply chain are calculated in the input-output model. (b) Four planetary boundaries, including five control variables (CO_2, N, P, BW, and HANPP), are chosen and then downscaled to the subnational scale representing the absolute limits of subnational regions. (c) To determine whether studied regions are absolutely sustainable, a consumption-based absolute environmental sustainability assessment is conducted using the AESR which is evaluated by the ratio of EFs to absolute limits. (d) environmental overshoots and surpluses are measured based on the difference between EFs and downscaled PBs and responsibility for overshoot is quantified by the ratio of subnational overshoot to national overshoot. (e) Priorities of absolute environmental sustainability management are identified using the integrated environmental sustainability index (IESI) which is constructed based on environmental overshoot and surplus.

2.2. Consumption-Based Environmental Footprint Accounting

We choose four kinds of environmental pressure, including three impact-oriented indicators (GHG emission, Nitrogen (N) loss, and Phosphorus (P) loss) to characterize environmental impacts and two resource-oriented indicators (bluewater footprints and land use) to characterize resource consumption level.

2.2.1. Environmental Inventory

2.2.1.1. Impact-Oriented Indicator

For GHG emissions, this study considers three key greenhouse gases (CO_2, CH_4, and N_2O) to obtain an inventory of greenhouse gases related to climate change based on the Kyoto Protocol. China's official statistics do not publish GHG emissions data every year, so estimates need to be based on energy consumption and emission coefficients. This is further subdivided into an energy module and a non-energy module. Energy balance sheets were used and uniformly mixed or divided into 35 sectors for this study's estimation of GHG emissions using the IPCC methodology.

For N and P loss, the inventories were compiled using the material flow analysis (MFA). We mainly consider the reactive nitrogen and phosphorus emissions to the atmosphere and water bodies from the food production system through cascading flows model and input-output balances of subsystems. Specifically, the nitrogen and phosphorus emission (F) for food type f in region r was calculated by multiplying activity data (D) by emission factors (R) in all the production processes (p).

$$F_{f,r} = \sum_{p} D_{f,r,p} \times R_{f,r,p} \tag{1}$$

2.2.1.2. Resource-Oriented Indicator

For the calculation of the bluewater (BW) footprint, which reflects the freshwater use, five primary categories are considered (agriculture, industry, construction, services, and residential life). Each sector is calculated by multiplying the corresponding blue water footprint coefficient by the level of activity (e.g., crop and livestock production), which is used in our previous studies (Hu et al., 2020; Meng et al., 2022).

As for land use, we use human appropriation net primary productivity (HANPP) inventory to express. HANPP is the difference between the net primary productivity that a natural ecosystem may create in the absence of human disturbance (NPP_{pot}) and the net primary productivity that is still there in the ecosystem after human harvesting and usage (Liu et al., 2020). The equation looks like this,

$$HANPP = NPP_{pot} - NPP_{act} - NPP_{harv} \quad (2)$$

where NPP_{pot} denotes the natural ecosystem's potential net primary productivity created in the absence of human interference, NPP_{act} denotes the natural ecosystem's actual net primary productivity, and NPP_{harv} denotes the net primary productivity harvested. The estimates in this research only account for above-ground biomass due to the existing ambiguity in calculating below-ground biomass. The total is expressed as kg C/yr.

2.2.2. Environmental Footprints Accounting

Consumption-based environmental footprints are calculated using the environmental extended-multiscale input-output (EE-MSIO) model. This model was built based on the fundamental linear multiregional input-output (MRIO) model $\mathbf{X} = (\mathbf{I} - \mathbf{A})^{-1}\mathbf{Y}$.

It is extended by incorporating the environmental satellite account ($\mathbf{E}$) to calculate EFs and identifies the environmental pollutant emissions or resource uses of each sector, expressed as follows:

$$EF_{i,j} = e(\mathbf{I} - \mathbf{A})^{-1}\mathbf{Y} \quad (3)$$

where $EF_{i,j}$ is the environmental impact embodied in goods and services used for the final demand for the environmental issue i in region j, and e is the sectoral environmental intensity per unit output.

Based on the equations of the fundamental EE-MRIO model, the EE-MSIO model utilized in this research was constructed by linking the Chinese MRIO to the World Input-Output Database (WIOD) table in the global economic system; this model was widely used in our previous study (Hu et al., 2020; Meng et al., 2018a, 2018b, 2022). The Chinese input-output table in the WIOD is subdivided into 30 subnational levels since China is one of the 41 regions in the WIOD. Excluding Tibet, Hong Kong, and Macau, the model considers 30 provinces (including four municipalities).

Based on the availability of data, we used the MRIOT of China for 2010 to test the framework. Based on provincial exports and imports in the Chinese MRIOT, the WIOD's international import and export matrices for China were similarly divided and assigned to the 30 provinces. Each province's international exports were allocated to foreign importing sectors in the same proportion as China's overall exports.

2.3. Downscaling the Biophysical Boundaries

2.3.1. Selection of Planetary Boundaries

Considering the relationship between planetary boundaries, four planetary boundaries (climate change, land system change, freshwater use, and biogeochemical flows) are downscaled to 30 provinces (including four Municipalities and excluding Tibet, Hongkong, and Macao) based on population, per land area, and Gross Domestic Product (GDP).

2.3.1.1. Climate Change

Due to the difficulty in translating the planetary boundary for atmospheric CO_2 concentration into a meaningful per capita boundary, we base our calculations on the goal of limiting global warming to 2°C (Rockström et al., 2009), as emphasized in the Paris Agreement. The value of the control variable in this study is 11.21 $GtCO_2$ e yr^{-1}.

2.3.1.2. Biogeochemical Flows

The planetary boundaries for biogeochemical flows contain two parts, including the nitrogen cycle and the phosphorus cycle. We follow O'Neill's (2018) study to focus on the amount of nitrogen and phosphorus discharged to water bodies and soil. The limits for P and N loss are 6.20 and 62.00 Mt respectively.

2.3.1.3. Freshwater Use

In terms of freshwater use, we follow Hu et al. (2020). We obtained the renewable water resource of China (28,400 million m^3) from the Food and Agriculture Organization of the United Nations (FAO) and the water resources of each province from The China Agricultural Yearbook (National Bureau of Statistics, 2011a). The amount of renewable water resources in each province is determined by the proportion of each province's water resources to the national level. The downscaled freshwater use boundaries are 40% of provincial renewable water resources.

2.3.1.4. Land-System Change

As a measure of land-system change, we use a novel indicator, namely human appropriation of net primary production (HANPP), which has been proposed as a control variable for the planetary boundary. HANPP measures the amount of biomass that is killed during harvest but not used and biomass that is lost due to land-use change. According to previous research, the limit for HANPP (O'Neill et al., 2018) is 18.2 Gt C yr^{-1}.

2.3.2. Allocation of Planetary Boundaries

To allocate planetary boundaries without considering human interest, equal per capita (EPC), equal per land area (EPL), and equal per GDP (EPG) approaches are used, namely downscaling the three PBs (climate change, land system change, and biogeochemical flows) based on population, land area, and Gross Domestic Product (GDP). Since the PB for biogeochemical flows is represented by two separate indicators (N and P), four indicators are considered in total. All four indicators are consumption-based measures that account for international trade. For freshwater use, we used 40% of the locally renewable water resources to define the downscaled PBs. This method takes into consideration the regional water scarcity and the potential adverse impacts of excessive water withdrawals on the necessary environmental flow requirements.

Specifically, the three methods are based on different principles and considerations. Allocation based on population is the most widely used and accepted method (Williges et al., 2022), as it allocates based on Egalitarian principles and guarantees the rights of every person. The distribution based on occupied land area follows the Acquired Rights principle (Ryberg et al., 2020), and considers the area's capacity to contain pollutants. This method is mostly used to evaluate the sustainability of the region's nitrogen and phosphorus levels (Fanning & O'Neill, 2016). GDP-based distribution, on the other hand, assumes that richer regions can have more permits. This is similar to the consensus principle, which distributes permits based on relatively fair negotiations (Rose, 2009).

2.4. Consumption-Based Absolute Environmental Sustainability Assessment

We constructed the absolute environmental sustainability ratio (AESR) for consumption-based AESA in this section. It helps quantify the level at which anthropogenic environmental stress reaches or surpasses a critical capacity threshold, namely, whether it is absolutely sustainable or not, and provides a baseline for policymaking in the future, equations are as follows:

$$\mathrm{AESR}_{i,j} = \mathrm{EF}_{i,j}/\mathrm{EB}_{i,j} \tag{4}$$

where, $\mathrm{AESR}_{i,j}$ is the Absolute Environmental Sustainability Ratio for the environmental issue i in region j. $\mathrm{EF}_{i,j}$ is the footprint for the environmental issue i in region j; $\mathrm{EF}_{\mathrm{i},j}$ is the boundary for the environmental issue i in region j; when $\mathrm{AESR}_{i,j} > 1$, the footprint metric exceeds the corresponding boundary metric, namely not absolute environmentally sustainable for the environmental issue i in region j; and when $\mathrm{AESR}_{i,j} < 1$, the situation is absolute environmentally sustainable and keeps the environmental impact of human activities within the specified capacity range.

2.5. Environmental Overshoot and Surplus

Environmental overshoot and surplus based on environmental distance (ED) (Fang, Heijungs, Duan, et al., 2015) are considered to clarify responsibility, which subtracts EF (reflecting the current state) from the environmental boundary (EB) (reflecting the critic threshold), representing the environmental pressure under current human activities.

$$\mathrm{ED}_{i,j} = \mathrm{EF}_{i,j} - \mathrm{EB}_{i,j} \tag{5}$$

where, $\mathrm{ED}_{i,j}$ is the environmental distance for the environmental issue i in region j. When $\mathrm{ED}_{i,j} < 0$, the footprint is lower than the boundary, representing an environmental surplus; when $\mathrm{ED}_{i,j} > 0$, the footprint is beyond the boundary, there is an environmental overshoot; and when $\mathrm{ED}_{i,j} = 0$, the footprint equals to the boundary.

And the responsibility for environmental overshoot of each province is quantified referring to Hickel et al. (2022), as follow:

$$\text{Responsibility} = \frac{\text{Evironmental overshoot}_{i,j}}{\sum_j \text{Environmental overshoot}_{i,j}} \tag{6}$$

2.6. Identification of Priorities for Consumption-Based Absolute Environmental Sustainability Management

To identify priorities of consumption-based AES management from a nexus perspective, we construct a composite indicator, namely the integrated environmental sustainability index (IESI), combining the values of ED through weighting.

First, ED is made comparable by eliminating the differences in magnitudes and units of each element using a standardized method. Here, we use the extreme difference method to standardize the environmental distance.

Normalized environmental distance (NED) can be calculated as:

$$\mathrm{NED}_{i,j} = (\mathrm{ED}_{i,\max} - \mathrm{ED}_{i,j})/(\mathrm{ED}_{i,\max} - \mathrm{ED}_{i,\min}) \tag{7}$$

where, $\mathrm{NED}_{i,j}$ is the normalized environmental distance for the environmental issue i in region j; $\mathrm{ED}_{i,\max}$, $\mathrm{ED}_{i,\min}$ are the maximum and minimum values of the environmental distance of the environmental issue i among Chinese provinces, respectively.

And then, IESI is calculated as:

$$\mathrm{IESI}_j = \sum_i^j (\mathrm{NED}_{i,j} * \omega) \tag{8}$$

where, IESI_j is the integrated environmental sustainability index for subnational region j, and ω is weighting coefficient, which is equal for each environmental indicators (Müller et al., 2021) in each province. IESI ranges from 0 to 1. Specifically, four sustainable ranks are defined as follows: I (IESI: 0.75–1.00), II (IESI: 0.50–0.75), III (IESI: 0.25–0.50), and IV (IESI: 0–0.25).

2.7. Data Sources

In this study, we consider five environmental elements, including CO_2, BW, N, P, and HANPP. For 40 global regions, these data are taken from the WIOD database.

For CO_2 emissions, energy balance sheets for each province in China were obtained from the China Energy Statistics Yearbook (National Bureau of Statistics, 2011b) and the China Statistical Yearbook (National Bureau of Statistics, 2011c). The obtained sheets were uniformly mixed or divided into 35 sectors to estimate CO_2 emissions in this study using the IPCC methodology (IPCC, 2019). China's subnational regions are divided into five primary categories based on the corresponding water consumption: agriculture, industry, construction, services, and residential life. The China Agricultural Yearbook (National Bureau of Statistics, 2011a) provided information on the production of different types of crops. The China Statistical Yearbook (National Bureau of Statistics, 2011c) provided information on the production of livestock products by region, and Hoekstra et al. (2011) provided information on the BW footprint coefficients for China by regional crop type and livestock product type. Water consumption data for industrial subsectors are obtained by extrapolating the amount of water abstracted and subtracting the amount of wastewater. The volume data of water consumption for China's subnational sectors were described in our previous study (Meng et al., 2022). For nitrogen and phosphorus emissions, we refer to (Hu

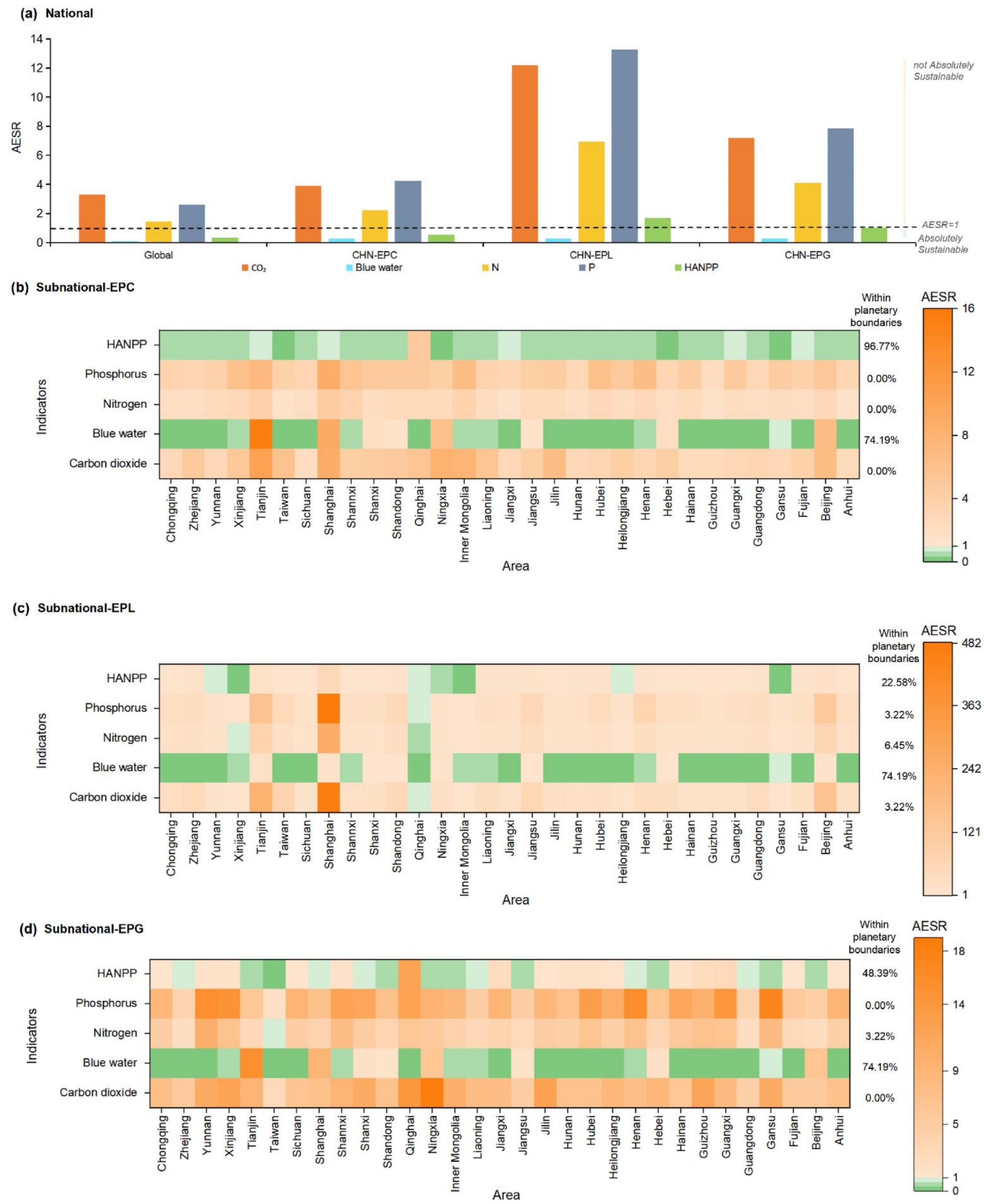

Figure 2. Consumption-based Absolute Environmental Sustainability of China (CHN) at national and subnational scales (a) national result (b) subnational result based on EPC method, (c) subnational result based on EPL method, (d) subnational result based on EPG method. Note: The black dotted line in (a) represents the threshold (AESR = 1) beyond which a state of not absolute sustainability is indicated.

et al., 2020). As land use footprint, the data representing the NPP of the actual vegetation (NPP_{act}) were taken from the Moderate-resolution Imaging Spectroradiometer (MODIS) product MOD17 (Dietzenbacher et al., 2013), and the potential NPP (NPPpot) data were derived using a modified Carnegie-Ames-Stanford Approach (CASA) model. The detailed calculation steps can be found in our previous studies (Liu et al., 2020).

3. Results

3.1. Subnational Absolute Environmental Sustainability in China

The global and Chinese AESR values of five indicators are shown in Figure 2. Overall, China and the world both transgressed three (CO_2 emissions, N, and P) of the five PBs, meaning not absolutely sustainable, which has been confirmed in the study of Han et al. (2023). The global AESR values of three impact-oriented indicators (CO_2

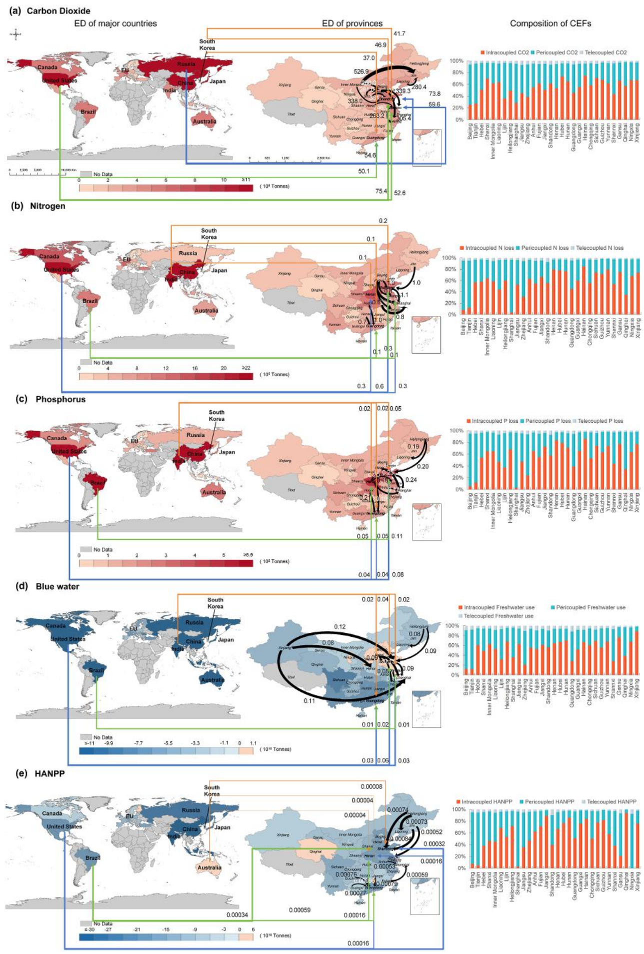

Figure 3. Flow-based environmental responsibility of subnational regions (a) metacoupled CO_2 emission and its overshoot and surplus at the global and subnational scale (b) metacoupled N loss and its overshoot and surplus at the global and subnational scale (c) metacoupled P loss and its overshoot and surplus at the global and subnational scale (d) metacoupled BW and its overshoot and surplus at the global and subnational scale (e) metacoupled HANPP and its overshoot and surplus at the global and subnational scale. Note: The area in red represents environmental overshoot and the area in blue represents environmental surplus.

emissions, N, and P) reach 3.3, 1.4, and 2.6, respectively. Two resource-oriented indicators (BW and HANPP) are absolutely sustainable with AESRs of 0.1 and 0.4, indicated by Dao et al. (2018) and Lade et al. (2020). As for China, the AESR values under the EPC method are smaller than the other two methods for China, and the HANPP is absolutely sustainable only under this allocation method.

Most provinces perform well under the EPC method at the subnational scale. The EPL method is favorable for provinces with large land areas in West China, such as Qinghai, Xinjiang, and Yunnan. Under the EPG method, high-income province performs better than low-income provinces, which may lead to inequality.

As the EPC method is widely used for responsibility allocation from a consumption perspective, we analyze the results using this method in the following parts. The AESR values of impact-oriented indicators are higher than 1 in all provinces under this method. Regarding carbon emissions, the AESRs of the 31 regions range from 2.3 to 10.7. The picture is better for the resource-oriented indicators. For BW, 23 provinces are absolutely sustainable. The HANPP performs best, with the AESRs ranging from 0.2 to 4.8, and only one region (Qing Hai) is not absolutely sustainable. Overall, 30 regions transgress at least two biophysical boundaries, and most regions transgress three.

3.2. Flow-Based Environmental Management of Subnational Regions

Globally, China contains 19.76% of the global population but accounts for 25.26%, 41.11%, and 39.67% of global overshoot of CO_2 emissions, N, and P loss, respectively. Subnational efforts are needed to address such issues. Figure 3 shows the environmental distance between major countries (on the left side) and subnational regions in China. Figure S1 in Supporting Information S1 shows the environmental overshoot and surplus of six major economies (occupying 73.6% of the GDP and 52.5% of the global population) under three allocation methods.

In Figures 3a–3c, all countries and subnational regions analyzed in this study have an overshoot of three impact-oriented indicators. For CO_2 emission, relatively developed regions with large populations, such as Beijing-Tianjin-Hebei (BTH), Guangdong, Shandong, and Yangtze River Delta (YRD), have the most considerable overshoot. The BTH region, a major urban agglomeration in China, absorbs around 7.70% of its population and contributes 11.56% of its carbon emission overshoot (about 0.75 Gt). It has the responsibility to change its large consumption of carbon-intensive products. As shown in the left and middle of Figure 3a, its consumption mainly drives the intracoupled (39.21%) and pericoupled (56.17%) carbon emission, mainly from subnational regions around it, including Inner Mongolia and Shanxi. As for YRD, it consumed carbon-intensive products mainly from itself and BTH, especially Hebei. Overall, pericoupled CO_2 moves from west to east and north to south in China. As for telecoupled CO_2, China primarily imports carbon-intensive products from the US, Russia, and South Korea, and Guangdong, Henan, Shandong, and Jiangsu mainly consume these products. For N and P (Figures 3b and 3c), the overshoot of major food consumption regions (Li et al., 2019), including Shandong, Henan, Sichuan, and Guangdong, is substantial. According to China's National Bureau of Statistics, Shandong Province ranks second in the country in terms of per capita egg consumption, with a nitrogen and phosphorus overshoot of 0.76 and 0.16 Mt, respectively, responsible for about 5.08% and 4.14% of the country's overshoot. Moreover, it mainly drives the intracoupled and pericoupled N and P loss from Northeast and Hebei, China's main granaries. Shanghai, as the economic centre of China, overshoot N and P boundaries of 0.52 and 0.16 Mt, respectively, is responsible for about 3.51% and 3.97% of the country's overshoot. Its consumption mainly causes the pericoupled N (92.62%) and P loss (93.84%), especially from northern China, including Hebei, Shandong, and Henan. As for

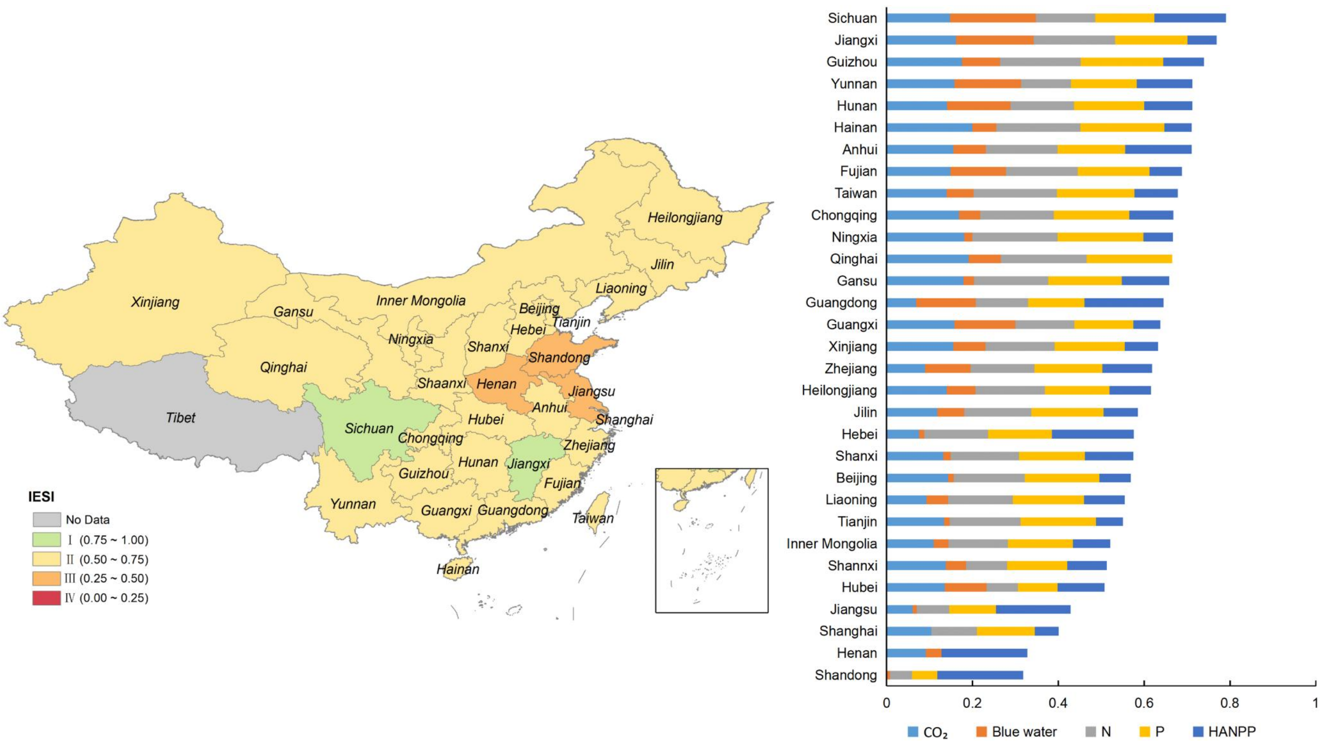

Figure 4. Priority of absolute environmental sustainability management and contribution of different indicators. Note: The rank of IESI is shown on the map on the left and the contribution of each environmental pressure is shown in the chart on the right.

telecoupled N and P loss, China primarily imports N, P-intensive products from the US, Brazil, and India, and Guangdong, Henan, Shandong, and Jiangsu mainly consume these products.

Regarding two resource-oriented indicators, environmental surplus occurs in most of China's countries and subnational regions. For BW (Figure 3d), only Shanghai, Shandong, Jiangsu, Shanxi, Ningxia, and BTH regions overshoot boundaries. BTH and Shanghai have the most considerable overshoot of 14.64 and 10.90 Gt, sharing 33.71% and 25.10% of the overall overshoot, respectively, as these provinces have high population and food consumption. Moreover, they should mainly focus on their pericoupled consumption of BW-intensive products, especially from Xinjiang and Northeast regions. Regarding the HANPP (Figure 3e), all regions have environmental surpluses except Qinghai, which has 56.69 Mt C of HANPP overshoot. Since their assigned limits are more significant, regions with a higher population have more surpluses. We also analyze the flow of HANPP-intensive products to manage the surplus better. We find that Guangdong and Shanghai mainly cause the HANPP consumption of adjacent provinces. As for telecoupled HANPP, China primarily imports HANPP-intensive products from the US, Brazil, and Australia, and Guangdong, Henan, and Shandong mainly consume these products.

3.3. Priorities of Consumption-Based AES Management

As shown in Figure 4, four ranks are defined based on the sustainability values of each province to identify areas that are the priorities of AESA management.

In Figure 4, from the population-based perspective, none of the regions are at the IV level of sustainability. From a nexus perspective, Shandong, Henan, Shanghai, and Jiangsu, which have the lowest values of IESI, are in the III level of sustainability. Shandong and Henan provinces are two of the top three in China in terms of population, with the lowest IESI values of 0.32 and 0.33, respectively. The consumption of Shandong is CO_2 and BW-intensive, as the contribution of CO_2 and BW to IESI is nearly zero. The consumption of Henan is N and P intensive, as the contribution of N and P to IESI is nearly zero. With China's highest GDP per capita, Shanghai has an IESI value of 0.40. Compared with other provinces, it prefers to consume bluewater and HANPP-intensive products. The contribution of bluewater and HANPP to IESI of Shanghai is lower among the five indicators,

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only 6.04% and 13.03%, respectively. Sichuan and Jiangxi are in the I level, with the highest IESI values of 0.79 and 0.77, respectively. They are all in South China. It is worth noting that the contribution of each indicator is nearly the same. The remaining regions (80.64%) are at II level with an IESI range from 0.51 to 0.71. From the analysis above, it is evident that the economically developed and populous provinces are the priority areas for sustainable management.

4. Discussion

4.1. Using a Subnational Consumption-Based Absolute Environmental Sustainability Management Framework to Mitigate Inequality

We propose a new environmental sustainability management framework that assesses the absolute sustainability of individual environmental indicators at the subnational scale and integrates them for environmental sustainability management priorities identification at the subnational scale. We analyze the current overshoot or surplus level of embodied pollution and resource dimension in this study based on metacoupling analysis and test the framework in China's 30 provinces, aiming to achieve environmentally sustainable consumption at the subnational scale. This integrated framework can further guide consumption-based AES-related policy for subnational regions worldwide. In contrast to the previous studies, we compare subnational environmental boundaries and CEFs obtained from three top-down downscaled approaches, further clarify the responsibility of each region in the national overshoot or surplus, and finally identify priority regions for AES management.

From an equity perspective (EPC downscaling method), consumption in significant economies contributes more to global environmental pollution overshoot. Despite holding 19.76% of the global population, they contribute 25.26%, 41.11%, and 39.67% to the global overshoot of CO_2 emissions, N, and P loss. Subnational efforts are deemed crucial to address these issues (Figure S1 in Supporting Information S1). Using China as a case study, we find that inequality exists in the country regarding the consumption of pollution-intensive and resource-intensive products. Developed provinces with large populations in China (e.g., Beijing-Tianjin-Hebei, Guangdong, Shandong, and the Yangtze River Delta) have consumed more than their fair share. This overconsumption has not only led to significant pollution emissions within these regions but also contributed to pollution problems in China's energy and fertilizer-intensive regions. Notably, there is an embodied pollution flow moving from the west to the east, for example, Inner Mongolia and Shanxi emit 33.8 and 28.1 billion tonnes of carbon dioxide to satisfy Shandong's consumption (Figure 3a), as well as from the north to the south, for example, Hebei loss about 25 kt phosphorus to satisfy Shandong's consumption (Figure 3c). Addressing these problems requires strengthening inter-regional cooperation and exploring reallocation measures like carbon pricing through taxes or emissions trading systems to curb excessive consumption (Cao et al., 2023). Furthermore, establishing compensatory mechanisms between developed regions and pollution-intensive product-producing areas is essential (Zheng et al., 2023). Subnational regions characterized by heavy industrial production should receive subsidies from "downstream" provinces within the supply chain to address imbalances and promote sustainable development.

Consumption of resource-intensive products is absolutely sustainable, that is, there is a surplus in major countries of the world and most subnational regions of China. Most provinces consume more pericoupled resource use than intracoupled resource use, especially for some provinces in the north-west, for example, Shaanxi, which is a water-scarce province, consumes 3,446.8 Mt of BW-intensive products from other provinces, accounting for 64.47% of Shaanxi's total consumption-based BW (Figure 3d). The province of Hebei is a significant contributor, which faces even more severe water scarcity. Failure to reasonably assign responsibility for mitigating water stress is likely to worsen inequalities due to variations in water resources. Hence, it is crucial to compensate for the water cost in regions facing water scarcity. This understanding allows us to recognize that trade can still benefit such regions (Motoshita et al., 2023; Wei et al., 2023).

Integrated sustainability assessment helps policymakers identify priorities of AES management in China from a comprehensive perspective and find critical environmental pressures through supply chains that affect the sustainable level of the global environment. For example, Shanghai has an IESI value of 0.40, and the component that contributes the least is BW, with a weight of approximately zero. This indicates that freshwater use driven by Shanghai's consumption exceeds the corresponding boundaries and needs to be addressed as a priority. Therefore, this study proves that the proposed framework can be used to allocate responsibilities for environmental sustainability at subnational scales and to inform policymakers about comprehensive sustainable management.

Concentrating on allocation methods, we downscaled the PBs based on the egalitarian, area-dependent, and GDP-dependent principles. The egalitarian principle advocates that each person has an equal right to use resources and emit pollutants; thus, the PBs are shared proportionally among the population of each entity (Rose, 2009). This is a strictly top-down approach to allocation and has been widely used in previous studies (Dao et al., 2018; Fang, Heijungs, Duan, et al., 2015; Fanning et al., 2022; O'Neill et al., 2018), representing a normative choice. The GDP-dependent and area-dependent principles are downscaled according to the GDP and land area. Under the area-dependent principle, PBs tend to be allocated to regions with relatively large land areas, causing a more significant portion to sparsely populated areas with low consumption levels. Less is allocated to metropolitan areas with trim and high consumption levels. Under the GDP-dependent principle, PBs tend to be assigned to large economies. So, the results differ under three distribution methods (See Figures S1 to S4 in Supporting Information S1), especially for HANPP.

4.2. Methodological Limitations

This study has some methodological limitations, including the selection of planetary boundaries, the granularity of the input-output tables, and the limitations of the weighting method.

First, the soundness of the five leading biophysical indicators selected in this text is worth considering. In the case of water resources, only BW was considered, while gray water was ignored. This was because when combining the indicators to characterize a country's environmental impact, attention needs to be paid to the mutual exclusivity of the accounts. As N and P lead to the eutrophication of water bodies, these nutrients are essential items affecting gray water (Hu et al., 2020). In addition, other spatially heterogeneous and mutually exclusive elements, such as biodiversity (Koslowski et al., 2020; Wilting et al., 2017), could be considered in the future. Also, we only use three-liner allocation methods to downscale the planetary boundaries, which are considered inappropriate for metrics with spatial heterogeneity (Tan et al., 2022).

Second, there are limits to the Input-Output (IO) table. Due to the data limitation of the IO table, we only tested our framework in China in 2010. It can not accurately reflect the current situation in China. However, it is worth it, as our framework can be widely used worldwide. On the other hand, the Input-Output table's granularity needs to be improved. WIOD includes only one agricultural sector. The chain-wide effects on water, nitrogen, phosphorus, and biomass (HANPP) consumption exhibit a significant degree of heterogeneity due to regional differences in dietary composition. In order to determine the effects of the various sectors (Cheng et al., 2024; Meng et al., 2021; Ogunmoroti et al., 2022) and create suitable policy suggestions (Cheng et al., 2023; Tahir et al., 2022), this calls for the construction of more accurate input-output tables. Therefore, further consideration will also be given to this in the future, as data allows.

Moreover, we used various environmental sustainability assessments in the PB category in this study. We weighted the results, but the weighting approach inevitably increased the uncertainty and subjectivity of the final estimates. Sensitivity analysis of the weights was performed by increasing and decreasing the weight by 20% of each environmental indicator (Details can be seen in Supporting Information S1). When the change rate of IESI is more significant than 4%, the region is sensitive to corresponding indicators. For example, Sichuan is sensitive to the change of two resource-oriented indicators (BW and HANPP), with IESI change rates of −5.1–5.1% and −4.2–4.2%, respectively.

4.3. Future Directions

The following three aspects summarize the future research directions of the PBs-EFs integrated framework.

First, consideration should be given to the SDGs' two additional dimensions (social and economic). Initial research has been done at the national level, but more research at the subnational level is still needed. The concept of the "safe and just operating space" was previously proposed by Raworth (2012) and her "donut economics" intuition. Fanning et al. (2022) used the Safe and Just Space (SJS) framework to examine the sustainability of more than 140 nations. They discovered that, on average, each nation achieves an additional social threshold at the expense of going over a biophysical limit. Based on the principles of Donut Economics (Raworth, 2017), appropriate models should be developed in the future at the subnational scale to investigate how socioeconomics and the environment are coupled, explore the impact of the same policy on both pressures and weigh the policy measures that are suitable for future development and in line with the principles of the circular economy (Kirchherr et al., 2017).

Moreover, the significance of the management framework lies not only in historical assessments but also in offering policy guidance and technical programs. Looking ahead, formulating scenarios (Huo et al., 2023) aligned with the time and target values of the SDGs plays a crucial role in the exploration of optimized options. Simultaneously, classifying subnationals for management purposes and identifying model regions within the same category can serve as a reference for other provinces within the unified region.

Second, if data are available to describe certain information, more ecological pressures, such as gray water and biodiversity, could also be considered. Third, absolutely sustainable consumption is also needed at the urban scale, as large urban clusters absorb large populations and have more demands for goods and services, such as the Beijing-Tianjin-Hebei region's situation analyzed above.

Conflict of Interest

The authors declare no conflicts of interest relevant to this study.

Data Availability Statement

The Input-Output tables for 40 global regions (Timmer et al., 2015) used in this study can be downloaded at (https://dataverse.nl/api/access/datafile/199123). The CO_2 inventory is calculated based on the method from the IPCC report (https://www.ipcc-nggip.iges.or.jp/public/2006gl/index.html). BW footprint coefficients for China by regional crop type and livestock product type obtained from Hoekstra et al. (2011). The volume data of water consumption for China's subnational sectors were described in our previous study (Meng et al., 2022). For nitrogen and phosphorus emissions, we refer to Hu et al. (2020). As land use footprint, the data representing the NPP of the actual vegetation (NPPact) were taken from the Moderate-resolution Imaging Spectroradiometer (MODIS) product MOD17 (Dietzenbacher et al., 2013), and the potential NPP (NPPpot) data were derived using a modified Carnegie-Ames-Stanford Approach (CASA) model (Ji et al., 2021). The detailed calculation steps can be found in our previous studies (Liu et al., 2020). Subnational boundaries and absolute environmental sustainability under three downscaled methods for this study are available in Meng et al. (2024).

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