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Metrics for a nature-positive world: A multiscale approach for absolute environmental sustainability assessment

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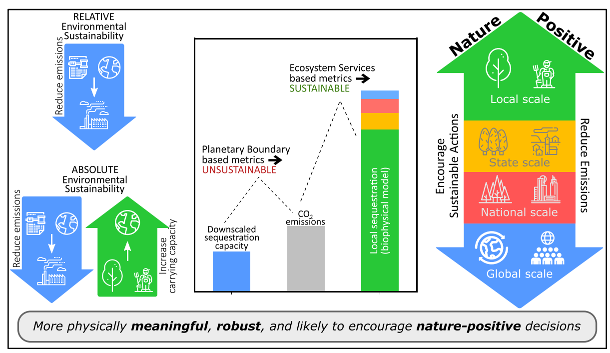
HIGHLIGHTS

- Provides novel insights into absolute environmental sustainability (AES) metrics
- Relates techno-ecological synergy and planetary boundary (PB) based metrics
- Proposed framework quantifies ecosystem capacity by multiscale biophysical models.
- Metrics are more precise, less subjective and encourage nature-positive decisions.
- Concludes that direct downscaling of PB can be misleading.

GRAPHICAL ABSTRACT



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ABSTRACT

Absolute environmental sustainability (AES) metrics include nature's carrying capacity as a reference to provide insight into the extent to which human activities exceed ecosystem limits, and to encourage actions toward restoration and protection of nature. Existing methods for determining AES metrics rely on the frameworks of Planetary boundaries (PB) and Ecosystem Services. This work provides new insight into the relationship between these methods and demonstrates that AES metrics based on the framework of techno-ecological synergy (TES) are better suited to encouraging nature-positive decisions. PB-based AES metrics downscale planetary boundaries or upscale local ecosystem services, but they partition available services among all users across the planet and make limited use of biophysical information. In contrast, TES-based metrics follow a multiscale approach that accounts for local ecosystem services estimated by biophysical data and models, and combine them with downscaled services from multiple coarser scales. These metrics can provide credit to stakeholders for local ecosystem services, thus encouraging ecosystem protection and restoration. Generally, the PB framework focuses on processes of global importance which currently include nine planetary boundaries that are critical for global stability. The TES framework considers ecosystem services from local to global scales and can be used for determining absolute environmental sustainability precisely at any spatial scale. Theoretical analysis shows that TES-based metrics are more general and can be specialized to PB-based metrics under certain conditions. Through case studies at multiple spatial scales and for various ecosystem services, we show that TES-based metrics are more robust, less subjective, and better suited for encouraging transformation to a nature-positive world.

1. Introduction

"Nature Positive by 2030" has recently been proposed as a global goal to stop and reverse the loss of nature (*Global Goal for nature*, n.d.). This goal complements the goal of equitable development which is the focus of the

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United Nations Sustainable Development Goals and the goal of carbon neutrality which is the focus of the United Nations Framework Convention on Climate Change. The goal of a nature-positive world aims to achieve Zero Net Loss of Nature from 2020, Net Positive by 2030, and Full Recovery by 2050 (Locke et al., 2021).

A fundamental requirement to encourage progress toward meeting this goal of being nature-positive is to have metrics that quantify the degree of "nature-positiveness" and encourage decisions toward restoration and protection of nature. Even though virtually every definition of sustainability includes the requirement that human activities should not exceed nature's carrying capacity (Brundtland et al., 1987; Fiksel, 2006), popular metrics for assessing environmental sustainability ignore the role of nature in supporting human activities and well-being (Bakshi et al., 2018). For example, metrics for assessing environmental sustainability in methods such as life cycle assessment (Hauschild and Huijbregts, 2015) and carbon footprint analysis (Wiedmann and Minx, 2008) are based on quantifying the impact of emissions and resource use without considering nature's ability to mitigate emissions or provide resources. Such metrics are useful for comparing the environmental impacts of alternatives and quantify relative sustainability. They encourage efforts to reduce environmental impact, usually by identifying activities with the largest contribution to the total impact, and determining ways of reducing their impact. Such efforts attempt to reduce the demand imposed by human activities on goods and services provided by nature (Bakshi et al., 2015) and encourage doing 'less bad' on the environment as compared to the alternative (McDonough and Braungart, 2013).

Efforts to include nature's carrying capacity in sustainability metrics to quantify "absolute environmental sustainability" have been increasingly popular over the last decade. The carrying capacity may be interpreted as nature's capacity to supply goods and services that are demanded by human activities. The demand for specific ecosystem services (ES) is represented by emissions and resource use, while their supply is determined by the capacity of relevant ecosystems (Bakshi et al., 2015). These metrics compare the environmental impact of human activities with ecological carrying capacity to quantify the "absolute environmental sustainability" (AES) (Bjørn and Hauschild, 2013; Bjørn et al., 2015, 2016). In addition to encouraging reduction of environmental impact, AES metrics also encourage ecosystem protection and restoration to enhance their carrying capacity. Thus, AES metrics could encourage doing 'more good' along with 'less bad' (Bakshi et al., 2015; McDonough and Braungart, 2013; Liu and Bakshi, 2019). This is in line with encouraging the 'Zero Net Loss' objective for becoming nature-positive which requires mitigating natural losses, and compensates for unavoidable losses through ecological restoration (Locke et al., 2021).

For calculating AES metrics, it is necessary to quantify the relevant carrying capacities. Many AES metrics rely on the framework of planetary boundaries (PB) (Rockström et al., 2009a,b; Steffen et al., 2015) for such quantification. PBs define the 'safe operating space' (SOS) for human development and are represented by nine essential earth system processes. Each process is related to an ecological boundary which is used as the reference point in assessing AES. These boundaries were identified due to their relevance to global sustainability and the possibility of large-scale disruption due to their violation. The PB framework was developed at a global scale, but most sustainability assessments are at scales that are much smaller than the planetary scale. To address this spatial mismatch, various approaches have been developed for downscaling planetary boundaries from their global scale to a local scale. Top-down methods allocate the global SOS in proportion to a quantity such as population, land area, emissions, GDP, etc. along with a specific sustainability perspective based on production, consumption or life cycle (Fang et al., 2015a). Planetary boundaries for impacts such as freshwater use have a significant local component due to the geographical separation of water availability in watersheds (Steffen et al., 2015; Bjørn et al., 2020). For example, water sustainability depends mainly on local availability. To address such localized requirements, bottom-up approaches have been developed that use information about water availability at local scales to establish sub-global boundaries at a watershed scale (Steffen et al., 2015; Bjørn et al., 2020). SOS at this sub-global level is then downscaled to the spatial scale of the selected systems. The hybrid AES approach combines top-down and bottom-up calculations. It modifies local availability with the global sustainability goal (Chen et al., 2021; Zipper et al., 2020). Despite their popularity, PB-based AES methods suffer from several shortcomings.

- Approaches for downscaling of PB are highly subjective and the results can vary significantly depending on the choice.
- Sustainability relies on many contributions from nature, but PB based approaches consider only some of the contributions. Ecosystem services such as pollination, air quality regulation, water quality regulation, and cultural services are essential for sustainability, but they are either ignored or considered implicitly and in a highly aggregated manner.
- Current downscaling, upscaling, and hybrid approaches implicitly assume that nature's capacity in one location may be shared with other locations. Such metrics are likely to discourage ecosystem protection and restoration, and decisions toward becoming nature-positive. Such sharing may also be geographically infeasible.

In parallel with work on planetary boundaries and AES, there has also been significant effort on quantification of ecosystem services and including them in assessment and design of sustainable systems. Such efforts rely on sophisticated measured data and biophysical models, which are available for determining nature's capacity at a selected spatial scale. This includes models such as i-Tree (Nowak, 2020), WinEPIC (Texas A&M AgriLife Research, 2017), InVEST (Nelson et al., 2009) and many others. The framework of Techno-Ecological Synergy (TES) (Bakshi et al., 2015) uses such data and models for quantifying absolute sustainability (Liu and Bakshi, 2019; Liu et al., 2018) and for the assessment and design of integrated networks of human and natural systems and their life cycles (Rugani et al., 2019; Guerry et al., 2015; Lee et al., 2021; Gopalakrishnan et al., 2016; Shah and Bakshi, 2019; Ghosh and Bakshi, 2019). However, the similarities and differences of AES metrics based on PB and TES, and their ability to encourage nature-positive decisions are not yet clear.

This work provides novel theoretical and practical insight into AES metrics based on PB and TES. We show how the framework of TES utilizes data and models to quantify local ecosystem capacity and combine it with downscaled contributions from larger scales. This approach operationalizes planetary boundaries and aligns them with local scales where decisions are typically made (Häyhä et al., 2016). If ecosystem services are considered to belong to the local owners or stakeholders and are not distributed among other users then such an approach respects private ownership of ecosystem services and provides incentives for stakeholders to protect and restore nature. This will encourage decisions toward a nature-positive world. If ecosystem services are considered to belong equally to everyone, TES metrics become identical to many PB-based AES metrics. Such metrics may not encourage or may even discourage nature-positive decisions. With the help of equations of various metrics, we also show how the multiscale approach of TES-based AES metrics is more general than PB-based AES metrics and can subsume them. Practical applications to an individual farm, U.S. states, and other regions for carbon sequestration and water provisioning demonstrate the properties of TES- and PB-based AES methods. The TES-based approach combines the attractive characteristics of PB and ES framework which provides more accurate and meaningful AES metrics that incentivize ecosystem protection and restoration, reduce subjectiveness, and consider a wider array of 'local planetary boundaries' that need to be respected for sustainability. Our applications also demonstrate the greater robustness of TES-based metrics to the selected partitioning approach and greater likelihood of encouraging ecosystem restoration and protection which are essential right away for meeting the needs of achieving the 2030 nature-positive objective (Locke et al., 2021). We show that TES-based metrics can encourage decisions toward synergies between ecosystem services and human activities, which are essential for meeting sustainability goals.

The rest of this article is organized as follows. The next section provides the background on the approaches of PB and TES and their application in quantifying AES metrics. The mathematical formulation of TES-based metrics and its relation to PB-based metrics is provided in the third section. The value of the TES framework in AES assessment is discussed next through case studies and comparison with PB-based methods. The last section summarizes the key findings of this work and discusses future work for improving AES metrics to encourage decisions toward a nature-positive world.

2. Background: absolute environmental sustainability metrics

2.1. AES based on planetary boundary

Proposed by Rockström et al. (2009a) and later updated by Steffen et al. (2015), the conceptual framework of Planetary Boundaries is considered as "a bid to reform environmental governance" (Galaz, 2012). It identifies nine processes that regulate the stability and resilience of the Earth system. Transgressing these limits increases the risk of generating large-scale abrupt or irreversible environmental changes. Control variables are defined as projections of the ecological threshold which quantify the state, pressure or driving force of the environment depending on the Earth's processes (Dao et al., 2018). PB framework defines the "Safe operating space" (SOS) for human development which represents the region where anthropic activities respect the earth system (Rockström et al., 2009a). Based on the Planet's bio-physical processes, SOS provides a science-based reference of the risks that human interventions will substantially alter the Earth system (Steffen et al., 2015). The first planetary boundary paper (Rockström et al., 2009b) only estimated global boundaries. However, the earth system is spatially heterogeneous (Steffen et al., 2015) and some earth system processes such as freshwater consumption and the global hydrological cycle do not have a global boundary. Assuming SOS to be spatially generic oversimplifies the complexity of earth system processes since regional instabilities could propagate and affect other regions (Hughes et al., 2013). Research has been done in defining sub-global or regional boundaries (Bjørn et al., 2020). In AES metrics, the SOS is considered as the environmental carrying capacity. For downscaling full SOS to local context, PB-based approaches can be categorized into top-down, bottom-up and hybrid, as described below.

Top-down PB-based AES metrics allocate the global safe operating space, SOS^{glo} to a smaller scale by multiplying it by a partitioning factor, P (Fang et al., 2015a; Dao et al., 2015, 2018; Chandrakumar et al., 2019; Lucas et al., 2020; Chandrakumar et al., 2020). As depicted in Fig. 1a, this approach considers two scales ($J = 2$) since it downscales the SOS from the global to a selected local scale. The top-down approach has strong Earth System relevance but with limited local relevance. For downscaling, most studies use the principle of equal shares (Fang et al., 2015a; Hoff et al., 2014; Nykvist et al., 2013), or equal per capita shares compatible with inter-generational equity for PB downscaling (Dao et al., 2015, 2018). Climate change is one such global-scale process. The annual global carbon budget can be calculated on account of the 2 °C target (29.9 Gt CO_2eq per year) (Chandrakumar et al., 2019). Top-down PB-based AES metrics assign a portion of this global carbon budget to a specific activity by means of a selected sharing principle. This downscaling process can be expressed as,

$$aSOS = SOS^{glo} \times P \tag{1}$$

where $aSOS$ is the assigned share of SOS for the selected process and SOS^{glo} is SOS at the global level. P represents the sharing principle. Status quo or current environmental impact based (Bjørn et al., 2020; Grasso, 2012), gross value added, per capita, final consumption expenditure are commonly used sharing principles (Ryberg et al., 2016, 2018).

Bottom-up PB-based AES metrics combine local or regional data to a coarser scale such as national and then downscale it to the relevant process, as illustrated in Fig. 1b. Such an approach may not have an explicit relationship with earth system stability since it does not consider the global value of the safe operating space (Bjørn et al., 2020; Cole et al., 2014; Rockström et al., 2014; McLaughlin, 2018). This approach is suitable for regionally specific processes without global thresholds (Zipper et al., 2020). Freshwater use is one such process. Rockström et al. estimated a global water boundary based on local environmental water flow requirement (Rockström et al., 2014) and then allocate it to selected processes. Steffen et al. developed the spatially specific basin-scale boundary which accounts for environmental flow requirements (EFRs) (Steffen et al., 2015). EFR is a local constraint on water use which could be estimated at small scales. Blue water (BW) available for human use is a portion of the mean monthly flow (MMF). This amount could be added up from finer to coarser scales then downscaled to selected activities (Bjørn et al., 2020; Gerten et al., 2013). One way of upscaling from finer to coarser scales that has been applied for freshwater use in South Africa (Cole et al., 2014) is based on the following equation,

$$SOS^{reg} = \sum_{wma} \gamma S_{mar} \tag{2}$$

Here, wma represents the water management areas, S_{mar} denotes the mean annual run-off (average natural run-of-river flow per year) at each water management area, and γ represents the ecological reserve percentage. Such aggregation from local or regional boundaries to the national level through a bottom-up approach allows for a reasonably refined

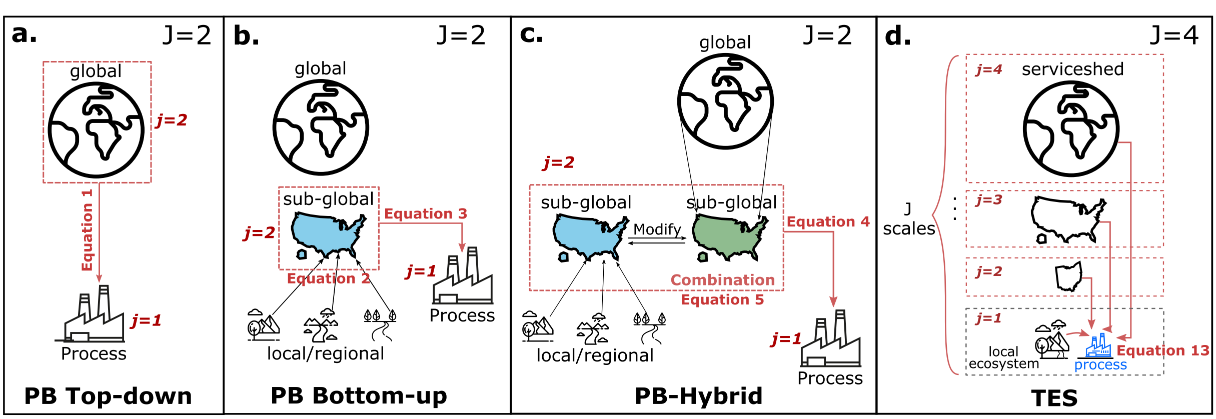

Fig. 1. Comparison of Different PB-based and TES-based methods, J represents total number of scales. (a) Top-down method defines a threshold at global scale then downscales it to local level. (b) Bottom-up method defines a threshold at regional scale based on local information, then downscale regional boundaries to local level. (c) Hybrid method defines a harmonized threshold at regional scale connecting local and global information, the threshold is then downscaled to local level. (d) A 4-level TES method example which defines threshold at each scale including local scale. The Local threshold is added to allocated thresholds from other scales.

estimate of national boundaries (Fang et al., 2015b). Downscaling of the regional SOS value is done as follows,

$$aSOS = SOS^{reg} \times P \tag{3}$$

Top-down and bottom-up approach both have benefits and drawbacks. The top-down method is less accurate in estimating regional earth system processes and whether the local threshold is overshot while the bottom-up method does not provide any information of potential impact at the global scale.

Hybrid PB-based AES metrics combine top-down and bottom-up approaches to simultaneously safeguard global and sub-global SOSs (Chen et al., 2021; Zipper et al., 2020; Gerten et al., 2013; Fang et al., 2015b; Teah et al., 2016; Hjalsted et al., 2021; Zhang et al., 2022) This includes combining bottom-up aggregation (from province to nation) and top-down (global to nation) adjustment for downscaling five crucial PBs (Zhang et al., 2022). Another approach (Teah et al., 2016) conducts a regional sustainability assessment based on downscaling PBs from a production-based perspective in combination with local perceptions which reflect local threshold behaviors. In determining the water sub-boundary, the hybrid framework in Zipper et al. (2020) compares the allocated fair shares versus the local SOS and selects the stricter (smaller) one. The globally accessible volume of blue water that was calculated by Rockström et al. has been modified by considering regional impacts on aquatic ecosystems related to EFR (Gerten et al., 2013). Quantitative assessment is done on EFRs from all grid cells. Then the SOS is estimated based on averaging the medium and maximum of EFRs. A two-step hybrid method where the SOS is first downscaled to the individual level and then scaled up to a higher organizational level based on different upscaling methods has also been proposed (Hjalsted et al., 2021). In general, the allocated SOS for a selected process in the hybrid method can be expressed as:

$$aSOS = SOS^{adj} \times P \tag{4}$$

Here SOS^{adj} is calculated using both regional and global ecological information. For instance, in Zipper et al.'s method (Zipper et al., 2020),

$$SOS^{adj} = \ min\left(SOS^{reg}, aSOS^{glo}\right) \tag{5}$$

SOS^{reg} is the regional SOS at the watershed level which is aggregated from local scale through bottom-up approach like that in Eq. (2), $aSOS^{glo}$ is the SOS downscaled from global planetary boundary to watershed level as in Eq. (1).

Using these top-down, bottom-up and hybrid methods, PB-based AES metrics are calculated by comparing the environmental impact, *EI* with its allocated SOS, *aSOS*. Then the sustainability metric can be expressed as,

$$Occ.aSOS = \frac{EI}{SOS \times P} \tag{6}$$

where the denominator calculates the assigned share of *SOS* for a certain planetary boundary indicating the allowed demand emission or usage amount for selected activity. Here *SOS* is a general notation representing global *SOS*, or sub-global *SOS* which can be calculated through Eqs. (1), (3) and (4). The choice of sharing principle, *P* is a key determinant in the AES metric which will influence the resulting decision (Ryberg et al., 2016; Sandin et al., 2015). Choice of various sharing principles could introduce large uncertainty and Monte Carlo simulation could be used to quantify this uncertainty (Ryberg et al., 2016). *EI* is the environmental impact of this activity. The system will be considered as absolutely sustainable when $Occ.aSOS < 1$, and unsustainable if it is larger than 1. Methods discussed in this subsection will be employed and compared in Section 3 through a water provisioning (freshwater use) case study.

2.2. AES based on techno-ecological synergy

The Millennium Ecosystem Assessment defines 24 ecosystems services and categorizes them into four groups: supporting, provisioning, regulating and cultural (Millennium Ecosystem Assessment, 2005). It classifies 15 out these 24 ecosystem services as degraded. Aiming at reducing ecological overshoot and establishing synergies with ecosystems, the framework of Techno-Ecological Synergy is developed to bridge the gap between human and natural systems (Bakshi et al., 2015). This framework has resulted in the systematic approach of techno-ecological synergy in life cycle assessment (TES-LCA) to include ecosystem services (ES) in conventional LCA. This framework enables quantifying absolute environmental sustainability (Liu and Bakshi, 2019) by comparing human demand for ES (emissions, resource use) with natural supply (carrying capacity of ecosystems). Instead of relying on direct downscaling to determine the local carrying capacity as in PB-based methods, the TES framework relies on various biophysical models such as iTree (i-Tree Canopy, n.d.), InVEST (Nelson et al., 2009), EPIC (Gerik et al., 2013) and remote sensing data.

The TES framework is inherently multiscale in nature and can easily account for the nested character of ecological and other systems. Smaller ecosystems are nested in larger ones, and technological systems are located within the ecosystems resulting in a hierarchical techno-ecological system. The coarsest ecological scale is the serviceshed while the finest scale is a user-defined region (local scale). The serviceshed of an ecosystem service is the area that provides the good or service to specific users of that service. For example, for the water provisioning ecosystem service, the serviceshed is the watershed while for carbon sequestration, it is the entire planet. The interaction between ecosystem services and human well-being takes place at multiple scales and can cross scales (Millennium Ecosystem Assessment, 2005). Thus, the TES framework explicitly accounts for ES demanded by technological systems and the supply of these services from relevant ecosystems at multiple spatial scales (Bakshi et al., 2015) which enables environmental decision-making at any scale. Technological systems in TES range from individual processes to supply chains and life cycles. Absolute environmental sustainability metrics developed in TES compare the demand from the technological system with the supply from the relevant ecosystem at each scale (Liu and Bakshi, 2019).

In the TES framework, the total supply for a selected process consists of local supply and allocated supply from other scales. The allocation process is shown in Fig. 1d which also illustrates its multiscale nature. Two allocation schemes are considered: public and private ownership. Private ownership implies that land owners own the ecosystem services available from their land, while public ownership considers the goods and services to belong equally to every activity inside the serviceshed (Liu and Bakshi, 2019). Note that TES considers servicesheds of various sizes ranging from global for carbon sequestration to a few kilometers for animal pollination.

The absolute environmental sustainability metric in TES compares the supply and demand at local and serviceshed scales. This indicates the extent to which the technological activity is within the relevant ecosystem's carrying capacity (Liu and Bakshi, 2019). For the *k*th ES, the sustainability metric, V_k (Bakshi et al., 2015) is defined as,

$$V_{i,j,k} = \frac{S_{i,j,k} - D_{i,j,k}}{D_{i,j,k}} \tag{7}$$

Here, $S_{i,j,k}$ and $D_{i,j,k}$ are the supply and demand of the *k*th ecosystem service for each techno-ecological system $i = 1, 2, \ldots, I$, at each ecological scale $j = 1, 2, \ldots, J$. The term 'supply' in TES is analogous to the 'safe operating space' in the PB framework. Both illustrate the capacity of nature but for PB, the full SOS is at a global or sub-global scale, while for TES it is quantified at all scales specified by the user, with the serviceshed ($j = J$) being the largest scale. If $V_{i,j,k} < 0$, the ecosystem at the selected scale is unable to meet human needs (take up emissions or provide resources). Such as system lacks local environmental sustainability. A necessary, but not sufficient condition for absolute sustainability is defined at the serviceshed scale as (Liu and Bakshi, 2019),

$$V_{i,J,k} \geq 0, \quad \forall i, \forall k \tag{8}$$

Due to the multiscale nature of the TES framework, V_k will be calculated at any scale. When $V_{i,\, j,\, k} \geq 0$, it indicates the kth ecosystem service is locally sustainable at scale j (Bakshi et al., 2015). The most desirable situation is when $V_{i,j,k} \geq 0, \quad \forall i, \forall j, \forall k$, which implies activities stay within the carrying capacities at all scales. If $V_{i,j,k} \geq 0, \quad j \neq J$ is satisfied while $V_{i,J,k} < 0$, the activity is an 'island of sustainability' (Wallner et al., 1996). In the opposite, when at the serviceshed scale $V_{i,J,k} \geq 0$ with some $V_{i,j,k} < 0$, this is an 'island of unsustainability'. AES metrics based on the PB framework estimate the supply (ecological threshold) for a selected activity through direct downscaling of the global safe operating space or supply, while the TES framework relies on biophysical models at the scale of the serviceshed or smaller scales. The PB framework focuses on staying within planetary limits while TES considers limits at local and larger scales for an array of ecosystem services that are relevant to sustainability but whose planetary implications may not be known.

3. Framework for multiscale absolute environmental sustainability assessment

This section describes general equations for AES metrics based on the TES-LCA framework (Liu and Bakshi, 2019). This provides new insight into the relationship between metrics based on PB and TES and enables AES assessment of diverse systems to encourage decisions toward becoming nature-positive.

3.1. Partitioning of nature's capacity

How to partition or allocate available benefits from nature (also referred to as supply of ecosystem services or safe operating space (SOS)) among multiple users is important for any AES assessment method. The allocation method could directly influence the metric and subsequent decision making. AES metrics based on the PB and TES frameworks may be understood in terms of their implicit assumptions about ownership of ecosystem services.

As a simple illustration, consider Fig. 2 which shows the publicly and privately owned ecosystem services in a two-scale system. Total supply is $(S_A + S_B + S_C)$.

- *PB-based metrics* assume the ownership of ecosystem service supply by the public body and every individual or organization can get equal access to the supply. An individual's right to use depends on the choice of the sharing principle, as summarized in Section 2.1. Unlike the PB framework which insinuates public ownership, in the TES framework private and public ownership exist simultaneously at multiple spatial scales. If public ownership is assumed for all ecosystem services, as adopted by PB-based methods, the allocated operating space or supply for process A can be written as, $(S_A + S_B + S_C)P_A$. Here S_A, S_B and S_C represent the SOS or supply for regions A, B and C; P represents a selected sharing principle for process A.
- *TES-based metrics* consider supply from publicly owned land and water to be public supply that can be shared among stakeholders. The world has "international waters" or "high seas" that are publicly owned and do not belong to any country. Many countries have areas that are public lands such as national parks and other government-owned land. Ecosystem services provided in such regions are considered to belong to all users in that region. Services in public land will be downscaled to smaller scales. Services on privately owned land belong to individual owners, and are not shared with others. This is also applied to the finest scale such as a state or nation. For the illustration in Fig. 2, region C is public land so its supply, S_C belongs to all users, and may be split between A and B. However, supply in regions A and B belong only to those regions. Then, the total supply available to process A is $S_A + S_C P_A$, and to B is $S_B + S_C P_B$. Note that if all land is considered to be publicly owned, TES-based metrics can become identical to PB-based metrics (Liu and Bakshi, 2019).

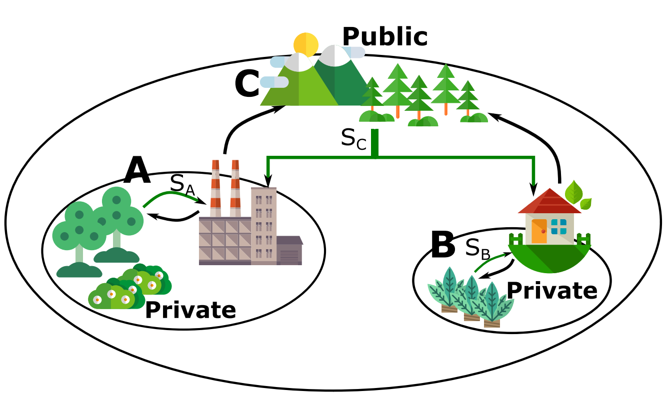

Fig. 2. Illustration of private and public Ownership. Arrows represent emissions and resource flows to and from the ecosystem.

Applying the TES allocation method with private ownership, stakeholders could get considerable rewards for their actions that enhance the supply of ecosystem services on their land. Their local supply will not be shared with others, so their own 'natural capital' will be protected.

3.2. General framework

In this subsection, we build on the insight and equations from Section 3.1 to develop general equations for multiscale AES metrics, and explain the theoretical relationship between PB-based and TES-based AES metrics. Supply, $S_{i,j,k}$ is for the i-th process at the j-th scale and for the k-th ecosystem service (Bakshi et al., 2015). The finest scale is represented by $j = 1$ and the coarsest by $j = J$. The number of scales is determined by the user, but to determine absolute sustainability, the coarsest scale should represent the serviceshed. Trade-off exists between the number of scales and the amount of data required. More scales require more regional information but result in more precise metrics.

Part of the total supply at any scale is reserved for the functioning of ecosystems. The fraction of the supply required for the environment is denoted by β_j ($0 \leq \beta_j \leq 1$): this part ensures the basic functioning of ecosystems. For instance, for the water provisioning service, a certain amount of water should be left in or released into an aquatic system to maintain its use values (King et al., 2003), and this part is the EFR which in this framework is represented by β_j. For ES that provide only indirect benefits to people, such as biogeochemical cycles, $\beta_j = 1$. Thus, supply available for human activities is $S_{i,\, j,\, k}(1 - \beta_j)$. As discussed in Section 3.1 we only partition the public supply, the private supply belongs to private owners. The fraction of supply that can be allocated at scale j is denoted by α_j ($0 \leq \alpha_j \leq 1$). Thus, the supply available for public use can be written as:

$$S^{pub}_{i,j,k} = S_{i,j,k}\alpha_j\left(1 - \beta_j\right) \tag{9}$$

The supply that can be considered to be privately owned is:

$$S^{pvt}_{i,j,k} = S_{i,j,k}\left(1 - \alpha_j\right)\left(1 - \beta_j\right) \tag{10}$$

In TES-based metrics, under the assumption of private ownership, the entire supply at the finest scale ($j = 1$), $S_{i,\, 1,\, k}(1 - \beta_1)$ is considered to belong to the system at this scale and is not shared with other scales. Thus, $\alpha_1 = 0$ and system's private supply is:

$$S^{pvt}_{i,1,k} = S_{i,1,k}\left(1 - \beta_1\right) \tag{11}$$

$P_{j,j-1}$ represents the sharing principle when supply is allocated from scale j to scale $j-1$. For a selected system, the total supply is the sum of supplies from scale J to 1. Fig. 3 is an example of the allocation process with four scales ($J=4$). The total supply available to the selected Process A is:

$$S_{i,k}^{total} = S_{i,1,k}^{pvt} + S_{i,2,k}^{pub}P_{2,1} + S_{i,3,k}^{pub}P_{3,2}P_{2,1} + S_{i,4,k}^{pub}P_{4,3}P_{3,2}P_{2,1} \quad (12)$$

Generally, for a TES model with n scales, total supply available for a selected system can be written as:

$$S_{i,k}^{total} = S_{i,1,k}^{pvt} + S_{i,2,k}^{pub}P_{2,1} + S_{i,3,k}^{pub}P_{3,2}P_{2,1} + \ldots + S_{i,J,k}^{pub}P_{J,J-1}\ldots P_{2,1} = S_{i,1,k}^{pvt} + \sum_{j=2}^{j=J} S_{i,j,k}^{pub}\prod_{m=1}^{m=j} P_{m+1,m} \quad (13)$$

Here m is a dummy variable representing the scale of ecosystem. From a mathematical point of view, Eq. (13) can also be used to express Eqs. (1), (3) and (4) that represent PB-based top-down, bottom-up and hybrid methods. SOS^{glo} represents the safe operating space at global scale such as the global carbon budget for climate change. SOS^{reg} represents a sub-global safe operating space representing a value upscaled from local thresholds at smaller scales to a coarser scale. SOS^{adj} represents the safe operating space considering both global SOS and local context. PB-based method is single scale: $J=2$, and applies public ownership: $\alpha_1 = 1$. Considering all these conditions, Eq. (13) could be rewritten as:

$$S_{i,k}^{total} = S_{i,1,k}^{pvt} + S_{i,2,k}^{pub}P_{2,1} = S_{i,1,k}(1-\alpha_1)(1-\beta_1) + S_{i,2,k}^{pub}P_{2,1} = S_{i,2,k}^{pub}P_{2,1} \quad (14)$$

Eq. (14) is of the same form as Eqs. (1), (3) and (4). This shows that the multiscale framework of TES metrics can become identical to PB-based AES metrics. However, PB-based metrics cannot become identical to TES metrics since none of the PB-based methods account for the local private supply, $S_{i,1,k}^{pvt}$. Equations for PB- and TES-based methods (Eqs. (13) and (14)) also indicate their single scale and multiscale nature. For any PB-based method, the allocation process is multiplying SOS by an allocation factor. While for TES-based method the allocation is summing multiple products of supply and allocation factor. The single scale and multiscale nature of these two frameworks affect metrics variability, as will be discussed in Section 4.3.

TES-based assessment of absolute environmental sustainability for the i-th techno-ecological system and the k-th ecosystem service involves metrics at multiple scales,

$$\overline{V}_{i,k} = (V_{i,1,k}, V_{i,2,k}, \ldots, V_{i,J,k}) \quad (15)$$

As discussed in Section 2.2, Eq. (8) defines a necessary, but not sufficient condition for absolute environmental sustainability. Metrics at smaller scales provide further insight into local environmental sustainability. It helps identify cases such as "islands of sustainability" that are locally sustainable but unsustainable at the serviceshed scale. Similarly, these metrics can also identify islands of unsustainability and systems that are environmentally unsustainable at local and serviceshed scales (Liu and Bakshi, 2019).

4. Case studies

The case studies show how the TES-based method is applied and the value of this method. Different ecosystem services and systems at different scales show the generality of this framework. Comparing different sharing principles demonstrates the robustness of our approach.

4.1. Corn farming and carbon sequestration

In this case study we focus on the carbon sequestration ecosystem service for a corn farm located in Hamilton County, Ohio. Absolute environmental sustainability for carbon sequestration is determined by comparing the GHG emission of this agricultural activity against the ecological threshold. The agricultural production-risk management software WinEPIC (Gerik et al., 2013) is used to simulate the annual crop yield, carbon cycling, etc. Predefined farming operations, local weather and soil data are input variables. Fuel combustion from machinery is one of the CO_2 emission sources. Due to the dynamic nature of ecosystems, it is important to define a temporal boundary by selecting a time period for a fair comparison. In this case study, the simulation in WinEPIC has been run for a 20-year period and

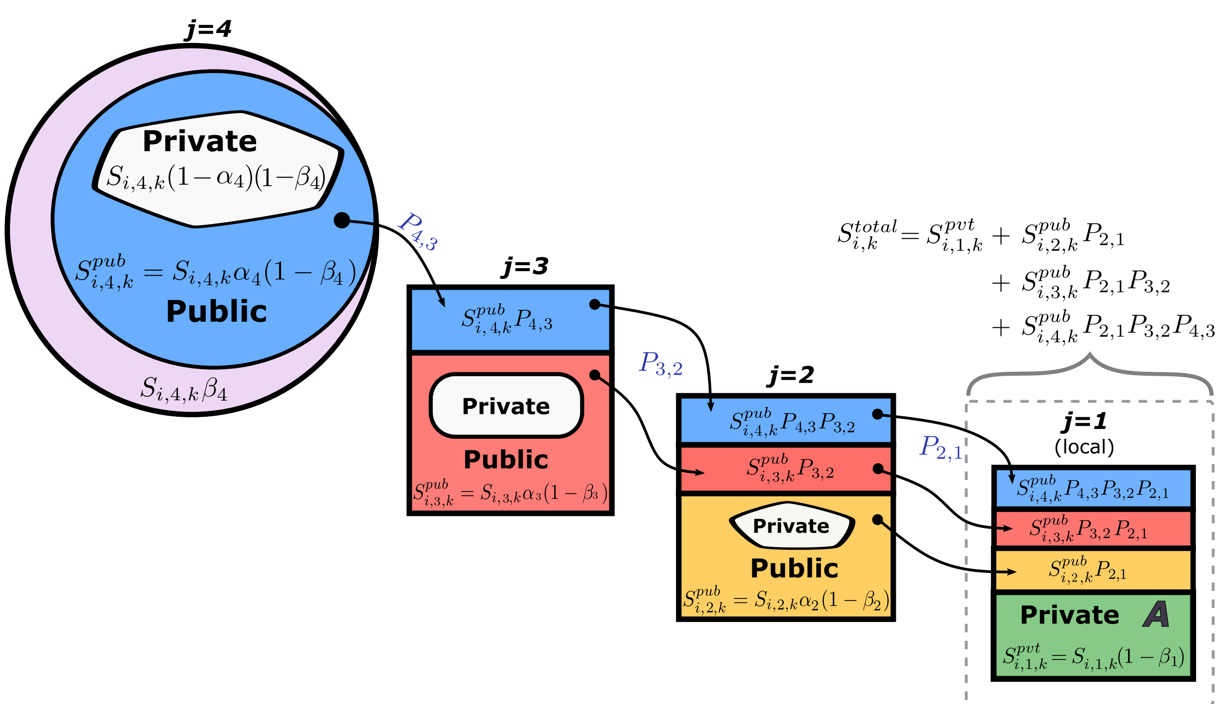

Fig. 3. Allocation of Supply for process A in a 4-level TES Model. For each level, only public supply will be allocated. $P_{j,j-1}$ represents downscaling from scale j to $j-1$. Total supply Process A can get consists of allocation from scales $j=4, 3, 2$ and private supply at local scale ($j=1$).

the soil carbon loss is normalized to per year. A unique characteristic of farming is that through the photosynthesis process, crops pull CO_2 out from the atmosphere and incorporate it into biomass. After harvest, crop residues are converted into soil organic matter. The soil may also take up carbon. These constitute the supply of the carbon sequestration ES from the farm. The demand for the carbon sequestration ES is due to greenhouse gas emissions from the farm and farming activities. Thus, the region of a corn farm can be considered as its local ecosystem.

CO_2 emissions from the farming system are shown by the left gray bar in Fig. 4. This is the demand from the farm for the carbon sequestration ecosystem service. The supply is calculated by the PB- and TES-based methods. Since carbon sequestration is a global activity, its planetary boundary is defined at the global scale. For the PB-based method, the farm-level SOS is calculated by downscaling the global SOS to the farm based on demand for the carbon sequestration ES (emissions of CO_2). The resulting SOS is shown by the middle bar in blue with black dots in Fig. 4. Comparing the demand and PB-based supply, we can see that this system is not sustainable for carbon sequestration since the demand exceeds the SOS or supply.

The TES approach is applied at four scales: farm, state, country and the planet. The public supply at each scale is determined as follows. At the global scale, public supply of CO_2 sequestered is from the high seas in global oceans. At the national scale public supply is in federally owned land. At the state scale public supply is in state-owned land. CO_2 sequestered inside the farm belongs to the land owner and is not allocated to others. In this case study, we allocate the public supply of carbon sequestration from global to national and national to state levels in proportional to population. From state level to the farm the allocation is in proportion to the demand for carbon sequestration which is equal to CO_2 emissions. Results for allocation at all scales in proportion to demand for carbon sequestration are provided in the Supplementary information, and are similar to those in the manuscript.

Comparing the left-most (gray) and right-most (multi-colored) bars in Fig. 4 shows that the total supply from TES-based method is larger than demand indicating that this farm is absolutely environmentally sustainable. In the TES-based method, the farm gets supplies allocated from public lands at each scale. Furthermore, according to WinEPIC result, considerable amount of CO2 is sequestered inside the farm which is its local supply. This private part of the supply (illustrated by the green block) is included in the PB-based method, but it is allocated to each planetary denizen. In contrast, in the TES approach, the carbon sequestration ecosystem service from the farm is allocated only to the landowner.

For this case study, PB- and TES-based methods give opposite conclusions about absolute environmentally sustainability of the farm for carbon sequestration. To appreciate whether and how the AES metrics can encourage nature-positive decisions, consider two cases where the farmer uses conventional tillage versus conservation tillage. The latter approach is known to sequester more carbon in the soil (Lal, 2016) and is more nature-positive. If PB-based metrics are used for assessment and guiding decision making, carbon sequestration inside the farm is not quantified independently, instead it is lumped with the global carbon budget. Therefore, the action of the farmer is diluted by wide distributed across the world. The effect of the farming practice is hardly felt in the PB-based AES metric giving the farmer little incentive to adopt the nature-positive practice of conservation tillage. In contrast, TES-based AES metrics are much more sensitive to farmer decisions and the entire credit for the outcome of the decisions goes to the farmer. This is because of the private ownership option in the TES approach.

TES-based AES metrics at all scales calculated by Eq. (15) for this corn farming system are $\overline{V}_k = (-0.52, -0.88, -0.85, 1.79)$ with each elements corresponding to global, national, state, and farm scales, respectively. Except the farm scale all other scales are environmentally unsustainable. This result reflects that this corn farm is an ‘island of sustainability’. Specific actions are needed at state, national and global levels to attain absolute sustainability. This is a much richer set of results in contrast to what is provided by the PB-based metric, which identifies this farm as being unsustainable.

4.2. U.S. great lakes states and carbon sequestration

In this case study, we investigate AES of the CO_2 sequestration service for five states in the great lakes region of the U.S. Due to the global relevance of carbon sequestration, PB-based metrics rely on the top-down approach while TES-based metrics consider global, national and state levels. Population-based sharing principle is used. Demand and supply results are plotted in Fig. 5.

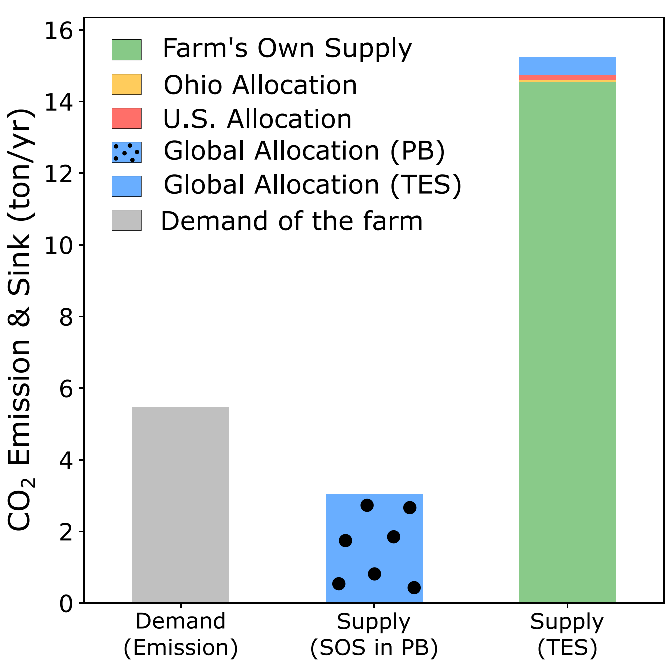

Fig. 4. Comparing PB-based and TES-based absolute environmental sustainability metrics for carbon sequestration services in a corn farm in Ohio. Supply from PB-based top-down approach is smaller than demand indicating unsustainability of farming. TES calculates the supply to be larger than demand indicating absolute sustainability.

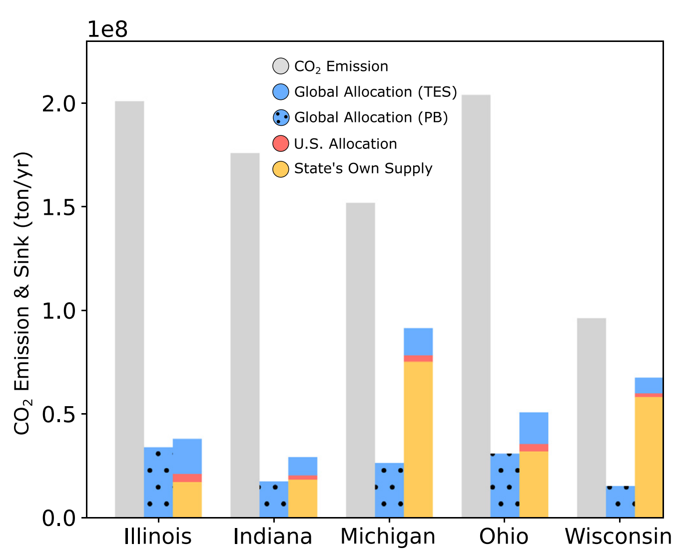

Fig. 5. CO_2 Emission and Sequestration from PB-based top-down and TES-based methods. Canopy cover percentage for IL, IN, MI, OH and WI: 10.6 %, 17.7 %, 44.6 %, 26.8 %, 35.8 %.

For the PB-based approach, allocated SOS or supply for each state are shown by the blue bars with black dots in Fig. 5. For TES, the local supply of the carbon sequestration ecosystem service in each state is from forest sequestration and is obtained from the iTree model (i-Tree Canopy, n.d.). Thus, the quantity of carbon sequestered depends on canopy cover and forested area. This quantity is depicted by the yellow sections of the bars in Fig. 5. Downscaled supply from national and global scales is also included in TES, as shown.

As illustrated by the yellow bars, states like Michigan and Wisconsin that have relatively high canopy cover also have high local supply of carbon sequestration. However, this local carbon sequestration information in each state has little effect on PB-based metrics due to it being partitioned across the global population. One extreme case is Wisconsin where CO_2 sequestration is high inside the state, which indicates presence of substantial capacity to sequester carbon. Allocated SOS by the top-down method (blue bar with black dots) is 78.8 % lower than the local supply (yellow bar) for Wisconsin. This is because in PB-based approaches, the state's own carbon credit (local supply) is distributed across the whole world. The opposite extreme case is Illinois which has the lowest local CO_2 sequestration inside the state but still gets the highest assigned share of SOS (blue bar with dots) compared with other states. Different results between PB-based and TES-based methods are due to the single scale and multiscale nature of the methods. In the PB-based method, only one spatial scale is considered, which could be at global or sub-global levels. However, in the TES-based approach, the ecological threshold is quantified at each scale and summed together.

These results from direct downscaling show how PB-based metrics are unlikely to encourage states to take action toward sustainability like restoration to enhance their own carbon sequestration capacity. States like Wisconsin with high capacity will have little incentive to protect nature and increase nature's carrying capacity if their efforts have little benefit to their own state metrics. While for states like Illinois that have low local capacity may not realize the severity of its regional environmental issues. These results also demonstrate how PB-based metrics can be less physically meaningful than TES-based metrics.

4.3. Effect of different sharing principles

PB- and TES-based AES metrics rely on sharing principles whose selection is subjective. Here we compare five different sharing principles: population, GDP, inverse of GDP, area, and emission for the five-states case study in Section 4.2. From the results in Fig. 6, we can see that the emissions of CO_2 or demand for the carbon sequestration ecosystem service in each plot, indicated by gray bars, are identical for a given state. However, comparing the supply or assigned SOS from the PB-based method for each state shows larger variability than the supply for the same state for the TES-based method. These results are based on direct downscaling with the selected sharing principle. In contrast, results from TES-based method show less variation since the local supply (yellow bar) moderates the effect of downscaling. For a quantitative comparison, the AES metric at the state level is calculated by using Eq. (7) for each sharing principle. For the PB-based approach, the standard deviation of the metric among five sharing principles for IL, IN MI, OH and WI are 0.42, 0.23, 0.27, 0.34 and 0.21, respectively. For TES-based metrics, the standard deviations for the states are 0.22, 0.12, 0.18, 0.17 and 0.17. The average standard deviation of PB-based metrics for each state is 71.7 % higher compared with TES-based metrics. Details are provided in the Supplementary information. Allocation based on GDP assigns economically active regions more of the SOS indicating that these regions could emit more. While the idea of partitioning based on the inverse of GDP assumes developed regions have used up their right to emit and now should have tighter SOS (emission 'budget'). Both allocation principles are based on a specific sustainability perspective but both of them are biased in some aspects. TES-based method disaggregates biggest ecosystems to multiple scales and partially allocates the public 'budget' at each scale. Integrating the physical model at each scale enables estimation of the regional 'budget' at a high resolution. These results convey that TES-based metrics can be more robust and less sensitive to subjective choice.

4.4. Water provisioning services for corn farming

The TES framework is designed to cover all ecosystem services and this case study focuses on water provisioning, which is identical to freshwater use in the PB framework. Unlike climate change, freshwater use has a more regional serviceshed, commonly referred to as the watershed. The case studies in Sections 4.1 and 4.2 relied on a top-down approach to downscale the global PB of climate change. For ecosystem services like water provisioning which have significant regional components, bottom-up and hybrid methods are commonly used to calculate PB-based AES metrics. The bottom-up approach generates locally meaningful control variables, response variables, and boundary values defining the local stable conditions

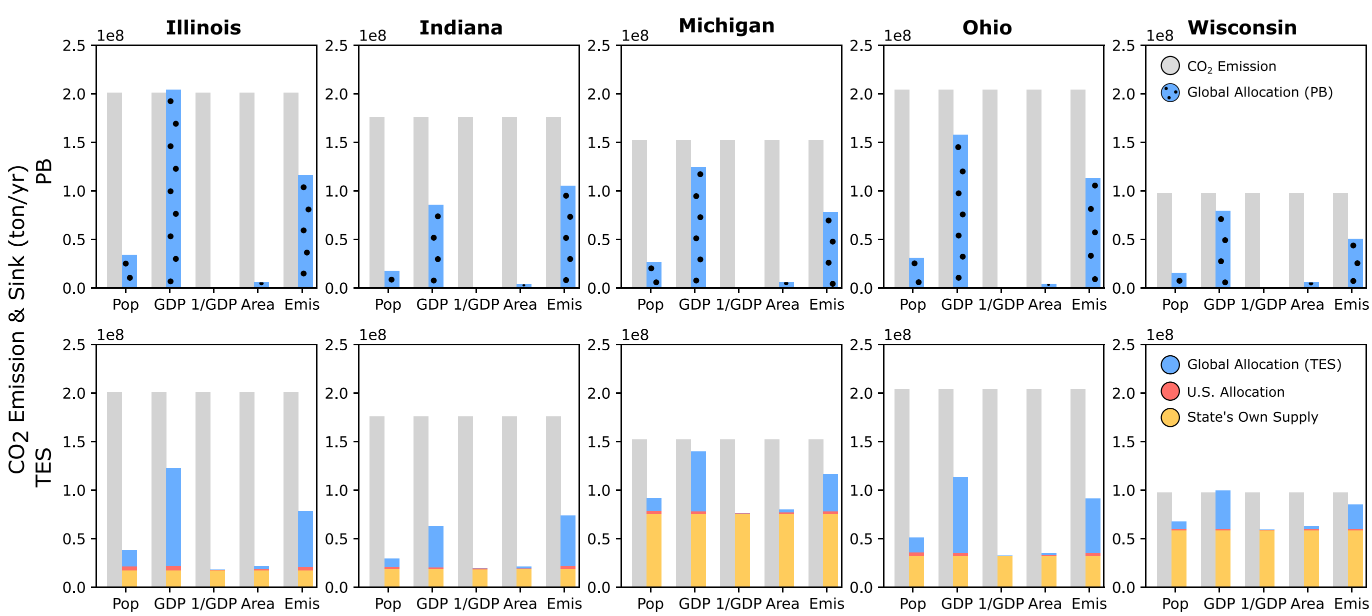

Fig. 6. Comparison of PB-based and TES-based metrics for different sharing principles: Population, GDP, inverse of GDP, Area and Emission. TES-based metrics are less affected by the sharing principle.

for different earth system processes (Zipper et al., 2020). The hybrid approach takes advantage of the strength of these two methods (Zipper et al., 2020; Gerten et al., 2013). Details about these approaches are in Section 2.1.

This case study is of the same corn farm in Hamilton County that was studied in Section 4.1. Two-level TES, PB-based bottom-up, top-down and hybrid methods are applied and compared. For biophysical model at a local scale, we assume natural precipitation as the local water supply of the corn farm. Runoff of the precipitation is estimated to be 15 % (Stuntebeck et al., 2011). Irrigation water is an important demand for farming activities however not a necessity. For regions that have sufficient rainfall, only a small proportion of corn farm is irrigated (Mubako and Lant, 2008; Mishra and Yeh, 2011). The majority of water demand is the water that leaves the plant through evapotranspiration instead of being consumed by plants, thus the amount of evapotranspiration from the farm is taken as the local demand on the farm. The serviceshed in this case is the watershed. In the PB framework, the global blue water availability was estimated to be in the range of 39,700 to 42,800 km^3/yr with an average value of 40,700 km^3/yr (Rockström et al., 2009a,b). Subtracting water runoff to uncaptured region, the amount of blue water accessible to humans is 12,500 km^3/yr. In this case study, total water consumption in the watershed (m^3/month) is modeled by WaterGAP (Ryberg et al., 2016) which contains 11,050 watersheds. The mean monthly flow (MMF) and SOS data for this watershed are estimated by using the AWARE methodology (Ryberg et al., 2016). All allocations are based on area.

The demand of water in this farm is shown by the gray bar in Fig. 7. According to USDA, Ohio has less than 1 % irrigated agricultural acreage, and for Hamilton county no irrigation is needed for the corn farm in this study (*U.S. acres of irrigated land by county 2017*, n.d.). The other bars show the result of various PB-based approaches and TES. We can observe that the PB-based hybrid method (Zipper et al., 2020) calculates the same water supply as the PB-based top-down method. This is because this hybrid method always selects the stricter boundary, and the threshold downscaled from global blue water availability is smaller than the water supply at the watershed scale. For all the PB-based methods (top-down, bottom-up and hybrid), allocated SOS (supply) of the farm is much lower than the demand indicating that the farm is unsustainable with respect to water provisioning. This is a counter-intuitive result for the selected location of this farm since it should mean that the region is drought prone. However, according to Drought Conditions for Hamilton County (*Drought Conditions for hamilton county*, n.d.), 0 % of Hamilton county is facing abnormal drought, which is short-term dryness that slows planting, and growth of crops or pastures. These results convey that PB-based AES metrics could be misleading.

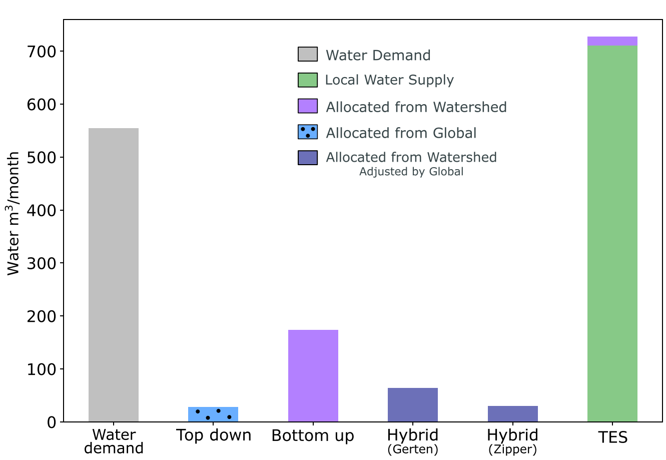

Fig. 7. Freshwater Use and Provisioning for the Corn Farm. The downscaling processes for top-down (Rockström et al., 2014), bottom-up (Cole et al., 2014), hybrid (Gerten) (Gerten et al., 2013), hybrid (Zipper) (Zipper et al., 2020) and TES-based are illustrated in Fig. 1a, b, c, d accordingly.

In contrast to PB-based metrics, TES metrics rely on biophysical models with high geographical resolution to account for the local threshold of water, and quantify a more reasonable water supply for the farm. The bar for TES in Fig. 7 has a large local contribution that exceeds the water demand on the farm. The downscaled allocation from the watershed is also present, but is quite small. This TES-based metric indicates that plenty of water is available to the selected farm, which aligns with the fact that Ohio is a water-rich region.

5. Discussion and conclusions

Meeting the urgent need of stopping and reversing nature loss to develop a nature-positive world requires metrics to quantify the extent to which human activities respect nature's constraints. Metrics for absolute environmental sustainability measure the extent to which human activities exceed ecological carrying capacity. This work results in a multiscale AES metric which is more precise and robust, has high geographical resolution and encourages restoration and protection of nature. AES metrics belong to two broad categories: those based on planetary boundaries and those based on ecosystem services. PB-based metrics quantify the extent to which human activities respect the safe operating space in which human activities need to remain to reduce the risk of global change. Since most decisions are made for individual products, activities, and regions, the global nature of planetary boundaries requires their localization to the relevant scale. Existing methods rely on top-down, bottom-up and hybrid strategies, but none account fully for the availability of ecosystem goods and services at the local scale. Biophysical data and models about nature's capacity find relatively limited use in this class of methods, particularly at small scales. Furthermore, all the PB-based AES metrics distribute ecosystem services evenly among everyone across the planet based on factors such as population, land area, gross domestic product, etc. The resulting metrics are sensitive to this highly subjective partitioning method. As shown by the case studies in this work, such an approach can be perverse by discouraging protection and restoration of ecosystems and transformation to a nature-positive world. One reason for the popularity of PB-based AES metrics is their ease of computation since data for downscaling is readily available. However, we conclude that such direct downscaling is prone to misleading results and should not be used.

Among AES metrics based on ecosystem services are those that rely on the framework of techno-ecological synergy. These TES-based AES metrics rely on biophysical data and models to estimate the overshoot between the demand imposed by human activities on goods and services from nature and nature's capacity to supply these goods and services. TES-based AES metrics consider multiple spatial scales. At the finest scale, biophysical models are used to estimate nature's capacity. In the private ownership approach, local stakeholders are given full credit for the supply of ecosystem services from the region they control. Publicly owned ecosystem services at larger scales are evenly downscaled to the stakeholders' scale in the same manner as PB-based metrics. Such an approach is less subjective, more robust, and more accurate than PB-based metrics since the local ecosystem services are estimated by the biophysical models. TES-based metrics are also better suited for encouraging nature-positive decisions along with reduction of environmental impact due to human activities. The multiscale nature of TES also provides AES metrics at local, intermediate and serviceshed scales which can be used to identify islands of sustainability or unsustainability, and opportunities for improvement. PB-based AES metrics are unable to provide such insight. In addition, TES-metrics with a public ownership approach become identical to PB-based metrics. This indicates the greater generality of TES-based metrics.

The PB framework includes nine earth system processes that are critical for global stability, while TES considers ecosystem services that are essential for sustainability from local to global scales. Ecosystem services such as pollination, air and water quality regulation, cultural services are essential for environmental sustainability but are not covered or are highly aggregated in PB-based metrics. The PB framework is very useful for focusing on processes of global importance. However, using this framework for guiding decisions toward environmental sustainability poses practical challenges and can provide misleading results that disincentivize nature-positive decisions. Instead, an ecosystem services framework like TES is better suited for determining absolute environmental sustainability and guiding nature-positive decisions at any spatial scale.

Challenges still exist for improving AES metrics and using them to encourage nature-positive decisions. More effort is needed toward quantifying all ecosystem services and including them in AES metrics. This includes approaches and data for defining the service flow in appropriate physical, information, or financial units that can quantify relevant ESs, developing biophysical models for ESs assessment, database development for ecological inventory, etc. A theoretical framework is needed to bring together data and models about human and natural systems at multiple spatial scales and at multiple levels of aggregation such as process-based and environmentally-extended input-output models. This will enable calculation of AES metrics for individual processes and their life cycles. The present framework is best for static systems, but dynamics such as the effect of seasons on availability of ecosystem services should also be considered. Additional work needs to consider the use of AES metrics in designing for absolute sustainability, include the effect of uncertainties, and develop tools for practical application of AES metrics to encourage transformation to a nature-positive world.

CRediT authorship contribution statement

Ying Xue: Conceptualization, Methodology, Software, Investigation, Writing – original draft, Writing – review & editing. **Bhavik R. Bakshi:** Conceptualization, Methodology, Writing – review & editing, Funding acquisition, Supervision, Project administration.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.scitotenv.2022.157373.

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