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Editorial: The crucial issue of spatial and temporal scale in ecological indication

1. Rationale

The theoretical foundation of ecological indication is based on measurable indicators and indices that are conducive to the provision of aggregate information regarding ecosystem health, functioning, and changes (Turnhout et al., 2007). These instruments serve a dual purpose: they facilitate the interpretation of systems and the communication of complex ecological information to various stakeholders, including policymakers, practitioners, and the public. This, in turn, facilitates more effective decision-making processes concerning environmental conservation and restoration. Consequently, decision-makers frequently employ ecological indication to engage with the public. It is therefore crucial that ecological indicators and indices, which are the focus of the journal Ecological Indicators, are defined and quantified in a scientifically defensible way.

In the real world, we are dealing with hierarchically nested landscapes (Gunderson and Holling, 2002), which can lead to problems in our selection of appropriate spatial and temporal scales of investigation. Therefore, for an indicator to be suitable for describing a particular ecological aspect, it is necessary to explicitly consider the scales at which key ecosystem processes, disturbances and observations occur. This editorial is precluded from delving into the most suitable methods and scales for studying the spatial dynamics (real or potential) of ecological indicators and indices, due to the numerous ways in which system dynamics can be conceptualized and operationalized through ecological indication. The principal objective of this text is to direct the attention of researchers toward salient issues pertaining to spatial and temporal scales, with special emphasis on the latter, which is often the most neglected aspect. In addition to underscoring these concerns, the text puts forward a few recommendations aimed at enhancing the quality and reliability of research outcomes.

To understand ecological phenomena, it is necessary to observe their behavior on multiple spatial and temporal scales (Wiens, 1989, Steele, 1991, Levin, 1992), and this is also true for ecological indication. Since these scholars emphasized this necessity, many technological advances have considerably improved the capacity to collect and analyze data on multiple scales of space and time. However, the increased emphasis on spatial scales stems from the direct application of technological tools such as remote sensing, geographical information systems (GIS), global positioning systems (GPS) and ecological and ecosystem services (ES) modeling software to support environmental planning and management, as well as the availability of high-resolution data to support local investigations (Rau et al., 2020). These developments have also been aided by increased availability of satellite and Earth observing system data at a range of spatial and temporal scales and resolutions (Zhao et al., 2022). Satellite and airborne sensors provide structural (e.g., vegetation) information about ecosystems, as well as dynamics, functions, and processes (e.g., net primary productivity) affecting ecological conditions and trends. Moreover, data from certain sensors, like LIDAR, when flow on aircraft, provide finer-scale data (in some cases with at cm resolutions) on vegetation as well as topography, which is often a critical determent of ecological function and condition (Lohani and Ghosh, 2017).

In particular, powerful spatial analysis tools, such as Fragstats (McGarigal and Marks, 1995), have been developed and made widely available, facilitating the examination of spatial patterns and relationships and allowing ecologists to develop consistent evaluations and to observe spatial patterns that were previously inaccessible. However, given the scarcity of long-term, ecologically relevant data, which precludes past data for predicting future outcomes, spatial environment-biota relationships have frequently been employed as proxies to predict biotic responses to environmental change over time. These "space-for-time substitutions" (Lovell et al., 2023) have become almost ubiquitous in ecological and environmental assessments.

The need for analyses at multiple spatial and temporal scales has been underscored by the systems perspective of ecological resilience (Holling, 1973, 1978, 1996), which emphasizes the maintenance of structure, function, and identity through persistence and change. This perspective is fundamental to understanding sustainability, resilience, and resource management. The theory of social-ecological systems (SES) — which emerged in the 1970s and was formally articulated by Berkes and Folke (1998) and Gunderson and Holling (2002) — embraced this perspective. Social-ecological systems (SES) are defined as integrated systems in which biophysical and social factors are intimately interconnected and co-evolve across multiple spatial and temporal scales. Due to the increasing complexity of sustainability challenges (Millennium Ecosystem Assessment, 2005), SES theory has evolved over decades, drawing on various disciplines including ecology, sociology, and systems theory. The overarching concept is that human societies and natural ecosystems are inherently linked, making it challenging, if not impossible, to study one component without considering the other.

Today, a socio-ecological perspective is regarded as pivotal in fostering adaptive capacity and transformability within the broader context of SES (Walker and Salt, 2006). SES theorizing concurrently engages with the concept of time through the heuristics of the adaptive cycle (Gunderson and Holling, 2002), wherein change is conceptualized through a four-stage cycle. Nevertheless, the integration of space and time remains a concern, as they are frequently examined independently (Lovell et al., 2023). In practice, spatial aspects are typically analyzed first, and temporal aspects are subsequently addressed, albeit to a lesser

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extent (Rau et al., 2020).

Actual spatiotemporal studies are more arduous and exacting to execute, yet they yield substantially more reliable results than other approaches. These studies seek to elucidate the mechanisms through which variations in spatial patterns changes over time. Alternatively, they explore the factors that give rise to discrepancies in temporal variations between different geographical locations (Legendre and Gauthier, 2014).

In the fields of ecology and conservation biology (Frankham and Brook, 2004), as well as in SES management and planning (Opdam et al., 2006; Jones et al., 2013), there is an increasing emphasis on the importance of understanding the role of both spatial and temporal scales in ecological indication. Indeed, while spatial scales are increasingly prioritized, it is crucial to recognize the profound interaction between spatial and temporal scales in SES. Acknowledging the varying temporalities within SES facilitates engagement with and the application of diverse knowledge and experiences, thereby fostering conditions conducive to enhanced sustainability (Gramatakos et al., 2024).

Although spatial ecology has greatly improved our understanding of the ecological consequences of landscape fragmentation and habitat loss (Wickham et al. 1999; Riitters et al., 2009; Riitters, 2019), the accelerating effects of climate change, precipitated by effective human manipulation of time, have necessitated the establishment of an analogous temporal ecology framework (Wolkovich et al., 2014).

2. The case of ecological indication to assess and monitor ecosystem services

In the contemporary context, ecosystem services (ES) have become an integral component of ecological indication. These services are generally defined as the benefits that humans derive from ecosystems, playing a pivotal role in human well-being and ecological health. Their valuation is essential for comprehending the economic value of natural capital and for incorporating these values into policy and land management decisions Millennium Ecosystem Assessment, 2005; Costanza et al., 2014). The provision of ES is contingent on the functioning of ecosystems in SES, which in turn is driven by ecological processes that operate across a range of spatial and temporal scales (de Groot et al., 2010; Haines-Young and Potschin, 2010; Bastian et al., 2012). Consequently, the assessment of ES is imperative for land-use planning, conservation, and natural resource management decisions.

ES encompass various types of services, including provisioning, like food, water, and wood; regulating, like climate control, pollination, and water treatment; supporting, like nutrient cycling and soil formation; and cultural, like amenity, aesthetic, and spiritual (Millennium Ecosystem Assessment, 2005; Wilkinson et al., 2013). In recent decades, ES research has undergone substantial diversification and growth. This evolution is marked by a growing recognition of the intricate interactions between ecosystems and human well-being in the provision of ES, as well as a broader range of methodologies and theoretical frameworks (Rau et al., 2020). Spatial and temporal scales are connected and a particular scale can influence what happens at a broader or finer scale. To illustrate, a large-scale process (e.g., climate change) can exert a profound influence on phenomena occurring at finer scales. It can exert a substantial influence on the extremes that manifest at finer scales, such as the capacity to sustain crops and forests. Similarly, fine-scale changes that occur over large areas can dramatically alter larger-scale processes (e.g., deforestation, urbanization, etc.). These cross-scale relationships have important implications for management and policy options (Gunderson and Holling, 2002).

Historically, research has focused on biophysical structure and function, with a predominant focus on the spatial distribution of ES, particularly concerning supply and demand (Burkhard et al., 2012), although we still need to be able to measure and understand how horizontal flows in landscapes affect ES. The spatiotemporal dimensions of ES flows have received comparatively less attention (Abson and Termansen, 2011; Birkhofer et al., 2015; Rau et al., 2020). This oversight carries the potential for far-reaching consequences, particularly with respect to the sustainable management of ES, which is critical for humanity's survival. Indeed, numerous assessments of ES dynamics, including supply–demand flow balances, habitat quality, ecological security, vulnerability, and resilience, are frequently based on a limited number of snapshots in space and time and do not necessarily accurately represent the flow of ES (Rau et al., 2020). This phenomenon is not exclusive to ES, but rather pertains to the most ecological and environmental indicators and indices used.

Additionally, the issue of interpreting the ecological indication measurements themselves must be addressed, that is, the determination of what constitutes a good or poor value. One evolving approach in ecology involves the evaluation of indication values based on expected versus observed values for a particular ecosystem, landscape, or ES. A notable illustration of this methodology can be found in a remote sensing example in Wylie et al. (2012), which evaluates historical patterns of landscape conditions and trajectories forward. In this approach, historical values represent the expected results, while newer measures are observed results. Field based surveys of this approach have been used for birds (O'Connel et al., 2007) and fishes (Van Sickle et al., 2005).

ES operate on different time scales, which, in general, can be classified as follows: Short-term services, which occur over hours or days, such as pollination or pest control; Medium-term services, occurring mainly during every year, such as crop production, seasonal water regulation or crop pollination; Long-term services, which extend over decades or centuries, such as soil formation, carbon sequestration, or nutrient cycling (Rau et al., 2020). The choice of scale (extent and grain) should always be discussed and justified in relation to the objectives of the study (Table 1).

Hydrological sciences have demonstrated a superior capacity to deal with the horizontal flows of environmental processes and resources (e.g., water quality, flood risk, etc.). This is facilitated by the fact that "directional flow-related" services are contingent on the flow of water from upstream to downstream, as evidenced by the provision of water supply and water regulation. Additionally, hydrological sciences have demonstrated a profound understanding of nested spatial hierarchies, such as nested catchments and surface flows, local catchments to watersheds, to basins (Fischer et al., 2021) (Table 1).

Changes in ES over time may appear linear, periodic, or characterized by sudden events, depending on the temporal granularity and scope of the study (Rau et al., 2018). The sequence and timing of such events and processes are fundamental. This phenomenon is referred to as the "initiation condition." This condition refers to the status of the processes at the inception of the ecological events and the sequences of which other processes and perturbations ensue. This condition is inherently dynamic, contingent on the definition of the temporal origin (Gough et al., 2024). This inherent variability poses a significant challenge in the field, as it complicates the process of making accurate forecasts and predictions.

A periodic dynamic may manifest as monotonically linear when measurements are aggregated over an extended time frame. However, this does not imply that the selected scale is the most efficient for the study's objectives. This oversight can lead to an imbalance between supply and demand, resulting in the implementation of unsustainable management practices that jeopardize the long-term accessibility of services. Underestimating the spatiotemporal variability of individual and bundles of ES can often produce misleading results (Fisher et al., 2009; Renard et al., 2015).

A systematic review found that only a small percentage of studies (2%) adequately considered temporal patterns of ES supply and demand, often focusing on linear changes rather than acknowledging evidence of nonlinear dynamics or shocks (Rau et al., 2020). Indeed, it is often short-term shocks to ES that are more problematic than long-term trends for maintaining human well-being (Chapin et al., 2010), with ES showing nonlinear responses to increasing anthropogenic pressures (Liu

Table 1
Checklist of space and time scale issues as exemplified by the EU Water Framework Directive (modified from Bastian et al., 2012).

Position	Issue	Implementation in WFD (examples)	ES – example: groundwater recharge
1. Space			
1.1	*Areal requirements*	Minimum sizes of standing waters (50 ha) and catchments (of flowing waters: 10 km^2) in the WFD monitoring and reporting taken into account; catchment alignment instead of administrative units	Areas and state of groundwater bodies
1.2	*Spatial composition*	Combined consideration of surface and groundwater, management of entire catchments	Patterns of aquifers and infiltration areas; distribution of groundwater recharge (supply) and groundwater extraction (demand)
1.3	*Spatial configuration*	Configuration issues only partially implemented with mappings of the waters' structure; fish migration ability considered; confined to big-and medium-sized water bodies (i.e. two-thirds of streams are not considered in terms of their structure)	Spatial structure and shape of landscape elements (e.g. infiltration areas)
1.4	General: *functional connection*	Orientation towards human health, quality of life, joint consideration of biological, chemical and ecological quality	Maps of groundwater protection; spatial allocation of measures, benefits and payments
2. Time aspects			
2.1	*Time requirements*	Differentiating management measures by graduated time periods	Time aspects of groundwater recharge and flows, monitoring (water-level gauge)
2.2	*Temporal sequences*	Targets in accordance with ecological processes are differentiated according to specific time periods; flexible management priorities	Natural conditions can vary (precipitation necessary for water infiltration, crop rotation), trends (e.g. climate change)
2.3	*Time lags*	Strict application of the precautionary principle, (flood) risk minimization	For example, the establishment of water protection areas
3. Scale and dimension			
3.1	*Suitable dimension*	Combined top-down and bottom-up approach, planning and management regional, but with local measures	Hierarchy of catchment areas
3.2	*Transition*	Partly considered: effects on climate protection goals	Many local measures can affect groundwater recharge regionally (or regarding the whole water body)

et al., 2024). Nevertheless, simple linear regressions remain a prevalent method for demonstrating trends in time series, overlooking the significantly more informative nonlinear cyclical patterns. Nonlinear changes in demand can lead to threshold effects, where small shifts in demand lead to significant changes in service provision. For instance, modest upticks in agricultural demand may necessitate substantial land conversion, precipitating abrupt declines in other ES, along with biodiversity and water regulation (Li et al., 2023). Consequently, prioritizing immediate benefits, such as heightened agricultural yields, may come at the expense of the long-term sustainability of critical supporting services, such as soil health (Baveye et al., 2016).

In this context, nonlinear time series analysis (Kantz and Schreiber, 2004), such as Recurrence Quantification Analysis (RQA; Marwan et al., 2007; Petrosillo et al., 2021), can be very useful even for short time series like we often have. This is due to the fact that the underlying processes exhibit complex relationships that are not well captured by linear models (Gret-Regamey et al., 2014).

The dramatic changes in ES observed globally have stimulated recent work on the characterization of their interactions, including the identification of their trade-offs and synergies (Tomscha and Gergel, 2016; Zheng et al., 2019). Such understanding is essential to better manage multifunctional ecosystems and minimize costly trade-offs (Baiqiu et al., 2019), which is considered one of the most important current sustainability issues (Aryal et al., 2022). Although time should be implicit in trade-offs and synergies, these interactions are usually inferred only based on the spatial relationships between ES (for example, the spatial concordance of ES indicates synergies, while inconsistency indicates trade-offs) (Tomscha and Gergel, 2016), creating a typical case of "space-for-time substitutions" (Lovell et al., 2023).

Last but not least, engaging local communities and stakeholders in research is essential for several reasons (Hauck et al., 2016). Local communities and stakeholders often possess a unique perspective on ES derived from their daily interactions and historical knowledge. Involving these communities helps researchers understand the values and needs associated with ES, as well as their spatial dynamics. This is due to the fact that ES can exhibit significant variations across regions and over time, and local knowledge can underscore these nuances. When local communities are engaged in the decision-making process, there is a greater probability of support for and implementation of management strategies, enhancing the likelihood of success. In this way, management strategies are more likely to be aligned with local needs and expectations, ensuring their maintenance and sustainability over time.

3. Landscape ecology and planning

Landscape ecology, with its emphasis on patterns and processes, can usefully inform environmental decision-makers about how to plan and design landscapes that will support key landscape functions and ES at multiple scales (Jones et al., 2013). This discipline also constitutes the natural research domain for the spatiotemporal approach. Despite the inherent interconnectedness between landscape ecology and planning, which should ideally manifest as a seamless and intuitive relationship (Opdam et al., 2002), the integration of these disciplines has become increasingly intricate. This increase in complexity can be attributed to the expanding scope of landscape ecology, which addresses the pressing challenges posed by the sustainable development of human-environment systems (Wu, 2010).

To address these challenges, landscape ecology must enhance its capacity to develop problem-solving methodologies that are spatially and temporally explicitly related to landscape sustainability (McAlpine et al., 2010). In this respect, the conceptualization of landscapes as SES (Berkes and Folke, 1998) offers a more pragmatic foundation for imagining how the world works and how we would like it to be since landscapes represent the spatially explicit integration of sociopolitical and ecological scales in the actual geographic world. However, it is imperative to transcend the conventional perspective prevalent among landscape and urban planners, who have conceptualized sustainability as an enduring and stable state that, once attained, can be perpetuated for subsequent generations (Ahern, 2011).

Ecologists have embraced and linked landscape planning and management to the theory of complex adaptive systems (Levin, 1999). They have framed the scientific questions that can guide different scenarios of landscape change to be perceived and evaluated as environmentally beneficial and sustainable at multiple scales (Opdam and Wascher, 2004; Musacchio, 2009; Wu, 2010). Applied fields such as resilience thinking (Berkes et al., 2003; Walker and Salt, 2006; Folke et al., 2010), vulnerability studies (Adger, 1999; Beroya-Eitner, 2016), environmental security (Petrosillo et al., 2008), landscape planning and design (Opdam et al., 2006; Musacchio, 2009; Jones et al., 2013), adaptive management (Allen and Garmestani, 2015; Birgé et al., 2016), and urban resilience (Childers et al., 2014; Nunes et al., 2019) increasingly seek to inform managers and policymakers on issues of scale. In this regard, the concept of resilience has recently gained significant importance in several disciplines. The ability to comprehend the scaling constraints imposed on local communities by broader-scale ecological and environmental processes is paramount for effective planning and implementation of actions aimed at mitigating the likelihood of ecosystem collapse and enhancing the probability of recovery. An illustrative example of this approach is the augmentation of dam height and reservoirs, a strategy employed to mitigate the consequences of flooding and ensure the reliable delivery of water during periods of drought, both of which are consequences of climate change.

The introduction of the resilience concept to urban systems, regarded as complex adaptive systems, has led to the expansion of its theoretical scope (Davoudi et al., 2013; Nunes et al., 2019; Meerow et al., 2016). Consequently, "urban resilience" has become a buzzword that frequently appears in a variety of documents and discourses. However, its conceptualization varies depending on the individual's knowledge background and the specific objectives of the research (Liu et al., 2019).

Although landscape ecological concepts such as ES are recognized as valuable, their integration into practical planning processes is often underdeveloped and inconsistent across regions. A clear disconnection exists between scientific research and practical application, as planners often lack the ecological knowledge necessary to implement effective strategies (Eikaas et al., 2023).

Indeed, integrating ES into landscape planning poses several significant challenges (de Groot et al., 2010). One of the main obstacles is the lack of a comprehensive framework that effectively incorporates ES into landscape planning (Jones et al., 2013). Many practitioners are still struggling to define and quantify these services (Hersperger et al., 2021; de Groot et al., 2010) at different scales (Rau et al., 2020), despite increasing recognition of the benefits of incorporating ecological considerations into planning. This ambiguity complicates ES assessment and valuation, making their effective application in planning contexts and generalization of results difficult.

Planners must analyze the impact of different land cover decisions on various ES. This requires sophisticated spatial analysis and dynamic modeling tools; however, measuring and accurately assessing ES is not easy since they operate at multiple scales, ranging from local to global (Millennium Ecosystem Assessment, 2005). This variability complicates their integration into landscape planning, as planners must consider how decisions at one scale may affect outcomes at another (Qiu et al., 2022). Existing methodologies are often not standardized, leading to variability in the way services are measured and valued across scales and limiting the ability to understand trade-offs. This inconsistency can hinder effective decision making. In addition, comprehensive data on ES are often lacking, limiting the ability of planners to make informed decisions, and many frameworks do not provide clear guidance on data collection scales and use strategies. As a result, the number of ES considered in urban planning is still very limited (Cortinovis and Geneletti, 2018).

The selection of data and the scale considered necessary for analysis will greatly influence the results produced by the tools used for modeling, mapping and ES assessment. The growing popularity of software tools such as Random Forest (Breiman, 2001) for classification and mapping, MaxEnt (Phillips et al., 2006) for species distribution/niche models, or InVEST (Sharp et al., 2020) for ES assessment, often raises common issues related to their uncritical application that facilitates spatial versus temporal analyses which can overshadow temporal dynamics (Rau et al., 2020). The efficacy of these models is contingent upon the availability of in-situ measurements of habitat and species distribution models, thereby ensuring enhanced accuracy. Those tools are often used without a critical understanding of their limitations or the context of the data being used, and in the case of modeling, often without validation and evaluation (Aber, 1997; Augusiak et al., 2014). This can lead to a distorted representation of how ecological indication changes over time, potentially leading to inappropriate decision making.

Ecological networks, often referred to as ecological security networks (Liu et al., 2022), are critical structures for biodiversity conservation, ES enhancement, and mitigation of environmental degradation, especially in regions facing rapid urbanization and landscape fragmentation (Opdam et al., 2006). They consist of interconnected core areas, corridors, and buffer zones that facilitate the movement of species and the flow of ecological processes (Bennett and Mulongoy, 2006). Because persistence is the primary objective of conservation efforts, it is essential to ascertain the conditions under which landscape networks facilitate the persistence of ES flow (Opdam et al., 2002).

In living systems, such as landscapes or watersheds, the prevailing condition is characterized by fluctuations around a trend (either increasing or decreasing) or a stable average within established functional bounds. However, on occasion, this condition is subject to abrupt transitions to a radically different regime (Holling, 1973; Walker and Salt, 2006; Scheffer, 2009). Therefore, the temporal stability (persistence) of ecological corridors must be a subject of great concern, as their suitability and ES flows related can be subject to change or even disappearance with the progression of seasons and alterations in land use/cover.

The efficacy of ecological networks may be enhanced through the implementation of a spatiotemporal approach (Legendre and Gauthier, 2014) that delineates the spatial persistence over time (recurrence) of land use/cover elements and, therefore, of ES flows related. This approach involves, for instance, the use of nonlinear time series analyses (RQA) that incorporate seasonal and sub-seasonal variations at finer scales to identify and map the recurrence over time of these elements and associated ES but also to identify areas of chaotic behavior (Zurlini et al., 2012; Petrosillo et al., 2021). The recurrence rate in landscape elements of spatial patterns has been identified as a powerful indication of the reliability of those elements in representing true "stepping stones" for the design and management of ecological networks (Petrosillo et al., 2021). An alternative approach involves the comparison of interannual time-series analysis of ecosystem performance of vegetation types with their expected ecosystem performance (Wylie et al., 2012). However, to do so also requires an understanding of horizontal flows related to the ES of interest.

A primary challenge in planning for ES is comprehending the manner in which the amount, configuration, and positioning of landscape components influence specific ecological processes, associated ES, and environmental conditions. For instance, to promote groundwater recharge, the composition, configuration, and location of landscape elements, such as water infiltration areas, should be considered (Bastian et al., 2012; see Table 1). Other examples are provided by Wickham et al. (1999) regarding forest connectivity, and by Jones et al. (2006), as to the reduction of nitrogen inputs to streams in urbanized watersheds by maintaining and restoring riparian buffer zones. Given the financial constraints that limit the restoration of natural landscape elements to specific areas, it is essential to ascertain the locations where such investments would yield the greatest environmental benefits.

In summary, to recognize the repercussions of disregarding the historical underpinnings of spatial patterns is fundamental. This oversight can yield erroneous conclusions, even in the context of sophisticated spatial tools such as Morphological Spatial Pattern Analysis (MSPA) (Soille and Vogt, 2009). Thus, the "learning by doing" approach in adaptive planning (Kato and Ahern, 2008) is not the only effective method of acquiring knowledge. It is also essential to draw insights from the evolution of existing landscape patterns (Jones et al., 2013), that is "learning from what has been done."

4. Conclusions and recommendations

Despite the significant body of knowledge accumulated over the past several decades emphasizing its importance, the scale issue still appears to be a low priority in much ecological research (Estes et al., 2018). This oversight contributes to the broader problem of scientific reproducibility but also increases the risk that observations will poorly represent the phenomenon of interest, thereby limiting the generalizability of any derived ecological knowledge and the reliability of subsequent decisions. However, it is crucial to acknowledge that the numerous methodologies employed to conceptualize spatial dynamics in the operationalization of ecological indication, including ES, within study designs for diverse research objectives, may be a contributing factor to the apparent neglect of scale patterns in the ecological literature.

It is imperative to consider the spatial and temporal variability of ecological indicators and indices, such as ES with their horizontal flows and trade-offs (Schirpke et al., 2019; Aryal et al., 2022), to ensure accurate assessments and the development of sustainable management strategies (Allen and Garmestani, 2015; Birgé et al., 2016; Rau et al., 2020). Failure to consider these spatial dynamics and trade-offs can excessively simplify complex ecological interactions and compromise the long-term health of the ecosystem.

Future landscape and urban planning studies should adopt a spatiotemporal approach to facilitate a more comprehensive understanding of the interactive spatial dynamics of ES. It is important to note, however, that the design of this approach must be balanced and appropriately aligned with the spatial dynamics of the processes being analyzed (Cortinovis and Geneletti, 2018) and the local needs and expectations of stakeholders and local communities (Hauck et al., 2016).

It has been shown here that incorporating socio-ecological indication into landscape planning is a multifaceted process. The adaptive management of SES acknowledges that the scientific evidence upon which initial decisions regarding landscape planning are made is frequently incomplete and characterized by significant uncertainty regarding potential outcomes (Aber, 1997; Williams, 2012). Implementing an adaptive management framework, underpinned by the precautionary principle, is one possible solution to the challenges encountered on scale issues (Allen and Garmestani, 2015). This framework can analyze ES trade-offs occurring at multiple spatial and temporal scales (Birgé et al., 2016). Without this cross-scale approach, managers will lose the ability to identify potential vulnerabilities, such as synchronization of scale-up effects or top-down constraints, that could ultimately limit management success (Birgé et al., 2016).

A foundational component of adaptive planning and management of SES is the implementation of comprehensive in-situ monitoring networks incorporating ecological indication to assess the response of environmental targets and ES to specific landscape pattern designs and to make adjustments to existing management options and policies (Jones et al., 2010, 2013; Allen and Garmestani, 2015). This is essential because most models constructed from existing knowledge are almost always wrong in some ways (Aber, 1997). We also need full-cycle adaptive management case studies. These should show how new knowledge from monitoring led to changes in existing management approaches. These should include studies involving remote sensing (Butterfield and Malmstrom, 2006) and collection of survey data on a specific ES (Johnson and Williams, 1999). This should improve ES evaluation.

The scale dimensions are often inadequately documented in literature, with temporal scales being significantly more neglected than spatial scales (Rau et al., 2020). To address such issue, it would be advisable for academic journals in the field of ecology to require authors to explicitly document and substantiate the values of spatiotemporal resolution, extent, and duration (Estes et al., 2018). A number of journals have recently adopted such policies, requiring the inclusion of information regarding the spatial, temporal, and taxonomic scale of studies in the abstract.

The expanding scope of ecological observations facilitated by remote sensing and the growing, albeit slow, recognition of scale issues among ecologists indicate a gradual shift in the scale domains of ecology (Estes et al., 2018). The advances in the study and observation of climate change are leading to a better understanding of the fundamental variability of the Earth's climate system at multiple scales, how it may respond to changes in radiative forcing, and how humanity may respond through corresponding changes in policies, economies, lifestyles and technology (Moss et al., 2010). In this regard, the imminent acceleration of technological progress and analytical methods (Han et al., 2023) and results from in-situ monitoring networks incorporating socio-ecological indication will empower researchers with novel and unrivaled capabilities to meticulously examine and address the most conspicuous gaps in observational areas. This will contribute significantly to a more precise determination of the most suitable spatial and temporal scales of socio-ecological indication to confront these challenges.

In summary, the Editorial Board has determined that the following recommendations are necessary to enhance the quality and reliability of the scientific research presented in Ecological Indicators.

Explicitly incorporate spatiotemporal scales. It is imperative to refrain from incorporating scales into the study design a priori. A prerequisite to proceeding further is a thorough evaluation and discussion of these scales in relation to the stipulated objectives and the observed historical variation in the socio-ecological functions of interest. This discussion should include ES horizontal flows and trade-offs in particular. Actual spatiotemporal studies are concerned with how and why variation in the spatial pattern changes over time or, conversely, how and why temporal variation may differ from one point (pixel) on a map to another. A study design with socio-ecological indication that does not match the relevant scales may fail to capture significant changes, thus compromising the reliability of the results.

Avoid the uncritical application of tools that facilitate spatial versus temporal analyses. Analytical and modeling tools are frequently utilized without a thorough comprehension of their limitations or the context of the data employed, as well as their validation and evaluation with survey data collection. This can result in analyses that are oversimplified, though superficially sophisticated, and which fail to adequately capture the intricacies of SES spatial dynamics.

Respect the precautionary principle, recognizing that the science to support initial decisions on landscape planning through socio-ecological indication, such as ES supply and demand, is incomplete, often with high levels of uncertainty about potential outcomes. The adaptive management approach ("learning by doing") at multiple spatial and temporal scales provides a framework for implementing and modifying environmental planning, management and policy over time as more information is gathered through comprehensive in-situ monitoring networks incorporating ecological indication.

Not only "learning by doing" but also "learning from what has been done" (historical context perspective). It is imperative that any research under consideration incorporates an analysis of the evolution of socio-ecological indication over the course of time. This analysis must encompass both short-term fluctuations and long-term trends. The mapping of variations in spatial patterns of socio-ecological indication over time can facilitate the identification of both recurrence and chaotic behavior in landscape elements as well as their ES flows (including horizontal flows) and trade-offs. These identifications can provide a more robust understanding of current and future dynamics, leading to more effective planning (e.g. ecological networks) and adaptive management practices that promote resilience to future change.

Engaging SES stakeholders and communities for ES, since their involvement in research endeavors can facilitate the identification of pertinent scales and capture diverse perspectives on the values and needs of ES demand and supply. This involvement can ensure that adaptive management strategies are more spatially and temporally aligned with actual conditions and expectations.

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G. Zurlini*
Department of Biological and Environmental Sciences and Technologies, University of Salento, 73100 Lecce, Italy

Y.J. An
Department of Environmental Health Science, Konkuk University, Seoul 05029 Republic of Korea

E. Franklin
National Institute of Amazonian Research, CBio Av. André Araújo, 2936 – Aleixo Manaus, Amazonas 69060-001, Brazil

H. Hamalainen
Department of Biological and Environmental Science, University of Jyväskylä, FIN-40014, Finland

A. Kaklauskas
Department of Construction Management and Real Estate, Gediminas Technical University, Sauletekio al. 11, LT-10223 Vilnius, Lithuania

P. Pert
CSIRO Ecosystem Sciences, Cairns 4870 Qld, Australia

I. Petrosillo
Department of Biological and Environmental Sciences and Technologies, University of Salento, 73100 Lecce, Italy

M. Sánchez-Pinillos
Centre for Forest Research, Université du Québec à Montréal, Montreal, QC H3C 3P8, Canada

T. Selvan
Department of Forestry and Biodiversity, Tripura University, Suryamaninagar, Agartala 799022 Tripura, India

D. Valente
Department of Biological and Environmental Sciences and Technologies, University of Salento, 73100 Lecce, Italy

F.L. Xu
College of Urban & Environmental Sciences, Peking University, 5 Yihuyuan Road, Haidian District, Beijing 100871, China

J. Zuo
School of Architecture and Civil Engineering, University of Adelaide, Adelaide, SA 5005, Australia

* Corresponding author.
E-mail address: giovanni.zurlini@unisalento.it (G. Zurlini).