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Opinion

Resilience and vulnerability: distinct concepts to address global change in forests

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Resilience and vulnerability are important concepts to understand, anticipate, and manage global change impacts on forest ecosystems. However, they are often used confusingly and inconsistently, hampering a synthetic understanding of global change, and impeding communication with managers and policy-makers. Both concepts are powerful and have complementary strengths, reflecting their different history, methodological approach, components, and spatiotemporal focus. Resilience assessments address the temporal response to disturbance and the mechanisms driving it. Vulnerability assessments focus on spatial patterns of exposure and susceptibility, and explicitly address adaptive capacity and stakeholder preferences. We suggest applying the distinct concepts of resilience and vulnerability where they provide particular leverage, and deduce a number of lessons learned to facilitate the next generation of global change assessments.

Highlights

Resilience and vulnerability are widely used concepts in global change research.

Resilience and vulnerability are related, but they are not synonymous and should not be used interchangeably.

We offer a joint perspective on these two concepts, highlighting their strengths and synthesising ways forward to use them to advance the assessment of global change impacts in social–ecological systems.

Facing global change needs a strong conceptual underpinning

Forest ecosystems worldwide face increasing threats due to global change and intensifying disturbances, including wildfires, drought, and insect outbreaks [1–4]. Consequently, forests may undergo changes in structure, composition, and functioning, with important impacts for ecosystem services and biodiversity [5–7]. Global change effects include reducing the forest carbon sink [5,8] and timber production [4], as well as modifying nutrient cycling [9] and hydrological regulation [10], and impacting cultural values [11,12]. However, our understanding of how and why short- and long-term impacts of global change vary among forest stands, landscapes, and regions remains limited [13,14]. Two of the concepts commonly applied to understand, anticipate, and manage these impacts are **resilience** (see Glossary) and **vulnerability** [15–17].

Resilience is here defined broadly as the capacity of a social–ecological system to absorb or withstand global change impacts, whereas vulnerability is the propensity to be adversely affected by global change, embedded within the more general concept of **risk** [18]. A number of common elements exist between the two concepts. For example, they both consider change in relevant forest properties in response to environmental hazards [19]. In doing so, they facilitate comparative analyses across different levels (sites, management regimes, ownership categories, countries, etc.), spanning natural to human-modified systems, and enabling generalization from individual cases to broader contexts [14,20]. In addition to assessing and quantifying the effects of global change, these concepts serve as important means for effective communication to policy-makers and managers, and provide powerful frameworks for evaluating management alternatives. Specifically, they are used for identifying processes and properties that can make ecosystems more resilient [16], and for pinpointing areas that are particularly vulnerable as priority areas for intervention [21].

While resilience and vulnerability are related, they are distinct concepts and not simply interchangeable antonyms. Although they address a common challenge – how social–ecological

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systems respond to global change – their origin, unique elements, and past usage distinguish them from each other. Resilience studies in forest research originated from applications of ecological theory to ecosystem dynamics [22] and have expanded greatly in recent decades [23]. By contrast, vulnerability applications to forests emerged from the broader field of disaster risk reduction, and thus addressed a more social–ecological perspective already in early applications [18]. As a social–ecological perspective on forest systems is gaining importance [24], forest vulnerability assessments are also increasing [6,7,25,26]. Given the commonalities in their goals, it is not surprising that elements of vulnerability and resilience assessments are often mixed or even used interchangeably. For instance, previous studies have explored mechanisms of resilience while also referring to vulnerability [27,28], or even used both terms as antonyms [29,30]. Others have incorporated vulnerability components (e.g., **susceptibility**) into the resilience framework [31]. This varied and sometimes interchangeable use of the two concepts leads to confusion. The implications of this confusion are more than merely academic, as they can lead to misunderstandings in communications with policy-makers and managers. For instance, the muddled use of both concepts may reduce the clarity and effectiveness of large-scale syntheses for policy-makers [32,33], such as those undertaken by the Intergovernmental Panel on Climate Change (IPCC) or the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES). In the worst of cases, a confusing use of these concepts may lead decision makers to ignore evidence, hampering their ability to effectively address global change. Therefore, it is important to clarify the commonalities and differences between the two concepts, in order to optimally use their strengths in research and management of global change impacts on forests.

Here, we synthesize the similarities and differences of resilience and vulnerability in forest social–ecological systems, aiming to better define their scope in improving our understanding of forest responses to global change. In particular, we address the following questions. (i) What are the commonalities and differences between resilience and vulnerability, their respective contexts, and uses? (ii) What are the particular strengths of each concept for addressing forest change? (iii) What can we learn from past studies on resilience and vulnerability for the next generation of global change assessments in forest social–ecological systems? To answer these questions, we analyzed previous works that explicitly measured or quantified resilience or vulnerability of forests. Purely narrative or semantic uses of these terms (e.g., using vulnerable to mean weak [29,34]) were not considered here. Specifically, we focused on the concept of social–ecological resilience due to its more integrative nature and its particular relevance for forest policy and management [23]. Although we acknowledge that the vulnerability concept is often applied in the broader context of risk [18], we focused on vulnerability itself because it is frequently confused with resilience. Our focus is on forest social–ecological systems, yet our findings can be potentially expanded to other fields in which the two concepts are also used (e.g., freshwater ecosystems [35]).

Resilience and vulnerability are powerful concepts with distinct strengths

Resilience and vulnerability share common objectives (Figure 1). Both address how ecosystems respond to global change (e.g., disturbances, hazards, threats, or stressors [6,23]). Both concepts are concerned with the maintenance of certain properties, functions, or services, defined by a range of values or **indicators** that may represent a reference or target state [6,36]. A commonality between them is that both concepts are frequently used in management and policy contexts. Resilience is commonly advocated as a goal of forest management to increase the capacity of forests to cope with global change [16,17,37,38]. In turn, the vulnerability of forests to global change has been widely assessed across management units to identify areas of high priority for adaptation measures [39].

Glossary

Adaptive capacity: the potential or ability of a system, region, or community to adapt to the effects or impacts of disturbances.

Indicator: value derived from a function relating observable variables (indicating variables) to theoretical variables (i.e., referred to concepts). The simplest kind of indicator is a scalar indicator which maps one observable variable to one theoretical variable. A composite indicator or an index is an indicator that maps (or aggregates) a vector of observable variables to one scalar theoretical variable.

Predictor: variable or factor used to estimate or forecast a specific ecological outcome or response.

Recovery: capacity of a social–ecological system to bounce back after it has been subjected to disturbances or stressors.

Resilience: capacity of a social–ecological system to absorb or withstand global change impacts such that the system remains within the same regime, essentially maintaining its structure and functions. It describes the degree to which the system is capable of self-organization, learning, and adaptation. It includes three main conceptualizations: engineering, ecological, and social–ecological resilience. Engineering resilience is the ability of the system to recover the properties altered by a disturbance; it describes the behavior of a dynamic equilibrium state that experiences the impact of disturbance. Ecological resilience is the ability of the system to maintain its properties in the face of environmental variability (including disturbances and stressors), without surpassing a threshold that implies a shift to an alternative state. Socioecological resilience is the ability of the whole social–ecological system to reorganize in response to unexpected shocks or under gradual changes and to adapt through multiscale social and ecological interactions.

Resistance: ability to persist during a disturbance, measurable through the immediate impact of the disturbance on relevant variables characterizing the study system.

Risk: the potential for consequences where ecosystem services are at stake and where the outcome is uncertain, which results from the interaction of vulnerability (of the affected forest to a given disturbance), its exposure over

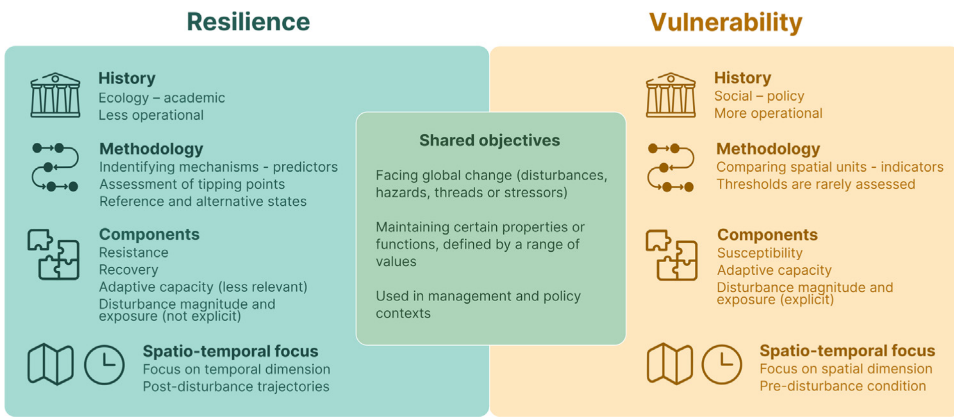

Figure 1. Main shared objectives and differences between the resilience and vulnerability concepts. The differences are classified into four groups: history, methodology, components, and spatiotemporal focus.

In spite of the commonalities in their objectives, resilience and vulnerability differ in their origin and history, methodology, components, and spatiotemporal focus (Figure 1). The resilience concept has been applied in ecology for decades [40,41]. More recently, it has also become prominent in social–ecological assessments, by merging ecological and social dimensions and specifically considering adaptation [42]. By contrast, the vulnerability concept developed primarily in a more socio-economic context (initially addressing civil protection and risk management against disasters), yet its use is quite diverse (e.g., within environmental, geophysical, and political–economic contexts [43–45]). In forest ecological research, studies related to resilience are more common than those related to vulnerability (Table S1 in the supplemental information online) [23]. A broad range of interpretations and methodologies of forest resilience have emerged, including the focus on **recovery** from disturbance (termed engineering resilience [41]) and the dynamic maintenance of the system within a given attractor or equilibrium state (termed ecological resilience). Despite (or because of) the many different ways to assess resilience, the concept has often been criticized for its lack of operationality and applicability [36,46,47], and a number of attempts have been made to explicitly operationalize it [17,48]. By contrast, the vulnerability concept has been conceived as an operational approach to inform policy decisions and planning from the very beginning, not least because of its central role in IPCC assessments since 2001 [49]. However, vulnerability assessments have a shorter history of application in the context of forest social–ecological systems [6,50].

Resilience and vulnerability also differ in the methodologies applied for their assessment (Figure 1). Resilience describes a dynamic response (capacity to withstand and recover through time from disturbances), whereas vulnerability is typically focused on describing a static condition (the ability to cope with and adapt to disturbance at a given time). Resilience studies typically aim to identify the mechanisms underlying resilience [51] – see later – and the associated **predictors** [52]. Also, resilience is often focused on identifying **thresholds** and tipping points [47,53] beyond which a system shifts abruptly from a reference state to an alternative one [54,55]. Instead of identifying mechanisms, vulnerability frequently uses indicators as heuristic tools for quantification [56,57], and thresholds are rarely assessed. Furthermore, the main components of resilience and vulnerability are distinct. **Resistance** and recovery describe resilience to disturbance and follow an explicit temporal sequence (with resistance being relevant during disturbance, and recovery after disturbance [58,59]), whereas vulnerability focuses on susceptibility and **adaptive capacity** with temporality frequently being only implicit [60]. Adaptive capacity is considered rarely in resilience assessments, and if so, it is in the context of social–ecological resilience (typically considered

time to disturbance, as well as the disturbance magnitude and the likelihood of its occurrence.
Sensitivity/susceptibility: system characteristics (e.g., structural, functional) that modulate the immediate effects of the disturbance.
Threshold: level or amount of a controlling, often slowly changing variable such that, when surpassed, a change in critical feedback occurs, thus causing the system to self-organize along a different trajectory; that is, shifting towards a different stable state or attractor.
Vulnerability: propensity or predisposition to be adversely affected by a hazard, including sensitivity or susceptibility to harm, and lack of capacity to cope and adapt. Note that in the context of climate change impacts, risks result from dynamic interactions between climate-related hazards with the exposure and vulnerability of the affected human or ecological system to the hazards. Note, however, that definitions of risk and vulnerability have evolved over time in the IPCC context.

as an important mechanism to enhance recovery) [23,42,61]. In addition, the inclusion of disturbance differs depending on the concept. In resilience, disturbances are identified as the type of pressure in face of which we want to maintain the system (resilience to what? [62]), and they are often not explicitly included in the assessment but are rather considered as an external forcing of the system (however, see [63]). Vulnerability, in turn, is often embedded in a broader context of risk assessment, which requires the explicit quantification of disturbance magnitude and exposure [6]. These differences are also evident in the spatiotemporal focus of both concepts, as resilience mainly focuses on the temporal dimension [53,64] and vulnerability on the spatial dimension [57,65] (however, see also [25,66]). Vulnerability tends to be prospective, typically referring to threats or hazards that have not yet occurred, whereas resilience is more retrospective, referring to disturbances and stressors that have already occurred (yet promoting future resilience is a common goal, which in many cases is inferred by identifying relevant resilience-related processes [67]).

Because of these differences, we pose that the resilience and vulnerability concepts have distinct strengths in the assessment of forests in the face of global change (Figure 2). Although

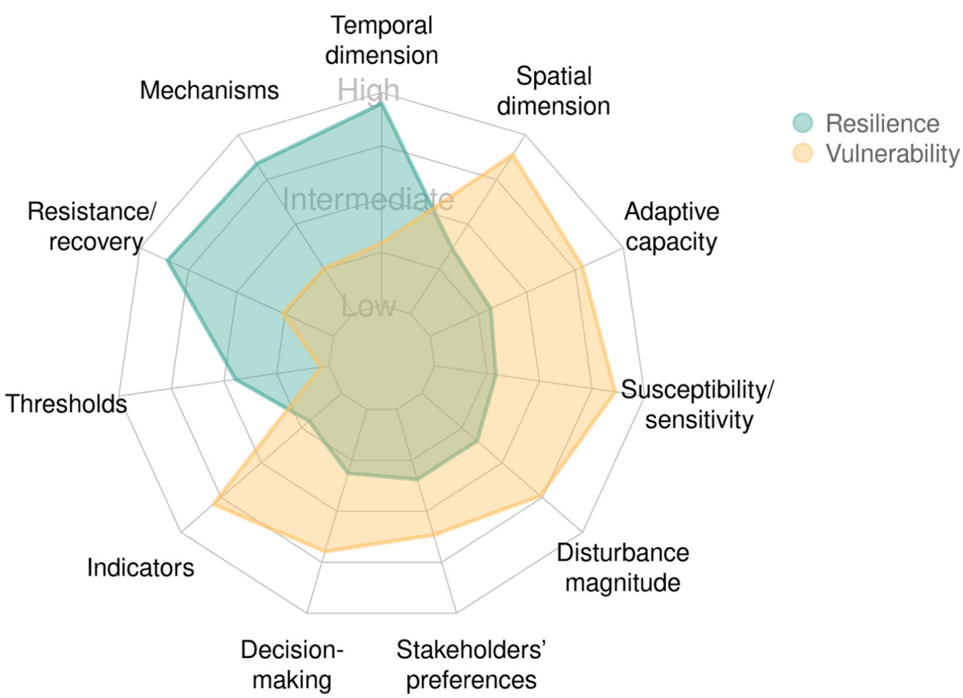

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Figure 2. Radar chart synthesizing our perspective on the distinct strengths of the resilience and vulnerability concepts: including the temporal dimension (temporal dimension); considering the spatial dimension (spatial dimension); including adaptive capacity (adaptive capacity); including susceptibility/sensitivity (susceptibility/sensitivity); explicitly assessing the disturbance magnitude (disturbance magnitude); including social preferences and views (stakeholders' preferences); using the concept in policy/decision-making (decision-making); using multiple indicators (indicators); assessing thresholds/tipping points (thresholds); quantifying resistance/recovery (resistance/recovery); and assessing the mechanisms behind resilience/vulnerability (mechanisms) (see Glossary for a complete definition of these elements). Each coauthor answered the questions in Table S2 (see supplementary information online) on how relevant each chart element is in the resilience (green) and vulnerability (yellow) frameworks, ranging from 0 (lowest relevance) to 100 (highest relevance). The importance of each element for resilience and vulnerability showed here is the average from individual scores assigned by each coauthor. The axis is classified into three categories to facilitate its interpretation: Low (0–33), Intermediate (33–66), and High (66–100). See supplementary information online for more details and Box 1 in the main text for specific examples from the literature.

this assessment is based on our expert opinion (see supplementary information online), in Box 1 we highlight some examples from the literature that illustrate these different strengths. When the temporal dimension and/or the mechanisms underlying social–ecological change are the main focus of the analysis, resilience may be more powerful than vulnerability. By contrast, if the focus is on mapping spatial patterns based on well-defined indicators, vulnerability likely offers higher inferential potential. The choice of concept also depends on the components a given study is most interested in. If the goal is to quantify resistance or recovery to disturbance (in an explicitly temporal context), or determine tipping points beyond which the system shifts, the resilience concept can offer powerful insights. If the aim is to quantify susceptibility and adaptive capacity, accounting for disturbance magnitude in a comparative and often spatial context, the vulnerability concept offers great potential. In addition, if the emphasis is on the social dimension, for instance, by including stakeholders in the decision-making process, the vulnerability approach is often more directly applicable, facilitating the use of the concept in the context of operational management and decision-making. As a result, the vulnerability concept may be more readily able to be mainstreamed into policy and management contexts, not least because of its integration in the broader concept of risk, which is a widely accepted and commonly used framework in socio-economic contexts.

Moving forward to face global change

Learning from resilience

Studies employing the resilience concept have shown that explicitly addressing underlying mechanisms and processes has great advantages [68]. Mechanistic understanding of resilience improves our ability to scale from specific settings to broader contexts and different situations, and is likely to be more robust in a rapidly changing environment [69]. For instance, knowledge about key mechanisms might enable us to identify which landscape configuration reduces disturbance propagation and severity, thus promoting resilience [70]; or which species are less resilient to disturbances based on their traits, thus guiding actions to aid their persistence. In general, functional diversity and response diversity increase resilience by enabling functional

Box 1. Examples from the literature applying the resilience and vulnerability concepts

To highlight the different applications of the resilience and vulnerability concepts, we analyzed examples from the literature for the dimensions identified (see Figure 2 in the main text). For each dimension and application, we derived a score from Low to Intermediate and High; High when the component is quantified/explicitly included, Intermediate when the component is included but not quantified, and Low when the component is not included or quantified (for more details, see supplementary information online). For the resilience and vulnerability strengths, we used the values derived in Figure 2 in the main text (i.e., the average from individual scores assigned by each coauthor).

- DeSoto *et al*. [75] (Figure IA) is a typical study of ecological resilience. They assessed tree resilience to drought using a pancontinental database and quantifying the resistance, recovery, and resilience indices by Lloret *et al*. [85], calculated from time series of tree-ring width and basal area increment. They mentioned mechanisms of drought resilience (e.g., hydraulic failure), although they did not directly measure them. The disturbance magnitude (aridity) is included as an explanatory variable in models.
- Réjou-Méchain *et al*. [60] (Figure IB) is a typical study of vulnerability. They assessed the vulnerability of African rainforests to global change by mapping and combining three indicators: (i) sensitivity to current climate; (ii) exposure to forecasted climate changes by 2085; and (iii) the adaptive capacity of tree communities using phylogenetic diversity as a proxy. They also developed a spatially continuous index representing human-induced forest-disturbance intensity.
- Forzieri *et al.* [50] (Figure IC) exemplifies a mixed approach between resilience and vulnerability, leaning somewhat towards a stronger consideration of resilience components. They quantified vulnerability to disturbances in Europe using the relative biomass loss following the occurrence of a given disturbance, considering a 40-year time series (i.e., considering the temporal dimension). They also analyzed key drivers of the underlying ecological processes (or mechanisms) and mapped vulnerability.
- Mildrexler *et al.* [26] (Figure ID) uses a mixed approach between resilience and vulnerability, with a stronger representation of vulnerability components. They mapped a forest vulnerability index to climate-induced physiological stress in the Western USA by combining indicators associated with drought and high temperatures, considering a 10-year time-frame.

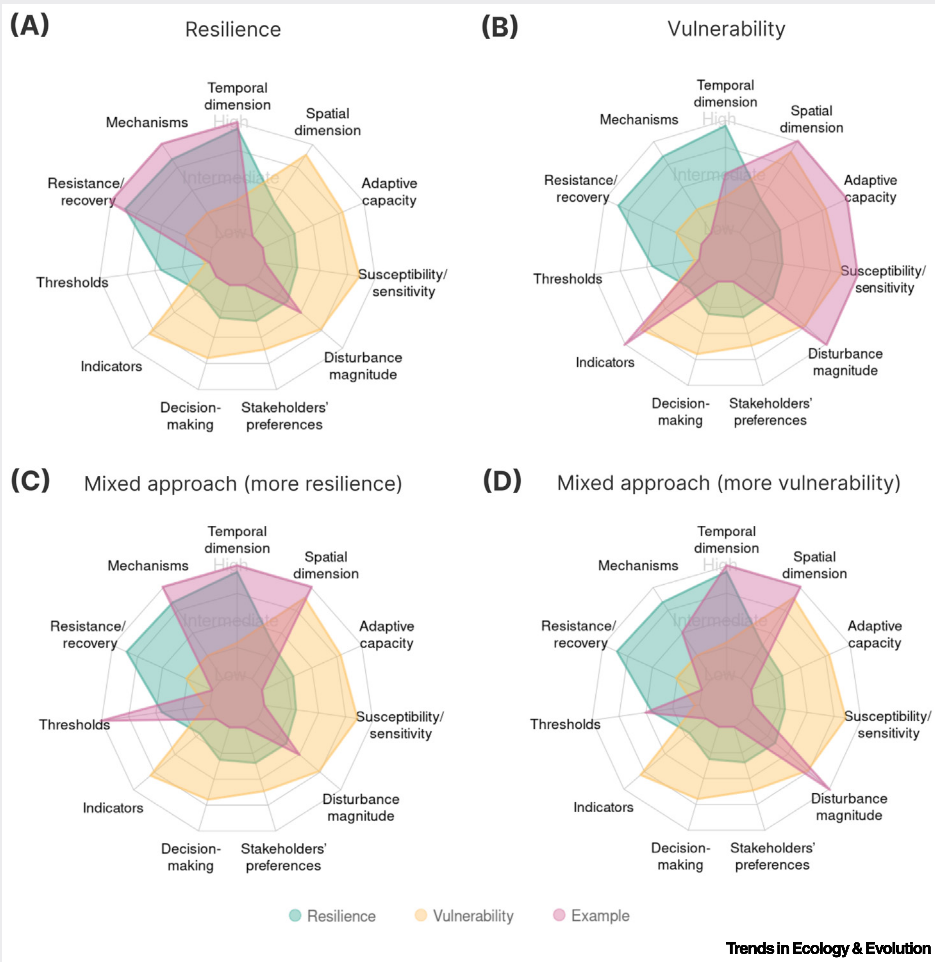

Figure I. Examples from the literature, applying different elements from the resilience and vulnerability concepts. The elements are: including the temporal dimension (temporal dimension); considering the spatial dimension (spatial dimension); including adaptive capacity (adaptive capacity); including susceptibility/sensitivity (susceptibility/sensitivity); explicitly assessing the disturbance magnitude (disturbance magnitude); including social preferences and views (stakeholders' preferences); using the concept in policy/decision-making (decision-making); using multiple indicators (indicators); assessing thresholds/tipping points (thresholds); quantifying resistance/recovery (resistance/recovery); and assessing the mechanisms behind resilience/vulnerability (mechanisms) (see Glossary for a complete definition of these elements). The examples shown in pink color are (A) DeSoto *et al*. [75], where the approach is strongly rooted in resilience; (B) Réjou-Méchain *et al.* [60], where vulnerability provides the conceptual background; (C) Forzieri *et al*. [50], a mixed approach between resilience and vulnerability, leaning towards resilience; and (D) Mildrexler *et al.* [26] a mixed approach leaning towards vulnerability.

complementarity, trait selection, or complex biotic interactions determining regulatory feedback [51,71]. Trait-based research related to functional diversity has improved our understanding of ecosystem dynamics and their ability to cope with global change [47,72]. However, many of the relevant processes remain incompletely understood, particularly due to inherent limitations to experimental research [73], and are thus poorly represented in resilience models (e.g., soil processes, regeneration, management, and legacy effects) [20]. Further research on these processes with particular focus on mechanisms that operate at longer temporal scales, such as nutrient cycling and plant trait adaptation, is needed [20].

Resilience analyses have also shown that explicitly including the temporal dimension is crucial for understanding the dynamic nature of social–ecological systems, including complex feedback mechanisms, as well as to identify factors that enhance or hinder adaptation over time [74]. Because resilience-based approaches often tend to focus on relatively short time scales, a key aspect that should receive more attention is the relationship between short-term and long-term resilience. Studies of tree mortality, for instance, suggest that short-term growth response to stress is a good predictor of long-term outcomes (drought-induced mortality) [75], but there are also well-known stabilizing processes at community and ecosystem scales that may decouple long-term resilience from short-term responses [76,77]. The temporal dimension is also essential for determining critical thresholds beyond which the system may undergo shifts to alternative states [78,79], and considering it explicitly holds the potential to improve ecosystem functioning and identify early-warning signals of change, which are crucial in the context of policy and management [80].

Learning from vulnerability

Vulnerability studies have shown that mapping where the impacts of disturbances are likely to occur – a key element of vulnerability assessments – can increase our understanding of the geographic extent and distribution of ecosystem responses to global change. These maps may be updated according to user needs by integrating more or better data and models when available [81]. Because vulnerability is embedded in the more general concept of risk, vulnerability maps can be used to identify priority areas for risk management, providing a powerful tool that is widely used in policy making. A major advantage of mapping is that the individual components of vulnerability (i.e., **sensitivity**/susceptibility and adaptive capacity) can be assessed and mapped separately, making the main drivers of vulnerability tangible for policy and management. In this sense, explicitly incorporating disturbance magnitude (embedded in risk) may facilitate our understanding of changing disturbance regimes in forest ecosystems. Mapping vulnerability draws on quantitative indicators that can be easily operationalized. These indicators can often be quantified from emerging new data sources such as remote sensing or trait-based indicators, and can be used to monitor changes in vulnerability across multiple spatial scales [6].

Vulnerability assessments have also demonstrated the importance of engaging society by explicitly including stakeholder preferences in management and policy decisions [82]. The human dimension is also important in the adaptive capacity of social–ecological systems, as social elements [e.g., gross domestic product (GDP), social networks, etc.] determine the capacity of the system to respond to disturbances or hazards. Including the human dimension is thus essential for future decision-making. However, it remains more challenging to integrate the social dimension into assessments compared with the ecological dimension. For instance, uncertainties may arise from social changes (e.g., resource availability, societal views and demands), which are often hard to anticipate. Further research is thus needed to understand and integrate societal changes into global change assessments for forest social–ecological systems [83].

Concluding remarks

Disregarding the complementary nature of vulnerability and resilience concepts reduces their value for global change research and can impair management and policy decisions. In this perspective piece, we highlight that resilience and vulnerability are complementary and should not be used interchangeably, since they focus on different aspects depending on specific goals and contexts. Acknowledging these differences and clearly defining the concepts used in any study will support scientific progress by helping scientists to contextualize and synthesize findings on global change impacts in forests. It will reduce confusion among managers and policy-makers, ultimately leading to better and more evidence-based decisions. We believe the next

Outstanding questions

How can we improve the mechanistic underpinning of vulnerability assessments to make them more generalizable?

How can we produce more operational resilience assessments, particularly making better use of spatial information and indicators?

How can we improve the use of resilience and vulnerability assessments by managers and policy-makers?

How can social uncertainty be integrated (e.g., from societal changes) in both resilience and vulnerability assessments?

How can resilience and vulnerability assessments be expanded across temporal and spatial scales?

Box 2. Lessons learned for future assessments of global change impacts

From past experiences of applying resilience and vulnerability assessments, several insights can be deduced to improve future assessments. We have identified eight insights of relevance for future assessments:

(i) Assessments should be dynamic and explicitly consider the changes in ecosystems over time and their responses to pressures. This is preferable over analyses that present snapshots in time, as it allows the explicit consideration of nonlinearities and dynamic feedbacks within the social–ecological system.
(ii) Assessments should be spatially explicit, as social–ecological systems are highly variable in space. Spatially explicit analyses further allow the consideration of spatial interactions and have essential advantages in the decision support context (e.g., identifying high priority areas for management).
(iii) Both retrospective and prospective assessments are valuable. Retrospective analyses allow us to learn from the past and identify relevant mechanisms (e.g., in the form of observational studies), while prospective studies simulate potential future conditions (e.g., in experiments or simulations) and thus give insights into the effects of potential new (combinations of) drivers.
(iv) Identifying and focusing on relevant mechanisms through which global change impacts social–ecological systems is essential. Addressing the underlying mechanisms of change ensures that assessments capture the root causes of systems responses, facilitates the use of process-based models, and increases the robustness of assessments under no analogous future conditions.
(v) Indicators are an important means of operationalizing assessments. Well-developed indicator systems exist for forest social–ecological systems [86]. These systems can be refined to better reflect relevant processes (see earlier) and can help to operationalize assessments and mainstream outcomes with management and policy documents.
(vi) Identifying and focusing on relevant mechanisms through which global change impacts social–ecological systems is critical. Addressing the underlying mechanisms of change ensures that assessments capture the root causes of systems responses and increases the robustness of assessments under no analogous future conditions.
(vii) Decomposing the overall response of forest social–ecological systems to global change into components (such as susceptibility and adaptive capacity in the case of vulnerability, or resistance and recovery in the case of resilience) helps operationalize the assessment and facilitates the communication of the overall assessment outcomes.
(viii) Explicitly including policy-makers, managers, and stakeholders in the assessment is key to robust outcomes. It will ensure that all relevant aspects of the problem are considered, facilitating the acceptance and utility of assessment results with decision makers and stakeholders.

generation of global change assessments can learn from the experiences gained by applying the resilience and vulnerability concepts, harnessing their main strengths towards improved insight and decision support in a rapidly changing world (Box 2). Our findings have broader application beyond forests, as the resilience and vulnerability concepts are also applied to other systems (e.g., freshwater [34,82], urban systems [84]) and should help to confront the current environmental emergency (see Outstanding questions).

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Declaration of interests

No interests are declared.

Supplemental information

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