Resilience thinking

A review of key concepts

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1 Introduction

Humanity is facing a triple challenge: ensuring the well-being of a growing human population, while mitigating and adapting to climate change and reversing biodiversity loss and ecosystem degradation (Baldwin-Cantello et al. 2023). A growing consensus suggests that landscape is the scale where many socioeconomic, environmental, cultural, political, and institutional challenges and issues unfold and intersect, and must be managed (Reed et al. 2021). Enhancing landscape resilience is emerging as a central way forward to address this triple challenge. Not only is it central in adaptation strategies (Nelson et al. 2007; GCA 2019),[1] it can also help address many sustainability challenges and advance most of the Sustainable Development Goals.

Landscape resilience, better described below, can be broadly understood as the capacity of a landscape to persist under changing conditions, and to adapt and transform, when necessary, in order to maintain its essential structure, functions, and identity (e.g., IPCC 2022: SPM,[2] 134). Landscapes can be seen as spatially bounded, complex, dynamic, and adaptive social-ecological systems, where humans and nature interact[3] (e.g., CE 2000; Walker and Salt 2006; Cumming 2011; Cumming et al. 2013; Liu 2019; Reed et al. 2021). The term social-ecological system (SES), introduced by Berkes and Folke (1998), emphasizes the integrated concept of 'humans-in-nature'. An SES can be seen as a "place of interest, along with its associated resources, stakeholders, institutions, and issues" (Resilience Alliance[4] 2010). This notion recalls that the social and ecological dimensions cannot be easily disentangled and that any distinction between them is artificial and arbitrary. It also highlights the need to give the same importance to both dimensions in analysis (Berkes et al. 2003; Folke 2006; Walker et al. 2006; Bahadur et al. 2013; Cinner and Barnes 2019). An SES is essentially defined by, and structured around, the complex and dynamic relationships and feedback among its subsystems and components (e.g., human societies, ecosystems, species). These relationships[5] shape both system functions and its possible responses to a given change (Holling 1973; Resilience Alliance 2010).

This paper explores key aspects of landscape resilience in complex SESs. The next section provides a brief overview of the emergence of the concept of resilience and its different meanings. Then, Section 3 describes the main attributes of resilient SESs emerging from the scientific literature.

1 This close link between resilience and adaptation is reflected, for instance, in the latest report on adaptation of the IPCC (2022), where the terms resilience, resilient or climate-resilient appear almost 4,000 times.

2 SPM stands for Summary for Policy Makers.

3 In line with the European Landscape Convention (Art. 1), a landscape can be defined as "an area, as perceived by people, whose character is the result of the action and interaction of natural and/or human factors" (CE 2000).

4 The Resilience Alliance is a consortium of research institutes, launched in 1999, which aims at stimulating interdisciplinary and integrative research on the dynamics of social-ecological systems, using the notion of resilience as an overarching framework. The Alliance edits the review Ecology and Society and hosts regular science meetings and international conferences on resilience. It also holds a record of over 1,600 publications among which is a workbook for practitioners on "Assessing resilience in social-ecological systems" (Resilience Alliance 2010). For more details, see: https://www.resalliance.org/

5 Mutualism, competition, and predation are examples of relationships among species in ecological systems, while norms, institutions, values, power relationships, and interpersonal relationships shape social systems (Resilience Alliance 2010).

2 Resilience: A multifaceted concept

The word ‘resilience’ can be traced to the Latin verb *resilire*, which means to jump back or rebound. The concept of resilience is thus inherently linked to the capacity to bounce back, recover, or spring forward in the face of adversity (Davoudi 2012; Dakos and Kéfi 2022). Resilience is not a new concept in the scientific literature, but it has gained much traction over the past two decades. A recent literature review covering 1950–2019 showed the number of relevant papers on resilience and sustainability continuously increased from less than 20 per year before 2007 to 270 publications in 2018 (Li et al. 2020).[6]

The concept of resilience has inspired many disciplines over the last century (Béné and Doyen 2018; Dakos and Kéfi 2022). It was already used in psychology in the 1940s to assess the vulnerability and resistance of individuals or groups to adverse life events (e.g., Masten et al. 1990; Egeland et al. 1993). In mechanics and material science, resilience describes the response of a material to pressure, deformation, or other physical stress and its capacity to return to its original shape after such a stress (Fisichelli et al. 2016; Béné and Doyen 2018). Holling (1973) introduced the concept of resilience in ecology science and defined it as “the persistence of relationships within a system,” i.e., “a measure of the ability of these systems to absorb changes of state variables, driving variables, and parameters, and still persist.”[7]

Three main definitions of resilience have progressively emerged and coexist in the literature. They are often respectively referred to as engineering resilience, ecological resilience, and social-ecological (or evolutionary) resilience.

Engineering resilience

The first school of thought adopts an equilibrium-centred view of resilience. It assumes that one single stable equilibrium exists for the system under study. Resilience, then, describes “how fast a variable that has been displaced from equilibrium returns to it” (Pimm 1991). In a seminal article, Holling (1973) called “stability” this kind of resilience and defined it as “the ability of a system to return to an equilibrium state after a temporary disturbance; the more rapidly it returns and the less it fluctuates, the more stable it would be.”

This deterministic view of resilience focuses on efficiency, constancy, and predictability, and command-and-control management systems. For this reason, it is usually referred to as *engineering resilience* (Holling 1996; Davoudi 2012) or *local stability* (Dakos and Kéfi 2022). This definition can describe a complex system only very close to the equilibrium where a linear response is a valid approximation (Ludwig et al. 1997; Folke 2006). For instance, if a small forest patch, within a larger forested landscape, is destroyed by fire, the seeds and species from nearby patches can enhance and speed up forest recovery after the fire. Predator-prey relationships can offer other examples of engineering resilience (Holling 1996).

In this definition, resistance to disturbance, amplitude, and frequency of oscillations around equilibrium, time of recovery, and speed of return to the equilibrium are the main characteristics

6 And, according to Liu (2019), the term “resilience” now gets more Google hits than “sustainable development”.

7 We also note the concept of anti-fragility introduced by Taleb (2012), which describes systems that not only endure but also benefit from shocks and stress. Unlike fragile systems that break or resilient ones that recover, antifragile systems grow stronger through adversity. However, this original idea, drawn from examples across many sectors, has faced criticism for relying on anecdotal evidence, ‘survivorship bias’, a vague framework, and the practical challenge of engineering such antifragile systems.

used to measure resilience (Holling 1973). One could be tempted to say: the shorter the time of recovery, the more resilient the system is. However, such judgement seems oversimplified. First, the time response threshold that would define a 'resilient' system is an endogenous characteristic specific to each system, depending on its biological characteristics and processes. Second, ecological succession does not necessarily occur at a pace that humans can easily observe – i.e., over decades to centuries. Hence, the time scale used as a reference is somewhat arbitrary. Distinguishing a slow but normal ecological succession after a disturbance from a permanent regime shift may not always be straightforward. Indeed, it may require decades of careful observation (Falk et al. 2019).

Ecological resilience

Over the past decades, scientists have evidenced that multiple stable states, bounded by thresholds, can exist for a given ecosystem (Folke 2006; Nelson et al. 2007). When such a threshold or tipping point is crossed, due to a change in external conditions or in the state of the system itself, a small initial change can make a big difference. A system that once used to absorb disturbance can switch, sometimes abruptly, to a very different state (e.g., van Nes et al. 2016; Dakos and Kéfi 2022; IPCC 2022, 447).

Two examples are often presented in the resilience literature (e.g., Carpenter et al. 2001; Elmqvist et al. 2003; Walker et al. 2004; Lebel et al. 2006). When phosphorus concentration crosses a certain threshold, a freshwater lake can switch from a clear-water oligotrophic state to a turbid-water eutrophic state. Similarly, fire suppression can make rangelands flip from an ecosystem dominated by grasses to one dominated to woody shrubs, the latter being more vulnerable to devastating fires.

In both cases, when the threshold is crossed, it is difficult or even impossible for the system to return to the initial state at reasonable costs. In this context, resilience is defined as the maximum amount of disturbance that a system can support while maintaining its current state, structure, and identity – variables, parameters, processes, interactions and feedback loops (Holling 1996; Walker et al. 2004; Folke 2006; Davoudi 2012; Scheffer et al. 2015). This more probabilistic view of resilience, emerging from ecology science, is generally called *ecological resilience* (Holling 1986; Folke 2006) or *non-local stability* (Dakos and Kéfi 2022). Here, resilience embraces variability, heterogeneity, non-linearity, thresholds, and abrupt changes, uncertainty, and surprise (Holling 1986; Folke 2003, 2006).

Ecological resilience can be illustrated in the "state space"[8] through the concept of stability landscape where "basins [or valleys] of attraction" represent the multiple stable states, i.e., the different regions in the state space where the system tends to remain. These basins are bounded by hills or ridges, representing the thresholds, i.e., the regions where the system becomes unstable and susceptible to flip abruptly to another, completely different state. There are two modes for a system to cross a threshold. First, the system can move in the stability landscape due to changing conditions affecting the state variables. Second, the stability landscape itself and its parameters can be modified due to external drivers or endogenous processes, or as an intentional or unexpected consequence of human interventions (Walker et al. 2004; Dakos and Kéfi 2022). This second phenomenon is at work, for instance, when species distribution ranges are shifted because of climate change.

Building upon this conceptual framework, Walker et al. (2004) identify four critical aspects of ecological resilience. The first – latitude – is the size of the basin of attraction, i.e., the maximum amount of disturbance a system can absorb before switching to another state.[9] The second – resistance of the system to changes – is represented by the depth of the attraction basin. The third – precariousness – reflects the vulnerability of the system, i.e., its proximity to a threshold where even a small disturbance can provoke a regime shift. The fourth – panarchy – reflects cross-scale interactions and is further developed below (see, in **Section 3**, the part on polycentric and multilayered governance).

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8 Each dimension in the state space represents a key state variable of the system.

9 However, a similar dilemma as the one identified above about arbitrary timescales also affects this idea, as a state's change is a qualitative concept that can be difficult to characterize clearly (consider slow-onset system degradation).

These multiple alternative stable states or basins of attraction can provide different sets of ecosystem services or disservices. Consequently, they generate various levels of economic, social, and environmental benefits or costs. They can thus be considered more, or less, desirable from a strict human perspective (Walker et al. 2006). Such considerations add a normative dimension to the concept of resilience (Nelson et al. 2007; Cinner and Barnes 2019).

Resilience is not always a good thing when it creates 'social-ecological traps' that help maintain the system in an undesirable state (e.g., in the above-mentioned lake and rangeland examples). This is why resilience is not only about resistance, stability, persistence, and recovery, but also about adaptation, reorganization, innovation, and transformation – even if these terms may seem antinomic in our common understanding (Carpenter et al. 2001; Gunderson and Holling 2002; Walker et al. 2004; Folke 2006; Folke et al. 2010; Haider et al. 2012; Ensor et al. 2016; Cinner and Barnes 2019; Falk et al. 2019; IPCC 2022: SPM, 123).

This tension and apparent contradiction between resilience and transformability, and between persistence and change (Folke et al. 2010; Béné and Doyen 2018) can be solved by considering cross-scale interactions, in line with the concept of panarchy (Walker et al. 2004, 2006). Indeed, a transformation at lower scales (e.g., genes, species) may be necessary to ensure the system's overall resilience at a larger scale (e.g., ecosystem) (Morecroft et al. 2012).

Social-ecological resilience

Although very different, engineering and ecological resilience both assume single or multiple stable equilibriums in the system under study. However, in the real world, disturbances can take the form of: (i) single events such as a storm, a war, or an economic crisis; (ii) periodic cycles, such as in the famous cases of the budworm forest community in Canadian spruce-fir forests and of fire regimes in Western US rangelands presented by Holling (1973); or (iii) continuous and progressive changes such as current global warming and sea-level rise.

Human activities are increasingly altering the duration, intensity, frequency, and spatial distribution of disturbance regimes. This can occur through active disturbance (e.g., fire) suppression; the transformation of former pulse events into persistent or chronic stress (e.g., water scarcity); or the introduction of new disturbances (e.g., invasive species, pest, or disease outbreaks) (Folke 2003).

Consequently, no stable equilibrium may exist in many real SESs. Most probably, they are continuously changing, driven by external forces and/or internal processes. As such, they likely spend most, if not all, the time in a transient state, far from any equilibrium (Holling 1973; Scheffer 2009; Davoudi 2012; Bahadur et al. 2013).

Once disturbed, a system hardly ever bounces back to the exact same state. Moving away from the vision of a deterministic, mechanically ordered, clockwork universe, this perspective introduces chaos, complexity, uncertainty, unpredictability, and surprise into the equation. This is why, for this school of thought, resilience is not defined as a return to normality but rather as "the capacity to adapt or transform in the face of change in socioecological systems, particularly unexpected change, in ways that continue to support human well-being" (Folke et al. 2016). This definition of resilience has been termed *social-ecological resilience* (Folke et al. 2010, 2016; Quinlan et al. 2015) or *evolutionary resilience* (Davoudi 2012; Li et al. 2020).

A continuum of resilience strategies

Building upon these three definitions of resilience, a continuum of resilience *strategies* emerges from the literature. They can be ordered in four broad categories (e.g., Walker et al. 2004; Nelson et al. 2007; Folke et al. 2010; Morecroft et al. 2012; Fisichelli et al. 2016; Béné and Doyen 2018; Cinner and Barnes 2019; Falk et al. 2019; Hamborg et al. 2020):

- *persistence,* i.e., resistance or toleration to change and conservation of existing functions and structure
- *recovery,* i.e., absorptive resilience or capacity to buffer temporary disturbances and restore the same system state, functions and structure

- *adaptation*, involving some reorganization or changes in the system's parameters to ensure its overall perennity
- *transformation* to another, more desirable state, when current conditions make the existing state untenable

As noted by Falk et al. (2019), these resilience strategies may operate at different *scales* – from individual (or single component) resistance to population (or subsystem) recovery and to ecological community (or whole system) reorganization. The first two can be related to the engineering definition of resilience, while the last one refers to the wider ecological or socioecological definitions of resilience.

These four strategies are ordered on a continuum associated with increasing levels of change which generally come with increasing social, economic, and environmental costs (Béné and Doyen 2018). In sum, following Bruneau et al. (2003), a resilient system shall demonstrate the right balance between strength (i.e., resistance and buffering capacity) and flexibility (i.e., adaptability and transformability), two notions, at first sight that, may seem antinomic in our common understanding.[10]

Beyond these four resilience strategies, commonly identified in the literature, Béné and others suggest yet a fifth, more subjective, resilience strategy: "adaptive preference". They defined this as the "deliberate or reflexive process by which people adjust their expectations and aspirations when trying to cope with deteriorating changes in their living conditions" (Béné et al. 2014; Béné and Doyen 2018). Unlike the four others, this strategy does not seek to modify either the system state or the stability landscape. Instead, it seeks to adjust only our own appreciation of the level of expected benefits, synergies, and trade-offs.

10 This antagonism is illustrated for instance in the famous fable of Jean de La Fontaine (1621–1695) entitled Le chêne et le roseau (i.e., the oak and the reed) where the oak is strong while the reed is flexible. A resilient system should be able to combine the respective qualities of the oak and the reed, or to adopt alternatively, as appropriate, the oak or the reed behaviour.

3 What are the main attributes of resilient systems?

Some authors consider resilience a slippery concept for two reasons. First, it has different meanings assumed over the past decades. Second, it is unclear how to translate this theoretical concept (whatever definition is used) in practical strategies and actions in the field in a particular context (Davoudi 2012; Morecroft et al. 2012; Fisichelli et al. 2016; Béné and Doyen 2018). The looseness and malleability of this concept leads to the absence of clear and consensual definitions, indicators, and metrics (Béné and Doyen 2018).

Therefore, many authors, aiming at further operationalizing this concept, have tried to identify and describe the main qualities expected to support and enhance resilience in a given SES (e.g., Bahadur et al. 2013; Ensor et al. 2016). Diversity or heterogeneity, redundancy, connectivity, flexibility, or adaptability are widely accepted in the literature among the most important characteristics of resilient systems (e.g., Bernhardt and Leslie 2013; Timpane-Padgham et al. 2017; Wiese 2016; Hamborg et al. 2020).

But resilient systems have many other characteristics. For instance, Timpane-Padgham et al. (2017) identified 51 specific resilience attributes categorized into individual-, population-, community-, ecosystem-, and process-level attributes. The same article highlighted six ecological themes conferring resilience that emerge from their literature review: connectivity, biological diversity, adaptability, habitat variability and conditions, presence of refugia or support areas, and natural disturbance history. Biggs et al. (2012) identified seven operational principles to enhance resilience in SESs against disturbances and ongoing changes: (i) maintain diversity and redundancy; (ii) manage connectivity; (iii) manage slow variables and feedback; (iv) foster an understanding of SESs as complex adaptive systems; (v) encourage learning and experimentation; (vi) broaden participation; and (vii) promote polycentric governance systems.

Elaborating upon previous studies, we suggest that resilience in SESs be characterized by the following key attributes, most commonly underlined and studied in the literature: (i) integrity; (ii) diversity; (iii) redundancy; (iv) connectivity; (v) flexibility; (vi) participation; (vii) polycentric and multilevel governance; and (viii) accountability.

Following the categorization suggested in the literature (Jentoft et al. 2007; Biggs et al. 2012), the first four attributes focus more on the key characteristics of the SES to be governed. Conversely, the last three relate more to the way the system is governed, i.e., to the way stakeholders act within and influence the system. Finally, the eighth criterion, of flexibility, can be classified under both categories because, as shown below, it reflects both a characteristic of the system and an ability of actors in this system. Long-term sustainability (e.g., Cinner and Barnes 2019), social justice (Lebel et al. 2006), and equity (e.g., Davoudi 2012; Bahadur et al. 2013; Ensor et al. 2016) are sometimes also mentioned as attributes of resilient systems. However, while the other attributes describe the means to enhance resilience in a system ("How to enhance resilience?"), sustainability, social justice, and equity should rather be viewed as the main goals or desirable outcomes of resilient systems ("Why enhance resilience?") (Lebel et al. 2006; Nelson et al. 2007; Davoudi 2012; Béné and Doyen 2018; Bates et al. 2019; Li et al. 2020).

This section focuses on the "How?", describing succinctly each of the eight attributes listed above. As highlighted by Biggs et al. (2012), these principles and characteristics are closely interlinked. Considered in isolation, they are unlikely to lead to enhanced resilience. For instance, response diversity goes hand in hand with functional redundancy. Connectivity is useless without diversity and spatial heterogeneity. Participation is a critical condition for the success of polycentric and multilevel governance but is meaningless without accountability.

Integrity

Integrity is not normally given first place in the context of resilience, but we see it as a fundamental attribute. In ecology and conservation science, the notion of ecological integrity (Leopold 1949),[11] denotes the quality of an ecosystem or landscape that, experiencing no or minimal modification from human activities, is similar to a natural habitat in terms of species composition and diversity, ecological processes, structure, and function (Parrish et al. 2003; Theobald 2013). This quality reflects the level of wilderness, pristineness, or intactness of an ecosystem (e.g., Manuel-Navarrete et al. 2004;[12] Hughes 2019).

The notion of intact landscape, and particularly of intact forest landscape, is widely studied in the literature as a central element of any ecosystem conservation or restoration strategy. An intact forest landscape is a "seamless mosaic of forest and naturally treeless ecosystems with no remotely detected signs of human activity and a minimum area of 500 km^2" (Potapov et al. 2017)[13] (although the threshold of 500 km^2 may seem somewhat arbitrary). Intact forests provide invaluable ecosystem services (biodiversity, climate change mitigation and adaptation, air quality, food security and nutrition, incomes, etc.) not only for local ecosystems and communities but also for the whole planet. Hence, their loss would disproportionately erode biodiversity, carbon storage, and other ecosystem services (e.g., Watson et al. 2016, 2018; Betts et al. 2017; Potapov et al. 2017).

In integral or intact ecosystems, a set of biological, physical, and chemical conditions, processes, and interactions, if kept within their naturally acceptable variation range,[14] enable a balanced, diverse, and adaptive community of organisms to persist over the long term. Therefore, ecological integrity is expected to enhance ecosystem resilience while ecosystem degradation is expected to exacerbate vulnerability (Parrish et al. 2003; Wurtzebach and Schultz 2016; Hughes 2019; IPCC 2022, 283). This is why Belote et al. (2017), for instance, called for building a more resilient network of wild, connected, and diverse protected areas that: (i) better represent the various ecosystems; (ii) facilitate biota movement in the face of disturbances; and (iii) promote species persistence within intact landscapes.

More precisely, the notion of ecological integrity encompasses various key attributes of resilient ecosystems, as identified by Timpane-Padgham et al. (2017). First, habitat conditions, in particular soil health and water availability, are critical for the productivity of healthy ecosystems and for quick ecosystem recovery after a disturbance. Second, the presence and conservation of refugia (against climate change or other disturbances) or of specific support areas (such as spawning or rearing habitats) are crucial to enhance resilience to climate change or to preserve vital ecosystem functions. Third, the natural disturbance history is often part of ecosystem integrity as it maintains habitat heterogeneity and variability at different scales, thus enhancing resilience and adaptability. A better understanding of the natural disturbance history is also critical to define the above-mentioned acceptable variation range to be used as a reference to assess ecological integrity.

11 "A thing is right when it tends to preserve the integrity, stability, and beauty of the biotic community. It is wrong when it tends otherwise" (Leopold 1949).

12 This is the conception of ecological integrity as developed in the "wilderness-normative discourse" (Manuel-Navarrete et al. 2004).

13 See also https://intactforests.org/concept.html

14 Parrish et al. (2003) distinguish "natural" and "acceptable" variation range because what is natural might be difficult to define. This is particularly the case where ecosystems have been so profoundly altered by human activities over time that they have no historical pristine counterfactual. In such cases, the historical variation range can serve as a useful reference. However, under rapidly changing climatic conditions, or in irrevocably degraded ecosystems where restoration may not be feasible or socially acceptable, even the historical variation range may become irrelevant as a benchmark (Wurtzebach and Schultz 2016; Falk et al. 2019).

In the literature, the concept of ecological integrity is used to qualify wild, natural, or intact ecosystems and landscapes. However, this notion may appear less relevant to describe agricultural or forested landscapes that have been shaped over millennia by continuous human-nature interactions and now cover most of the Earth's land surface. Indeed, it has been estimated that intact landscapes, free from substantial human impacts, today cover less than 25% of the Earth's land surface (Ellis et al. 2010; Watson et al. 2016; IPBES 2018).[15]

If current trends continue, less than 10% of the Earth's land surface could remain intact by 2050, mostly located in places unsuitable for human use or settlement, such as deserts, mountains, tundra, and polar systems (IPBES 2018). Hence, the concept of ecological integrity could be usefully broadened to also cover managed ecosystems with no natural counterpart. More generally, we suggest to call integral or intact an SES that is sustainably productive, resource-use efficient, well adapted to its environment and – building upon ecosystem services, processes, and functions – able to make the most of its environment in the long term. This definition could apply not only to some Indigenous and traditional production systems but also to more innovative nature-based solutions.

Diversity

Diversity can be characterized by three distinct but interlinked properties: variety (how many different elements); balance (how much of each element), and disparity (how different the elements are from one another) (Stirling 2007). Diversity in a resilient SES encompasses *biological diversity* and spatial heterogeneity[16] but also *functional diversity*, *response diversity*, and *social diversity*.

It is generally assumed that, by privileging short-term productivity over long-term sustainability, landscape homogenization and simplification erode resilience (Folke 2003). In other words, the higher the *biological diversity* at different scales (genes, species, ecosystems), the more resilient a system should be (e.g., Carpenter et al. 2001; Elmqvist et al. 2003; Biggs et al. 2012; Mijatović et al. 2013; Bahadur et al. 2013; Timpane-Padgham et al. 2017; Li et al. 2020; IPCC 2022, 217, 746).

Multiple equilibria, instability, and movement between states in a system maintain heterogeneity and diversity, which may provide resilience in the face of unexpected disturbances (Holling 1996). This is the so-called insurance hypothesis, which predicts that net productivity and resilience should be positively correlated with biodiversity and species richness (e.g., Yachi and Loreau 1999; Loreau 2000; Carpenter et al. 2001; Elmqvist et al. 2003; Cumming et al. 2013; Timpane-Padgham et al. 2017; Bates et al. 2019). In any case, the growing concerns about the observed and potential devastating impacts of current biodiversity loss on ecosystem functions, processes, and resilience call for the general application of a precautionary approach[17] to the management of biodiversity (e.g., Loreau et al. 2001; Rosenfeld 2002; van Ruijven and Berendse 2010; IPBES 2018).

However, a higher number of species in an ecosystem does not automatically lead to higher ecosystem performance and resilience. Indeed, the role of *biological diversity* on ecosystem functioning and resilience is mediated by both *functional* and *response* diversity. Functional diversity – the diversity of functional groups in a given ecosystem – affects ecosystem performance. For its part, response diversity – the variability of species' responses to a given change within the same functional group – influences ecosystem resilience (e.g., Holling 1996; Elmqvist et al. 2003; Folke 2006; Walker et al. 2006; Aquilué et al. 2020).

Response diversity is particularly important for ensuring resilience after a disturbance, and during periods of ecosystem renewal and reorganization. By enriching the range of available response options in a system (portfolio effect), response diversity is expected to strengthen adaptive capacity, and hence resilience, in the face of uncertainty and unpredictable changes (Carpenter et al. 2001;

15 The remaining 75%, substantially modified by humans, can be considered as an "anthrome", i.e., an anthropogenic biome (Ellis et al. 2010).

16 Closely linked to biodiversity at ecosystem and landscape scales.

17 Since 1992, this precautionary approach has been central in the implementation of the Rio Conventions, and particularly the UN Convention on Biological Diversity. See https://www.cbd.int/marine/precautionary.shtml

Elmqvist et al. 2003; Folke 2003, 2006; Biggs et al. 2012; Cumming et al. 2013; Belote et al. 2017; Bates et al. 2019).

Similarly, the concept of *social diversity* can characterize the different stakeholder groups and institutions involved in a social system as well as the diverse functions they perform in the system - *functional social diversity* (e.g., Berkes et al. 2003; Folke 2003; Osbahr 2007; Rockfeller Foundation 2009; Bahadur et al. 2013; Ensor et al. 2016). This social diversity encompasses, *inter alia,* the diversity of gender, age, and race; of level of income and power; of education, culture, and knowledge systems; of perspectives, views, norms, and values. The concept of response diversity can also be adapted to a social system to characterize how various stakeholder groups react to a given change, or the diversity of available management response options to address a given issue (portfolio effect).

Economic diversity is also important for resilience: economies dominated by a single sector or communities depending on a narrow range of resources will likely be highly vulnerable to a disturbance affecting their dominant sources of livelihoods and income (Norris et al. 2008; Cutter et al. 2010; Bahadur et al. 2013; Quinlan et al. 2015). The Intergovernmental Panel on Climate Change (2022, 99) identifies livelihood diversification as a key strategy to cope with and adapt to climatic and non-climatic risks.

Redundancy

In the realm of complex SESs, the concepts of response diversity and functional redundancy are intertwined (e.g., Elmqvist 2003; Walker et al. 2006; Biggs et al. 2012). They serve as vital components for resilience because they enlarge the range of available options to respond to changes, whether the change is predictable or not (Stirling 2007; Biggs et al. 2012). Functional redundancy – the capacity of some elements in a system to compensate fully or partially for others – is an insurance that essential system functions can persist even if some 'redundant' components are lost or fail (Lawton and Brown 1994; Rosenfeld 2002; Biggs et al. 2012; Bahadur et al. 2013; Pillar et al. 2013; Aquilué et al. 2020). However, diversity and redundancy come with costs for the system. Consequently, tracking and removing redundant components (i.e., components deemed as either useless or uncritical) is widely used as a strategy to reduce costs while increasing productivity and efficiency in agroecosystems, industrial processes, or governance structures (Walker et al. 2006). Yet, such a strategy may reduce the resilience that was inherently provided by the redundant elements.

However, this perspective that views redundancies as costly and expendable oversimplifies the dynamics of complex SESs (Rosenfeld 2002). Each component in such systems holds unique characteristics, and seemingly redundant species or system components will never totally overlap in their functions but may assume complementary or antagonistic roles when considering broader system functions. Additionally, such redundant elements, while serving apparently the same function, may respond differently to disturbances, illustrating response diversity. Functionally redundant components, often dismissed as unnecessary, can emerge as critical contributors during phases of system renewal and reorganization following disturbances (Rosenfeld 2002; Folke 2006).

Therefore, a tension always exists in complex social-ecological systems between efficiency on one hand, diversity and redundancy, which do not come without costs, on the other hand (Walker et al. 2006; Wilkinson 2012; Biggs et al. 2012; Wiese 2016). Too low levels of redundancy and diversity may produce brittle systems, maybe highly efficient in a given environment, able to resist to predictable variability and changes in the short term, but with low resilience to unpredictable changes in the long-term[18] (Holling 1986, 1996; Walker et al. 2006; Biggs et al. 2012). By contrast, too high levels of redundancy and diversity may lead to inefficiency and system stagnation, and finally undermine ecosystem productivity and resilience in the long term (Biggs et al. 2012).

18 Holling (1986) considers that such predictable, cyclic disturbances, which he calls "accidents designed to happen," can progressively become an internal component of the system, sometimes essential to preserve its structure, functioning, and identity (as in the case of fire regimes in grasslands). By contrast, an unpredictable, unusual disturbance, which Holling (1986) calls a "surprise," can reveal the vulnerability of a system, yet apparently well fitted to the natural variability of its environment.

Connectivity

Complex SESs can be studied using network theory (Janssen et al. 2006). They can be represented as networks where their different components (e.g. habitats, species, or actors) are the nodes. Meanwhile, the relationships between them (e.g., natural corridors, predator-prey relationship, competition for resources, pollination, market transactions, partnerships, etc.) are the links. The structural properties of these networks, among which are *connectivity*, *modularity* and *centrality*, are critical attributes shaping their resilience (e.g., Janssen et al. 2006; Biggs et al. 2012; Isaac et al. 2018; Cinner and Barnes 2019; Aquilué et al. 2020; Li et al. 2020).

Connectivity (i.e., the number and strength of the links between nodes) is generally considered to enhance resilience and facilitate adaptation (e.g., Biggs et al. 2012; Belote et al. 2017; Timpane-Padgham et al. 2017; IPCC 2022, 285). Indeed, connectivity facilitates exchanges of information, energy, materials, nutrients, species, or genes between nodes, thus supporting social and ecological functions and processes. In social systems, it contributes to create the trust needed for partnerships and collective action. In ecological systems, it supports the dissemination of species (seeds, propagules, larvae, or adults) to (re-)colonize a specific node, helps enrich the genetic and species diversity of the local population, and, more generally, facilitates recovery after a local disturbance (Janssen et al. 2006; Biggs et al. 2012; Timpane-Padgham et al. 2017). By contrast, habitat fragmentation, due for instance to infrastructure development, hampers the viability of populations, especially for large mammals (Beier and Noss 1998; Fahrig and Rytwinski 2009). This can be summarized with the motto “Better, Bigger, More and Joined” (Lawton et al. 2010; Isaac et al. 2018).

However, high connectivity can also accelerate the spread of disturbances, such as pests, diseases, invasive species,[19] wildfires or financial crises, across the network nodes. In so doing, it can support homogenization of ecological habitats or adoption of synchronized, yet unsustainable behaviours across actors (Janssen et al. 2006; Biggs et al. 2012; Aquilué et al. 2020; IPCC 2022, 285). Therefore, a higher connectivity in a randomly connected network may not lead automatically to higher resilience or stability, above all if the nodes are similar (low diversity) (May 1971; Holling 1986; Biggs et al. 2012). Hence, other structural network properties need to be examined when assessing resilience.

Modular networks comprise a set of clusters of highly connected nodes, more loosely connected to the other clusters (Biggs et al. 2012; Aquilué et al. 2020). *Modularity* also affects reachability, i.e., the ease with which all the nodes of the network can be accessed from each other (Janssen et al. 2006). Modular networks offer a space for local innovation or divergent evolution and can prevent or limit the spread of a disturbance across nodes, or cascading effects across scales. In so doing, they increase the overall resilience of the system, even if some nodes are severely affected by a disturbance, like pests or fire (Ash and Newth 2007; Biggs et al. 2012; Aquilué et al. 2020).

The notion of *centrality* offers another perspective on the way a network is organized. Central elements are the backbone of a network’s functioning and as such deserve specific attention. Aquilué et al. (2020) distinguish two categories of central elements: (i) ‘hubs’, which concentrate the greatest number of connections;[20] and (ii) ‘connectors’, which link the hubs.[21] Centrality favours resilience by facilitating reactivity, coordination, and control. However, centrality can also increase system brittleness by fostering homogenization and dependance of the whole system on a few nodes. A disturbance affecting a central hub can cascade across the whole system. A disappearing central hub can lead to a collapse of the entire system, leaving the remaining clusters unconnected and vulnerable. For instance, the disappearance of one keystone species can entail a wave of cascading extinctions (Janssen et al. 2006; Biggs et al. 2012).

Centrality relates to the notion of nestedness, which reflects a hierarchical organization where the set of neighbours of a specialist/peripheric

19 This is aggravated in the case of invasive species with higher adaptive and dispersal capacities than native, specialist, rare, or keystone species (Morecroft et al. 2012).

20 For instance, the main places or crossroads frequently used to connect two points on a city map.

21 Like ecological corridors between two protected areas, or between two forest patches in a landscape mosaic.

node (with few connections) is a subset of the neighbours of a more generalist/central, i.e., better-connected node (Biggs et al. 2012; Mariani et al. 2019). Some studies have demonstrated the contrasting effects of nestedness on diversity, stability, and resilience: positive when mutualistic interactions are considered, and negative if trophic or competitive interactions are considered (Mariani et al. 2019; Duan et al. 2023).

In sum, network theory suggests that, to increase resilience, a system will have to strike the right balance between connectivity, centrality, and modularity, i.e., between central coordination and exchange of information on the one hand and capacity for local innovation and divergent evolution on the other. Such a system shall be connected enough to support rapid recovery after a local disturbance but modular enough to limit the spread of perturbations and cascading effects across the whole system. Hence, preserving keystone elements and central hubs, encouraging diversity and heterogeneity among connected nodes, connecting the most vulnerable nodes more effectively, and introducing the right degree of modularity among similar nodes emerge as promising strategies to increase resilience (Janssen et al. 2006; Biggs et al. 2012; Wu 2013; Isaac et al. 2018; Li et al. 2020).

Flexibility

Flexibility is often quoted among the key attributes of resilience, affecting both the ecological and social dimensions of an SES. On the ecological side, as mentioned above, functional diversity, response diversity, and functional redundancy, by enlarging the panel of available response options, enhance flexibility in SESs. In so doing, they provide insurance against the catastrophic consequences of shocks (Cinner and Barnes 2019). However, flexibility reflects more than the diversity of available options and the adaptive capacity of system components and natural agents. It also embodies the capacity and willingness of human actors in the system to engage in alternative or innovative strategies (Cinner and Barnes 2019). In other words, on the social side, flexibility is a central condition for both adaptability – i.e., the capacity of actors in a system to deal with uncertainty and change and manage resilience (Walker et al. 2004; Bahadur et al. 2013) – and transformability – i.e., the capacity of actors to create a fundamentally new system when the current one becomes untenable (Walker et al. 2004).

Many authors (e.g., Carpenter et al. 2001; Berkes et al. 2003; Elmqvist et al. 2003; Folke 2003, 2006; Lebel et al. 2006; Nelson et al. 2007; Parry et al. 2007) consistently highlight three key attributes of socialecological resilience that contribute directly to enhance flexibility, adaptability, and transformability: (i) the ability of an SES to change in reaction to a disturbance while essentially retaining the same structure and function (absorptive capacity); (ii) its capacity of self-organization, or of self-reorganization after a shock; and (iii) its ability to learn and adapt.

Any system, to a certain extent, is capable of some self-organization or self-regulation – as opposed to lack of organization or organization imposed by external factors (Elmqvist et al. 2003; Folke 2003, 2006; Biggs et al. 2012). Self-organization capacity explains how complex structures and patterns can emerge from apparent disorder (Holland 1995; Levin 1999; Folke 2006; Scheffer et al. 2015), building upon diversity, interactions, and autonomous processes (Levin 1998), even without system-level intentionality or centralized control (Walker et al. 2006). According to Carpenter et al. (2001), self-organization capacity is enhanced by the presence of co-evolved ecosystem components, and of active social networks that enable flexible problem solving. In turn, flexibility is crucial in complex SESs to cope with uncertainty and surprise (Manuel-Navarrete et al. 2004) and maintain their self-organization.

Flexibility, capacity to innovate, openness to learning, and experimentation are crucial to cope with uncertainty, surprise, and non-linear dynamics in complex adaptive systems and increase their resilience (Lebel et al. 2006; Walker et al. 2006; Biggs et al. 2012; Cinner and Barnes 2019). Learning enables actors to recognize and better understand changes and their causes, as well as the complex dynamics, interactions, and feedback at stake at different scales in SESs.

Learning from past experience, actors can make choices and develop response strategies in an uncertain world (Bahadur et al. 2013; Ensor et al. 2016; Cinner and Barnes 2019). 'Learning by doing' through experimentation and learning from each other in an iterative process that fills the gap between knowledge and action are key pillars of adaptive management (or co-management) strategies (Walters and Holling 1990; Carpenter et al. 2001; Gunderson and Holling 2002; Folke 2003; Stringer et al. 2006; Walker et al. 2006; Armitage et al. 2007; Resilience Alliance 2010; Bahadur et al. 2013; Cumming et al. 2013; Ensor et al. 2016).

Scholars generally distinguish between three forms of learning: single-loop learning that questions the means ("Are we doing things right?"); double-loop learning that questions the goals ("Are we doing the right things?"); and triple-loop learning that questions more fundamental beliefs, values, and worldviews ("How do we know what the right thing to do is?"). Triple-loop learning, also called transformational learning, often entails a paradigm shift, the creation of new organizations and institutions, and the adoption of new management objectives and approaches (Armitage et al. 2007; Biggs et al. 2012; Cumming et al. 2013). Scientists also highlight the influence of institutional conditions and power dynamics on the learning process and its results (e.g., Biggs et al. 2012).

The tension between efficiency and flexibility underpins the whole literature on resilience. Already present in the foundational article of Holling (1973), this tension reflects the opposition between two visions of resilience. On one side, classical management methods, corresponding to the mechanistic or deterministic vision of engineering resilience, promote optimality, efficiency, stability, risk management, expert command and control. On the other side, adaptive management methods, corresponding to the ecological or social-ecological visions of resilience, consider non-linear and chaotic dynamics, uncertainty, and surprise, and promote diversity, redundancy, flexibility, participation, and adaptive learning (e.g., Holling 1973, 1986, 1996; Nelson et al. 2007; Leach 2008).

High efficiency or high adaptedness can undermine resilience in at least three ways: (i) increased resilience in one place can reduce resilience for other stakeholders or at another spatial or temporal scale; (ii) increased specific resilience (to identified threats) can decrease general resilience (to any kind of threats whether predictable or not); (iii) increased resource-use efficiency, resulting from an adaptation effort, can result in a loss of flexibility, redundancy, or response diversity (Walker et al. 2006; Nelson et al. 2007; Cifdaloz et al. 2010; Folke et al. 2010).

This reflects what Bates et al. (2019) called the "Protection Paradox", i.e., the protection from one selected set of pressures or threats can select species that are highly sensitive to other threats. Therefore, instead of trying to maximize efficiency or eliminate vulnerability for a limited set of identified risks, resilience management should aim at identifying acceptable levels of vulnerability and promoting flexibility to maintain the system's capacity to respond to unexpected changes (Holling 1973; Nelson et al. 2007). A system exposed to a variety of disturbances may become more adaptable, more flexible and, hence more resilient in the long term (Timpane-Padgham et al. 2017).

Participation

The quality of a decision depends on the (decision-making) process through which it is taken (Sayer et al. 2013). Inclusive participation brings around the table different perspectives and viewpoints, interests, norms, values and beliefs, and different experiences and sources of knowledge. Deliberation and continuous interactions among the diverse stakeholders involved progressively build mutual trust and shared understanding, reduce the risk of conflicts, and enhance the legitimacy of the decisions made. Participation also fosters social and collaborative learning, knowledge sharing and integration of different forms of knowledge. Hence, broad participation helps progress towards a consensual vision and strategy, and mobilizes resources and people, thus facilitating self-organization, cooperation, and collective action (Lebel et al. 2006; Stringer et al. 2006; Walker et al. 2006; Biggs et al. 2012; Bahadur et al. 2013; Cumming et al. 2013; HLPE 2018; IPCC 2022, 658; Ratner et al. 2022). Enhanced participation and deliberation, along with holistic landscape planning and management, can also help prevent conflicts or elite capture. They can also facilitate the negotiation and solving of trade-offs across actors, sectors, scales, or development goals (Biggs et al. 2012; Cumming et al. 2013).

Broad and meaningful participation, within strong institutional settings, is critical for monitoring and experimentation, which are central steps in adaptive management or co-management processes. This also ensures the most powerful actors do not capture the learning and decision-making processes (Stringer et al. 2006; Walker et al. 2006; Nelson et al. 2007; Biggs et al. 2012). In particular, Bahadur et al. (2013) stress, and illustrate with specific examples, the importance of involving and empowering local communities and considering Indigenous and local knowledge in building resilience. Participation of local communities is expected to strengthen local ownership and produce more accurate and locally relevant outcomes (Stringer et al. 2006). However, involving local stakeholders and communities in a large-scale project might be excessively complex, time-consuming, and expensive. This is particularly the case if the results from a context are so specific that they hamper their transferability, comparability, and scaling-up at a larger scale. In such cases, appropriate representation mechanisms become critical (Stringer et al. 2006).

How and under which conditions broadened participation supports adaptive management and enhance resilience is still a challenge for research (Stringer et al. 2006; Biggs et al. 2012). Some decision-making processes may be designed for greenwashing or window dressing. As such, they may actually serve the interest of powerful actors and the continuation of power inequalities (e.g., the case of Indigenous Peoples in Larson et al. 2022).

Participation may enhance or decrease resilience, depending on the actors, as well as on the decision-making process and governance structure. Much depends on answers to the following questions: Who are the key stakeholders? Are they all equitably involved? Are the participation rules clearly defined and the different roles clearly assigned? What are the power dynamics at stake? What is the adequate level of participation to ensure an inclusive but efficient management process, given the available time and resources? (Stringer et al. 2006; Biggs et al. 2012; Wiese 2016).

Three levels of participation have been distinguished, with different impacts on adaptive management processes: (i) *public communication*, where stakeholders are simply informed but not actively engaged in the process; (ii) *public consultation*, where stakeholders are given a voice but no power in the process; and (iii) *public participation*. At this third level, stakeholders are actively engaged and able to influence decision making. An active, interactive, and iterative dialogue is established at different stages of the management process – from initial diagnosis and planning to implementation, monitoring, social learning, and adjustment (Rowe and Frewer 2005; Stringer et al. 2006).

Polycentric and multilayered governance

The concept of *panarchy*[22] is central in the resilience literature. It illustrates cross-scale interactions and conceptualizes the dynamic of complex SESs as a series of nested adaptive cycles operating and interacting at different spatial or temporal scales, as illustrated in Figure 1 (Gunderson and Holling 2002; Walker et al. 2004; Folke 2006; Davoudi 2012; Allen et al. 2014). The adaptive cycle model usually consists of four phases: a phase of exponential change (noted r); a conservation phase (K) of growing stability and rigidity; a phase of release or collapse (Ω); and a phase of reorganization and renewal (α) (Holling 1986; Carpenter et al. 2001; Gunderson and Holling 2002; Folke 2006; Walker et al. 2006; Davoudi 2012). These α-phases of reorganization and radical changes in SESs usually happen only at certain critical times, during ‘windows of opportunity’ after a crisis that highlight the structural weaknesses of the current paradigm (Gunderson and Holling 2002; Cumming et al. 2013).

22 The term panarchy reflects “the interplay between change and persistence, between the predictable and unpredictable.” It refers to the Greek god Pan to capture an image of surprise and unpredictable changes and to the notion of hierarchical structures across scales “that sustain experiments, test results, and allow adaptive evolution” (Gunderson and Holling 2002).

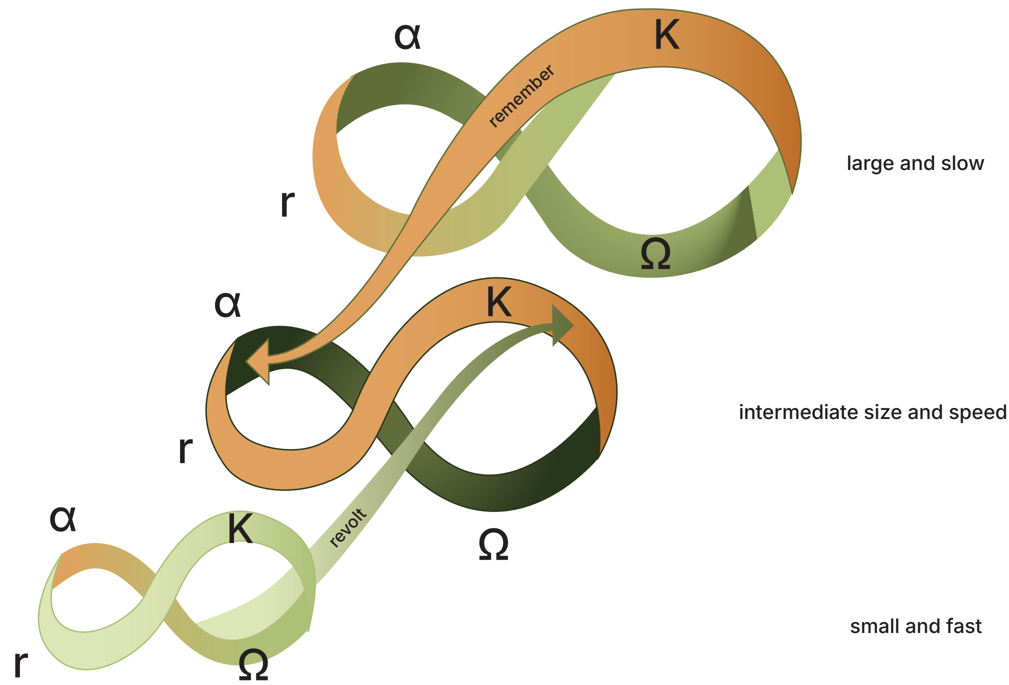

Figure 1. Panarchy: Nested adaptive cycles operating at different scales
Source: Own graphic, adapted from Gunderson and Holling (2002).

As illustrated in Figure 1, higher-scale level can provide 'memory', allowing lower-scale level to 'remember' and reorganize after a collapse. Lower-scale changes (called 'revolt') can propagate and cause the collapse of the system at higher scales (Holling 1996; Gunderson and Holling 2002; Berkes et al. 2003; Folke 2003, 2006; Walker et al. 2006).

Polycentric and multilayered governance mechanisms should be established or strengthened to deal appropriately with such cross-scale interactions in complex adaptive SESs (Folke 2003; Lebel et al 2006; Biggs et al. 2012; Cinner and Barnes 2019; Liu 2019; IPCC 2022, 658). Compared to more monolithic arrangements, these more iterative governance mechanisms enable a better alignment between knowledge and action. They also allow more flexible, adaptive, and innovative responses to change at the appropriate scale (Lebel et al. 2006; Osbahr 2007; Biggs et al. 2012; Bahadur et al. 2013; Cumming et al. 2013; Cinner and Barnes 2019; Liu 2019; IPCC 2022, 492). They foster social and collective learning and experimentation, including through more horizontal and collaborative learning models (peer-to-peer, learning networks or multistakeholder platforms) that integrate different forms of scale-specific knowledge (e.g., Indigenous, traditional, and local knowledge), critical to build social-ecological resilience (Folke 2003; Lebel et al. 2006; Biggs et al. 2012; Cumming et al. 2013; IPCC 2022, 110).

Adaptive co-management in polycentric and multilayered governance structures requires inclusive participation, strengthened deliberation, and continuous interactions among actors operating at different scales, within formal or informal networks. These interactions demand time and resources. For this reason, and because they create institutional redundancies, polycentric and multilayered governance structures may lose in efficiency when compared to monolithic arrangements. However, continuous interactions may improve mutual trust and connectivity among actors, which, along with institutional redundancy, are likely to enhance resilience and adaptability in the long term (Berkes et al. 2003; Lebel et al. 2006; Walker et al. 2006; Armitage et al. 2007; Biggs et al. 2012; IPCC 2022, 659).

Importantly, interactions among actors – whether horizontal (e.g., between different ministries or thematic agencies) or vertical (e.g., across local, provincial, and national levels) – cannot happen without key ‘mediating’ players, acceptable to all parties. Such players facilitate a continuous and fruitful dialogue among stakeholder groups, fostering coordination (Stringer et al. 2006; Biggs et al. 2012).

As mentioned above, appropriate representation is key to reduce transaction costs (in time and resources), improve efficiency, and ensure meaningful participation of the most vulnerable groups in such polycentric and multilayered governance structures and decision-making processes (Lebel et al. 2006; Stringer et al. 2006; Nelson et al. 2007). These governance systems also require strong leadership and a clear repartition of competences. Authority, responsibilities, and capacities must lie at the most appropriate scale to best address a given challenge or support a given ecosystem service or function. Flexible institutions and governance mechanisms at the most relevant scale, as well as efficient coordination, within and across scales, are instrumental to avoid “scale mismatches” that can occur between the societal demand for ecosystem services and the capacity of ecosystems to satisfy it sustainably (Folke et al. 2007; Biggs et al. 2012; Cumming et al. 2013; Wiese 2016; IPCC 2022, 110).

Accountability

Broadened participation and strong polycentric and multilayered governance mechanisms cannot strengthen resilience effectively without accountability (Lebel et al. 2006; Biggs et al. 2012). Accountability means that authorities are responsible for their acts vis-à-vis other stakeholders and the public. This implies full transparency in the provision and exchange of information and explanation of decisions made, independent monitoring and evaluation, independent mechanisms of control and sanction, separation of powers, free media, and freedom of expression.

Accountability must occur not only in vertical relationships (e.g., when a local administration is accountable to the central level) but also in more horizontal relationships (e.g., when a private forest company is accountable to local communities affected by its activities). This acts as a protection against elite capture of the political agenda and resources (Agrawal and Ribot 1999; Ribot 2002; Lebel et al. 2006). Effective accountability supports equity, social justice, and a fair repartition of risks and benefits. It contributes to empower the most vulnerable segments of society and protect their rights and interests, thus preventing conflicts and reducing the vulnerability of the whole SES (Lebel et al. 2006).

4 Conclusion

At its core, resilience entails the ability of systems to maintain essential structure and functions amid various stressors. Resilience is not just about bouncing back from disruptions but also about thriving under changing conditions and embracing transformation when necessary. Resilience thinking offers a robust framework for managers of SESs to navigate complexity, non-linear dynamics, uncertainties, and challenges. This involves understanding resilience through multiple perspectives, including engineering, ecological, and evolutionary resilience. This also entails embracing a range of resilience strategies – from persistence and recovery to adaptation and transformation – operating across different spatial and temporal scales within the system.

SESs face manifold challenges such as water scarcity, degradation, biodiversity loss, and climate change impacts. Embracing resilience principles is crucial for their sustainable management. The role of ecosystem managers (such as protection agencies, forestry and agriculture departments, private companies, civil society organizations, local communities, research institutions, and practitioners on the ground) is pivotal in safeguarding the resilience of these SESs for future generations. By prioritizing eight key attributes likely to foster resilience – i.e., integrity, diversity, redundancy, connectivity, flexibility, participation, polycentric and multilayered governance, and accountability – SES managers can effectively navigate uncertainties and disturbances while promoting ecosystem health and human well-being in the long term.

Adaptive (co-)management emerges as a key strategy for navigating uncertainty and facilitating resilience-building actions. Adaptation in itself is not an end point. Rather, it is a process or ability that emphasizes how resilience often defies our linear ways of engineering the world around us. Resilience attributes must not be seen as independent variables but rather as interlinked characteristics of dynamic systems that interact in complex and sometimes unexpected ways. Managing for resilience often involves navigating trade-offs between different resilience attributes, such as between efficiency, redundancy, and flexibility, or between connectivity, centrality, and modularity. Hence, efficient and sustainable management of SESs requires a transdisciplinary collaboration and a holistic understanding that transcends simplistic linear models. It demands embracing uncertainty, recognizing the non-linear dynamics inherent in these systems, and acknowledging the potential for surprise, emerging properties, and regime shifts. Continuous monitoring and evaluation of resilience indicators are crucial to track system changes, provide feedback, and inform adaptive management actions, highlighting the need for continual learning and adjustment in response to evolving conditions.

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Keywords: Landscape resilience; engineering resilience; ecological resilience; evolutionary resilience; diversity; redundancy; connectivity.

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