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ORIGINAL ARTICLE

ORF, an operational framework to measure resilience in social–ecological systems: the forest case study

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Abstract

Resilience is commonly addressed when dealing with the sustainable planning and management of social–ecological systems, but we lack a unified framework for its quantitative assessment and application. We present an operational resilience framework (ORF) based on recognizing and relating several elements: system variables (e.g., ecosystem services), disturbances and stressors acting at given spatiotemporal scales, a reference state, and metrics comparing the observed system variables to the reference state. These elements fit into a rationale aimed at identifying resilience predictors suitable to be managed and co-drivers which describe non-manageable context, reflecting the mechanisms involved in resilience. By a systematic search of the presence of the ORF concepts in 453 empirical studies assessing resilience, we corroborate that ORF can be applied to studies on forest social–ecological systems. This literature survey shows that ORF elements are commonly recognized, although the logical narrative relating them is not always explicit, particularly in socioeconomic-focused studies. We advocate that the proposed ORF allows to standardize the terminology and to frame and measure resilience, allowing sounder comparisons and better-supported recommendations for the improvement of resilience in social–ecological systems, particularly in forest systems.

Keywords Disturbances · Forest · Resilience · Socio-ecological systems · Stress

Introduction

Generally, resilience can be described as the capacity of a system to absorb disturbances or environmental transformations, and recover and reorganize in a timely and efficient manner, retaining essentially the same structure, identity, feedbacks, and functions (Folke et al. 2004; Walker et al. 2004). The resilience concept evolved as an emergent property of complex dynamic systems connected across scales (Holling 1973; Holling and Gunderson 2002). This has made resilience particularly suitable to frame the performance of human systems giving rise to the concept of social–ecological resilience (e.g., Folke 2006; Biggs 2015), which has developed its own distinctness by incorporating aspects such as adaptability and transformability (Folke et al. 2010). Following this system perspective, in ecology, the resilience concept has been used to assess the behavior and persistence of ecosystems around dynamic equilibrium states in the face of environmental variability (ecological resilience), or alternatively, when thresholds are surpassed, shifting to alternative states (Scheffer et al. 2015). Since disturbances

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constitutes a major driver of such changes, a great number of studies have focused on system's ability to recover the properties altered by a disturbance (engineering resilience) (DeAngelis 1980; Holling 1996).

The generality of the concept of resilience and its further application in multiple contexts have spread its use in environmental management and decision-making (Benson and Garmenstani 2011), especially in a context of sustainability (Xu et al. 2015; Elmqvist et al. 2019; Assarkhaniki 2023), and to support adaptation to climate change. In recent years, many proposals have emerged to build resilience conceptual frameworks considering the disturbance regime (Johnstone et al. 2016), the mechanisms involved (Elmqvist et al. 2003; Falk et al. 2022), the way to measure it (Ingrish and Bahn 2018; Bryant et al 2019), the scope of application (Garmestani and Benson 2013; Haider et al 2021), or its relationship with vulnerability (Miller et al. 2010), stability (Donohue et al 2016; Hillebrand et al. 2018; De Bello et al 2021; Van Meerbeeck et al. 2021), or sustainability (Redman 2014; Elmqvist et al. 2019).

Despite the proposals to assess and apply the resilience concept (e.g., Standish et al. 2014; Baho et al. 2017; Tamberg et al. 2021), the concept remains insufficiently implemented. These previous efforts generally build on a solid conceptual base aiming to address systems complexity (Folke 2006) and provide sound analytical insights, but fail to put in practice the enhancement of resilience in a comprehensive, synthetic way, encompassing both ecological and socio-economic perspectives (but see Camp et al. 2020). Thus, the current situation is that we miss a common, consistent, and unambiguous terminology, and we do not have a procedure to estimate and compare resilience across the vast range of domains in which the concept is used. Thus, we still lack an operational framework that integrates theoretical developments, empirical knowledge from distinct cases, and the views of social and decision-making agents to guide the selection and implementation of measures aimed at increasing the resilience of social–ecological systems (Donohue et al. 2016; Nikinmaa et al. 2020; Nikinmaa et al. 2023). To support the operational implementation of the concept, there is a need to: (i) supply information on current and future resilience; (ii) compare resilience among different contexts; (iii) establish targets for action plans; (iv) monitor the effects of specific policies on resilience after their implementation; (v) fit it into models to predict resilience; and (vi) support the identification of key factors that challenge or promote resilience.

Here, we present an operational framework to assess resilience (operational resilience framework ORF), in forests, but also suitable to be applied in different domains, from natural to socioeconomic ones. The proposed ORF provides a powerful tool to assess resilience in specific situations (specific resilience sensu Folke et al. 2010) and consists of a unified terminology with a glossary of terms necessary to assess resilience, and a sequence of steps needed for assessing resilience. We illustrate the applicability of the ORF by analyzing the content of a large number of empirical studies on the resilience of forest social–ecological systems. Specifically, we (1) test if ORF elements are found in publications studying resilience in forest social–ecological systems and (2) assess the different use of ORF elements in studies focused on ecological vs. socioeconomic aspects of forest resilience.

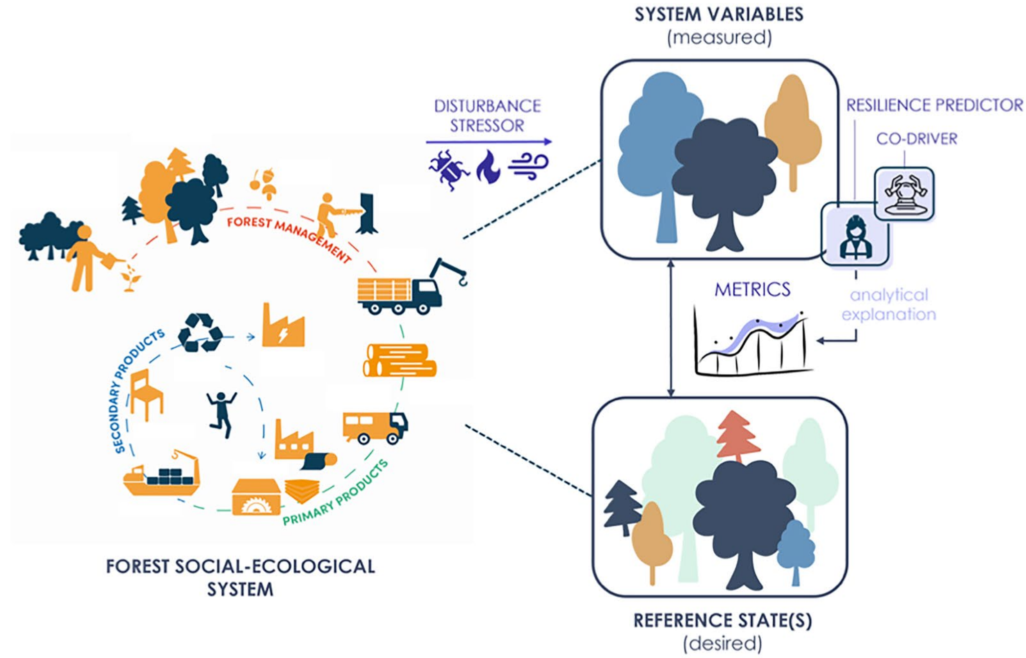
The operational resilience framework (ORF)

ORF's rationale

The structure of the ORF refers to the resilience of variables of interest in a given social–ecological system ("resilience of what", sensu Carpenter et al. 2001), and to the disturbances or stressors that threaten the system ("resilience to what", sensu Carpenter et al. 2001). Resilience can be then estimated by comparing system variables modified by disturbances or stressors with reference values that would correspond to the absence of disturbance or stress, or, alternatively, to situations in which the variables remain within acceptable thresholds (i.e., the reference state) (Fig. 1A). The closer the variables of the system affected by disturbances or stressors get to these reference values, the greater is the resilience. To the extent that resilience is an emergent phenomenon caused by underlying mechanisms (Weise et al. 2020), it should be possible to find explanatory factors that encompass these mechanisms. Thus, a change in the values of these explanatory variables indicates that the resilience of the system likely increases or decreases. Note that we can distinguish factors that can be managed (e.g., forest structure) and therefore may be useful in determining actions that can be taken to promote resilience (i.e., manageable resilience predictors), from other factors that describe context situations that can hardly be manipulated (e.g., climate) but also determine resilience (i.e., resilience co-drivers). By applying this procedure, the ORF provides a consistent and comprehensive rationale to formally assess and compare resilience in different contexts.

The application of the ORF (see Fig. 2 for a roadmap) involves eight steps and is case specific, thus exhibiting great flexibility. Even though the ORF application depends on the specific context, it provides a common framework for resilience assessments carried out in very different situations. To better understand the rationale connecting ORF elements, we provide hypothetical examples related to forest social–ecological systems in Fig. 1B and Supplementary Material 1. Also, we discuss in Supplementary Material 2 how several widely used concepts related to resilience (resistance and

A



B

Example 1

Assessing the effect of catastrophic windthrow(3) on harvested round wood timber volume and unit price(2) of the social-ecological system of **the National Forest Estate**(1) at regional scale(5). To that end, we use return time to pre-disturbance state(6) to quantify changes of harvested round wood volume and unit price(2) in comparison to pre-disturbance level(4). We assess the role of management systems and disturbance intensity(8) mediating this response, and we expect forest landscape heterogeneity and public-private ability to coordinate for quick harvesting deployment(7) as predictors of resilience.

Example 2

Assessing the effect of drought(3) on radial growth responses(2) of **Mediterranean tree species**(1) at plot scale(5). To that end, we use resistance, recovery and resilience indices(6) to quantify changes on basal area increment(2) in comparison to pre-disturbance conditions(4). To calculate the indices we define a period of three years before and after the disturbance(5). We assess the role of drought intensity and species distribution range(8) mediating this response, and we expect the mean tree age(7) as predictor of resilience.

(1) **Case study of socio-economic system**
(2) System variables (RESILIENCE OF)
(3) Disturbance or stressor (RESILIENCE TO)
(4) Reference state (COMPARED TO)
(5) Spatiotemporal scale (WHEN and WHERE)
(6) Metric (HOW TO MEASURE)
(7) Resilience Predictor (MODIFIABLE/MANAGEABLE)
(8) Co-driver (INFLUENCE)

Fig. 1 **A** Graphical abstract summarizing the main elements of the operational resilience framework (ORF). Note that system variables (top right icon) are a subset of selected variables describing the whole social–ecological system (left icon) and the reference system corresponds to a scenario that serves as a basis for comparison with the observed system variables (bottom right icon). **B** Recognition of the ORF elements in two hypothetical study cases of forest resilience focused on socioeconomic (Example 1) or ecological aspect (Example 2). For the two examples, the elements of the ORF are highlighted in the text. Both examples correspond to an engineering resilience approach

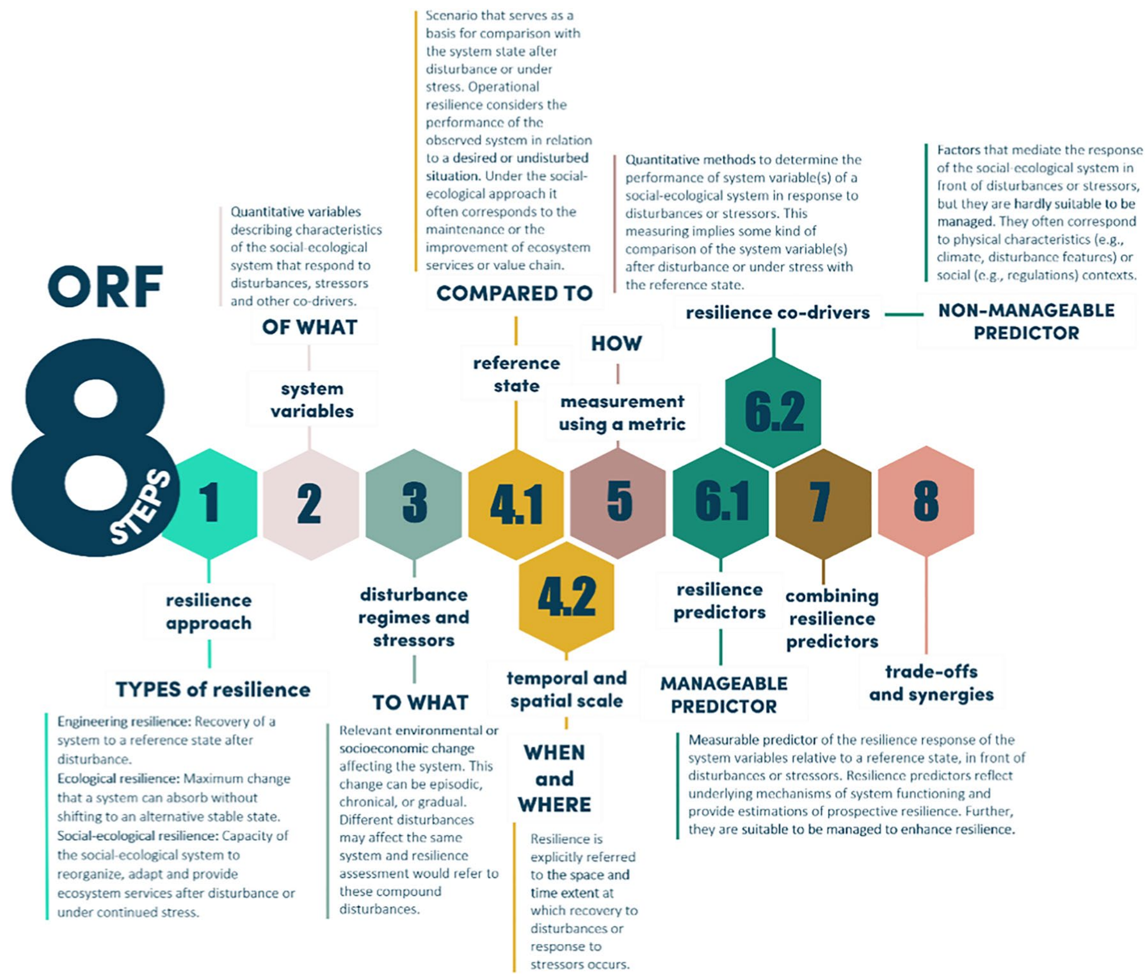


Fig. 2 Roadmap and glossary of terms for applying the operational resilience framework (ORF) to assess resilience in specific cases (see text for more details). The road map includes eight steps: (1) rcognition of the resilience approach used in the assessment, (2) selection and quantification of system variables, with a particular focus on those describing ecosystem services, (3) identification and description of potential disturbance regimes and stressors, (4) identification and quantification of the reference state, recognizing its spatial and temporal scale, (5) measurement of resilience by applying convenient metrics, (6) identification of resilience predictors and co-drivers, and assessment of their effects, (7) prioritization of key resilience predictors, or combination of sets of them, (8) integrative assessments of resilience considering trade-offs and synergies between system variables

recovery, stability, vulnerability) can be framed within the ORF.

Elements of the ORF

The operational resilience framework is based on the following elements (see Fig. 1B, and Supplementary Material 1 for examples):

Resilience approach

Among the vast literature addressing resilience conceptualization, we identify three basic approaches to resilience as described above, in which our operational approach can be framed: engineering, ecological, and social–ecological resilience. The determination of the approach used when assessing resilience will help to identify ORF's elements. These approaches put the focus on different aspects. Disturbances, which may stay within the historical range of environmental variability, or disrupt such variability, are key in engineering resilience, which has been commonly used to disentangle causal mechanisms determining the persistence of system properties under specific spatiotemporal scales. In turn, nonlinear dynamics, uncertainty, and regulatory controls and self-organization are definitory of ecological and social–ecological resilience. In ecological resilience, thresholds involving state shifts as a consequence of stressors—such as changing environmental or socioeconomic conditions—constitute a crucial target, while studies on social–ecological resilience commonly address the role of changes in management regimes and decision-making affecting the system' s capacity to adapt or transform. Despite these differences, our ORF identifies essential common elements, which allow the operational assessment of resilience under these different perspectives: system variables which characterize any system, the nature of disturbances or stressors, the selection of a reference state, and the application of suitable metrics to compare the observed state of system variables to the reference state.

System variables: resilience OF what?

System variables are quantitative variables describing the characteristics and performance of the social–ecological system that respond to disturbances, stressors, and other co-drivers (Nikinmaa et al. 2023). They provide a formal characterization of the whole system of interest accounting for their boundaries (Baho et al. 2017). These variables correspond to stocks or flows of energy, matter, or information, and can describe the system at different scales, from the individual (e.g., tree annual growth) and the local site (e.g., species richness), to the landscape (e.g., vegetation cover) and the whole country or state (e.g., timber production). System variables describe the system properties of interest whose resilience will be analyzed and correspond to the "of what" specification of Carpenter et al. (2001) or to "responses" (sensu Albrich et al. 2020). Some system variables commonly act as predictors of the resilience of other system variables (e.g., biodiversity may act as a system variable in itself or act as a predictor of ecosystem function variables). Our operational approach starts by identifying those system variables that are relevant for the analysis and promotion of resilience in a given context, and then searches for reliable predictors of that resilience. As ecosystem functioning and social and economic benefits are important aspects of social–ecological systems, system variables commonly correspond to ecosystem services. The use of ecosystem services as system variables is particularly useful since it allows connecting the functioning of ecosystems with the sustainability of the associated socioeconomic subsystem (Lecina-Díaz et al. 2020).

Although the complexity of a system should be recognized, it is convenient to select a limited number of system variables that define its functionality. Many system variables are likely to co-vary, due to causal relationships between them or because they are generated from common processes. For example, numerous variables may describe productivity or economic growth, and their resilience may show common patterns. However, these system variables may also represent complementary aspects of the system behavior. They may correspond to different subsystems, such as the ecological or the social one, and may even represent conflicting interests and cause trade-offs that must be balanced (Nikinmaa et al. 2023). For this reason, it is advisable to jointly analyze the resilience of different system variables. For this purpose, we can use: (i) multivariate approaches that describe the trajectory of the system in the face of disturbances or stressors across the space defined by different variables (Seidl et al. 2014), (ii) multi-criteria analysis (de Bremond and Engle 2014), or (iii) optimization models that maximize the joint resilience of different system variables (Pohjanmies et al. 2021).

Disturbance/stressor: resilience TO what?

Intense environmental or socioeconomic changes commonly affect the social–ecological system. These changes can be episodic (i.e., disturbances), gradual, or chronic (i.e., stress) and they may disrupt or be embedded within the historical functioning of the system. In the absence of such disturbances or stress, resilience does not actually apply and it cannot be measured. However, during periods without disturbances or significant stress, the system may acquire features that will improve (or reduce) its resilience when disturbances will eventually occur. For instance, an extensive and long-term institutional and legislative adaptation to forest multifunctional management may favor the resilience of the whole forest social–ecological system to the future shock-induced bark-beetle outbreaks (Hlásny et al. 2021), but this adaptation must be developed in advance of the outbreak.

The type of disturbances or stressors helps to guide the selection of the resilience approach to be used in the assessment. However, the distinction between disturbances and stressors is not always clear. Several types of disturbances have been recognized, from discrete, episodic pulses to press and ramp disturbances, and even small stochastic disturbances (Van Meerbeek et al. 2021), which would converge with the idea of stress (Grime 1974). Statistical criteria have been proposed to recognize extreme events and trends in relation to the historical series of the variability of environmental parameters, such as climate (Katz et al. 2005). In turn, stress extreme events can constitute disturbances when they involve the loss of stocks, such as biomass, accompanied by rapid changes in flows, which may be transitory. The set of characteristics of intensity, distribution in space, and sequence in time of the set of disturbances experienced by a system constitute its disturbance regime (Pickett and White 1985). Importantly, since the disturbance regime operates over time in a given territory, the spatiotemporal scale of disturbances needs to be defined to assess resilience. In turn, stress does not usually have such a clear episodic character as pulse disturbances, although it can exhibit clear trends associated with substantial variability in space and time. Disturbances and stressors do not usually occur in isolation; instead, different disturbance events together with stressors may affect the same social–ecological system.

The resilience assessment would then refer to the compound effects of several disturbance and stressor types (Johnstone et al. 2016). For example, climate change implies (i) a warming trend that can increase stress, particularly when combined with a decrease in precipitation, (ii) an increase in climate variability that leads to extreme episodes (e.g., heat waves, droughts, hurricanes), and (iii) a boost of other climate-related disturbances (e.g., wildfires, pest outbreaks) or stressors (e.g., socioeconomic changes). Therefore, the resilience of social–ecological systems to climate change must consider this entire set of factors (Seidl et al. 2017).

Reference state: resilience COMPARED to what?

The reference state corresponds to a scenario that serves as a basis for comparison with the system state after disturbance or under stress (Grimm and Wissel 1997). The reference state is a fundamental piece of the ORF, as it enables the operationalization of the idea of retaining the properties and functionalities of the system after the disturbance or stress, as established by the concept of resilience (Folke et al. 2004; Walker et al. 2004). Note that the return to a pre-disturbance situation does not necessarily imply the maintenance of sustainable functionality, and this scenario should be included in the resilience framework by considering the reference state as described by a range of values—consistent with the "safe operating space" framework (Dearing et al. 2014)—of desired conditions to be promoted, or undesired conditions to be reduced (Standish et al. 2014; Elmqvist et al. 2019). Therefore, the reference state is not an absolute value of the system, because according to the characteristics of the undisturbed or the desired state, different possible reference states may exist. Also, it is not necessarily a historical analog either, especially considering a climate change scenario. Particularly, when analyzing resilience under different scenarios (e.g., climate change or management), a specific scenario that may correspond to a baseline situation needs to be established as the reference state (Grimm and Wissel 1997), according to the considered resilience approach.

If we adopt an engineering resilience perspective, then the reference state corresponds to the undisturbed system. In a situation that assumes no historical legacies or high recovery rates, the reference state may correspond to the pre-disturbance situation, as used in many studies (e.g., Gazol et al. 2017; Stuart-Haëntjens et al. 2017). However, in systems affected by climate change or social and economic transformations, the past context cannot always be maintained, and the comparison with the system before being disturbed loses meaning. In such cases, comparison with a contemporary undisturbed reference may be more appropriate, at the cost of incorporating other sources of variability into the analysis (Bryant et al. 2019; Ibañez et al. 2019). Some of these difficulties can be overcome by the use of counterfactual approaches, which estimate the system state in the absence of the disturbance, everything else being equal (e.g., Martínez-Vilalta et al. 2012; Ovenden et al. 2021).

If the ecological resilience approach is adopted, the reference state corresponds to the range of system variable values that define the basin of attraction that separates it from different alternative states (Scheffer et al. 2001). So, in principle, discontinuous performance of the system—i.e., belonging to the different states—defines the reference state in the ecological resilience approach, differently from the engineering resilience. However, it is possible to identify early warnings of resilience loss when the variables of the observed system move away from values defining the basin of attraction, becoming unstable or experiencing critical behaviors, such as slow recovery after small disturbances (critical slowing down) (Scheffer et al. 2015).

In studies addressing social–ecological resilience, a persisting state may not be a suitable reference state as it may correspond to an undesirable situation (Standish et al. 2014), or belong to a metastable regime (i.e., an adaptive cycle in the panarchy framework, Gotts 2007). In fact, the system may follow an irreversible time path constrained by stressors (social changes, climate change), punctuated by crises in which past undisturbed or stable states do not constitute appropriate reference states. In these cases, the degree of functionality of the system corresponds to collective decisions, including actions taken by political and economic agents aiming at specific goals, such as maintaining or increasing the well-being of people, the production of goods, the economic activity, or the conservation of natural processes and biodiversity (Camp et al. 2020). From a social–ecological perspective, a sustained level of ecosystem services provisioning is a good candidate for characterizing the reference state. As said above, here, the desired levels, which are the object of management, constitute the reference state. In this case, the establishment of the reference state may suffer from arbitrariness and therefore requires adequate justification. Importantly, the reference state does not necessarily correspond to a static situation and can be subjected to change as the socioeconomic context evolves.

Spatiotemporal scale: WHEN and WHERE is resilience operating?

Resilience is a temporal concept that refers to specific timescales and periods which should be explicitly defined (Standish et al. 2014). Disturbances, social shocks, environmental modifications, and their consequences for ecosystems (recovery, state shifts, reorganization, and adaptation) occur at specific temporal scales. Moreover, regulatory feedbacks of the system do not operate instantaneously and delays in the responses to disturbance and stress are the rule (Meadows and Wright 2008). Therefore, resilience must be explicitly referred to the time extent at which recovery from disturbances or response to stressors occurs. For example, a system may be erroneously considered to have low resilience because it has been given little time to recover after a disturbance, or to have high resilience because the stress experienced has been of short duration.

In addition, the temporal scale is tightly linked to the spatial one. Social–ecological systems are located in territories, which determine the extent of stocks and fluxes, as well as the regulatory and social contexts. Disturbance regimes are by definition framed within time and space, and stress impacts are also strongly dependent on their duration and location. Importantly, key mechanisms determining resilience often change across such spatiotemporal contexts (Jentsch and White 2019), as reflected, for instance, by cumulative effects (Johnstone et al 2016). In turn, the spatial scale is often strongly related to the level of organizations involved in decision-making. In fact, social–ecological systems are cross-scale hierarchically structured adaptive systems, as recognized in panarchy theory (Gunderson and Holling 2002; Berkes and Ross 2016). In these systems, resilience emerges as the result of the interactions between multiple related subsystems (i.e., economics, cultural, geopolitics) with organizational structures that operate at different paces across the geographical space (Garmestani and Benson 2013). Thus, for a comprehensive assessment of the system, it is worthwhile to measure different components of the system selected based on their linkages and role in the overall structure.

As a general rule, resilience should be analyzed considering larger spatiotemporal scales than just covering the appearance of single disturbances or stress (Johnstone et al. 2016). For instance, from an ecological resilience perspective, a system may appear very resilient because it remains in a given state over time, until the cumulative effects of stress and/or disturbances reach an ecological threshold that leads to a tipping point (Lenton 2011; Scheffer et al. 2015). Alternatively, mechanisms that promote resilience, such as the accumulation of stocks or the generation of trade networks or information flows, often operate before a shock occurs. In other words, a decoupling between the generation of the mechanisms that increase or reduce resilience and the moment of impact or recovery is common. Therefore, from the operational perspective of promoting resilience before the occurrence of disturbance or stressors, the effects of these mechanisms must be extrapolated to situations that have not yet occurred, including high-intensity disturbances. This forces us to consider broad spatiotemporal scales, as well as intensities and frequencies of disturbances and stressors that may not correspond to historical regimes.

Resilience metrics: HOW is resilience measured?

In the ORF, resilience metrics refer to formal procedures—quantitative or qualitative—to compare the observed system variable(s) after disturbance or under stress with those at a given reference state. There are many different quantitative methods to measure resilience according to the resilience approach, disturbances or stressors, number and attributes of the system variables, and features of the reference state. In addition, resilience metrics may vary according to the specific features of the system considered (e.g., its biogeographic or political context), the assessment goals, and the available information. Examples of resilience metrics focusing on disturbance analysis include indices based on comparison to undisturbed states (Lloret et al. 2011; Hillebrand et al. 2018), recovery parameters—such as recovery rate (Meng et al 2020), time to full recovery (Thum et al. 2016), or recovery to resistance biplot analysis (Ingrisch and Bahn 2018)—, significant differences in statistical models (e.g., Waltz et al. 2014), and multivariate trajectories and distances in relation to a reference state (e.g., Sánchez-Pinillos et al. 2019). Examples of resilience metrics dealing with variability around a dynamic equilibrium include analysis of the system maintenance within a given state (Hirota et al 2011), variability estimations (Jourdan et al. 2020) and time series analysis (Gazol et al. 2016). Finally, early warning signals or critical slowing down (Forziery et al. 2022) have been proposed to assess the proximity to thresholds leading to alternative states.

The selected procedure to compare the observed state with the reference one is key for resilience analysis. It must allow the assessment of the effect of resilience predictors and co-drivers (see below) and, ideally, the intensity of their effect on different situations. In fact, the estimation of resilience may be strongly dependent on the specific metric used, since different methodologies focus on different temporal scales, or emphasize different components of resilience (e.g., resistance vs. recovery, see Zheng et al. 2021). Thus, for a comprehensive assessment of the system, measurements of different system's parts, selected according to their linkages and role in the overall structure, should be the rule. This selection is a crucial step in the assessment of resilience to deal with the multi-scalar complexity of social–ecological systems and avoid overly simplistic approaches (Garmestani and Benson 2013).

Resilience predictors: are there parameters that can be MODIFIED/MANAGED to enhance resilience?

In the ORF, resilience predictors are factors that allow the estimation of the resilience of the system and can be modified through management. For instance, in forests, higher tree functional diversity may lead to higher resilience of primary production in the face of drought and other disturbances (Grossiord 2019). Resilience predictors are a key concept within the ORF: first, because they inform on specific targets to be acted upon to enhance the resilience of altered ecosystems (Standish et al. 2014), but, also because they can provide estimations of expected resilience—i.e., estimate the capacity of the system to absorb disturbances or stresses that have not yet occurred—that can be used in prospective decision-making and scenario planning. Note that although resilience cannot be measured properly in the absence of disturbances or stress, resilience predictors inform about the expected resilience of the system when these environmental changes may eventually occur and can become a target of management aiming to promote resilience.

There is a link between the resilience predictors and the system variables for which resilience is predicted. When statistical models are applied in the analysis of resilience, the predictors will correspond to significant explanatory factors of the resilience of specific system variables in terms of response to disturbances, or system behavior leading to alternative states. Importantly, operational resilience predictors need to be suitable to be managed to develop actions aimed at promoting resilience. In simulation models used to assess resilience, predictors can be selected for those factors that produce significant changes in the resilience of system variables. For example, forest management alternatives corresponding to different levels of tree diversity will act as resilience predictors, according to the forecasted resilience of, for instance, productivity. Importantly, resilience predictors are scale dependent. If they cease to be manageable at certain scales, they should be considered as co-drivers (see below). For example, the taxonomic identity of trees can be a good predictor of the resilience of forest primary production at the plot level, as it can be managed to favor certain species. However, at the regional level, this taxonomic identity appears to be constrained by biogeographical patterns and is difficult to manage, becoming a co-driver.

In addition, system variables are commonly subject to trade-offs which translate to trade-offs between resilience predictors (de Bremond and Engle 2014; Seidl et al. 2014; Pohjanmies et al. 2021). Thus, weight and threshold values should be integrated into algorithms or rationales (multivariate, structural equation models and causal analysis, network analyses, optimization modeling) developed for a comprehensive assessment of resilience predictors and system variables. Importantly, the contribution of actors, such as decision-makers and stakeholders, is essential to establish these trade-offs and synergies, as well as to evaluate the utility of resilience predictors to implement management actions in specific contexts (Nikinmaa et al. 2023).

Since we assume some level of causality in the relationship between resilience predictors and system variables, this relationship reflects the mechanisms underlying system functioning. For instance, diversity, connectivity, and adaptive capacity have been recognized as important mechanisms for social–ecological resilience in forest systems (Nikinmaa et al. 2023). This recognition of the mechanisms that promote resilience is essential for several reasons: first, to avoid spurious relationships which can lead to undesired collateral effects when implementing predictors in management or decision-making; second, it allows extrapolating the assessment of resilience and its implementation to situations other than those initially analyzed. For example, functional diversity in forests can promote the resilience of primary production through functional complementarity (i.e., resource partitioning among individuals or species), which is particularly important in fluctuating environments (del Rio et al. 2022). Alternatively, functional diversity may be more decisive for resilience in the face of some types of stress, such as drought, through the selection of species with certain traits (Grossiord 2019). In general, systems with multiple regulatory feedbacks and reservoirs tend to be more resilient than simple, impoverished ones (Meadows and Wright 2008; Standish et al. 2014; Jentsch and White 2019).

Co-drivers: are there factors that INFLUENCE resilience but are hardly manageable?

In the ORF, co-drivers are factors that mediate the response of the social–ecological system to disturbances or stressors, but conversely to resilience predictors, they cannot be managed to increase resilience. Co-drivers are in fact contributing to establish ceilings of the safe and just operating spaces in which the social–ecological system can be maintained (Dearing et al. 2014). Co-drivers often correspond to physical characteristics (e.g., soils and topography) and climatic conditions, which have a geographical basis, as well as socio-political contexts (e.g., national regulations) and legacies or path dependencies (Johnstone et al. 2016). The distinction between resilience predictors and co-drivers is important from an operational perspective (Albrich et al. 2020), although this distinction is not commonly recognized in the literature. Co-drivers are usually sensitive to the spatiotemporal scale, and at some level, they can become resilience predictors if they are manageable (see previous section). Notably, co-drivers often interact with resilience predictors, thus modulating the predictor´s role and providing a context in which the effect of resilience predictors is more or less significant.

Strictly, memory, land-use legacy, and path dependency cannot be managed and should be considered as co-drivers, although they can inform about management actions promoting future resilience. Climate change should also be considered as a co-driver, particularly in the short-term and at local scales, since the effects of climate change mitigation are far from being operative at these scales; however, mitigation actions could be considered as predictors when assessments of resilience at regional or global scales are based on projected scenarios. Disturbance regimes often act as co-drivers, particularly when assessing resilience in the face of an existing disturbance regime that cannot be modified (Halpin et al. 2016). When the disturbance regime can be manipulated as a management action to promote resilience, it would act as a resilience predictor. For example, the intensity of wildfires a priori determines the resilience of vegetation cover and therefore acts as a co-driver, but the number, frequency, and extent of prescribed fires used to reduce fuel are best seen as predictors of resilience. Similarly, the general regulations that influence the forest value chain, or the degree of connection of the markets of forest-derived products, often act as co-drivers since they cannot be easily modified locally; however, at a broader regional or national level, regulations can be changed to improve the resilience of certain variables describing the value chain, thus becoming predictors. Thus, co-drivers should be comprehensively addressed considering organizational levels or geographical contexts other than those in which managers are directly involved.

Exploring ORF's applicability: presence of ORF elements in the research on forest resilience

Methods

To validate the elements of the ORF, we carried out a systematic bibliographic research using recent (2000–2022) scientific literature addressing resilience in forests (Scopus database, search string TITLE–ABSTRACT–KEYWORDS ("resilience" AND "forest") ALL ("measur*" OR "manage*") PUBYEAR > 1999, see Supplementary Material 3 for details). We distinguished those studies that mostly focused on ecological aspects of forest ecosystems (399 out of the 453 studies) from those addressing the socioeconomic aspect related to forests (56 out of 453 studies). In two cases, both focuses were considered in the same study. We screened each of the 453 studies, interpreting them in the light of ORF, thus, searching for the presence of the ORF' s elements and recording the categories considered for each element. See Supplementary Material 3 for a detailed account of the categories of the ORF elements that are used in both ecological- and socioeconomic-focused studies.

Results

Among ecological-focused studies, most of them followed an engineering resilience approach (74% of studies), while the ecological resilience approach addressing stability, thresholds, transitions, and trajectories to alternative states represented 26% of studies.

Most ORF elements are commonly found in the literature, although noticeable differences appeared between ecological- and socioeconomic-focused studies. System variables were well recognized in 90% of ecological-focused studies (Fig. 3), while this percentage dropped to 62.5% in socioeconomic-focused ones (Fig. 4).

Disturbances or stressors were described in a similar proportion (~ 80%) in ecological- and socioeconomic-focused studies. The reference state was identified in all ecological-focused studies, but this identification was only attained in less than half of the studies addressing forest socioeconomic aspects (39.3%). Although the methodology to assess resilience was commonly explained (~ 98% of studies, regardless of their approach), quantitative metrics to compare the affected system to the reference state were less commonly applied: 78% of ecological-focused studies and in a very low number (15%) of socioeconomic-focused ones. Finally, potential resilience predictors were identified in both types of studies (85% and 89% in ecological- and socioeconomic-focused ones, respectively), while co-drivers were also commonly identified in ecological-focused studies (92% of cases), but much less in socioeconomic-focused ones (19% of cases).

The most commonly used system variables in ecological-focused studies corresponded to forest structure, functioning, and composition (Fig. 3), while in socioeconomic-focused ones the system variables referred mostly to social and economic capital and activity (Fig. 4). The most usual stressor investigated in both types of studies was climate, particularly associated with extreme episodes, such as drought. Wildfires and intensive management were also commonly studied in ecological-focused studies, while socio-political and economic pressures were analyzed in socioeconomic-focused ones. The most frequent reference states were pre-disturbance or undisturbed situations in both ecological- and socioeconomic-focused studies. Temporal scales mostly ranged from yearly to decadal in both types of studies. While ecological-focused studies exhibited a wide range of spatial scales, socioeconomic-focused ones mostly addressed local resilience. Statistical comparison between the affected system and the reference state was the preferred approach for measuring resilience in ecological-focused studies. These statistical procedures often involved metrics that distinguish different components of resilience (i.e., resistance and recovery). In contrast, resilience estimations in socioeconomic-focused studies were mostly based on bibliography or questionnaires and interviews. Resilience predictors in ecological-focused studies were usually obtained from statistical analyses and they often

Fig. 3 ORF elements found in recent (2000–2020) literature studying the resilience of forest social–ecological systems, considering 399 papers focused on ecological aspects: **A** categories of system variables; **B** types of disturbance or stressor; **C** types of reference state; **D** temporal scale; **E** spatial scale; **F** types of metrics; **G** methodological approach; **H** types of resilience predictors; **I** types of co-drivers; "not specified" indicates that the ORF element could not be identified in the publication; "none" in H and I means that neither significant predictors nor co-drivers, respectively, were found in the publication. For each ORF element, the percentage of studies with a particular category or type is shown. See Supplementary Material 3 for a description of the categories or types

corresponded to forest structure, function, and composition, which were commonly associated with management, including forestry planning and silvicultural practices. In socioeconomic-focused studies, the most important predictors were related to management practices and planning, and governance. Finally, co-drivers identified in ecological-focused studies corresponded mainly to climate, geographical and biological context, and soil characteristics, while the assessment of co-drivers in socioeconomic-focused studies was generally poor. See Supplementary Material 3 for a detailed account of the prevalence of the different categories in ORF' s elements in the analyzed empirical studies.

Representation of ORF elements in empirical studies of forest resilience

Our search in empirical studies on forest resilience provided evidence that ORF's elements can be recognized in them, which supports the applicability of this framework. The vast variety of situations covered by these studies underlines the potential of the ORF to constitute a common framework to assess resilience in forests and likely in other social–ecological systems. Although our interpretations are subjected to some degree of subjectivity or uncertainty, we unfold that the logical connections between ORF elements were not always explicit in many of the studies, hindering

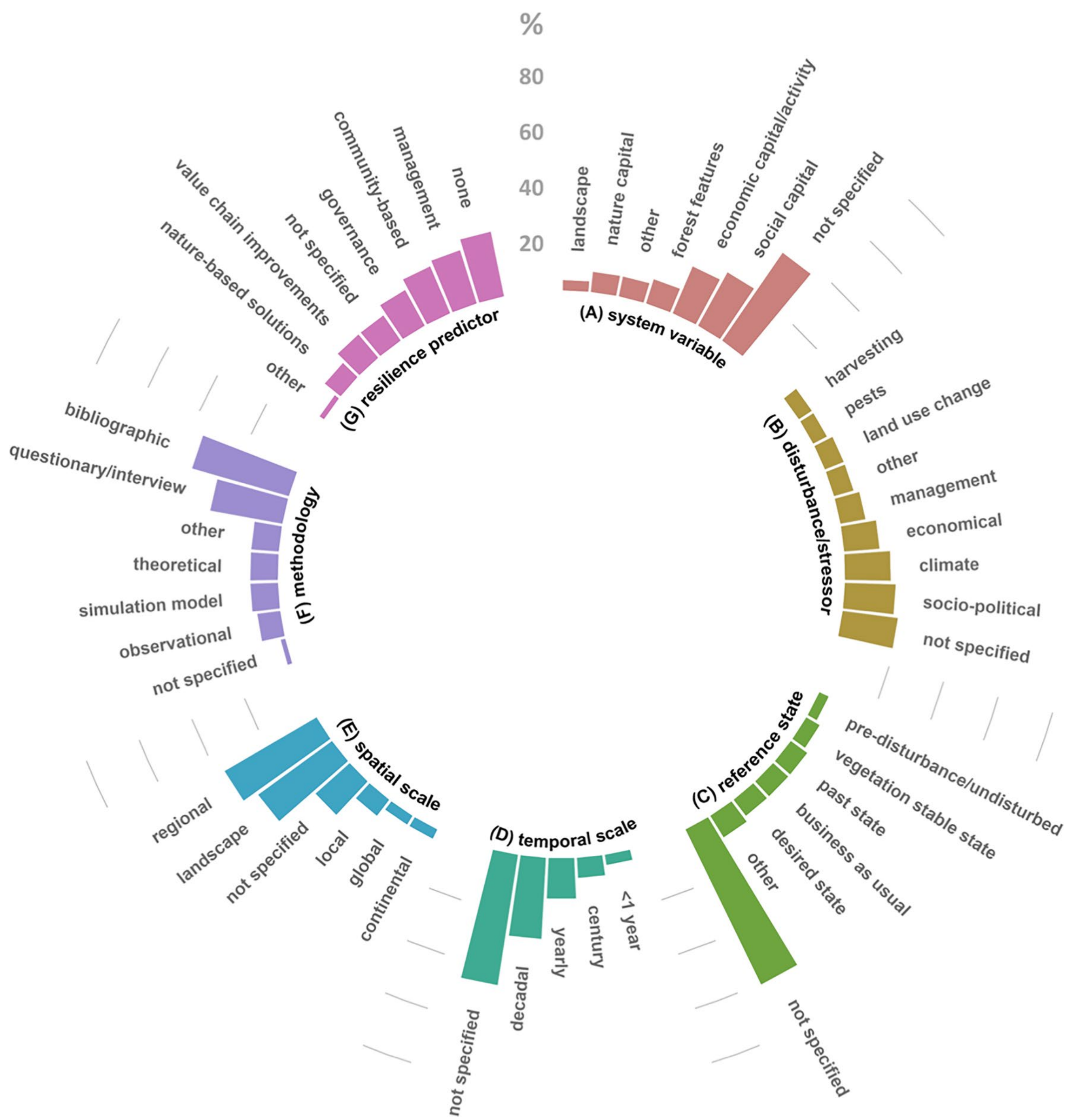


Fig. 4 ORF elements in the recent literature studying the resilience of forest social–ecological systems, considering 56 papers focused on the socioeconomic aspects: **A** categories of system variables; **B** types of disturbance or stressor; **C** types of reference state; **D** temporal scale; **E** spatial scale; **F** methodological approach; **G** types of resilience predictors; "not specified" indicates that the ORF element could not be identified in the publication; "none" in G means that no significant predictors were found in the publication. Not enough data were recorded for metric types. For each ORF element, the percentage of studies with a particular category or type is shown. See Supplementary Material 3 for a description of the categories or types

comparisons and the establishment of general patterns and recommendations for promoting resilience.

We found important differences between ecological- and socioeconomic-focused studies. In ecological studies, the ORF elements are mostly recognized and resilience is quantified and statistically assessed, allowing a neat application of the "resilience of what to what" framework and a solid identification and evaluation of predictors and co-drivers. In contrast, in socioeconomic studies, the robustness of the relationships between resilience predictors and system variables is often based on the particularities of each case. Thus, virtually no specific parameters (either predictors or system variables) are consistently used across studies. In addition, some parameters that could be considered as predictors are very broad (e.g., human demography, resources of the community) and difficult to connect with the ecological system, and therefore the effect on resilience would be at most indirect. In such studies, the ORF could help to discern more systematically the relevance of decision-making powers and processes (Olsson et al. 2014), as well as to frame questions about resilience "to whom"—i.e., as systems variables (Cretney 2014). Finally, in many socioeconomic-focused studies, resilience predictors have not been explicitly quantified. In this type of studies, qualitative analysis is common, and categorical predictors (e.g., managed vs. unmanaged forests) are likely to be adopted. Using the ORF framework as guidance could encourage researchers to identify a reference state also in these socioeconomic-focused studies, which would offer methodological rigor and stimulate the use of more quantitative measures for enhancing resilience.

The search in the forest literature allowed identifying the main categories within each element of ORF that are employed when assessing resilience in forests (see Supporting Material 2). The literature search also recognized noticeable gaps in our knowledge of forest resilience. For instance**,** many studies failed to obtain a significant effect of the hypothesized predictors and co-drivers on resilience, discarding preconceptions about resilience. Studies explicitly addressing the resilience of ecosystem services are very rare (but see Cantarello et al. 2017), despite the link that they provide between ecosystem functioning and social demands. Whereas several commonly studied system variables are associated with ecosystem services (e.g., carbon flows for climate change mitigation and timber provisioning), the specific goal of studying the resilience of ecosystem services is rarely addressed explicitly. Moreover, forest resilience associated with important sources of tree mortality, such as pathogens and pest outbreaks, seems underconsidered, probably because most studies analyzing their effects focus on direct, short-term impacts rather than on later forest recovery. When considering the methodologies used to analyze resilience, experiments are rarely applied, likely due to the difficulties in performing them at stand or wider levels. The use of model simulations for studying forest resilience also appears underappreciated despite their suitability to assess future resilience under scenarios of climate change and management regimes. As expected, the number of theoretical studies and meta-analyses is also low.

General discussion and conclusions

We argue that the ORF provides a narrative of resilience that can be universally applied in operational assessments of resilience, which is currently lacking. This addresses important shortcomings identified in past research and applications of resilience concepts. The ORF is particularly valuable because it provides a comprehensive terminology and rationale, leading efforts towards the identification of predictors of resilience which could be the object of decision-making and management in operational situations. This encompasses both ecological and socioeconomic perspectives and is soundly based on the essentials of the resilience concept.

Thus, the ORF contributes to clarify the disparity of conceptual interpretations and the associated terminology by providing a set of elements applicable to different perspectives around resilience. In fact, the ORF is consistent with different concepts related to resilience (see Supplementary Material 2 for details) and sustainability. ORF' s reference state explicitly recognizes the key role of the undisturbed state in the stability-related engineering resilience approach (Holling 1996) and, in fact, recovery and resistance (Grimm and Wiesel 1997; Lloret et al. 2011, Ingrisch and Bahn 2018) can be considered as distinct components of resilience which are estimated by different metrics, closely dependent on the time scale and the period considered (Standish et al. 2014). The ORF also supports assessments following the ecological resilience approach, in which stability plays a key role (Grimm and Wissel 1997; Van Meerbeek et al. 2021; Donohue et al. 2016), by (i) highlighting the importance of selecting integrative and relevant variables describing the behavior of the system, (ii) promoting, through comparison with a reference state, the recognition of the boundaries defining stability and thresholds leading to tipping points; (iii) promoting the assessment of the underlying mechanisms, through the selection of significant predictors and co-drivers, (iv) incorporating variability measures and early warning signals as resilience metrics. Finally, the complementary relationship between resilience and vulnerability (Miller 2010) can be appraised by the correspondence of ORF's elements with the risk/vulnerability framework (Lecina-Díaz et al. 2024). This correspondence highlights the role of stressors and disturbance regimes in both frameworks, the common mechanisms, reflected in predictors and co-drivers, that determine sensitivity or susceptibility—within the vulnerability framework—and resilience, and the role that adaptation capacity—within the vulnerability framework—can play in the recovery after disturbances and stressors. Therefore, the proposed ORF encompasses these concepts and provides a common narrative which recognizes shared goals and elements, while distinguishing their differences.

The explicit distinction between predictors and co-drivers in the ORF is a key contribution to clarify existing applications of the resilience concept, since it distinguishes actions predicted to enhance resilience from contexts (i.e., determined by co-drivers) in which these actions are likely to be more or less successful. Notably, these operational tools—resilience predictors and co-drivers—are firmly based on the mechanisms promoting resilience. In our literature search, we found evidence that the ORF elements allow implementing a consistent resilience assessment in a wide range of contexts of the analyzed literature on forest socio-ecological systems. Although not addressed explicitly here, this result also suggests that the ORF framework could be applicable to other, non-forested socio-ecological systems.

A common shortcoming for the operational assessment of resilience is the frequent vagueness of resilience enhancing measures (Baho et al. 2017; Moser et al. 2019), and this is particularly clear when resilience to climate change is considered. In this case, the ORF application allows (i) the identification of measurable characteristics of the system (e.g., ecosystem services) that are at risk under climate change; (ii) the clarification of specific drivers associated with climate change which are significantly impacting the systems (i.e., increase in temperature, extreme weather events, associated disturbance regime); and (iii) a formal assessment of the factors whose management is likely to improve resilience to climate challenges together with contextual co-drivers that modulate them and determine the boundaries of resilience.

ORF is also very flexible in the use of metrics, scales, disturbances or stressors, and particularly in the establishment of the reference state, which can be adapted to specific cases that not necessarily correspond to past situations and should dismiss undesired scenarios. Also, the ORF can also embrace qualitative analyses based on categorical parameters, which are more common in assessments based on stakeholder elicitation and on comprehensive social–ecological perspectives. The ORF's procedure is mainly aimed at identifying a minimum set of elements needed to assess specific resilience (sensu Folke et al. 2010). In contrast, the analysis of general resilience (sensu Folke et al. 2010) in social–ecological systems usually follows an agent-based approach (Miller et al. 2010), to the detriment of the operability of the analysis and its further application. The narrative proposed by ORF can complement more holistic approaches, contribute to identifying descriptors of the whole system, and help to find predictors of the system behavior in terms of resilience.

In conclusion, we endorse the creation of a common protocol in resilience studies and applications, explicitly identifying the elements of the ORF and adopting its rationale and corresponding roadmap. This protocol will facilitate comparisons and the establishment and evaluation of decision and management goals, providing a unified approach to produce more robust and operational resilience assessments.

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Declarations

Conflict of interest The authors disclose no potential sources of conflict of interest and competing interests, including funding, as established by the journal "Sustainability Science" policy.

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