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A balancing act: principles, criteria and indicator framework to operationalize social-ecological resilience of forests

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Abstract
Against a background of intensifying climate-induced disturbances, the need to enhance the resilience of forests and forest management is gaining urgency. In forest management, multiple trade-offs exist between different demands as well as across and within temporal and spatial scales. However, methods to assess resilience that consider these trade-offs are presently lacking. Here we propose a hierarchical framework of principles, criteria, and indicators to assess the resilience of a social-ecological system by focusing on the mechanisms behind resilience. This hierarchical framework balances trade-offs between mechanisms, different parts of the social-ecological system, ecosystem services, and spatial as well as temporal scales. The framework was developed to be used in a participatory manner in forest management planning. It accounts for the major parts of the forest-related social-ecological system and considers the multiple trade-offs involved. We demonstrate the utility of the framework by applying it to a landscape dominated by Norway spruce (*Picea abies* (L.) Karst.) in Central Europe, managed for three different management goals. The framework highlights how forest resilience varies with the pursued management goals and related management strategies. The framework is flexible and can be applied to various forest management contexts as part of a participatory process with stakeholders. It thus is an important step towards operationalizing social-ecological resilience in forest management systems.

Keywords: forest management; forest management planning; Principles, Criteria and Indicators framework; resilience mechanism; strategic planning; trade-off

1. Introduction

Forests are social-ecological systems (SES) that play a major role in the provisioning of essential ecosystem services (Brockerhoff et al., 2017). Demand for these services is increasing as societies transition away from fossil fuels (Böttcher et al., 2012; Prins, 2022). Simultaneously, forests face multiple disturbances linked to global environmental change (McDowell et al., 2020; Trumbore et al., 2015). To ensure a stable provision of forest ecosystem services, policy makers and scientists advocate for increased forest resilience (European Commission, 2021; Messier et al., 2013). However, operationalizing forest resilience remains difficult (Nikinmaa et al., 2020), due to the ambiguity of the concept as well as the lack of appropriate metrics and best practice examples (Greiner et al., 2020; Kerner and Thomas, 2014). Forest managers may have a heterogeneous set of goals and restrictions that influence the type of forest management they are willing and able to do. There is a need to provide tools to forest managers to assess the resilience of their management strategies and give indication of how to achieve their goals in the most resilient manner.

Resilience is a heavily debated concept used in many fields and has many definitions (Brand and Jax, 2007; Moser et al., 2019; van Meerbeek et al., 2021). In the literature, three main resilience concepts dominate: engineering resilience ("recovery to a previous state"), ecological resilience ("remaining within the prevailing system domain through maintaining important ecosystem processes and functions") and social-ecological resilience ("the capacity to reorganize and adapt through multi-scale interactions between social and ecological components of the system") (Quinlan et al., 2016; Seidl et al., 2016b). In social-ecological systems (SES), a multitude of ecosystem functions and services need to be assessed at different scales while considering a broad range of public demands and expectations (Messier et al., 2019). To examine the resilience of forests and their multiple use, we adopt the social-ecological resilience concept in this paper and consider resilience from a normative perspective to be a desired property of a system.

The increasing interest in incorporating resilience into management has led to efforts developing assessment and measurement tools, with assessment methods aiming at deepening our understanding of the system dynamics and measurement methods quantifying resilience to facilitate comparison between different systems or points in time (Quinlan et al., 2016). Resilience can be assessed for the overall SES of a forest with its socio-economic links, for the ecological and social subsystems separately, or for the flows of different ecosystem services from the ecological to the social subsystem (Biggs et al., 2012). However, assessing resilience for subsystems and flows separately without accounting for their interconnections may lead to biased conclusions regarding the overall resilience of the SES. For example, diversity in forest ownership structure can create a more diverse landscape if forest owners have diverse management objectives. This diversity can generate a mosaic of varying forest structures (Rammer and Seidl, 2015; Schaich and Plieninger, 2013), yet the presence of many small owners in an area can also constrain integrated landscape-scale management and thus result in a lack of coordinated action in e.g., disturbance management. The average size of privately-owned forest may vary significantly from a few hectares in southern and central Europe to tens of hectares in northern Europe (Wiersum et al., 2005). We refer to small-scale forest owner as an owner having less than 5 ha of forest. The previous example illustrates that there is a need to identify and balance the trade-offs between different facets of resilience and to consider their interrelations, which necessitates transparent guidance for forest managers who wish to implement resilience in practice. We note that with balancing we do not refer to the balance of nature (Jelinski, 2005; Wu and Loucks, 1995) but rather to navigating between different resilience facets of ecological and social subsystems, including between different stakeholder demands and preferences. To aid implementing social-ecological resilience thinking into forest management, we propose a framework to assess social-ecological resilience and balance the emerging trade-offs in support of specific, predefined forest management goals.

According to Quinlan et al. (2016), any resilience assessment framework should be based on theory and enriched with case studies. In a context of sustainable forest management, indicators are often used to assess the sustainability of forest management (e.g., certification by the Forest Stewardship Council). Lammerts van Bueren and Blom (1997) argued that a rigorous and consistent indicator framework should be built hierarchically on *principles* (fundamental laws or rules, serving as a basis for reasoning and action), *criteria* (states of the dynamic ecosystem processes or the interacting social system, which should be in place as a result of adherence to a principle), and *indicators* (a qualitative or quantitative variable that can be assessed to check compliance with a criterion). The principles, criteria and indicator frameworks has been widely adopted, e.g., to allow intercomparison between forest sustainability standards (Holvoet and Muys, 2004; Salas-Garita and Soliño, 2021), or for assessing the sustainability of agricultural systems (van Cauwenbergh et al., 2007) and land use, land use change and forestry (LULUCF) projects in the context of climate change mitigation efforts (Madlener et al., 2006). To include trade-offs and stakeholder preferences in the framework, PCI can be enriched with active stakeholder involvement and other elements from multi-criteria decision making, evaluating multiple indicators and their importance to stakeholders (Wolfslehner et al., 2012). In this paper, our aim is to build a PCI framework for assessing resilience, which is based on the concept of social-ecological resilience. The framework provides guidance for understanding the resilience trade-offs in practice and we here present a hypothetical case study to demonstrate its utility. Specifically, the objectives of this paper are to (1) explore the trade-offs in forest management which affect resilience; (2) present a PCI framework for balancing resilience trade-offs in the context of strategic forest management planning; and (3) demonstrate the applicability of the proposed resilience framework under different forest management contexts.

First, we summarize the theoretical foundations for our approach, which is to identify the trade-offs in forest systems that may constrain the overall resilience of the system. Then we introduce our framework by proposing principles and criteria to assess resilience in forest systems and providing guidance on how to determine suitable indicators to validate principles and criteria. We subsequently apply the framework in the context of three alternative forest management goals for the same forested landscape, to demonstrate how different resilience trade-offs could be addressed in forest management.

2. Developing the framework

2.1. Resilience mechanisms, trade-offs, and balancing

SES are open systems with interlinked social and ecological subsystems (Berkes and Folke, 1998). The subsystems are linked through the ecosystem services provided by the ecological system and their contribution to human well-being in one direction; and by the feedbacks of the social subsystem in terms of intentional ecosystem management aiming to optimize the flow of services or unintentional human impacts on the ecosystem in the other direction (Muys, 2013; Thonicke et al., 2020) (Fig. 1).

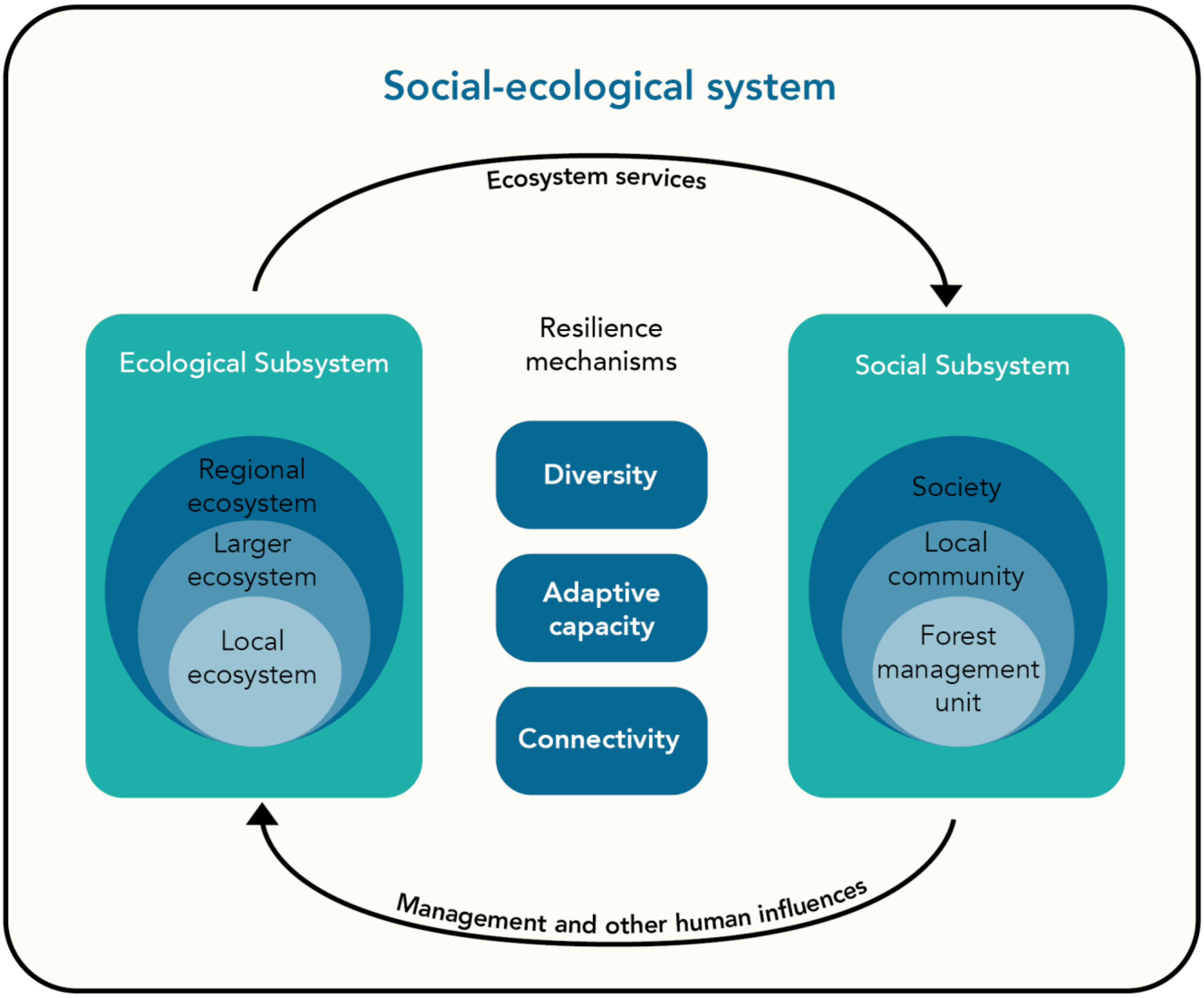


Fig. 1. The social-ecological resilience concept applied in this study. The arrows represent the flows that connect the social subsystem and ecological subsystem of a forest SES whereas the coloured boxes represent the three resilience mechanisms relevant for both subsystems. Adapted from Colding and Barthel (2019).

Resilience of ecosystem services can be enhanced by managing the mechanisms that support it (Biggs et al., 2012; Sarkki et al., 2017; Weise et al., 2020). Resilience mechanisms are system properties or functions that facilitate the resilience of the system (Weise et al., 2020). Various resilience mechanisms have been described in the literature, including redundancy, heterogeneity, diversity, modularity, adaptive capacity, memory, learning capacity, and connectivity (Kay, 2000). We chose to focus on diversity, connectivity, and adaptive capacity (Fig. 1) to explore the balancing of these resilience mechanisms within and between the ecological and social subsystems, as these three mechanisms are considered to be the most essential for resilience (Angeler et al., 2019; Bernhardt and Leslie, 2013; Cumming, 2011). Diversity of the ecological system may be expressed by the diversity of living organisms, their assemblages and biotic communities (DeLong, 1996), while diversity in the social system may be expressed by social actors and their interactions at different levels (Walker et al., 2006). Diversity enables different responses to disturbances and facilitates system persistence and recovery (Sousa-Silva et al., 2018). Connectivity (sometimes also referred to as connectedness) is the manner and the extent to which available resources, species, or social actors interact, disperse, or migrate across ecological and social landscapes (Bodin and Prell, 2011), and contributes to the self-organisation of the system. Connectivity also spreads knowledge, boosts innovation and increases well-being (Berkman and Glass, 2000; Egerer et al., 2020). However, high connectivity may also decrease resilience (Holling, 1973) as systems become sensitive to spreading disturbances, e.g., pathogens or invasive species. Adaptive capacity enables systems to tolerate stress, acclimate to changing situations and reorganise into something new (Bernhardt and Leslie, 2013). Adaptive capacity can be defined as the ability of a system to adjust to change, to moderate potential damages, to take advantage of opportunities, or to cope with consequences (IPCC, 2007).

In a SES, enhancing resilience of different subsystems can also lead to conflicting situations, where measures to increase resilience of one subsystem can have detrimental effects on another (Cumming, 2011). Such trade-offs are not limited to human-nature interactions, but occur also in natural systems without human presence, e.g., between plant species' adaptation strategies to drought (Lu et al., 2021). The existing trade-offs and their effect on the management of forests need to be identified, understood, and managed in the context of given management goals and objectives. Several types of trade-offs exist in SES: trade-offs within resilience mechanisms, trade-offs between ecosystem services (Rodríguez et al., 2006), trade-offs between different temporal and spatial scales (Guerrero et al., 2013), and trade-offs between ecological and social subsystems (Armitage et al., 2012). The trade-off types are described in Table 1.

Table 1. Types of trade-offs within SES, illustrated with examples.

Type of trade-off	Description	Example	Example reference
Trade-off within resilience mechanisms	Resilience mechanisms may be beneficial to parts of the system but simultaneously can increase vulnerability in other parts.	In highly connected SESs, species can repopulate disturbed areas but also a pest or disease can spread to large areas and its effects may cascade through the system.	Honkaniemi et al., 2020
Trade-off between ecosystem services	The provision of certain ecosystem services affects the provision levels of other services.	Delivery of harvested wood may decrease the regulating services of carbon sequestration and erosion control.	Lu et al., 2021; Turkelboom et al., 2018
Trade-off between the ecological and social subsystems	There can be trade-offs between mechanisms that confer resilience to the ecological subsystem and mechanisms that confer resilience to the social subsystem.	Establishing a large strict conservation area may restore connectivity of the ecological system but may prohibit further use of natural resources by the local human community.	Stræde and Treue, 2006
Trade-off between spatial, temporal and hierarchical scales	Resilience mechanisms operate across temporal and spatial scales. Some management decisions might enhance resilience of a SES over a short time	Strict forest fire control in fire prone areas might protect forests in the short term, but through long-term biomass accumulation it can lead to increased risk of a megafire.	Halofsky et al., 2020

	frame but erode it in the long run, and vice versa.		

The described trade-offs need to be balanced to reduce detrimental effects on parts of the system. Balancing is an exercise where minimum levels of the variables creating trade-offs are used to determine a balance for the contrasting variables. For example, to balance the vulnerability caused by highly connected SESs, processes enhancing modularity (e.g., limiting the spread of introduced species to new areas) may be increased. Minimum levels for variables are set to make sure that all aspects relevant for management are addressed, avoiding a focus on certain variables or subsystems while disregarding others. Setting minimum levels will not replace the need for balancing as there likely remain multiple management options possible with minimum requirements satisfied. Analysing trade-offs and looking at their effects can be done by e.g. involving multi-criteria decision-making tools (Borges et al., 2017; Kangas and Kangas, 2005; Wolfslehner et al., 2012). Multi-criteria decision-making tools and techniques are prominently used in studies assessing sustainability with criteria and indicators (Diaz-Balteiro et al., 2017), and can thus be applied in this study. They are commonly used in group decision-making context (Diaz-Balteiro et al., 2017), as they enable the incorporation of stakeholders' preferences into the decision-making process and therefore support the exploration of alternative solutions and preferences in a transparent manner (Borges et al., 2017; Wolfslehner et al., 2012). Multi-criteria decision-making methods can also incorporate pre-defined rules, e.g., minimum values for variables (Ananda and Herath, 2009).

Balancing should be performed holistically by balancing within and across the resilience mechanisms, between subsystems of the SES, between ecosystem services, and between scales (Table 2). The most suitable balance depends on the goal of the management: some outcomes may be more favourable to a specific management goal than others.

2.2. A framework to assess the resilience of forest management

We developed a PCI framework to aid identifying the trade-offs that need to be balanced to achieve a resilient system. Our framework has seven principles and 20 criteria addressing resilience mechanisms and balancing of trade-offs at the landscape level, which is the relevant spatial scale for considering socio-ecological resilience (Keane et al., 2018). The first three principles and nine criteria address the resilience mechanisms of the ecological and social subsystems in isolation whereas the last four principles and 12 criteria (Table 2) address the resilience trade-offs within the system more holistically by balancing within and between mechanisms, subsystems, ecosystem services and scales.

Table 2. Principles and Criteria for assessing the social-ecological resilience of forest systems.

Principle	Criterion
1.System diversity should be developed and fostered	1.1. Ecological diversity is maintained or enhanced
	1.2. Socio-economic diversity is maintained or enhanced
	1.3. Social-ecological diversity is maintained or enhanced
2. System connectivity should be developed and fostered	2.1. Ecological connectivity is maintained or enhanced
	2.2. Socio-economic connectivity is maintained or enhanced

	2.3. Social-ecological connectivity is maintained or enhanced
3. System adaptive capacity should be developed and fostered	3.1. Ecological adaptive capacity is maintained or enhanced
	3.2. Socio-economic adaptive capacity is maintained or enhanced
	3.3. Social-ecological adaptive capacity is maintained or enhanced
4. Balancing within and across mechanisms should be addressed	4.1. There is a balance within resilience mechanisms
	4.2. There is a balance across resilience mechanisms
5. Balancing between subsystems should be addressed	5.1. Diversity of ecosystem and social subsystem are balanced
	5.2. Connectivity of ecosystem and social subsystem are balanced
	5.3. Adaptive capacity of ecosystem and social subsystem are balanced
6. Balancing between ecosystem services should be addressed	6.1. Provisioning and cultural services are balanced
	6.2. Provisioning and regulating services are balanced
	6.3. Regulating and cultural services are balanced
7. Balancing between scales should be addressed	7.1. Resilience mechanisms are balanced between time scale levels
	7.2. Resilience mechanisms are balanced between spatial scales
	7.3. Resilience mechanisms are balanced between hierarchical levels

While the principles and criteria introduced here can be universally used for any forest related SES, their verification requires indicators that are appropriate to the context and should therefore be selected in a participatory manner involving both a broad set of relevant stakeholders and forest experts according to the management context. The selection of appropriate indicators may depend on the size and location of the forest, the forest management goals and the primary use as well as the temporal horizon of forest management. For example, an owner of a small forest patch may prefer indicators that can be observed even in small forest areas such as the number of different tree species (Varela et al., 2018), whereas a large-scale forest owner could also use indicators describing the connectivity of forest patches in the landscape (Arroyo-Rodríguez et al., 2020). Similarly, an owner whose management goal is to ensure continued profitability of the forest might need indicators that describe economic flexibility (e.g., option value of the stand (Jacobsen, 2007; Jacobsen and Thorsen, 2003) whereas an owner that is interested in nature conservation might need to look at the presence of suitable habitats for different species (Asbeck et al., 2021). Defining indicators for each criterion is needed to ensure a comprehensive assessment of resilience. We have provided examples of indicators for each criterion in the supplementary material (Table SM1).

In forest management, decision-making may involve stakeholders who may perceive and value the trade-offs differently from one another. Therefore, the choice of the management strategy achieving the most resilient outcome for a specific management goal is subjective and stakeholder dependent. Stakeholders' preferences on indicators and trade-offs can be considered by using available multicriteria decision-making methods where indicators are weighted (Ananda and Herath, 2009). The results of stakeholder preference analysis can be incorporated in the balancing exercise by using different weights for indicators and comparing the outcomes of the exercise.

The resilience of a system is dynamic and can change and evolve over time (Cabell and Oelofse, 2012). Consequently, an indicator value can have a different effect on resilience depending on the context and temporal scale of the assessment. Therefore, in our framework, we consider that indicators have response curves, meaning that indicator values may not have a linear effect on the resilience of a system. Indicator response curves are functions that show the effect of an indicator value on resilience (Fig. 2). The weights assigned to indicators by stakeholders scale the respective response curves by multiplying each point on the response curve with the weight factor. For balancing trade-offs, the indicator response curves are used in the following manner: 1) the shape of the indicator response curves is determined based on the available knowledge and information, and 2) the future values of the indicators and their effect on resilience are determined from e.g., simulation models. Based on the changes in the level of resilience for the indicators over time, an average resilience score at a certain time in the future can be calculated by combining the level of resilience of all the measured indicators (Fig. 4).

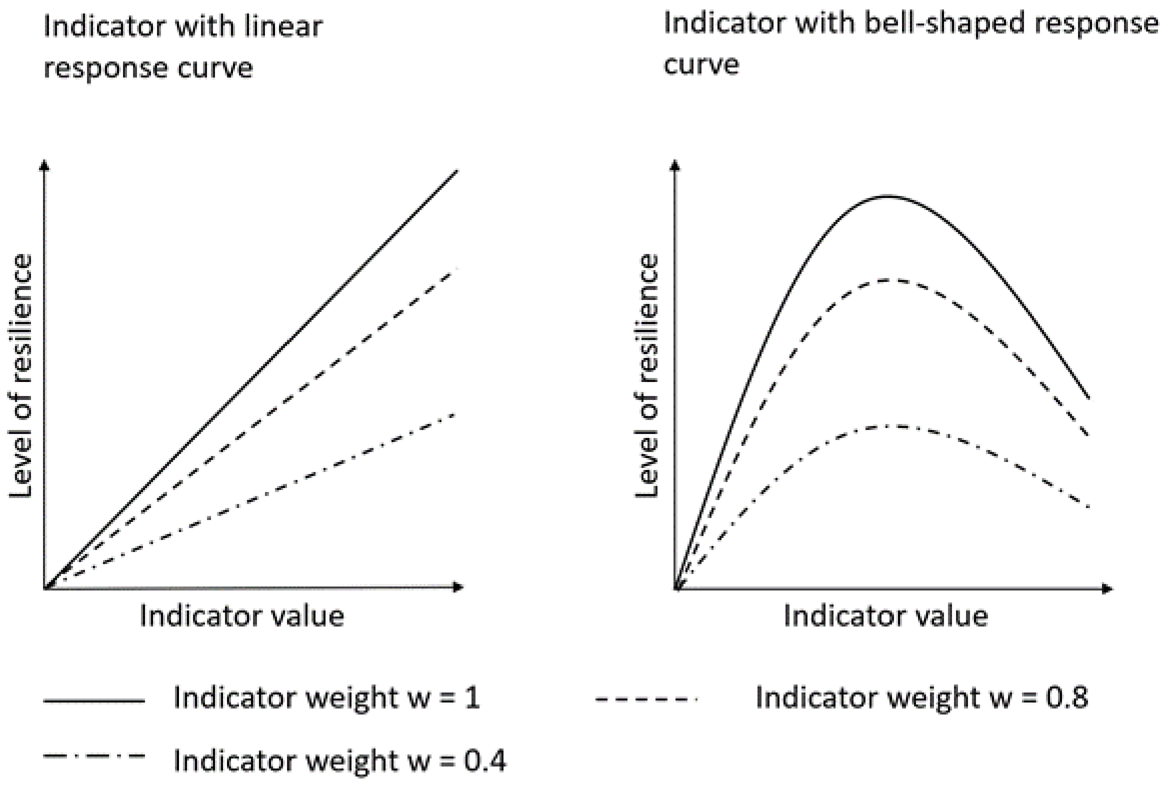


Fig. 2. Two examples of indicator response curves. For each response curve weighting of the indicators affects the height of the curve and therefore the impact on the level of resilience.

3. Application of the framework

The framework follows the essential elements of adaptive management, where the phases of planning, executing, monitoring and adjusting of the management are repeated iteratively (Williams and Brown, 2014). The framework is applied in ten steps (Fig. 3). The steps are designed to present both the deliberative (defining the different parts of the decision-making situation) and iterative phases (actual decision-making and learning) of adaptive management (Williams and Brown, 2014). The deliberative phase includes the steps from 1 to 5 and the iterative phase includes the steps from 6 to 10. The steps are: i) establish a stakeholder panel; ii) identify the system and its boundaries at the landscape level; iii) define management goals and main trade-offs; iv) identify indicators, their response curves, and their weights; v) project future scenarios for each management goal; vi) evaluate projected management outcomes; vii) revise the management strategy if needed; viii) perform resilience assessment; ix) revise the resilience assessment; and x) agree on accepted management strategy (Fig. 3). The cycle of the framework steps should be performed in regular intervals to form a recurrent cycle of decision-making (Williams and Brown, 2014).

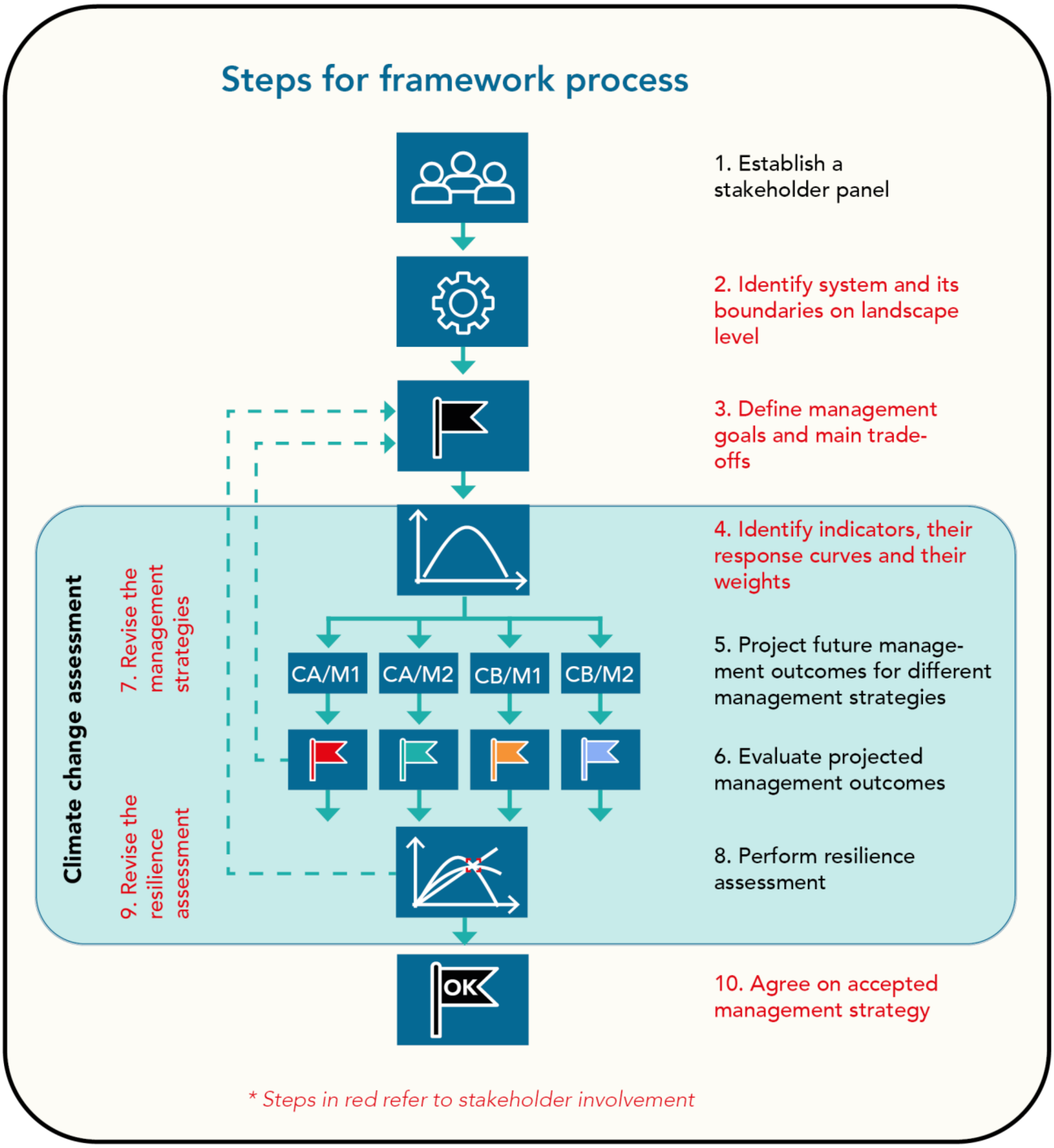


Fig. 3. Steps for applying the framework in forest management decision-making. Stakeholder engagement takes place in steps 2, 3, 4, 7, 9 and 10. CA, CB, M1 and M2 refer to different climate and management scenarios, the flags of different colours refer to different management outcomes. The steps are discussed in depth in the text below.

In the following, we demonstrate how the framework can be applied to a hypothetical even-aged homogenous Norway spruce (*Picea abies* (L.) H. Karst.) forest management unit in Central Europe and illustrate how the indicator values described above can change with management goals and how trade-offs between indicators will influence outcomes.

3.1. Step 1: Establish a stakeholder panel

The proposed framework requires a deeper understanding of both the ecological and social subsystems being analysed. Stakeholder involvement is here an integral part of any framework assessing social-ecological resilience. Stakeholders can help to define system boundaries and establish important attributes of the system (Walker et al., 2002), notably the resilience of what, to what and for whom (Carpenter et al., 2001; Lebel et al., 2006).
The stakeholders may vary greatly depending on the biophysical and socioeconomic settings of the respective forest landscape. As a rule, all the actors who use or are affected by the use of the landscape should be given the opportunity to participate in the stakeholder panel. This includes stakeholders with strong access right to the forest, such as forest owners and managers or forest enterprises, but importantly also the wider spectrum of societal and policy groups connected to the forest, such as forest and nature conservation administration, local NGOs, experts, and other relevant civil society representatives. The different actors can be identified through stakeholder mapping, using all available means of information and snowball sampling (Reed 2008). Mapping can happen at different connected governance scales and along different forest value chains. Having a largely representative stakeholder panel is important, but the size of the panel should allow for an enabling dialogue where each participant has a real potential to influence the decision making (Reed 2008). Depending on the landscape and societal interests connecting to it, the size of the panel may vary from five to thirty. Regardless of the panel size, the different actor groups should be fairly presented, and no group with an interest in, or being affected by, the use of the landscape should be excluded. It should be noted that successful stakeholder engagement requires the building of trust, good facilitation and therefore an impartial facilitator should be the initiator of the stakeholder engagement (Reed 2008).

The stakeholder panel should be involved in the process as early as possible (Reed 2008). Stakeholders should be contacted personally and provided with clear and accessible background material on the forest management project. In the first meeting, the panel should discuss and agree among themselves on the procedures of the panel, including a transparent information about the stakeholder panel's mandate, and the protocol to deal with potential disagreements or conflict situations that may arise. The facilitator may help with formatting the agreement and make sure that it is followed during the whole project.

For our case, we use three hypothetical forest management districts that are dominated by even-aged monoculture Norway spruce stands in different age classes. The landscape has many recreational visitors. Consequently, our stakeholder panel would consist of forest researchers, representatives of forest owners (public, communal and private), regional forest value chain representatives (harvest contractors and wood processing mills), a nature protection organisation and representatives of the recreational forest users.

3.2. Step 2: Identify the system and its boundaries on the landscape level

The system and its boundaries need to be defined to identify the factors affecting the capacity to reorganize or adapt. Defining the system boundaries needs to consider both the ecological and socio-economic units simultaneously to account for the complexity of SESs (Martín-López et al., 2017; Ostrom, 2009). System boundaries may be defined by identifying homogeneous biophysical and socio-economic variables in a region to form landscapes and socio-economic units that create the SES (Martín-López et al., 2017), e.g., a forest management unit. The biophysical variables may for example be similar soil type, water catchment area, or a forested area. It is important to note that the forest under investigation may be smaller than the larger biophysical system connected to it, e.g., the water catchment area. In these cases the system boundary may be defined based on the size of the forest, however the land use of the surrounding area and its effects on the forest need to be considered in the resilience analysis, as some of the resilience trade-offs can only be dealt with at large spatial scales. For example, forest management in the upper reaches of a catchment area may affect water quality and use in the lower parts of a catchment, or the pesticide treatments in surrounding agricultural fields may affect insect populations at forest edges. In relation to socio-economic units, identifying the main local stakeholders, e.g., the municipal administration, the wood buyers and other land users may enable the forest owners to make more holistic decisions. A consultation with other forest owners is beneficial especially for small-scale forest owners as e.g., forest associations can help to facilitate forest work and present the forest owners' interest in policy and decision making (Kronholm, 2015; Weiss et al., 2019). Identifying the major disturbances affecting the SES (the resilience to what) is important as systems may be robust to some disturbances at the expense of system performance under other disturbances (Schoon and Cox, 2012). Remote sensing can be used to identify the prevailing disturbance regimes in the landscape (Senf and Seidl, 2021). In addition, it is necessary to define the desired temporal, and hierarchical scales and to recognise the trade-offs in resilience that might occur between the defined system boundaries and the scales outside the defined boundaries (Armitage et al., 2012).

In our example, we look at the management of 100 ha of forested landscape dominated by Norway spruce over the time span of 30 years (from 2021 until 2050). We assume that three forest management goals are applied in the landscape separately by different forest owners so that each goal is applied on a 100 ha landscape. Norway spruce is a tree species with a high ecological and economic importance in Europe (Jansson et al., 2013). Its wood is used for multiple purposes, ranging from solid wood products to pulp and paper (Spiecker et al., 2004). However, the species is increasingly vulnerable to disturbances such as windthrow (Gardiner et al., 2013; Jansson et al., 2013), drought (Zang et al., 2014), and bark beetles (Hlásny et al., 2021; Seidl et al., 2016a). These disturbances have been projected to increase significantly with climate change, especially outside the natural range of Norway spruce (Seidl et al., 2014). In our example, the forests are especially affected by drought and bark beetles.

3.3. Step 3: Define management goals, management strategies and main trade-offs

The management goals and possible strategies to reach them should be defined together with the stakeholders to understand who is affected by the management decisions (resilience for whom). Having a management goal and feasible alternative management strategies that the stakeholders have agreed upon is crucial for the success of management (Williams and Brown, 2014). The process may start from current business-as-usual management but can include historic management approaches as well as potential future management alternatives (Seidl et al., 2018). Defining management goals and outcomes is required to identify the main trade-offs affecting resilience.

We consider three forest districts with a common management legacy located in the same forested landscape, but with diverging management goals: targeting provision of multiple ecosystem services; timber production; and biodiversity conservation. These examples allow us to illustrate the challenges that different management goals imply for increasing the resilience of even-aged monoculture stands of Norway spruce. Each goal setting results in different viewpoints of forest resilience. For each management goal, we consider two alternative management strategies. While the starting point for each management goal is a monoculture Norway spruce forest, species replacement or admixtures are possible management strategies for the three goals.

Each management goal may have several identified trade-offs. We chose three possible ones for our example. For management targeting multiple ecosystem services, the provisioning of several ecosystem services automatically causes trade-offs between services that can affect resilience e.g., by causing disputes between stakeholders. For management targeting timber production, a main trade-off could be between short- and long-term resilience where measures to increase long-term resilience decrease the short-term resilience, e.g., thinning to increase storm and drought resistance. For management targeting biodiversity conservation, a main trade-off could be between social and ecological parts of the system, for example when storm-felled trees are left unsalvaged in the forest to increase biodiversity which decreases the economic and possibly recreational value of a forest and may cause conflicts with some groups. Management strategies involve both rotation forest management, where forests are managed in repetitive cycles of clearcuts and planting, and continuous cover forestry, where selective harvesting and natural regeneration result in continuous forest cover with uneven-aged structures (Pukkala and von Gadow, 2012). The management goals, related strategies, and trade-offs are described in Table 3.

Table 3. Description of management objectives and alternative strategies as well as trade-offs relevant for managing resilience.

Management goal	Management for multiple ecosystem services	Management for timber production	Management for biodiversity conservation
Example management objective	Maintain or enhance the resilience of multiple ecosystem services to satisfy a great variety of stakeholders.	Earn the highest possible profit from sustained timber production.	Protect and increase the biodiversity of the forest.
Management strategy M1	Perform group cutting to open the canopy to improve light conditions on the ground. Retain all the regenerating species. Retain large and iconic trees. Plant oak in the gaps.	Convert forest into a mixed beech-spruce continuous cover forest by opening canopy and planting beech.	No further active forest management, spruces are left as they are in the forest. Natural disturbances acting as main drivers for regeneration and modification of structural diversity.
Management strategy M2	Perform single tree cuttings to develop structural diversity to convert to continuous cover forest. Promote structural diversity by removing trees of different heights.	Spruce is maintained with intensive forest management with reduced rotation periods and little to no thinning before clearcut. Regeneration is done by planting improved spruce seedling material from breeding programs with higher growth rates (Haapanen, 2020; Hayatgheibi et al., 2021).	Active restoration. Gap and single tree cutting conducted to create dead wood and increase the light conditions. Broadleaved species (e.g. maple, aspen, birch) are planted.
Main trade-offs	Trade-offs between ecosystem services.	Trade-off between short- and long-term resilience.	Trade-off between social and ecological parts of the SES.

3.4. Step 4: Identify indicators, their response curves, and their weights

This step requires that stakeholders jointly determine with scientists and experts the indicators they deem important for the resilience of the forest-related SES (resilience of what) to a certain disturbance (resilience to what). The response curves of the indicators (how the indicator values affect the level of resilience) should be determined by scientists and experts who have significant knowledge about the analysed SES. The determination of the response curves should be based on the scientific evidence on how the social-ecological resilience is influenced by the selected indicators as well as the local knowledge of the management context. We identified common response curves for the example indicators presented in the Supplementary Material (Table SM2 and Table SM3) based on literature and our expertise. Here, we show two examples: indicators 'Genetic diversity from natural regeneration' and 'Planting of more adapted non-local species and provenances'. An overview of all the identified response curves is given in Supplementary Material (Table SM2 and Table SM3). It is important to note that these curves are an interpretation of how resilience responds for different indicators in specific circumstances, and they might take other forms depending on the social-ecological context and the identified trade-off. Furthermore, the stakeholders should decide on the minimum threshold values for each indicator before the indicator weighting to ensure that all indicators are represented in the analysis.

Once all indicators have been decided on, the stakeholders should assign weights for each of them in accordance with their importance for reaching management objectives. Here we illustrate this with weights of two indicators for each management goal. For management targeting multiple ecosystem services, 'Genetic diversity from natural regeneration' receives high importance (w = 1), while 'Planting of more adapted non-local species and provenances' receives medium importance (w = 0.8). Natural regeneration is often more cost effective than artificial regeneration with seedlings (Löf et al., 2021), which can be beneficial if the resources for management are limited. Natural regeneration does also result in high genetic diversity in the regrown forest (García Gil et al., 2015; vander Mijnsbrugge et al., 2010), and may provide better habitat requirements for forest dwelling species than planted trees (Martínez-Jauregui et al., 2016). However, increasing the species diversity is important for improving resilience to disturbances (Messier et al., 2021), and therefore, in our case, relying only on natural regeneration scan be insufficient if it would result in a Norway spruce dominated forest. In gap areas, oaks that are adapted to local site conditions are planted, whereas Norway spruce is naturally regenerated. For management targeting timber production, 'Genetic diversity from natural regeneration' receives medium importance (w = 0.8), while 'Planting of more adapted non-local species and provenances' receives high importance (w = 1). Improved seedling material, e.g., from southern provenances, may perform better than natural regeneration if maintaining spruce forest is desired (Serrano-León et al., 2021). It should be noted, however, that planting seedlings from remote provenances comes with risks as the conditions might be considerably different in the new location than in the original provenance, which may result in growth loss and other negative effects (Montwé et al., 2018). For management targeting biodiversity conservation, 'Genetic diversity from natural regeneration' receives high importance (w = 1), while 'Planting of more adapted non-local species and provenances' receives low importance (w = 0.4). Enabling natural regeneration of the species naturally present in the landscape may be more beneficial for biodiversity than planting more adapted non-local species, as the natural species have co-evolved with the other native species and therefore are more likely to provide suitable habitats (Felton et al., 2013; Goßner et al., 2009; Martínez-Jauregui et al., 2016). However, if in our case the natural regeneration is only Norway spruce, there might be need to pro-actively support the regeneration of native broadleaved trees to promote biodiversity in the changing climate.

3.5. Step 5: Project future scenarios for each management goal

Projecting the future indicator values for the defined management strategy based on climate change and socio-economic change helps to visualise possible future outcomes of management. Future changes in the environmental conditions should be assessed and analysed, for instance in relation to the question of how species viability is affected. Similarly, scenarios for future changes in policies and demands related to forests should be assessed. Both could result in different scenarios that can be used for simulation of future management outcomes. This step concludes the deliberative phase of adaptive management.

We estimated the future context for the hypothetical forest districts based on the literature. The expected temperature in Germany is on average 1 to 3 °C higher in the period 2040-2070 than in the period of 1971-2000 and precipitation patterns are expected to change, with a decrease in spring precipitation and increase in summer precipitation (Deutscher Wetterdienst, 2022). In such conditions, the vulnerability of Norway spruce to disturbances will increase (Honkaniemi et al., 2020) for each management strategy. In addition, there may be pressure to produce more wood to substitute for non-renewable materials (Verkerk et al., 2020) and to conserve biodiversity (Selva et al., 2020), while providing continued recreational opportunities (Derks et al., 2020). These demands may influence the decision which management strategy to choose.

3.6. Step 6: Evaluate projected management outcomes

This step starts the iterative phase of adaptive management where the management strategies are evaluated and learned information is implemented in the following decision-making (Williams and Brown, 2014). Here, projected management outcomes are evaluated against management goals. The purpose of this step is to recognise if the proposed management strategy is feasible for achieving the management goal or if another strategy should be considered for further analysis. In our example, the outcome of the management strategies would refer to the level of different ecosystem services provided (management targeting multiple ecosystem services), the income received from timber production (management targeting timber production), and the number and abundance of different species (management targeting biodiversity conservation). If the outcome of the management strategy is undesirable, the management strategy should be revisited with the stakeholders (Step 7). If the outcomes are desirable, the resilience assessment can be done (Step 8). Arguably, in the case of forest management, considerable time horizons apply to evaluate the success of a management concept, calling for long term evaluation intervals and iterative adaptations of management concepts.

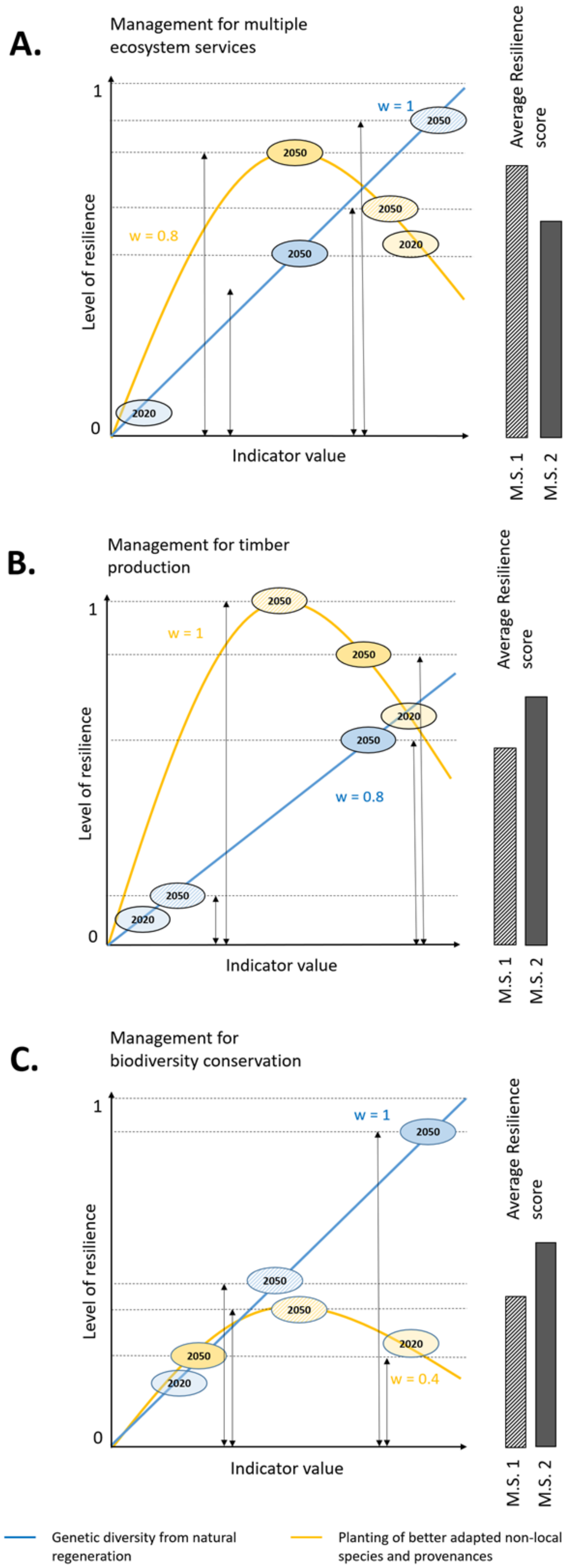
3.7. Step 7: Revise the management goals and strategy if needed

If the management strategy fails to achieve the management goal, it should be revised and redefined with stakeholders by incorporating the acquired information in the planning of a new management strategy. Essentially, this step is the learning phase of adaptive management (Rist et al., 2013; Williams and Brown, 2014), where Step 3 is repeated with improved understanding on how the analysed SES might develop and what new ecological and social patterns might emerge. The stakeholder involvement is crucial here, as the new information about the projected management strategy outcomes might change their perspective of the desired management strategy and even of the management goal (Williams and Brown, 2014).

3.8. Step 8: Perform resilience assessment

Once the projected management strategy outcomes are deemed acceptable by the managers and stakeholders, the influence of the different management strategies on the social-ecological resilience of the SES should be assessed. In other words, this step investigates how resilient the outcome of the management strategy is. To assess how a management strategy influences social-ecological resilience, indicators representing all the principles and criteria from Table 2 should be included.

Based on the evaluation of the current situation and the projected development of the landscape, indicator values and their movement on the indicator response curves can be determined (Fig. 4). Balancing takes place after the individual values for the considered temporal period are known by examining the results with the stakeholders. In the balancing phase questions to consider are e.g., whether the low level of social-ecological resilience indicated by certain indicators are acceptable if other indicators suggest high levels of social-ecological resilience, or whether the social-ecological resilience increases are sufficient for stakeholders. For example, having indicator values at extreme ends might result in a medium average score of social-ecological resilience but many low indicator values might indicate weak points of the system or even a risk that social-ecological resilience could erode over time. Balancing might result in leaving some of the proposed management strategies out of the resilience assessment if they are considered by the stakeholders as not suitable. If the balancing exercise results in a disagreement, the management strategies might need to be revised again in the light of the new information.



A.
Management for multiple ecosystem services
1
0
Level of resilience
Indicator value
w = 1
w = 0.8
2050
2050
2050
2050
2020
2020
Average Resilience score
M.S. 1
M.S. 2
B.
Management for timber production
1
0
Level of resilience
Indicator value
w = 1
w = 0.8
2050
2050
2050
2050
2020
2020
Average Resilience score
M.S. 1
M.S. 2
C.
Management for biodiversity conservation
1
0
Level of resilience
Indicator value
w = 1
w = 0.4
2050
2050
2050
2050
2020
2020
Average Resilience score
M.S. 1
M.S. 2
Genetic diversity from natural regeneration
Planting of better adapted non-local species and provenances

Fig. 4. Illustration of how weighting of indicators and different management scenarios affect the resilience outcome of two indicators. The indicator values presented are in accordance with the management scenarios described in Table 3, with (A) management targeting multiple ecosystem services, (B) timber production, (C) biodiversity conservation. The solid lines represent the indicator response curves and the height of the solid line represents the weight the indicator has for the management goal. The dashed line represents the proposed minimum indicator threshold value. The slashed and filled bubbles represent the indicator value in time for the two management scenarios and the slashed and solid bars show the average resilience score of the indicators for the two management scenarios (M.S. 1 and M.S. 2).

Once the balancing is done and the selection of the management strategies is clear, the resilience assessment is done by calculating the average resilience score of the indicators for each management strategy (Fig. 5). In a case with multiple stakeholders, this exercise can be conducted in expert-led workshops where stakeholders can provide their preference input and experts can include the frames of the SES (Borges et al., 2017). Different multi-criteria decision-making tools can be used to deal with multiple indicators simultaneously. For example, multi-criteria analysis using a PROMETHEE II algorithm can be used to weight and aggregate multiple indicators resulting in relative rating of resilience for different management strategies (Wolfslehner et al., 2012). In that method, stakeholders give their preference by weighting the different indicators and by comparing pairwise different alternative indicator values resulting from different management strategies. The comparison leads to a ranking of alternative management strategies (Wolfslehner et al., 2012).

Each management strategy involves a different set of interventions with different timings and therefore the temporal development of the average resilience score might change with time. Therefore, the resilience assessment should be done for regular timesteps, e.g., every 5 or 10 years. The use of multi-criteria decision-making tools may facilitate the reassessment of resilience as the information behind the tool models can be updated (Borges et al., 2017). Depending on the resilience assessment outcome, the management strategy can be either accepted or it should be revised again if the assessment results fail to find a resilient system.

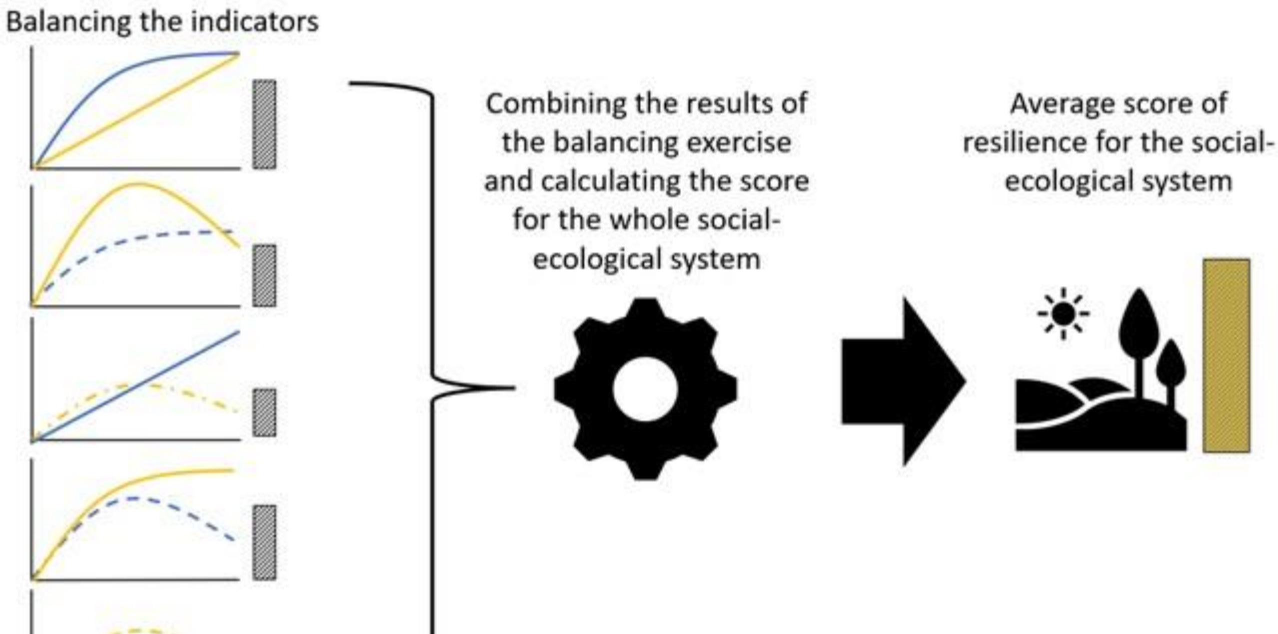


Fig. 5. The process of calculating the average resilience score. First, all the identified indicators are balanced and the average score of social-ecological resilience is calculated. Then all the individual balancing exercises are combined with the help of multi-criteria decision-making tools and the average score of social-ecological resilience is calculated for the whole SES.

3.9. Step 9: Revise the resilience assessment

If the stakeholders are content with the results of the balancing exercise, i.e., they deem the level of resilience acceptable, the management strategy can be accepted. In this step, it is important to present the results of the whole balancing exercise for the stakeholders to have an understanding of the resilience of the different parts of SES. Having an overview of the level of resilience in the different parts of SES allows for transparent decision-making where the highly resilient and vulnerable parts of the system are both presented. A transparent decision-making also results in better approved decisions from all the stakeholders (Reed, 2008; Williams and Brown, 2014). If the resilience assessment gives an unsatisfactory result, the management strategy should be revised again with the stakeholders with attention paid to the vulnerable parts of the system where the indicator values showed low levels of resilience. The resilience impacts of the newly defined strategy should then be reanalysed following the previous steps.

3.10. Step 10: Agree on accepted management strategy

If the stakeholders agree that the level of resilience achieved with a specific management goal is enough, they may choose that management goal and related strategy to be implemented. The effects of the actual management should be carefully monitored to understand how the SES develops. As the dynamics of SES might have significant changes to the social-ecological resilience, the framework process should be reconducted periodically every five to ten years.

4. Discussion

This study aimed at developing an approach to mainstream social-ecological resilience in forest management. We have presented a novel way to interpret the context dependency of resilience (resilience of what and to what; sensu Carpenter et al. (2001)) and to deal with the different trade-offs by using resilience mechanisms and indicators to assess them. This framework demonstrates how the resilience of a forest is dependent on the context and objectives of forest management. Here we discuss the foundations of the framework, its applicability to practical forest management, and the future pathways of research.

4.1. Foundations of the framework

The first objective of this study was to explore trade-offs in SES. While many possible resilience mechanisms could have been considered (Weise et al., 2020), our focus was on those seen as being most relevant in the literature on forest-related SES, namely diversity, adaptive capacity, and connectivity (Bernhardt and Leslie, 2013). In the forest management context, diversity may represent the range of resources at the manager’s disposal, connectivity may refer to the ability and possibility to coordinate action, and adaptive capacity may refer to the capacity and ability to act. If any of them are weak, it could hamper the resilience of the system. The complexity of forest-related SESs leads to several possible trade-offs that affect the resilience of the system (Allen et al., 2018). We identified four classes of trade-offs that have strong effects on resilience in the forest management context: trade-offs between resilience mechanisms, trade-offs between ecosystem services, trade-offs between the ecological and social subsystems, and trade-offs between spatial and temporal scales (Table 1). Some of these trade-offs are better documented than others. For example, trade-offs between ecosystem services are well-studied (Rodríguez et al., 2006; Turkelboom et al., 2018) whereas trade-offs between resilience mechanisms are less studied and harder to analyse (Weise et al., 2020).

Balancing and compromising between trade-offs is not new in natural resource management. For example, forest managers have long had to balance measures to increase forest productivity with the costs of management. Therefore, applying a balancing approach to manage forests for social-ecological resilience is likely to be intuitive to managers. In contrast, using a multicriteria decision-making process to express human preferences in a participatory way may not be so common in the forest sector (but see Ananda and Herath, 2009; Gilliams et al., 2005) . The challenge of this approach is to engage with a panel of stakeholders and experts, where they can agree upon the relevant resilience indicators, their response curves, their weights, and how these might change depending on the management context and across spatial and temporal scales.

4.2. Applying the framework to management

Our second and third objectives were to present a PCI framework for resilience assessment and demonstrate its use in different forest management contexts. Our approach recognizes how resilience is dependent on the forest management context and goals. In natural resource management, managers face both ecological and social drivers that they cannot influence (Standish et al., 2014), as well as rules and regulations that may constrain what they consider the optimal management for resilience (Schmitt-Harsh and Mincey, 2020). Therefore, an approach which can be tailored to fit these external constraints is beneficial.

Our framework highlights the importance of involving stakeholders when assessing social-ecological resilience, as that is the start for identifying the system, its management goals and most relevant indicators. Initially, we started to look for a way where forest owners could assess the social-ecological resilience of forests without consulting many stakeholders, as this process may be challenging to conduct and end without satisfactory results (Sheppard and Meitner, 2005). However, it became apparent that to adequately capture the complexity of the situation, knowledge of and experience from different parts of the SES is needed. Local stakeholders with the support of experts hold the key information of the system in their knowledge and mental models (Walker et al., 2002) and could therefore provide a more accurate view and projections of social-ecological resilience than what a single decision-maker is able to do. A holistic view of the analysed system is particularly important for defining the indicator response curves, as different stakeholders may perceive the effects of indicators differently or they may have different priorities in enhancing social-ecological resilience. Jointly determining the indicator response curves may incorporate the potential conflicts of individual objectives tighter to the resilience assessment. Nevertheless, the framework can provide food for thought even to managers that are unable to engage in the full stakeholder process. The framework represents a helpful tool that ensures each of the key principles and criteria are considered and the implications of any actions or any choices are considered.

While our framework is flexible to be applied in various situations, it does require defining the temporal and spatial scale in which social-ecological resilience is considered. The framework also needs information on how indicator values might change in the future. As social-ecological resilience is a dynamic property of a system that changes over time (Cabell and Oelofse, 2012), target indicator values can change with temporal and spatial scales. Furthermore, forest managers operate simultaneously at multiple nested scales and hierarchies from local stands to national forest land, and in turn, are affected by outside influences such as international forest policies (Fischer, 2018). The results of the initial determination of the indicators and their response curves should be revised regularly by a stakeholder panel to account for possible changes in the system or surrounding conditions (Fischer et al., 2009) as well as to check if the indicator values are developing as projected. For example, pulse (e.g., a storm) and press (e.g., climate change) types of forest disturbances can have different effects on forests and their ecosystem resilience (Cantarello et al., 2017) and might change both the major trade-offs and the response curves of resilience indicators in our framework.

Furthermore, disturbances can lead to varying management responses depending on the management goal. If emphasis is laid on reducing disturbance impact, more attention is paid to measures that increase short-term resilience (or resistance sensu Bryant et al. (2019)), e.g., to more frequent thinning and centralized emergency response. If emphasis is laid on a system being resilient far into the future, attention is paid to measures that increase long-term resilience, with e.g., measures that ensure regeneration of the system (Xu et al., 2017). Our example clearly shows that the average score of social-ecological resilience for each management goal is dependent on the selected indicators and the weights assigned to them. While the example was made to illustrate the use of the framework, it also shows that no single management strategy leads to a generally more resilient system than the others. Therefore, the definition of the indicator response curves and regularly reviewing them is a crucial step in the application of the framework.

4.3. Future pathways of research

To advance the operationalization of a resilience assessment framework as presented in this paper, future research should aim at carrying out regional case studies (as in Nagel et al. (2017)) with participatory stakeholder engagement. Such research would address two questions: i) how to determine the locally relevant indicators to assess resilience, and ii) how different types of stakeholder panels function under different circumstances and influence the resilience assessment. The first question requires an initial assessment of the forest management goals and the social context as well as an outlook on the future social-ecological pathways. The research should involve simulating future forest conditions and market development as well as exploring the development of social demands on forests. Against such an analysis, relevant indicators need to be selected and context specific response curves for these resilience indicators determined. The second question requires a sensitivity analysis on how stakeholder panels with different number of participants, compositions and facilitation influence the outcome of the resilience assessment.

The framework could be combined with other promising methods to assess resilience, for example functional response traits and network analysis (Aquilué et al., 2020; Mina et al., 2020), to identify relevant indicators. With developing experience from diverse regional case studies, common stakeholder preferences related to the indicator selection and weighting can be expected and potentially used in multi-criteria decision-making tools, which should reduce the required implementation efforts and facilitate the uptake of such assessment methods. However, the collection of indicators would need to be accompanied with guidance on how to select the relevant indicators for the case of interest. Such guidance could be for example a checklist where forest type and size are considered. Furthermore, climate change impact assessments using forest simulation modelling should be expanded with quantification and evaluation of resilience indicators (Albrich et al., 2020), which would also support the operationalization of the approach.

5. Conclusion

We present a novel framework to assess the resilience of forest-related SESs based on resilience mechanisms and trade-offs. This approach was designed to perform a resilience assessment in an intuitive way adopting a logical framework of PCI and complementing it with multi-criteria decision-making. We show how resilience of a forest system is context dependent and determined by the management goal of the system, and that the proposed framework may be a tool to highlight these. We illustrate this context dependency by applying the framework to a landscape dominated by pure Norway spruce stands in Central Europe managed with three different management goals. The new approach has significant potential to make the concept of resilience easier to apply in forest management as it explicitly explores forest resilience within the context of specific management goals.

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