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Reviewing the Use of Resilience Concepts in Forest Sciences

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Abstract

Purpose of Review—Resilience is a key concept to deal with an uncertain future in forestry. In recent years, it has received increasing attention from both research and practice. However, a common understanding of what resilience means in a forestry context and how to operationalise it is lacking. Here, we conducted a systematic review of the recent forest science literature on resilience in the forestry context, synthesizing how resilience is defined and assessed.

Recent Findings—Based on a detailed review of 255 studies, we analysed how the concepts of engineering resilience, ecological resilience and social-ecological resilience are used in forest sciences. A clear majority of the studies applied the concept of engineering resilience, quantifying resilience as the recovery time after a disturbance. The two most used indicators for engineering resilience were basal area increment and vegetation cover, whereas ecological resilience studies

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Compliance with Ethical Standards

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frequently focus on vegetation cover and tree density. In contrast, important social-ecological resilience indicators used in the literature are socioeconomic diversity and stock of natural resources. In the context of global change, we expected an increase in studies adopting the more holistic social-ecological resilience concept, but this was not the observed trend.

Summary—Our analysis points to the nestedness of these three resilience concepts, suggesting that they are complementary rather than contradictory. It also means that the variety of resilience approaches does not need to be an obstacle for operationalisation of the concept. We provide guidance for choosing the most suitable resilience concept and indicators based on the management, disturbance and application context.

Keywords

Forest management; Engineering resilience; Ecological resilience; Social-ecological resilience; Disturbance; Indicators

Introduction

Global change causes shifts in forest disturbance regimes [1, 2] that can potentially reduce the capacity of forests to provide ecosystem services [3]. The change may furthermore alter the distribution of species [4, 5] including forest-dependent species that, if not able to migrate as their habitat shifts, can face extinction [6]. Interacting disturbances can alter forest development pathways [7], and an increased disturbance frequency can erode the capacity of forests to recover [8, 9]. In addition to environmental changes, societies and societal demands towards forests are changing, and therefore, forest-related policies must change as well to meet these demands, e.g. in relation to climate change mitigation [10] or the development of a wood-based bioeconomy [11]. It has been suggested that neither the traditional command-and-control forest management nor classical risk management in forestry is able to respond adequately to this multitude of changes and challenges [12, 13].

Resilience is one of the current buzzwords in science and policy, and fostering resilience has been proposed as a solution to deal with the uncertainty caused by global change [14–16]. However, resilience is a difficult concept to define, as demonstrated by the numerous definitions and approaches available in the literature [17, 18••]. This ambiguity is partly due to the widespread use of the term in different disciplines and systems. As a result, the scientific literature diverges on whether resilience should be considered as a system property, process or outcome of management [18••]. In the literature on social-ecological systems, three broad conceptualisations of the term resilience have emerged: engineering, ecological and social- ecological resilience [19]. Engineering resilience is often cited as first defined by Pimm [20]. Following a disturbance in a given system, it is characterised as the time that it takes for variables to return to their pre-disturbance equilibrium. This definition assumes the existence of a single equilibrium state. Ecological resilience, defined by Holling [21], is “a measure of the persistence of systems and of their ability to absorb change and disturbance and still maintain the same relationships between populations or state variables”. Holling’s theory includes the proposition that systems can be in multiple equilibria (i.e. have multiple basins of attraction). A basin of attraction is a concept from systems science describing a portion of the phase space in which every point will eventually gravitate back to the attractor [22]. A disturbance can move the system from one basin to another and cross a threshold during the process. Finally, the concept of social-ecological resilience considers natural and social systems to be strongly coupled social-ecological systems [23]. Social-ecological resilience considers the maintenance of the current regime and the adaptive capacity of a coupled human-natural system [24•]. Several variants of social-ecological resilience exist, but all focus on the adaptive capacity of the social-ecological system as a whole [25]. Among them, the Resilience Alliance, the school of thought in the footsteps of Holling, defined resilience as “the capacity of a social-ecological system to absorb or withstand perturbations and other stressors such that the system remains within the same regime, essentially maintaining its structure and functions. It describes the degree to which the system is capable of self-organisation, learning, and adaptation” [26, 27].

While resilience is widely considered in forest ecology, the resilience concept has not been implemented widely in the daily practice of forest management [28]. However, elements of resilience thinking, e.g. the necessity to learn and adapt, are a necessity for forest managers who are confronted with the frequent challenge of unexpected disturbance patterns interfering with well-planned management procedures. A primary limitation to implementing resilience in forest management is that, despite the growing body of research, forest resilience continues to be a vague concept for decision makers. Reviews of existing resilience concepts and their relevance to natural resource management in general [29, 30] and forest management in particular [31] have been conducted previously, yet there is no common agreement to date on how resilience in the context of forestry should be defined or applied. Different resilience concepts are used in seemingly similar situations without much effort paid to the justification of the selected concept. Guidance for developing and implementing measurement, monitoring, and evaluation schemes of resilience is widely lacking [18••, 32]. These challenges in operationalizing resilience prevent a widespread implementation of resilience thinking in forest management. In order to answer a core question of forest managers today, namely, how to manage forests to increase their resilience to global change, a clearer understanding of the use of the resilience concepts in forest science is needed to provide a way forward for both researchers and forest managers.

This paper aims at facilitating the application of resilience in the context of forestry by clarifying its meaning and purpose through performance of a systematic review of the resilience concepts and their assessment approaches used in forest science. We had three objectives:

1. To evaluate the adoption of the three mentioned concepts in resilience research in forest sciences. We were particularly interested in the current use and geographical spread of the concepts, the trend in their use, as well as the methods and indicators applied to assess resilience.
2. To analyse similarities and differences between the applied resilience concepts and to examine how conflicting they are with each other.
3. To develop guidance for the use of the resilience concepts in forest management and policy.

We hypothesised that:

- In the context of facing global change, the use of more holistic resilience concepts, such as social-ecological resilience, is increasing.
- Forest resilience is a widely adopted concept in forest science, but its large variety of approaches prevents its mainstreaming into forestry practice.

Materials and Methods

We reviewed how forest resilience is currently assessed in the scientific literature. We searched the literature using the *Scopus* database (Relx Group, 2018) using the search string TITLE-ABS-KEY (“resilience” AND “forest”) ALL (“measur*” OR “manag*”) PUBYEAR > 1999. Applying the search string in the Scopus database guaranteed that results were published in scientific journals. As resilience related research started to increase dramatically after 1999 [24•], the focal time period was 2000–2018. The cut-off date for including new publications was August 19th, 2018. We screened all identified abstracts. All abstracts that (1) were published in a peer-reviewed scientific journal in English, (2) had the word “resilience” in relation to an active verb (e.g. manage, calculate, enhance, improve, assess) and (3) focused on forest-related systems (e.g. tree species or forest-dependent communities), natural resource management or landscape management were further screened. We also accepted studies that proposed a way to assess resilience for non-specified ecosystems as these could also apply to forests. Further screening of the full papers checked if they (4) have definition of resilience and (5) propose a method to assess resilience either in qualitative or quantitative terms. Only the studies that fulfilled all five criteria were selected for further analysis.

To examine how widely the three different resilience concepts were adopted in the literature, the studies were classified into three groups based on their concept of resilience: engineering, ecological and social-ecological resilience. The classification was done by recording the resilience concept used and comparing them with the foundational studies for the respective concept, see higher. If studies mentioned several concepts, we focused on the method used to evaluate resilience and derived the adopted concept from there. We also evaluated the trend in the number of studies published per year and in the share of the three concepts among studies. In addition, we assessed the biome where the study was conducted. For biome delineation, we used the definitions of Olson et al. [33]. The distribution across biomes was calculated in relation to the number of studies in the three resilience concept classes separately. Biomes that represented less than 5% of the studies in any of the resilience concept categories were grouped in “Other”.

To explore if the three resilience concepts conflicted with each other and in what situations they were applied, we assessed the response system/variable (resilience of what?) and the disturbance of concern (resilience to what?) of each study. The categories for the response system/variable were as follows: tree populations, non-tree vegetation, forest animal and fungal communities, soil, forest ecosystem, not specified ecosystem, forest-related social-ecological system, forest industry and other. The categories for the disturbance of concern were as follows: drought; fire; wind; climate change; other abiotic disturbances; biotic disturbance; forest management operation; land use; global change; societal, economic and policy shocks; multiple disturbances; and other. In addition, we assessed whether the proposed evaluation method in the studies was qualitative or quantitative. Furthermore, we recorded the main method used to assess resilience. The distinguished categories for the method used were as follows: treelevel sampling, vegetation sampling, animal population sampling, soil sampling, multiple agent (animal population, vegetation and soil) sampling, forest site inventory, conceptual modelling, empirical modelling, process-based modelling, geographical information system/remote sensing approach, historical records, meta-analysis, surveys and multi-tool (when there was no single prevalent method).

We examined the indicators used to assess resilience (see Online Resource 3). As most of the studies assessed more than one indicator, we recorded the total number of indicators used to assess resilience in each study. For example, if a study assessed resilience with regard to species richness, species composition, functional diversity, number of seedlings and drought index, we counted five indicators in total. We documented the ten most widely used indicators for each resilience concept by calculating the relative number of studies using them. In the case of the tenth most used indicator, we recorded all the indicators that were used with the same frequency. In addition, we classified the indicators according the Organisation for Economic Co-operation and Development's (OECD) Pressure-State-Response (PSR) framework [34]. We further organised the indicators into larger groups (see Online Resource 4). Grouping the individual indicators together gives a better overview of which compartments of a system are used to study resilience and how the compartments vary according to the resilience concept used. A compartment here describes the part of the system under study, e.g. forest structure, soil properties and socio-economic structure. The indicator groups were as follows: climate indicators, soil properties, disturbance effects, forest structure, forest regeneration, tree and ecosystem production and transpiration, biodiversity, land use, ecosystem management objective, socio-economic capacity, socio-economic diversity, finance and technological infrastructure, governance, time and other. In the previously described example of the study reporting five resilience indicators, we would have counted three indicators describing biodiversity, one for forest regeneration and one for climate. We analysed the trend of the average number of indicators used to evaluate resilience over time by fitting a linear regression to the time series of the average number of indicators in R [35]. To buffer extreme values, we used a 3-year moving average of the indicators used. In addition, we performed a non-metric multidimensional scaling (NMDS) to describe how studies were ordered based on the recorded indicator groups, and how this was related to the resilience concept they used. We used the metaMDS function with Gower distance and seed 123 from the package "vegan" [36] in R [35]. Figures were created with the package "ggplot2" [37].

Results

The initial search resulted in 2629 peer-reviewed studies that were all screened (see Online Resource 1). The abstracts that fulfilled the first three selection criteria were chosen for further analysis, narrowing the set down to 625 studies (see Online Resource 2). Of these a final set of 255 studies also fulfilled the selection criteria 4 and 5 [7–9, 13, 16, 31, 38–286]. One of the reviewed studies was in press during the review process and was published in 2019 but we included it in the studies published in 2018.

Trends in Forest Resilience Research

The 255 studies identified as relevant for our review were classified according to the resilience concept they used. The majority of the studies employed the engineering resilience concept (54%), while ecological and socio-ecological resilience concepts were applied in 31% and 15% of studies respectively.

The publication rate of studies assessing resilience had steadily increased over the investigated period (Fig. 1). The use of the engineering resilience concept appeared to have increased strongly after 2012. The use of ecological resilience had also increased but at a slower rate than engineering resilience. Social-ecological resilience was the least used concept and its application appeared to have increased only moderately.

Geographical Spread of Resilience Concept Applications

Our review contained studies from 11 different biomes (Fig. 2). Engineering resilience was mostly used in studies of temperate broadleaved and mixed forests and in Mediterranean forests, woodlands and scrubs (24% and 19% of the studies using engineering resilience concept, respectively). Ecological resilience was often used in studies that concerned either several biomes (20%) or temperate conifer forests (18%). Social-ecological resilience was used the most in tropical broadleaved forests (23%) as well as in temperate conifer forests (21%).

Resilience of What and to What

Forest ecosystems were the most studied system (34% of all studies). Engineering resilience was most used for studying either tree populations or forest ecosystems (35% of studies using the engineering resilience concept), whereas ecological resilience was the most used in forest ecosystems and non-specified ecosystem studies (49% and 24% of studies using the ecological resilience concept, respectively). Social-ecological resilience was used in forest-related social-ecological systems and studies on the forest industry (73% and 20% of the studies using the social-ecological resilience concept, respectively) (Table 1).

Drought was the most studied disturbance (22% of all the studies), and 32% of the studies applying the concept of engineering resilience focused on drought. Fire was the second most studied disturbance (13% of all the studies), and 17% of the studies of engineering resilience focused on fire. Ecological resilience was used equally for studying the effects of drought, climate change or other disturbances (15% of the studies using the ecological resilience concept, each). Finally, social-ecological resilience was most used in studies concerned with global change and more specifically climate change (28% and 21% of the studies using the social-ecological resilience concept, respectively).

For studies using an engineering resilience concept, the most common method was to either collect tree-level samples (26%) or other vegetation samples (24%). Studies assessing ecological resilience mostly relied on conceptual modelling (28%) or vegetation samples (19%). Studies using a social-ecological resilience concept also made use of conceptual modelling (45%) or socio-economic surveys (25%). The majority of the studies assessing engineering and ecological resilience were quantitative (78% and 65% respectively), whereas the majority of the studies focusing on the social-ecological resilience concept were qualitative (83%).

Indicators Used to Assess Resilience

The most used indicators for each resilience concept are shown in Table 2. Engineering and ecological resilience shared six of their respective top 10 indicators, whereas the top indicators used to assess social-ecological resilience were completely different from the other two concepts. The ecological indicators used in the social-ecological resilience concept were less specific, compared to the ones used in the engineering and ecological resilience concept. The state-type indicators dominated the most used indicators list (52.5%), whereas response- and pressure-type indicators were less common (32.5% and 15.0% respectively).

The most used indicator groups for engineering and ecological resilience were related to forest structure (20% and 24% respectively) and forest biodiversity (19% and 15% respectively). For studies focusing on social-ecological resilience, the most used indicators were related to the socio-economic capacities (41%) and the second most used indicator group was related to finances and technical infrastructure (14%). The NMDS analysis of studies based on the indicator groups used showed a clear separation between engineering/ecological resilience and social-ecological resilience (Fig. 3). Based on the similarity with regard to the indicator groups used, engineering and ecological resilience concepts have a strong overlap. In contrast, studies that used social-ecological resilience employed very different groups of indicators.

The average number of indicators used per study did increase over time (p value 0.01). However, the number of indicators used did not increase for all of the resilience concepts. For ecological resilience and social-ecological resilience, the average amount of indicators per study significantly increased (p values < 0.001 and 0.004, respectively), whereas it did not increase for engineering resilience (p value 0.5) (Fig. 4). Assessments of social-ecological resilience use on average more indicators than assessments of ecological or engineering resilience (7 indicators vs. 4 and 3, respectively).

Discussion

Adoption of the Three Resilience Concepts in the Forest Literature

Our results for the first objective show that forest resilience is globally studied and that each of the alternative resilience concepts is widely applied in the scientific literature. Of the three concepts, engineering resilience is clearly the most frequently used in forest science, with ecological resilience the second most frequently applied and social-ecological resilience being the least used concept.

The frequent and increasing use of engineering resilience in forest resilience literature was surprising, as we hypothesised that the more holistic concept of social-ecological resilience would get more commonly used in response to the serious problems caused by global change [287]. Other studies proposed several reasons for the widespread use of engineering resilience. First, the concept is very versatile and can be adapted to different systems, as recovery can be measured based on a variety of indicators [288]. Engineering resilience was the only concept where the average number of indicators used per study has not increased significantly during the last 18 years. One explanation might be that the key indicators for engineering resilience have been identified in previous research already and that there is no need to broaden the indicator set. For example, 31 out of the 136 reviewed studies using the engineering resilience concept adopted the approach presented by Lloret et al. [8] to examine the resilience of trees to drought by measuring the basal area increment before, during and after the drought. Second, the concept is clearly defined and intuitive to understand. This is in contrast to ecological and social-ecological resilience which are both debated concepts in terms of their exact definitions [17].

However, our search terms could also have caused a bias towards engineering resilience. It is conceivable that studies applying the social-ecological resilience concept would focus less on measuring or quantifying resilience, thus lacking an active verb connected with resilience. As such studies come from more diverse scientific backgrounds, perhaps they place less emphasis on how resilience is quantified or assessed. The strong presence of the reviewed articles belonging to the ecological literature, in which resilience is studied as a system property and the focus is on the capacity of systems to resist change and recover from a disturbance [18••], supports this interpretation. Furthermore, resilience receives considerable criticism from the social sciences [289–291] and it is therefore conceivable that some social science studies on resilience related research questions may not actually use the term, as they reject its conceptual approach [292]. Therefore, the scarcity of studies adopting the concept of social-ecological resilience in our review might be due to the recommendation to use social- ecological resilience as an analytical approach for social-ecological systems, rather than a descriptive concept of a system property [17]. Such an analytical approach does not necessarily aim to quantify resilience but rather to deal with uncertainty. Nevertheless, our results show that social-ecological resilience can be assessed in both qualitative [160, 166] and quantitative [173] ways.

The use of engineering resilience also has clear limitations. As the concept assumes the existence of only one stable state [20] and measures performance against the pre-disturbance state, it is thus mainly applied in studies over a short timeframe and for situations where the environmental conditions are variable but where a regime shift is unlikely. Yet, such a situation can rarely be assumed under global change [293]. In such a setting of continuous change, maintaining high engineering resilience might require a high level of anthropogenic inputs, e.g. fertilisers or intensive re-planting of selected tree species, which in turn would lead to so-called coerced resilience that mimics the response of a resilient ecosystem but is only possible with continuous human intervention and risks being highly maladaptive [294]. Furthermore, assessing resilience in a deterministic (as opposed to considering stochasticity) and short-term manner could lead to missing important system pathways and long-term trajectories. These shortcomings of the concept for the analysis of forest systems increase with the impact of global change, and the concept should hence be used only with a clear acknowledgement of its limitations.

The Differences and Complementarity Among the Resilience Concepts

As to the second objective, there is an apparent difference in the use of engineering and ecological resilience on the one hand and social-ecological resilience on the other hand with regard to the systems and disturbances studied and the indicators used (Fig. 3). Previous literature reviewing the concept of resilience has identified several disparities in the conceptualisation of the resilience definitions and the underlying assumptions, which are in line with our findings. Resilience has been perceived differently depending on the disciplinary background [18••]. Ecological literature, where engineering and ecological resilience are commonly used, regards resilience as a system property whereas the study of social-ecological systems looks at resilience as a strategy for managing complexity and uncertainty [18••]. Furthermore, the ecological literature focuses on the capacity of a system to resist change and recover from it, whereas the social-ecological systems literature has a strong focus on transformation and self-evolvement of the system as a crucial part of management [18••, 295].

On a conceptual level, the difference between the concepts lies in how they view the existence and shape of basins of attractions. For engineering resilience, resilience is measured by the steepness of the slope of the basin, indicating how quickly the system can return to the bottom after a disturbance [296]. For ecological resilience, the existence of multiple basins of attraction is assumed, and resilience is a measure for how much pressure is required for the system to move from one basin to another [296]. Social-ecological resilience assumes the existence of multiple basins of attractions as well [295], but the focus of this concept is on shaping the basin of attraction to keep the system contained in its current attractor via changing the social part of the system. This disciplinary disparity can explain why engineering and ecological resilience concepts use a very similar set of indicators, whereas social-ecological resilience uses distinctively different types of indicators (see Table 2 and Fig. 3).

Our results reflect this conceptual background. For example, drought resilience of trees was the most commonly studied topic and engineering resilience was the most adopted concept for that topic. While much of this popularity can be attributed to a key paper published by Lloret et al. [8], tree growth is also a system that is unlikely to have multiple stable states, making the use of ecological or social-ecological resilience concepts unnecessary. Similarly, the prominent use of engineering resilience to assess forest ecosystems in our results could be explained by the authors' perception of the existence of multiple basins of attractions for the studied system. While many scientists support the notion of forest ecosystems having multiple basins of attraction [297–299], some scientists see the evidence as limited [31] and therefore prefer to use the engineering resilience instead of the two other concepts. The aim and scope of the research clearly determined the researchers' choice of the resilience concept in the reviewed studies. For this reason, some authors adopt a different concept of resilience in different studies [9, 143, 197•], underlining the importance of precisely defining the term in each instance of its use [300], as well as reflections on the applicability of the chosen definition. Attention should furthermore be paid to whether or not resilience is used as a descriptive or normative concept as striving for enhanced resilience might lead to debates on the trade-offs of achieving a resilient system [18••].

The definitions of the three concepts further illustrate a difference in complexity: engineering resilience is purely defined as recovery of the system, ecological resilience includes aspects of both resistance and recovery of the system, whereas social-ecological resilience includes resistance, recovery, adaptive capacity and the ability to transform [295]. It should be noted that studies using engineering resilience do not necessarily ignore the resistance or adaptive capacity of the system, but they consider them as independent concepts besides resilience, rather than as integral parts of resilience [39, 94, 207]. Some scientists argue for separating resistance, resilience and adaptive capacity into their own concepts for conceptual clarity and better operationalisation of resilience [94, 288]. However, others argue that reducing resilience to such a simple dimension is focusing on maintaining the status quo of the system and this could actually lead to losing the resilience of social-ecological system [295].

We argue that instead of striving towards one single resilience definition, resilience could be understood as an overarching concept of nested hierarchies as described also by the theory of basins of attraction [26]. According to this hierarchy, engineering resilience is nested inside ecological resilience, which in turn is nested inside social-ecological resilience (Fig. 5). Moving from one concept to another either adds or removes different dimensions from the system under study and changes the system boundaries. The interest in a certain property together with the disturbance of concern therefore indicates the resilience concept that is most applicable for the respective question or system to be analysed. The increasing complexity with increasing hierarchical levels of resilience also suggests that a broader suite of indicators is required to assess higher levels of resilience, which was supported by the results of our review.

Guidance on Navigating the World of Resilience

Regarding our third objective on how to implement resilience in forestry practice, our review underlines that forest resilience is a flexible concept and can be adapted to many situations and questions. That is one reason for the popularity of the concept [17], as well as the widespread use in various biomes and research designs. For example, the engineering resilience concept was mainly used for studying pulse-type disturbances, such as drought and fire in the temperate and Mediterranean forest, ecological and social-ecological resilience were also used for press-type of disturbances, such as climate and global change, with more geographical spread.

Regardless of the resilience concept the authors use, variable study scopes, combined with either simplification tendency (engineering resilience) or complexity (social-ecological analysis) of the concepts may hinder the wider implementation of resilience thinking in forest management practice. The results of the review support our first hypothesis on how forest resilience lacks the consistent operational use that would be needed for implementation in practice. The lack of clarity in applying the concepts is a clear shortcoming. Some of the studies reviewed provide guidance and pathways for managing forests for resilience [31, 88•, 94, 197•], proving that the concept can be operationalised with sufficient effort invested. Nevertheless, the resilience concepts lack established indicator frameworks that could be adopted by forest managers. The classification of the indicators according the OECD's PSR framework showed that a majority of the indicators currently used in the forest resilience literature are state-type indicators. For a holistic indicator-based assessment, more focus should be placed on developing further indicators to assess both pressures and system responses to disturbances [301]. Guidance is needed to help forest managers to both choose which resilience concept could be the most suitable for their situation and identify proper indicators for assessing the selected concept. In the next sections, we will address how managing for resilience is different from the risk management in forestry and how to choose a suitable resilience concept.

Some might consider resilience thinking to be redundant with current forest management practices. Dealing with uncertainty via risk assessments is a well-established practice in forestry [302]. Risk is by definition the effect of uncertainty on objectives [303], frequently expressed quantitatively in probabilistic terms [304] and risk-based management strategies are most effective when hazard probabilities are known [305]. However, the impacts of changes in disturbance regimes as well as of shocks caused by political and societal changes are currently unknown [306], which can cause risk management approaches to fail [305]. In contrast, resilience prepares for minimizing the damage caused by unknown, novel risks [305], making it a suitable management approach also for situations where the character and the magnitude of the risks are hard to identify.

Based on our review of the literature on forest resilience, we provide some suggestions to guide practitioners and scientists in choosing the most suitable concept for them and which possible ways exist to assess these concepts.

Identify the Managed System—To choose the appropriate resilience concept, it is important to define the managed system [300]. Is the main interest to assess the resilience of one important tree species, ecosystem services provided or a regional supply chain of forest enterprise? Does this system have alternative basins of attractions? Are the environmental and social changes likely to push the system to another stable state? Engineering resilience is a powerful concept for relatively simple systems (e.g. tree species growth, plant or animal population) that are not likely to change in the near future. Therefore, it could be appropriately used in assessing short-term resilience [288]. If alternative states for the system are known, e.g. forests transforming into savannah [299], or the system is rather complex (e.g. forest ecosystem), ecological resilience should be used instead of engineering resilience. If the system also includes social parts, as for example in a community forest and forest enterprise, social-ecological resilience should be used to capture the interactions between social and ecological systems.

Identify the Stressors or Disturbances Affecting the System—In addition to defining the system, the disturbances affecting the system should be identified [300]. Is the scope to assess the resilience to one single disturbance event, e.g. storm, an interaction of several disturbances, e.g. drought, storm and bark beetles, or an ongoing change, e.g. climate or societal change? As engineering resilience measures the recovery to a pre-disturbance state, it should be used only in cases where the pre-disturbance state is still achievable, meaning the system is not strongly affected by press type disturbance as, for example, climate change. Ecological resilience is suitable for both pulse and press type disturbances as well as changes in disturbance frequency, if the system of interest is an ecological system. Finally, managers and researchers facing changes in forest policies, market demands or social use of the forest should use the concept of social-ecological resilience. While this concept is perhaps the most difficult to adopt, it emphasises the need to reflect on the resilience of the social system as an interdependent counterpart of the natural system [295].

Identify the Temporal Scale of Interest—Engineering resilience can be appropriately used for assessing resilience on a short temporal scale [288]. However, many scientists caution against using engineering resilience over longer time scales as social and environmental conditions change and focusing on short term recovery might lead to ignoring the slow variables ensuring resilience [288, 307, 308]. For longer management time scales, we recommend using either ecological or social-ecological resilience.

Consider the Trade-Off Between Accuracy and Cost-Efficiency in Indicator Selection—Our study revealed increasing requirements for indicator measurement, evaluation and/or assessment in going from engineering to ecological and social-ecological resilience approaches. While the selection of indicators depends on the studied system, the presented indicators (Table 2) show a selection of the most used ones that have been applied in different systems and variable disturbance assessments. However, the use of indicators should always be carefully considered as one indicator might declare a system resilient and another one vulnerable. Therefore, using a holistic set of indicators that describe both structures as well as functions of the system is recommended [288]. This might require considerably more work from the researchers and managers, but it reduces the risk of falsely assessing resilience.

Several other ways of defining and assessing resilience exist outside the social-ecological systems literature [18••, 309, 310]. However, the concepts of engineering, ecological and social-ecological resilience are very prominent in the forest science literature and we believe that our review contributes to clarifying the use of these concepts. More focus should be paid on how resilience concepts are implemented in practice. One further research direction should therefore look at how resilience is operationalised in forest management practice, e.g. by reviewing forest management plans and conducting social- empirical research with forest managers about how they deal with resilience related forest management decisions in practice. This work could result in recommendations on how scientific findings and concepts related to forest resilience can support forest management practice, such as a sophisticated decision support framework for the selection of the applicable resilience concept and indicators. More work will also be needed on how to interpret specific indicators and how to balance impacts on diverse management objectives across the proposed indicators.

Conclusions

In our rapidly changing world, resilience has gained wide popularity in forest management, but operationalizing the concept still lags behind. We show how three major resilience concepts for studying social-ecological systems are used in the forest science literature and how their assessment methods and interpretations differ. The variety of used resilience indicators is broad, with several popular ones emerging, such as basal area increment and the extent of vegetation cover.

Our first hypothesis was that in a context of global change, the use of broader resilience concepts, such as social-ecological resilience, would be increasing over time in comparison to more specific concepts, such as ecological and engineering resilience. This was not supported by the data, as the use of engineering resilience has clearly increased in comparison to ecological and social-ecological resilience. The context of the investigated studies appeared to be the main driver behind their choice for a resilience concept. However, we showed here that these resilience concepts are not exclusive but rather form a hierarchy with engineering resilience being an aspect of ecological resilience and ecological resilience being part of the overarching social-ecological resilience. In this context, we provide guidance to forest managers and policy makers on how to consider context-specific information on management type, disturbance regime, temporal scale of interest and indicator needs that will help in making forest resilience operational.

Our second hypothesis was that forest resilience is a widely adopted concept in forest sciences, but it shows a large variety of assessment approaches, which may prevent its mainstreaming into forestry practice. The ordination of the studies based on the indicators they used confirms the large variety of approaches forest scientists use to assess resilience. However, we also showed that these approaches can be clearly attributed to one of three nested resilience concepts, which may be a useful basis for further improved operationalisation. Consequently, we reject this hypothesis and give guidance for a context specific selection of a suitable resilience concept and a related set of indicators, as a first step to future operationalisation.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

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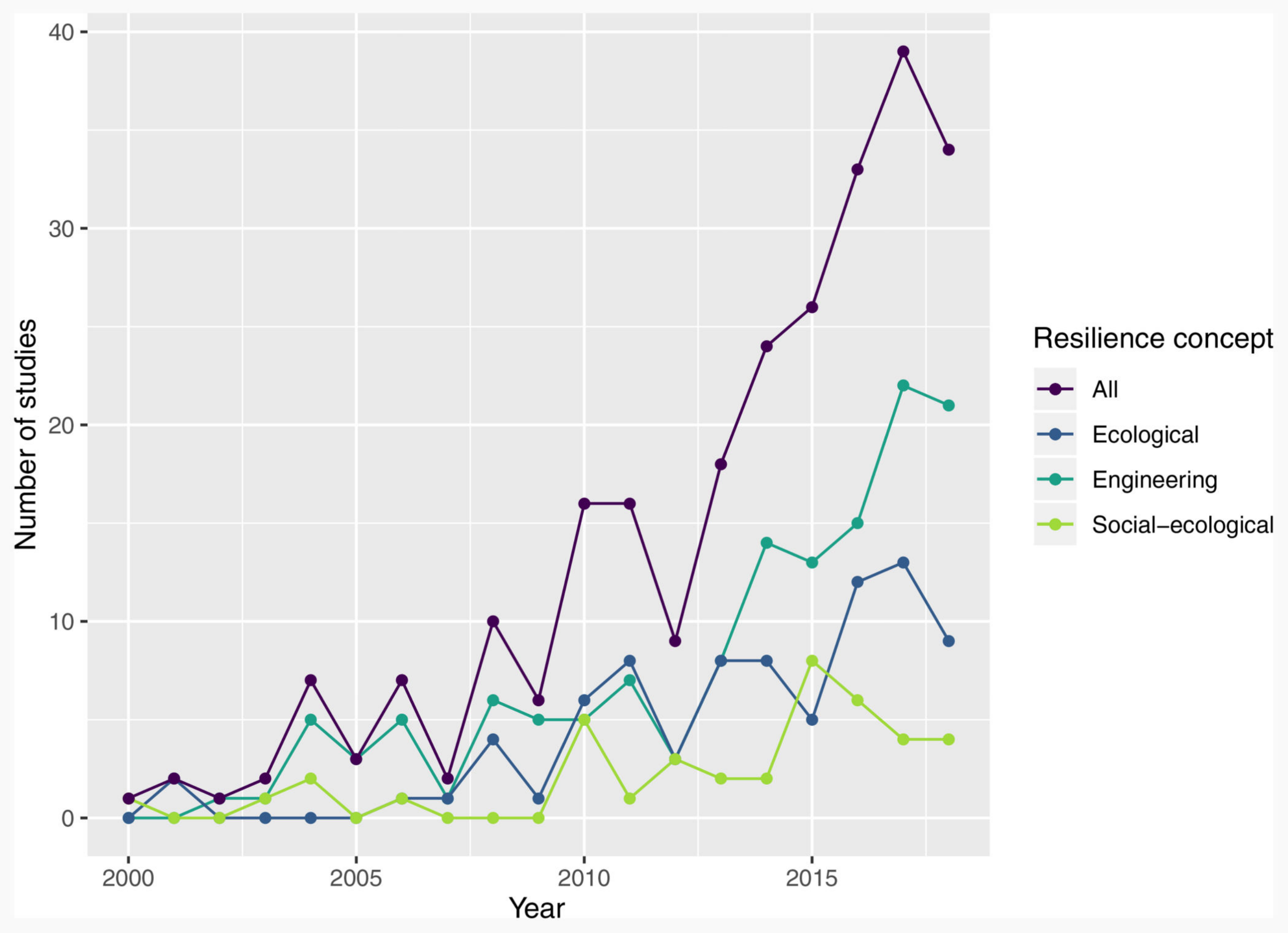

Fig. 1.

The development of the use of the three resilience concepts in forest resilience studies from 2000 to 2018. The figure shows the number of studies using engineering, ecological or social-ecological resilience concepts and the total number of forest resilience studies published per year. The cut-off date for the review was in mid-August 2018, and therefore, not all studies published in 2018 were included in the review

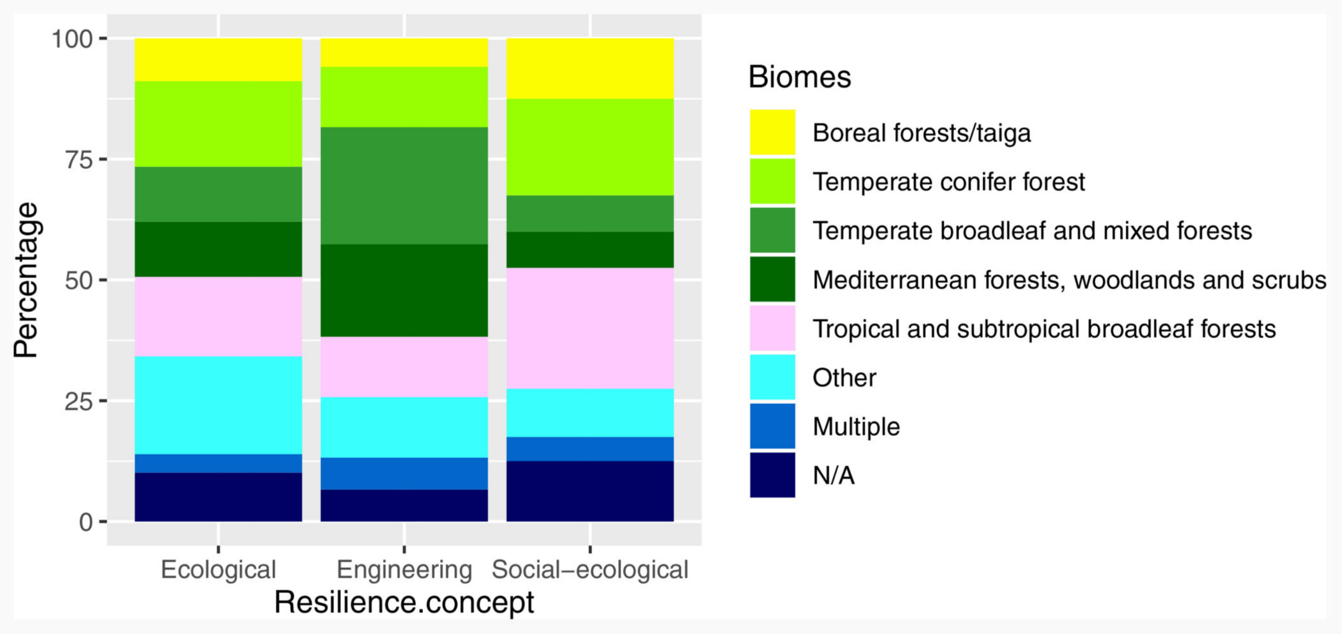

Fig. 2.

The use of the resilience concepts by forest biome. The figure shows the share of the biomes studied for each of the three resilience concepts. N/A means that no biome was mentioned in a study

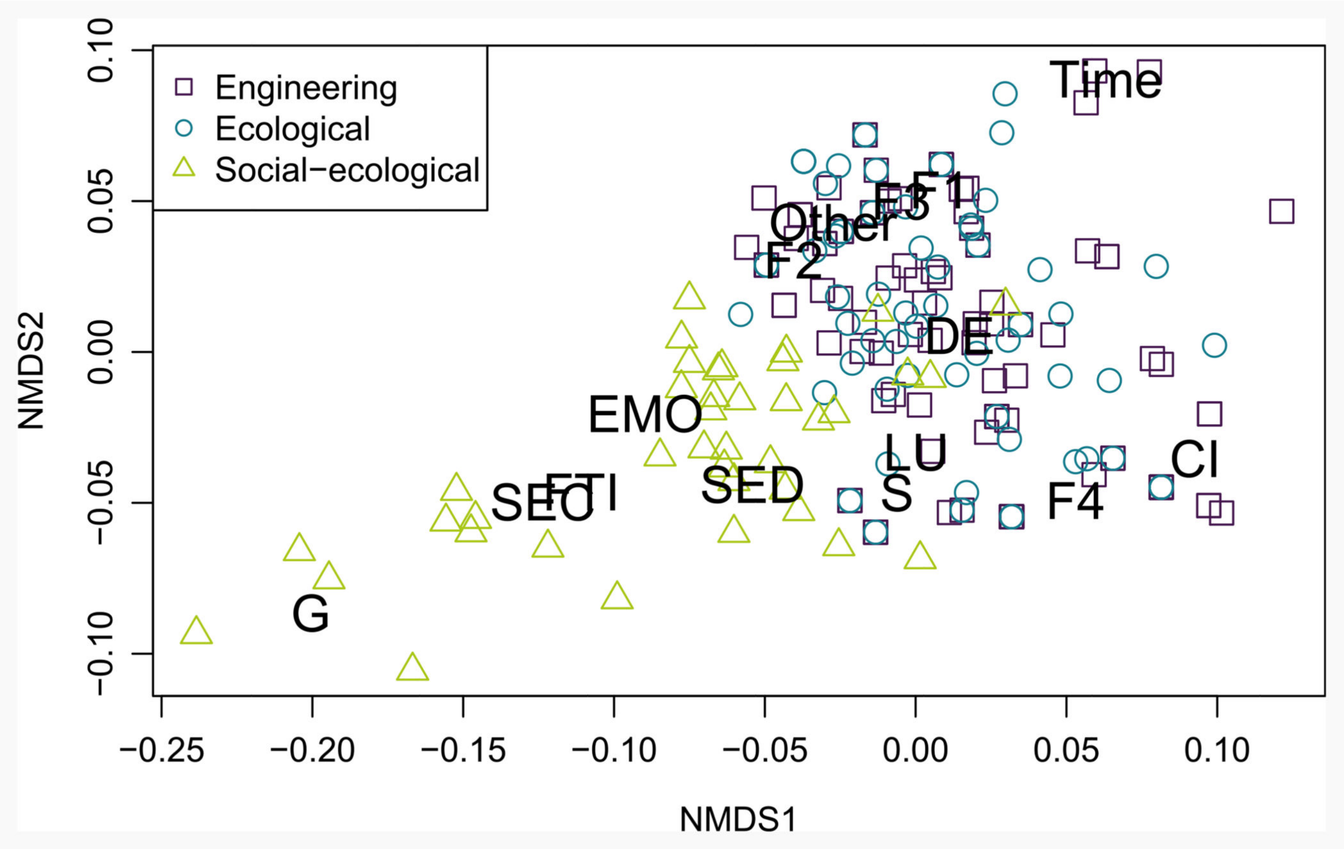

Fig. 3.

The indicator groups used to assess resilience, ordinated in two dimensions based on the NMDS analysis. The NMDS gives a representation of the relationship between objects (studies) and descriptors (indicator groups) in a reduced number of dimensions. The *x*- and y-axes are the first two axes with the highest explicative values in ordination space. The locations of different indicator groups are shown in letters. The indicator groups are forest structure (F1), biodiversity (F2), climate indicators (CI), forest regeneration (F3), tree and ecosystem production and transpiration (F4), disturbance effects (DE), soil properties (S), land use (LU), ecosystem management objective (EMO), socio-economic capacities (SEC), socio-economic diversity (SED), finances and technological infrastructure (FTI), governance (G), time, and other

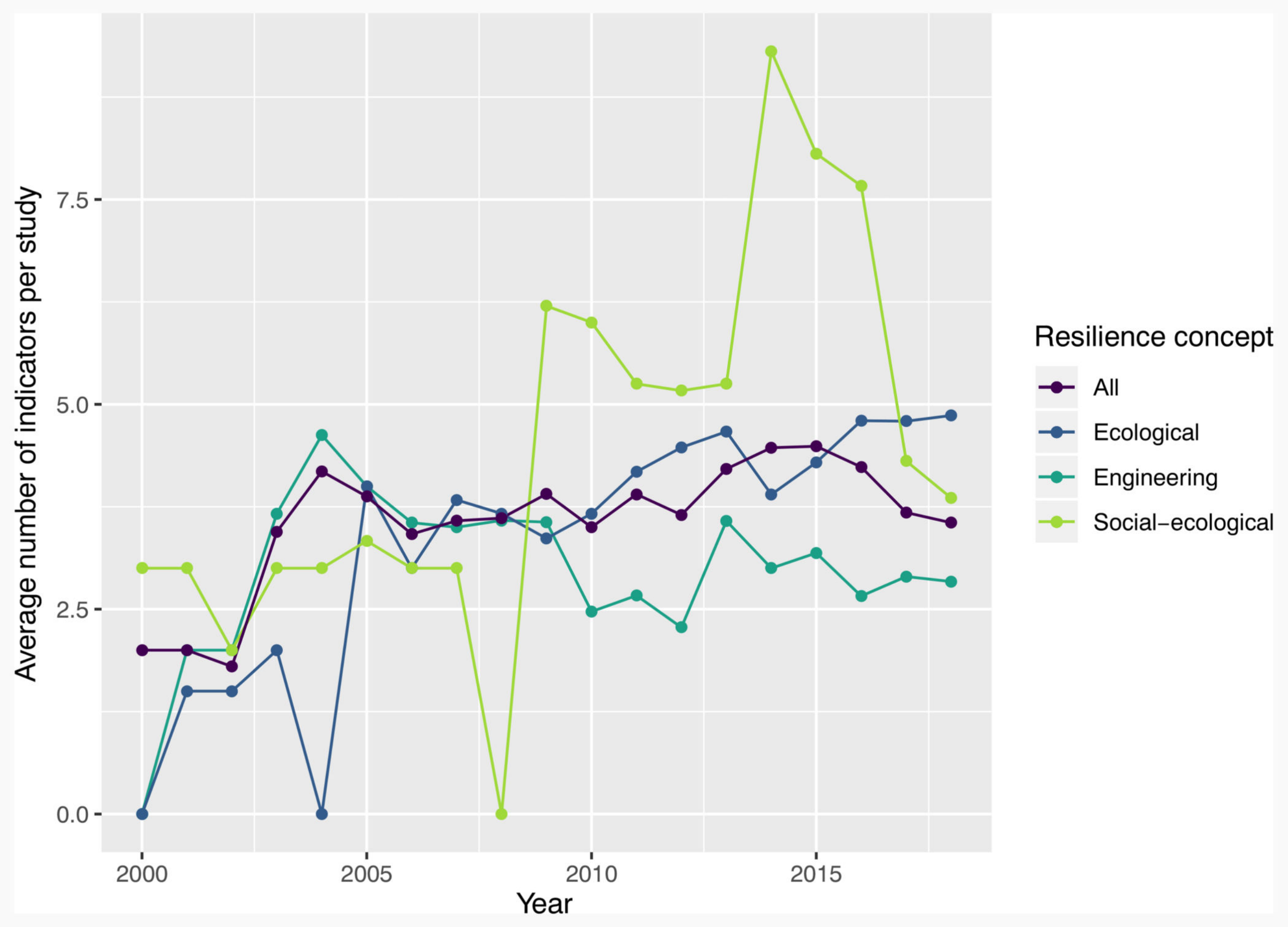

Fig. 4.

The moving average of number of indicators per study. The averages are calculated for 3-year periods except for 2000 and 2018, which were calculated for 2-year periods

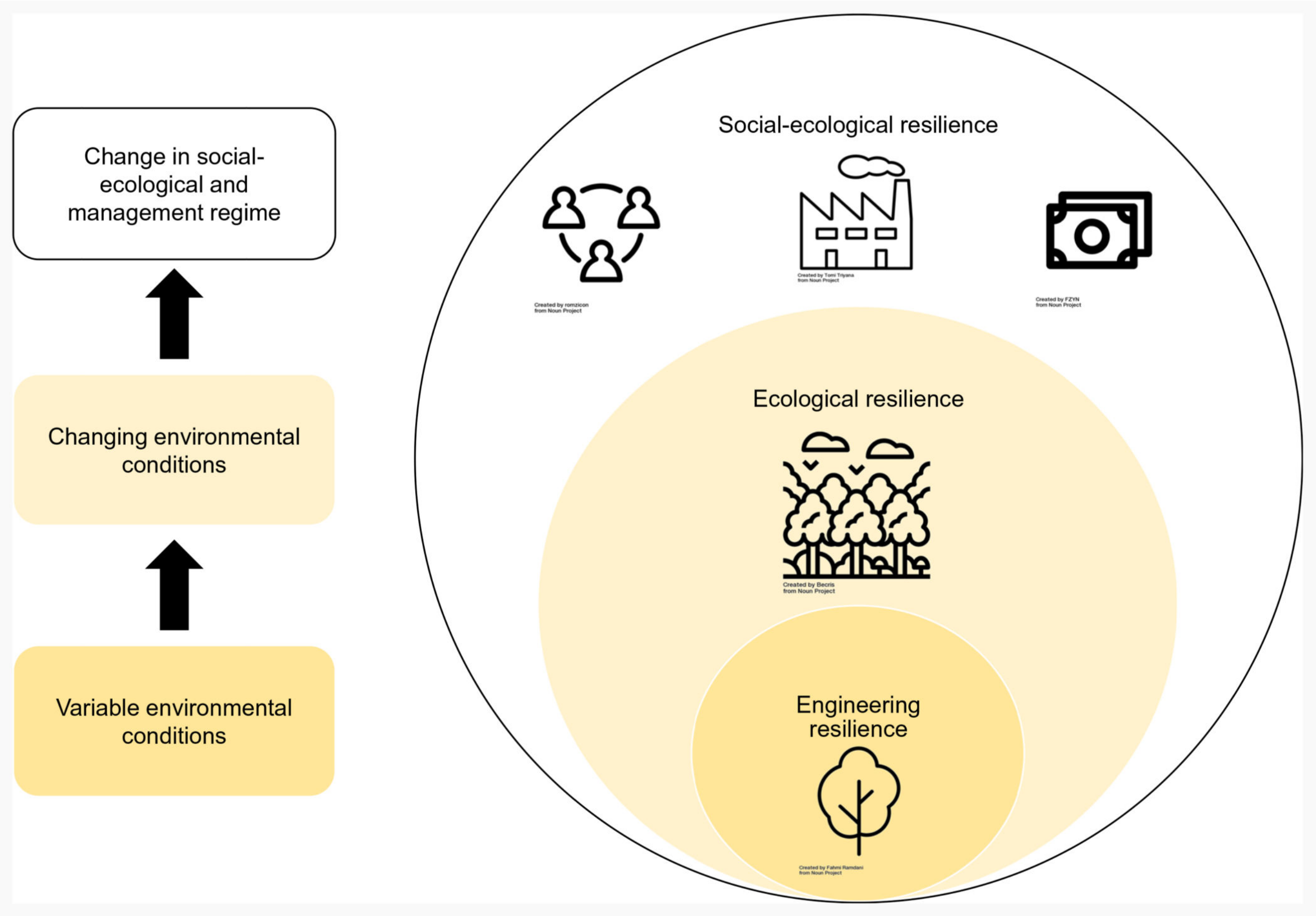

Fig. 5.

The hierarchy of resilience concepts and assumptions behind each concept. The circles on the right show how resilience concepts are related to one another. The boxes on the left indicate increasing complexity in the systems that are studied by the respective resilience concepts. Variable environmental conditions mean conditions where the conditions vary but remain in the historical range of variation. Changing environmental conditions mean that the conditions are no longer within the range of historical variation of the environment

Table 1

The percentages of the studied systems ("resilience of what") in relation to the three resilience concepts and all of the reviewed studies

System of interest	Engineering resilience (%)	Ecological resilience (%)	Social-ecological resilience (%)	All studies (%)
Trees (individual or populations)	35	15	0	23
Forest animal population	6	5	0	5
Forest ecosystem	35	49	0	34
Non-tree vegetation	12	4	0	7
General ecosystem	5	24	0	10
Soils	5	1	0	3
Forest industry	0	0	20	3
Forest related social-ecological system	0	1	73	12
Other	3	0	8	3

Table 2

The most frequently used indicators for each resilience concept. Numbers in parentheses indicate the percentage of studies applying a given resilience concept using the indicator. The emphases of the entries express the type of indicator according to the classification of OECD's environmental indicators [34]. Italicized entries are pressure-type indicators, bold entries are state-type indicators and bold-italics entries are response-type indicators

Indicator rank of occurrence	**Engineering resilience**	**Ecological resilience**	**Social-ecological resilience**	**All reviewed studies**
1	**Basal area increment (27.5%)**	**Vegetation cover (13.9%)**	***Socio-economic diversity (30.0%)***	**Basal area increment (17.6%)**
2	**Vegetation cover (15.4%)**	**Density or number of trees (13.9%)**	**Biodiversity (22.5%)**	**Vegetation cover (12.5%)**
3	**Species richness (10.3%)**	**Basal area increment (11.4%)**	**Stock of natural resources (20.0%)**	**Species composition (9.0%)**
4	**Species composition (10.3%)**	**Biomass (11.4%)**	***Networks (20.0%)***	**Species richness (8.2%)**
5	*Precipitation (10.3%)*	**Species composition (11.4%)**	***Knowledge (17.5%)***	**Biomass (7.5%)**
6	*Standardised Precipitation Evapotranspiration Index (9.6%)*	**Species diversity (10.1%)**	***Income (17.5%)***	**Regeneration (7.1%)**
7	**Density or number of surviving trees (9.6%)**	**Basal area (10.1%)**	*Access to resources (15.0%)*	*Precipitation (7.1%)*
8	**Regeneration (8.1%)**	**Regeneration (8.1%)**	***Participation in community organisations (15.0%)***	*Standardised Precipitation Evapotranspiration Index (6.3%)*
9	**Biomass (7.4%)**	**Species richness (8.9%)**	***Education (12.5%)***	**Density/number of surviving trees (5.1%)**
10	**Density or number of seedlings (7.4%)**	**Mortality (8.9%)** *Disturbance severity (8.9%)*	*Agricultural practices (10.0%)* *Human Population density (10.0%)* **Ecosystem services (10.0%)** ***Employment (10.0%)*** ***Housing (10.0%)*** ***Health services (10.0%)*** ***Individual health (10.0%)*** ***Water and sanitation (10.0%)*** ***Transport (10.0%)*** ***Skills (10.0%)***	***Socio-economic diversity (4.7%)***