Reviewing the use of resilience concepts in forest sciences

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ABSTRACT

Purpose of the 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, synthesising 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 frequently focus on vegetation cover and tree density. In contrast, important social-ecological resilience indicators used in the literature are socio-economic 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

ACKNOWLEDGEMENTS: We thank the German Federal Ministry of Food and Agriculture for providing the funding for this research (project SURE - SUstaining and Enhancing REsilience of European Forests).

1. 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 are 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 operationalising 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.

2. 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, and 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: 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: Drought, Fire, Wind, Climate change, Other abiotic disturbance, 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: Tree-level 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 Organization 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: 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 three-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].

3. Results

The initial search resulted in 2,629 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 [8,9,13,16,31,38–287]. 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.

3.1. 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.

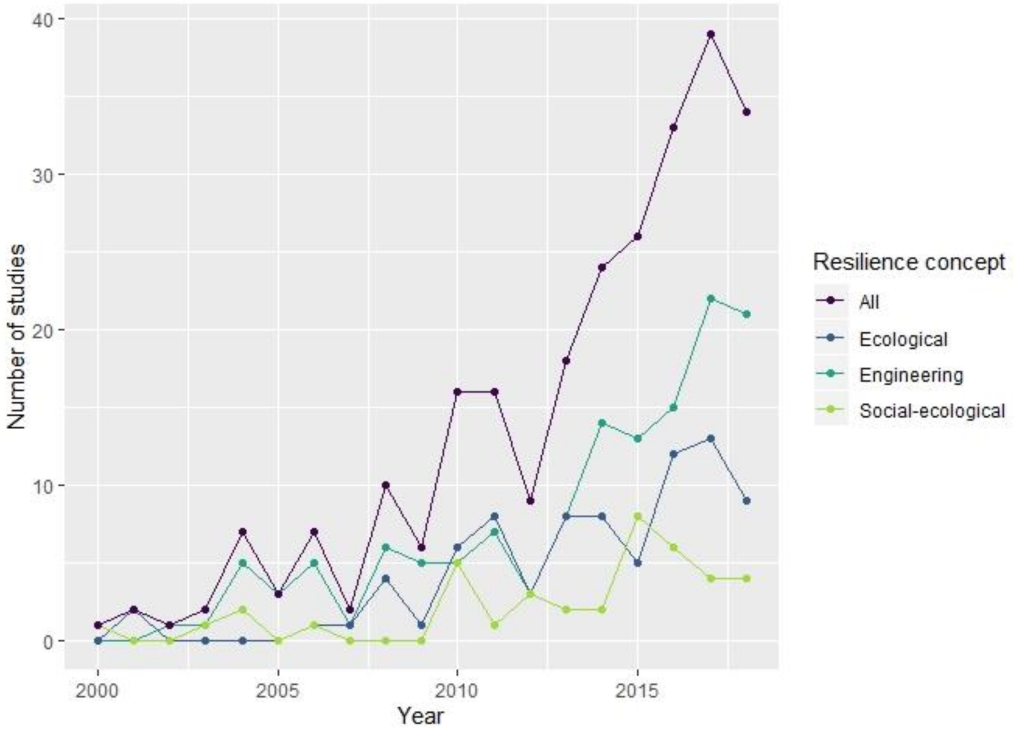

Fig. 1 The development of the use of the three resilience concepts in forest resilience studies from 2000 to 2018. The figure shows the number of studies using engineering, ecological or social-ecological resilience concepts and the total number of forest resilience studies published per year. The cut-off date for the review was in mid-August 2018, and therefore not all studies published in 2018 were included in the review.

3.2. 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 %).

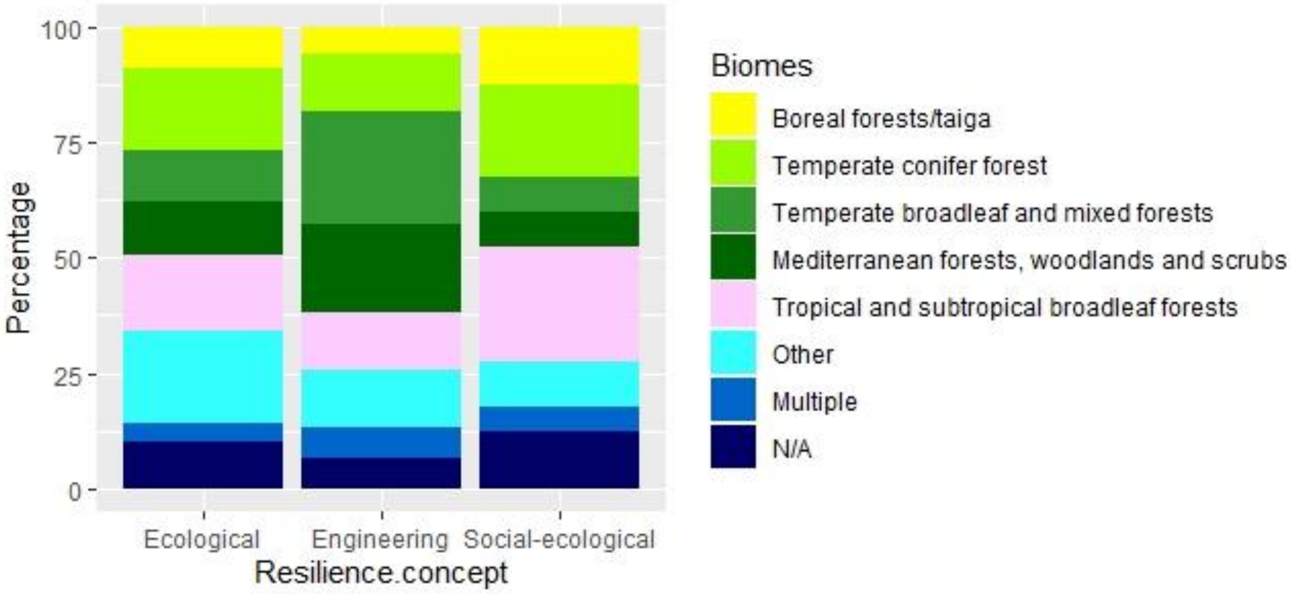

Fig. 2 The use of the resilience concepts by forest biome. The figure shows the share of the biomes studied for each of the three resilience concepts. N/A means that no biome was mentioned in a study.

3.3. 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).

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

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 %).

3.4. 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-ten 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).

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 colour of the cell expresses the type of indicator according to the classification of OECD’s environmental indicators [34]. Blue cells are Pressure-type indicators, green cells are State-type indicators and yellow cells 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 %)

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.

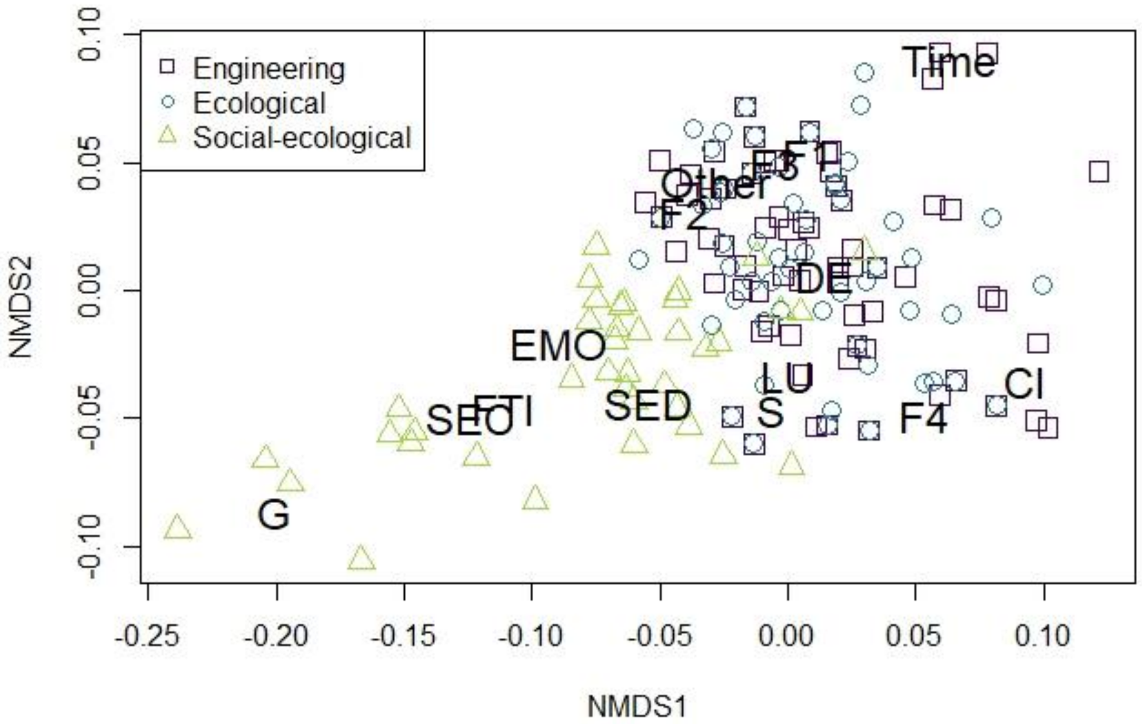

Fig. 3 The indicator groups used to assess resilience, ordinated in two dimensions based on the NMDS analysis. The NMDS gives a representation of the relationship between objects (studies) and descriptors (indicator groups) in a reduced number of dimensions. The x- and y-axes are the first two axes with the highest explicative values in ordination space. The location 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.

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).

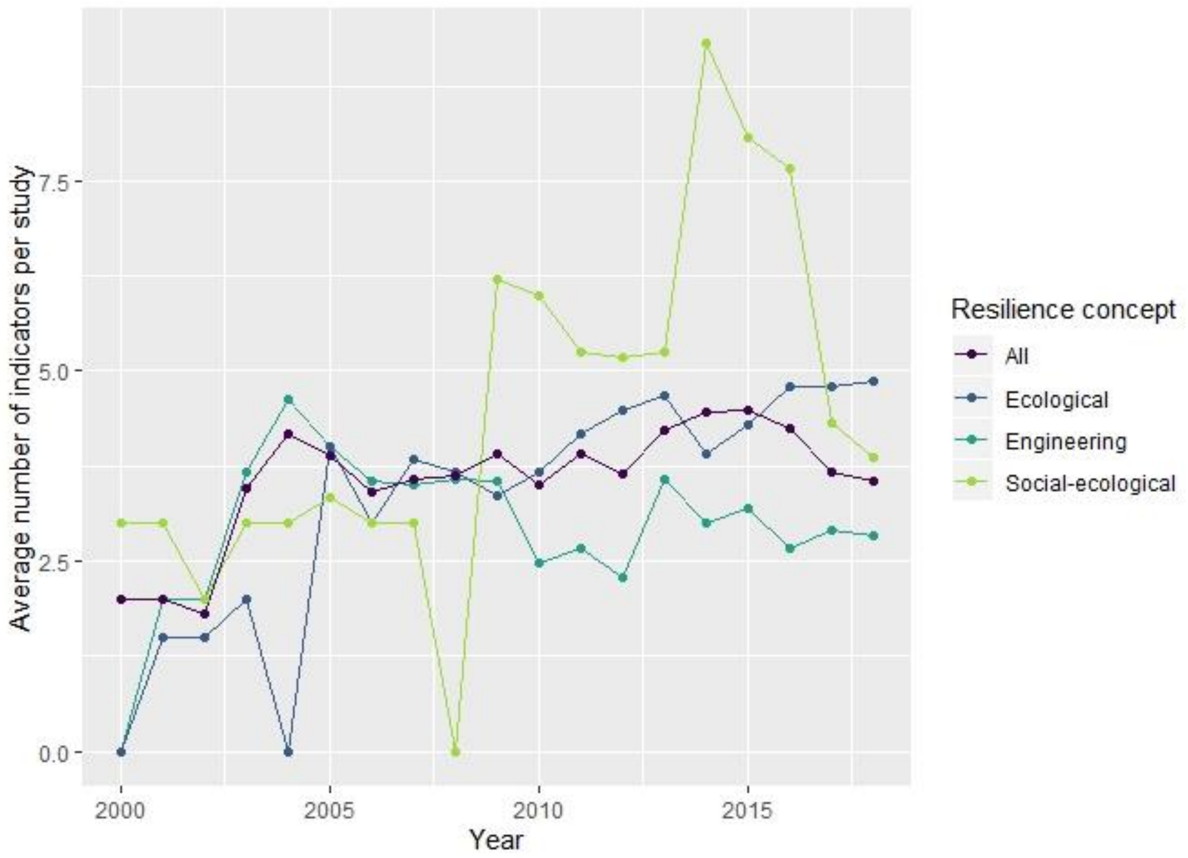

Fig. 4 The moving average of number of indicators per study. The averages are calculated for three-year periods except for 2000 and 2018, which were calculated for two-year periods.

4. Discussion

4.1. 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 [288]. 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 [289]. 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 [290].

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 [291–293] 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 [294]. 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 [290]. 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 [161,167] and quantitative [174] 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 [295]. 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 [296]. 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.

4.2. 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 [18,297].

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 [298]. 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 [298]. Social-ecological resilience assumes the existence of multiple basins of attractions as well [297], 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 Figure 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 [299–301], 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 [9,144,198], underlining the importance of precisely defining the term in each instance of its use [302], 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 [297]. 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 [39,94,208]. Some scientists argue for separating resistance, resilience and adaptive capacity into their own concepts for conceptual clarity and better operationalisation of resilience [94,289]. 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 [297].

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. 6). 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 indicate 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.

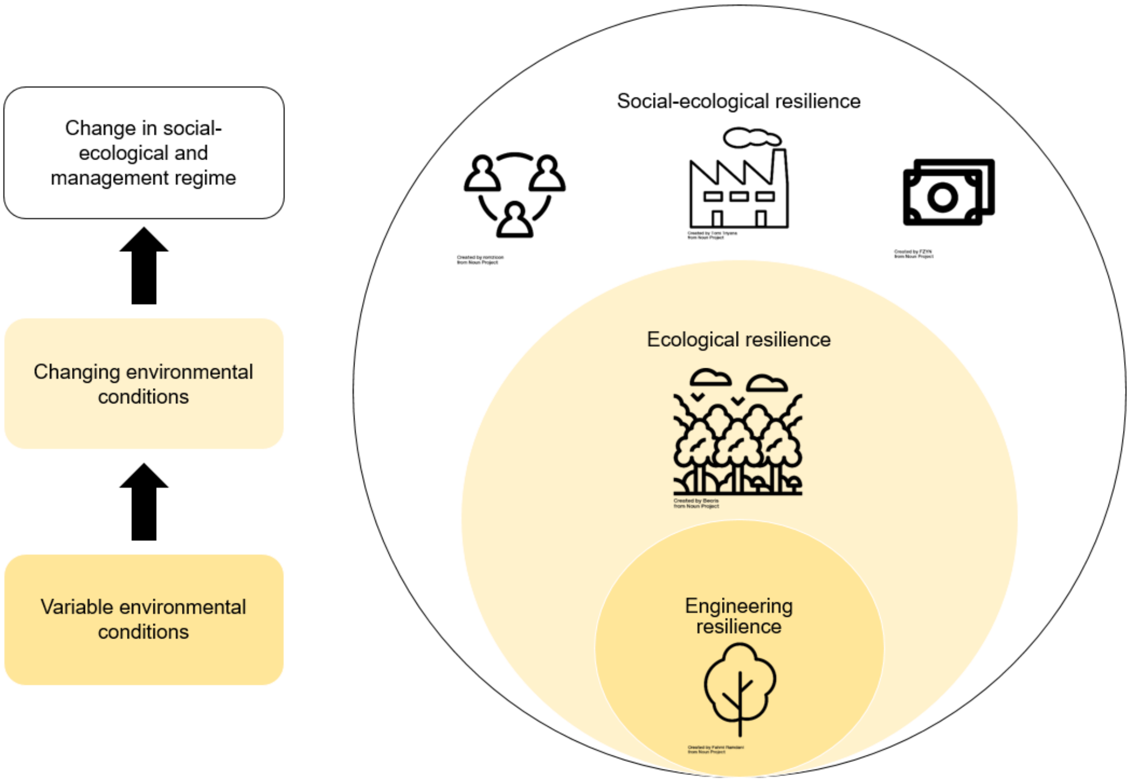

Fig. 6 The hierarchy of resilience concepts and assumptions behind each concept. The circles on the right show how resilience concepts are related to one another. The boxes on the left indicate increasing complexity in the systems that are studied by the respective resilience concepts. Variable environmental 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.

4.3. 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 [31,88,94,198], 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 [303]. Guidance is needed to help forest managers to both choose which resilience concept could be the most suitable for their situation as well as 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 [304]. Risk is by definition the effect of uncertainty on objectives [305], frequently expressed quantitatively in probabilistic terms [306], and risk-based management strategies are most effective when hazard probabilities are known [307]. However, the impacts of changes in disturbance regimes as well as of shocks caused by political and societal changes are currently unknown [308], which can cause risk management approaches to fail [307]. In contrast, resilience prepares for minimizing the damage caused by unknown, novel risks [307], 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.

1. *Identify the managed system*
   To choose the appropriate resilience concept, it is important to define the managed system [302]. 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 [289]. If alternative states for the system are known, e.g. forests transforming into savannah [301], 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.

2. *Identify the stressors or disturbances affecting the system.* In addition to defining the system, the disturbances affecting the system should be identified [302]. 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 [297].

3. *Identify the temporal scale of interest.* Engineering resilience can be appropriately used for assessing resilience on a short temporal scale [289]. 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 [289,309,310]. For longer management time scales, we recommend using either ecological or social-ecological resilience.

4. *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 [289]. 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 [18,311,312]. 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.

5. Conclusions

In our rapidly changing world, resilience has gained wide popularity in forest management, but operationalising 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 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, that 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.

Compliance with Ethical Standards

Conflict of interests

Laura Nikinmaa and Marcus Lindner have received part of their salaries from the project “Sustaining and Enhancing the Resilience of the European Forests” that is funded by the German Federal Ministry of Food and Agriculture.

Alistair Jump, Bart Muys, Elena Cantarello, Georg Winkel and Rupert Seidl declare that they have no conflict of interest.

Human and Animal Rights and Informed Consent

This article does not contain any studies with human or animal subjects performed by any of the authors.

Funding

Laura Nikinmaa and Marcus Lindner have received part of their salaries from a project that was funded by the German Federal Ministry of Food and Agriculture.

Rupert Seidl acknowledges support from the Austrian Science Fund (FWF) through START grant Y895-B25.

Alistair Jump, Bart Muys, Elena Cantarello and Georg Winkel received no funding for their work on this article.

6. References

Papers of particular interest, published recently, have been highlighted with:

● Of importance
●● Of major importance

1. Seidl R, Thom D, Kautz M, Martin-benito D, et.al. Forest disturbances under climate change. Nat Clim Chang. 2017;7:395–402.

2. Turner MG. Disturbance and landscape dynamics in a changing world. Ecology. 2010;91:2833–49.

3. Thom D, Seidl R. Natural disturbance impacts on ecosystem services and biodiversity in temperate and boreal forests. Biol Rev Camb Philos Soc. 2016;91:760–81.

4. Lindner M, Maroschek M, Netherer S, Kremer A, Barbati A, Garcia-Gonzalo J, et al. Climate change impacts, adaptive capacity, and vulnerability of European forest ecosystems. For Ecol Manage. 2010;259:698–709.

5. Thuiller W. Patterns and uncertainties of species’ range shifts under climate change. Glob Chang Biol. 2004;10:2020–7.

6. Thomas CD, Cameron A, Green R, Bakkenes EM, Beaumont LJ, Collingham YC, et al. Extinction risk from climate change. Nature. 2004;427:145–8.

7. Johnstone JF, Allen CD, Franklin JF, Frelich LE, Harvey BJ, Higuera PE, et al. Changing disturbance regimes, ecological memory, and forest resilience. Front Ecol Environ. 2016;14:369–78.

8. Lloret F, Keeling EG, Sala A. Components of tree resilience: Effects of successive low-growth episodes in old ponderosa pine forests. Oikos. 2011;120:1909–20.

9. Seidl R, Vigl F, Rössler G, Neumann M, Rammer W. Assessing the resilience of Norway spruce forests through a model-based reanalysis of thinning trials. For Ecol Manage. 2017;388:3–12.

10. Grassi G, House J, Dentener F, Federici S, Den Elzen M, Penman J. The key role of forests in meeting climate targets requires science for credible mitigation. Nat Clim Chang. 2017;7:220–6.

11. Philp J. Balancing the bioeconomy: supporting biofuels and bio-based materials in public policy. Energy Environ Sci [Internet]. Royal Society of Chemistry; 2015;8:3063–8. Available from: http://xlink.rsc.org/?DOI=C5EE01864A

12. Puettmann KJ, Coates KD, Messier C. A Critique of Silviculture - Managing for Complexity. Washington DC, USA: Island Press; 2009.

13. Messier C, Puettmann KJ, Coates KD. Managing Forests as Complex Adaptive Systems - Building Resilience to the Challenge of Global Change. 1st ed. Messier C, Puettmann KJ, Coates KD, editors. London: Routledge; 2013.

14. Spears BM, Ives SC, Angeler DG, Allen CR, Birk S, Carvalho L, et al. Effective management of ecological resilience - are we there yet? J Appl Ecol. 2015;52:1311–5.

15. DEFRA. The National Adaptation Programme and the Third Strategy for Climate Adaptation Reporting. 2018.

16. Chambers JC, Beck JL, Campbell S, Carlson J, Christiansen TJ, Clause KJ, et al. Using resilience and resistance concepts to manage threats to sagebrush ecosystems, Gunnison sage-grouse, and Greater sage-grouse in their eastern range: A strategic multi-scale approach. Gen Tech Report [Internet]. 2016;RMRS-GTR-3:143. Available from: https://www.fs.usda.gov/treesearch/pubs/53201

17. Brand FS, Jax K. Focusing the meaning(s) of resilience: Resilience as a descriptive concept and a boundary object. Ecol Soc. 2007;12.

18. ●● Moser S, Meerow S, Arnott J, Jack-Scott E. The turbulent world of resilience: interpretations and themes for transdisciplinary dialog. Clim Change. Climatic Change; 2019;153:21–40. **The authors performed a meta-analysis on review papers of resilience. They discuss the challenges in defining resilience and provide guidance around how to engage in a productive dialogue across the different resilience interpretations.**

19. Bone C, Moseley C, Vinyeta K, Bixler RP. Employing resilience in the United States Forest Service. Land use policy [Internet]. Elsevier Ltd; 2016;52:430–8. Available from: http://dx.doi.org/10.1016/j.landusepol.2016.01.003

20. Pimm SL. The complexity and stability of ecosystems. Nature. 1984;307:321–6.

21. Holling CS. Resilience and Stability of Ecological Systems. Annu Rev Ecol Syst. 1973;4:1–23.

22. Boeing G. Visual Analysis of Nonlinear Dynamical Systems : Chaos , Fractals , Self-Similarity and the Limits. Systems. 2016;4.

23. Folke C, Carpenter S, Elmqvist T, Gunderson L, Walker B. Resilience and Sustainable Development : Building Adaptive Capacity in a World of Transformations. 2002;31:437–40.

24. ● Folke C. Resilience [Internet]. Oxford Res. Encycl. 2016. p. 1–63. Available from: http://environmentalscience.oxfordre.com/view/10.1093/acrefore/9780199389414.001.0001/acrefore-9780199389414-e-8 **This encyclopedia article gives a useful explanation of the history of resilience as a term and how it has evolved.**

25. Quinlan AE, Berbés-Blázquez M, Haider LJ, Peterson GD. Measuring and assessing resilience: broadening understanding through multiple disciplinary perspectives. J Appl Ecol. 2016;53:677–87.

26. Walker B, Holling CS, Carpenter SR, Kinzig A. Resilience, Adaptability and

Transformability in Social – ecological Systems. Ecol Soc [Internet]. 2004;9:5. Available from: http://www.ecologyandsociety.org/vol9/iss2/art5/

27. Holling CS, Gunderson LH. Panarchy: understanding transformations in human and natural systems. Island Press; 2002.

28. Reyer CPO, Brouwers N, Rammig A, Brook BW, Epila J, Grant RF, et al. Forest resilience and tipping points at different spatio-temporal scales: Approaches and challenges. J Ecol. 2015;103:5–15.

29. Brown ED, Williams BK. Resilience and Resource Management. Environ Manage. Springer US; 2015;56:1416–27.

30. Xu L, Marinova D, Guo X. Resilience thinking: a renewed system approach for sustainability science. Sustain Sci. 2015;10:123–38.

31. Newton AC, Cantarello E. Restoration of forest resilience: An achievable goal? New For. Springer Netherlands; 2015;46:645–68.

32. Rist L, Moen J. Sustainability in forest management and a new role for resilience thinking. For Ecol Manage [Internet]. Elsevier B.V.; 2013;310:416–27. Available from: http://dx.doi.org/10.1016/j.foreco.2013.08.033

33. Olson DM, Dinerstein E, Wikramanayake ED, Burgess ND, Powell GVN, Underwood EC, et al. Terrestrial Ecoregions of the World: A New Map of Life on Earth. Bioscience. 2001;51:933–8.

34. OECD. Environment Monographs 83 - OECD Core Set of Indicators for Environmental Performance Reviews. Paris; 1993.

35. Team RC. R: A language and environment for statistical computing [Internet]. Vienna, Austria: R Foundation for Statistical Computing; 2018. Available from: https://www.r-project.org/

36. Oksanen J, Blanchet FG, Friendly M, Kindt R, Legendre P, McGlinn D, et al. vegan: Community Ecology Package [Internet]. R package version 2.5-4.; 2019. Available from: https://cran.r-project.org/package=vegan

37. Wickham H. ggplot2: Elegant Graphics for Data Analysis [Internet]. Springer-Verlag New York; 2016. Available from: https://ggplot2.tidyverse.org

38. Arnan X, Rodrigo A, Retana J. Post-fire recovery of Mediterranean ground ant communities follows vegetation and dryness gradients. J Biogeogr. 2006;33:1246–58.

39. Rivest D, Paquette A, Shipley B, Reich PB, Messier C. Tree communities rapidly alter soil microbial resistance and resilience to drought. Funct Ecol. 2015;29:570–8.

40. Roccaforte JP, Sánchez Meador A, Waltz AEM, Gaylord ML, Stoddard MT, Huffman DW. Delayed tree mortality, bark beetle activity, and regeneration dynamics five years following the Wallow Fire, Arizona, USA: Assessing trajectories towards resiliency. For Ecol Manage. 2018;428:20–6.

41. Roovers P, Verheyen K, Hermy M, Gulinck H. Experimental trampling and vegetation recovery in some forest and heathland communities. Appl Veg Sci. 2004;7:111–8.

42. Royer-Tardif S, Bradley RL, Parsons WFJ. Evidence that plant diversity and site productivity confer stability to forest floor microbial biomass. Soil Biol Biochem [Internet]. Elsevier Ltd; 2010;42:813–21. Available from:

http://dx.doi.org/10.1016/j.soilbio.2010.01.018

43. Rubio-Cuadrado Á, Bravo-Oviedo A, Mutke S, Del Río M. Climate effects on growth differ according to height and diameter along the stem in Pinus pinaster ait. IForest. 2018;11:237–42.

44. Rubio-Cuadrado Á, Camarero JJ, del Río M, Sánchez-González M, Ruiz-Peinado R, Bravo-Oviedo A, et al. Long-term impacts of drought on growth and forest dynamics in a temperate beech-oak-birch forest. Agric For Meteorol [Internet]. Elsevier; 2018;259:48–59. Available from: https://doi.org/10.1016/j.agrformet.2018.04.015

45. Rydgren AK, Økland RH, Hestmark G. Disturbance Severity and Community Resilience in a Boreal Forest. Ecology. 2004;85:1906–15.

46. Savage M, Mast JN. How resilient are southwestern ponderosa pine forests after crown fires? Can J For Res [Internet]. 2005;35:967–77. Available from: http://www.nrcresearchpress.com/doi/abs/10.1139/x05-028

47. Schäfer C, Grams TEE, Rötzer T, Feldermann A, Pretzsch H. Drought stress reaction of growth and δ13C in tree rings of European beech and Norway spruce in monospecific versus mixed stands along a precipitation gradient. Forests. 2017;8.

48. Schaffhauser A, Curt T, Tatoni T. The resilience ability of vegetation after different fire recurrences in Provence. WIT Trans Ecol Environ. 2008;119:297–310.

49. Arthur CM, Dech JP. Species composition determines resistance to drought in dry forests of the Great Lakes – St. Lawrence forest region of central Ontario. J Veg Sci. 2016;27:914–25.

50. Selwood KE, Clarke RH, Cunningham SC, Lada H, Mcgeoch MA, Mac Nally R. A bust but no boom: Responses of floodplain bird assemblages during and after prolonged drought. J Anim Ecol. 2015;84:1700–10.

51. Serra-Maluquer X, Mencuccini M, Martínez-Vilalta J. Changes in tree resistance, recovery and resilience across three successive extreme droughts in the northeast Iberian Peninsula. Oecologia [Internet]. Springer Berlin Heidelberg; 2018;187:343–54. Available from: https://doi.org/10.1007/s00442-018-4118-2

52. Shinoda M, Nandintsetseg B, Nachinshonhor UG, Komiyama H. Hotspots of recent drought in Asian steppes. Reg Environ Chang. 2014;14:103–17.

53. Silva Pedro M, Rammer W, Seidl R. Tree species diversity mitigates disturbance impacts on the forest carbon cycle. Oecologia. 2015;177:619–30.

54. Sohn JA, Saha S, Bauhus J. Potential of forest thinning to mitigate drought stress: A meta-analysis. For Ecol Manage [Internet]. Elsevier B.V.; 2016;380:261–73. Available from: http://dx.doi.org/10.1016/j.foreco.2016.07.046

55. Stevens-Rumann CS, Kemp KB, Higuera PE, Harvey BJ, Rother MT, Donato DC, et al. Evidence for declining forest resilience to wildfires under climate change. Ecol Lett. 2018;21:243–52.

56. Taeger S, Zang C, Liesebach M, Schneck V, Menzel A. Impact of climate and drought events on the growth of Scots pine (Pinus sylvestris L.) provenances. For Ecol Manage [Internet]. Elsevier B.V.; 2013;307:30–42. Available from: http://dx.doi.org/10.1016/j.foreco.2013.06.053

57. Temperli C, Hart SJ, Veblen TT, Kulakowski D, Hicks JJ, Andrus R. Are density reduction treatments effective at managing for resistance or resilience to spruce beetle disturbance in the southern Rocky Mountains? For Ecol Manage [Internet]. Elsevier B.V.; 2014;334:53–63. Available from: http://dx.doi.org/10.1016/j.foreco.2014.08.028

58. Thompson ID, Okabe K, Parrotta JA, Brockerhoff E, Jactel H, Forrester DI, et al. Biodiversity and ecosystem services: Lessons from nature to improve management of planted forests for REDD-plus. Biodivers Conserv. 2014;23:2613–35.

59. Trouvé R, Bontemps JD, Collet C, Seynave I, Lebourgeois F. Radial growth resilience of sessile oak after drought is affected by site water status, stand density, and social status. Trees - Struct Funct. 2017;31:517–29.

60. Bates JD, Davies KW. Seasonal burning of juniper woodlands and spatial recovery of herbaceous vegetation. For Ecol Manage [Internet]. Elsevier B.V.; 2016;361:117–30. Available from: http://dx.doi.org/10.1016/j.foreco.2015.10.045

61. Van Vierssen N, Wiersma YF. A Comparison of All-Terrain Vehicle (ATV) Trail Impacts on Boreal Habitats Across Scales. Nat Areas J [Internet]. 2015;35:266–78. Available from: http://www.bioone.org/doi/full/10.3375/043.035.0207

62. Vanha-Majamaa I, Shorohova E, Kushnevskaya H, Jalonen J. Resilience of understory vegetation after variable retention felling in boreal Norway spruce forests – A ten-year perspective. For Ecol Manage [Internet]. 2017;393:12–28. Available from: http://dx.doi.org/10.1016/j.foreco.2017.02.040

63. Verbesselt J, Umlauf N, Hirota M, Holmgren M, Van Nes EH, Herold M, et al. Remotely sensed resilience of tropical forests. Nat Clim Chang. 2016;6:1028–31.

64. Vitali V, Büntgen U, Bauhus J. Silver fir and Douglas fir are more tolerant to extreme droughts than Norway spruce in south-western Germany. Glob Chang Biol. 2017;23:5108–19.

65. Wakelin SA, Macdonald LM, O'Callaghan M, Forrester ST, Condron LM. Soil functional resistance and stability are linked to different ecosystem properties. Austral Ecol. 2014;39:522–31.

66. Wardle DA, Jonsson M. Long-term resilience of above- and belowground ecosystem components among contrasting ecosystems. Ecology. 2014;95:1836–49.

67. Willig MR, Presley SJ, Bloch CP. Long-term dynamics of tropical walking sticks in response to multiple large-scale and intense disturbances. Oecologia. 2011;165:357–68.

68. Wilson DJ, Ruscoe W a, Burrows LE, Mcelrea LM, Choquenot D. An experimental study of the impacts of understory forest vegetation and herbivory by red deer and rodents on seedling establishment and species composition in Waitutu Forest, New Zealand. N Z J Ecol. 2006;30:191–207.

69. Windmuller-Campione MA, Long JN. If long-term resistance to a spruce beetle epidemic is futile, can silvicultural treatments increase resilience in spruce-fir forests in the Central Rocky Mountains? Forests. 2015;6:1157–78.

70. Winter MB, Baier R, Ammer C. Regeneration dynamics and resilience of unmanaged mountain forests in the Northern Limestone Alps following bark beetle-induced spruce dieback. Eur J For Res. Springer Berlin Heidelberg; 2015;134:949–68.

71. Belote RT, Jones RH, Wieboldt TF. Compositional stability and diversity of vascular

plant communities following logging disturbance in Appalachian forests. Ecol Appl. 2012;22:502–16.

72. Wu CH, Lo YH, Blanco JA, Chang SC. Resilience assessment of lowland plantations using an ecosystem modeling approach. Sustain. 2015;7:3801–22.

73. Xu Y, Shen ZH, Ying LX, Ciais P, Liu HY, Piao SL, et al. The exposure, sensitivity and vulnerability of natural vegetation in China to climate thermal variability (1901-2013): An indicator-based approach. Ecol Indic [Internet]. Elsevier Ltd; 2016;63:258–72. Available from: http://dx.doi.org/10.1016/j.ecolind.2015.12.023

74. Yan H, Zhan J, Zhang T. Resilience of forest ecosystems and its influencing factors. Procedia Environ Sci [Internet]. 2011;10:2201–6. Available from: http://dx.doi.org/10.1016/j.proenv.2011.09.345

75. Zang C, Hartl-Meier C, Dittmar C, Rothe A, Menzel A. Patterns of drought tolerance in major European temperate forest trees: Climatic drivers and levels of variability. Glob Chang Biol. 2014;20:3767–79.

76. Zemp DC, Schleussner CF, Barbosa HMJ, Rammig A. Deforestation effects on Amazon forest resilience. Geophys Res Lett. 2017;44:6182–90.

77. Abbott I, Le Maitre D. Monitoring the impact of climate change on biodiversity: The challenge of megadiverse Mediterranean climate ecosystems. Austral Ecol. 2010;35:406–22.

78. Alongi DM. Mangrove forests: Resilience, protection from tsunamis, and responses to global climate change. Estuar Coast Shelf Sci. 2008;76:1–13.

79. Anjos LJS, de Toledo PM. Measuring resilience and assessing vulnerability of terrestrial ecosystems to climate change in South America. PLoS One [Internet]. 2018;13:e0194654. Available from: http://dx.plos.org/10.1371/journal.pone.0194654

80. Arianoutsou M, Koukoulas S, Kazanis D. Evaluating post-fire forest resilience using GIS and multi-criteria analysis: An example from Cape Sounion National Park, Greece. Environ Manage. 2011;47:384–97.

81. Ayala-Orozco B, Gavito ME, Mora F, Siddique I, Balvanera P, Jaramillo VJ, et al. Resilience of Soil Properties to Land-Use Change in a Tropical Dry Forest Ecosystem. L Degrad Dev [Internet]. 2017;325:315–25. Available from: http://doi.wiley.com/10.1002/ldr.2686

82. Bernhardt-Römermann M, Gray A, Vanbergen AJ, Bergès L, Bohner A, Brooker RW, et al. Functional traits and local environment predict vegetation responses to disturbance: A pan-European multi-site experiment. J Ecol. 2011;99:777–87.

83. Bahamondez C, Thompson ID. Determining forest degradation, ecosystem state and resilience using a standard stand stocking measurement diagram: Theory into practice. Forestry. 2016;89:290–300.

84. Baker WL. Transitioning western U.S. dry forests to limited committed warming with bet-hedging and natural disturbances. Ecosphere [Internet]. 2018;9:e02288. Available from: https://esajournals.onlinelibrary.wiley.com/doi/abs/10.1002/ecs2.2288

85. Bhaskar R, Arreola F, Mora F, Martinez-Yrizar A, Martinez-Ramos M, Balvanera P. Response diversity and resilience to extreme events in tropical dry secondary forests. For Ecol Manage [Internet]. Elsevier; 2018;426:61–71. Available from: https://doi.org/10.1016/j.foreco.2017.09.028

86. Buma B, Wessman CA. Disturbance interactions can impact resilience mechanisms of forests. Ecosphere. 2011;2:1–13.

87. Burkhard B, Fath BD, Müller F. Adapting the adaptive cycle: Hypotheses on the development of ecosystem properties and services. Ecol Modell [Internet]. Elsevier B.V.; 2011;222:2878–90. Available from: http://dx.doi.org/10.1016/j.ecolmodel.2011.05.016

88. ● Cantarello E, Newton AC, Martin PA, Evans PM, Gosal A, Lucash MS. Quantifying resilience of multiple ecosystem services and biodiversity in a temperate forest landscape. Ecol Evol. 2017;7:9661–75. **This article provides a quantitative way to assess forest resilience that includes some of the socio-economic aspects of forests. A good example on how resilience could be measured.**

89. Carrillo-Saucedo SM, Gavito ME, Siddique I. Arbuscular mycorrhizal fungal spore communities of a tropical dry forest ecosystem show resilience to land-use change. Fungal Ecol [Internet]. Elsevier Ltd; 2018;32:29–39. Available from: https://doi.org/10.1016/j.funeco.2017.11.006

90. Churchill DJ, Larson AJ, Dahlgreen MC, Franklin JF, Hessburg PF, Lutz JA. Restoring forest resilience: From reference spatial patterns to silvicultural prescriptions and monitoring. For Ecol Manage [Internet]. 2013;291:442–57. Available from: http://dx.doi.org/10.1016/j.foreco.2012.11.007

91. Clason AJ, Macdonald SE, Haeussler S. Forest response to cumulative disturbance and stress: Two decades of change in whitebark pine ecosystems of west-central British Columbia. Écoscience [Internet]. 2014;21:174–85. Available from: https://www.tandfonline.com/doi/full/10.2980/21-2-3686

92. Cole LES, Bhagwat SA, Willis KJ. Long-term disturbance dynamics and resilience of tropical peat swamp forests. J Ecol. 2015;103:16–30.

93. Bialecki MB, Fahey RT, Scharenbroch B. Variation in urban forest productivity and response to extreme drought across a large metropolitan region. Urban Ecosyst. Urban Ecosystems; 2018;21:157–69.

94. DeRose RJ, Long JN. Resistance and Resilience: A Conceptual Framework for Silviculture. For Sci [Internet]. 2014;60:1205–12. Available from: https://academic.oup.com/forestscience/article/60/6/1205-1212/4583924

95. Craven D, Filotas E, Angers VA, Messier C. Evaluating resilience of tree communities in fragmented landscapes: Linking functional response diversity with landscape connectivity. Divers Distrib. 2016;22:505–18.

96. Ding H, Pretzsch H, Schütze G, Rötzer T. Size-dependence of tree growth response to drought for Norway spruce and European beech individuals in monospecific and mixed-species stands. Plant Biol. 2017;19:709–19.

97. Dodd M, Barker G, Burns B, Didham R, Innes J, King C, et al. Resilience of New Zealand indigenous forest fragments to impacts of livestock and pest mammals. N Z J Ecol. 2011;35:83–95.

98. Drever CR, Peterson G, Messier C, Bergeron Y, Flannigan M. Can forest management based on natural disturbances maintain ecological resilience? Can J For Res [Internet]. 2006;36:2285–99. Available from: http://www.nrcresearchpress.com/doi/abs/10.1139/x06-132

99. Estevo CA, Nagy-Reis MB, Silva WR. Urban parks can maintain minimal resilience for Neotropical bird communities. Urban For Urban Green [Internet]. Elsevier; 2017;27:84–9. Available from: http://dx.doi.org/10.1016/j.ufug.2017.06.013

100. García-López JM, Allué C. A phytoclimatic-based indicator for assessing the inherent responsitivity of the European forests to climate change. Ecol Indic. 2012;18:73–81.

101. Gazol A, Ribas M, Gutiérrez E, Camarero JJ. Aleppo pine forests from across Spain show drought-induced growth decline and partial recovery. Agric For Meteorol [Internet]. Elsevier B.V.; 2017;232:186–94. Available from: http://dx.doi.org/10.1016/j.agrformet.2016.08.014

102. Gazol A, Camarero JJ, Anderegg WRL, Vicente-Serrano SM. Impacts of droughts on the growth resilience of Northern Hemisphere forests. Glob Ecol Biogeogr. 2017;26:166–76.

103. Gazol A, Camarero JJ, Vicente-Serrano SM, Sánchez-Salguero R, Gutiérrez E, de Luis M, et al. Forest resilience to drought varies across biomes. Glob Chang Biol. 2018;24:2143–58.

104. Bihn JH, Verhaagh M, Brändle M, Brandl R. Do secondary forests act as refuges for old growth forest animals? Recovery of ant diversity in the Atlantic forest of Brazil. Biol Conserv. 2008;141:733–43.

105. Girard F, Payette S, Gagnon R. Rapid expansion of lichen woodlands within the closed-crown boreal forest zone over the last 50 years caused by stand disturbances in eastern Canada. J Biogeogr. 2008;35:529–37.

106. Granda E, Gazol A, Camarero JJ. Functional diversity differently shapes growth resilience to drought for co-existing pine species. J Veg Sci. 2018;29:265–75.

107. Guimarães H, Braga R, Mascarenhas A, Ramos TB. Indicators of ecosystem services in a military Atlantic Forest area, Pernambuco—Brazil. Ecol Indic [Internet]. Elsevier; 2017;80:247–57. Available from: http://dx.doi.org/10.1016/j.ecolind.2017.05.030

108. Halofsky JS, Halofsky JE, Burcsu T, Hemstrom MA. Dry forest resilience varies under simulated climate-management scenarios in a central Oregon, USA landscape. Ecol Appl. 2014;24:1908–25.

109. Halpin CR, Lorimer CG. Trajectories and resilience of stand structure in response to variable disturbance severities in northern hardwoods. For Ecol Manage [Internet]. Elsevier B.V.; 2016;365:69–82. Available from: http://dx.doi.org/10.1016/j.foreco.2016.01.016

110. Hernandez-Montilla MC, Martinez-Morales MA, Vanegas GP, De Jong BHJ. Assessment of hammocks (Petenes) resilience to sea level rise due to climate change in Mexico. PLoS One. 2016;11.

111. Hood SM, Baker S, Sala A. Fortifying the forest: thinning and burning increase resistance to a bark beetle outbreak and promote forest resilience. Ecol Appl [Internet]. 2016;26:1984–2000. Available from: http://doi.wiley.com/10.1002/eap.1363

112. Ibarra JT, Martin M, Cockle KL, Martin K. Maintaining ecosystem resilience: Functional responses of tree cavity nesters to logging in temperate forests of the Americas. Sci Rep. 2017;7:1–9.

113. Jaramillo VJ, Martínez-Yrízar A, Maass M, Nava-Mendoza M, Castañeda-Gómez L, Ahedo-Hernández R, et al. Hurricane impact on biogeochemical processes in a tropical dry forest in western Mexico. For Ecol Manage [Internet]. Elsevier; 2018;426:72–80. Available

from: https://doi.org/10.1016/j.foreco.2017.12.031

114. Johnson AB, Winker K. Short-term hurricane impacts on a neotropical community of marked birds and implications for early- stage community resilience. PLoS One. 2010;5.

115. Borkenhagen A, Cooper DJ. Tolerance of fen mosses to submergence, and the influence on moss community composition and ecosystem resilience. J Veg Sci. 2018;29:127–35.

116. Johnstone JF, Chapin FS, Hollingsworth TN, Mack MC, Romanovsky V, Turetsky M. Fire, climate change, and forest resilience in interior AlaskaThis article is one of a selection of papers from The Dynamics of Change in Alaska’s Boreal Forests: Resilience and Vulnerability in Response to Climate Warming. Can J For Res [Internet]. 2010;40:1302–12. Available from: http://www.nrcresearchpress.com/doi/abs/10.1139/X10-061

117. Johnstone JF, Allen CD, Franklin JF, Frelich LE, Harvey BJ, Higuera PE, et al. Changing disturbance regimes, ecological memory, and forest resilience. Front Ecol Environ. 2016;14:369–78.

118. Kaarlejärvi E, Hoset KS, Olofsson J. Mammalian herbivores confer resilience of Arctic shrub-dominated ecosystems to changing climate. Glob Chang Biol. 2015;21:3379–88.

119. Kerkhoff AJ, Enquist BJ. The Implications of Scaling Approaches for Understanding Resilience and Reorganization in Ecosystems. Bioscience [Internet]. 2007;57:489–99. Available from: http://academic.oup.com/bioscience/article/57/6/489/236142/The-Implications-of-Scaling-Approaches-for

120. Knudby A, Jupiter S, Roelfsema C, Lyons M, Phinn S. Mapping coral reef resilience indicators using field and remotely sensed data. Remote Sens. 2013;5:1311–34.

121. Leuteritz TEJ, Ekbia HR. Not All Roads Lead to Resilience : a Complex Systems Approach to the Comparative Analysis of Tortoises in Arid Ecosystems. Ecol Soc. 2008;13:www.ecologyandsociety.org/vol13/iss1/art1/.

122. Luce C, Morgan P, Dwire K, Isaak D, Holden Z, Rieman B. Climate change, forests, fire, water, and fish: Building resilient landscapes, streams, and managers. Gen. Tech. Rep. RMRS-GTR-290. Fort Collins, CO; 2012.

123. Ludwig JA, Coughenour MB, Liedloff AC, Dyer R. Modelling the resilience of Australian savanna systems to grazing impacts. Environ Int. 2001;27:167–72.

124. Magnuszewski P, Ostasiewicz K, Chazdon R, Salk C, Pajak M, Sendzimir J, et al. Resilience and alternative stable states of tropical forest landscapes under shifting cultivation regimes. PLoS One. 2015;10:1–20.

125. Magruder M, Chhin S, Palik B, Bradford JB. Thinning increases climatic resilience of red pine. Can J For Res [Internet]. 2013;43:878–89. Available from: http://www.nrcresearchpress.com/doi/abs/10.1139/cjfr-2013-0088

126. Bottero A, D’Amato AW, Palik BJ, Bradford JB, Fraver S, Battaglia MA, et al. Density-dependent vulnerability of forest ecosystems to drought. J Appl Ecol. 2017;54:1605–14.

127. Malika VS, Lindsey G, Katherine JW. How does spatial heterogeneity influence resilience to climatic changes? Ecological dynamics in southeast Madagascar. Ecol Monogr. 2009;79:557–74.

128. Mallik AU, Kreutzweiser DP, Spalvieri CM, Mackereth RW. Understory plant community resilience to partial harvesting in riparian buffers of central Canadian boreal

forests. For Ecol Manage [Internet]. Elsevier B.V.; 2013;289:209–18. Available from: http://dx.doi.org/10.1016/j.foreco.2012.09.039

129. Martínez-Vilalta J, López BC, Loepfe L, Lloret F. Stand- and tree-level determinants of the drought response of Scots pine radial growth. Oecologia. 2012;168:877–88.

130. Mitchell PJ, O'Grady AP, Pinkard EA, Brodribb TJ, Arndt SK, Blackman CJ, et al. An ecoclimatic framework for evaluating the resilience of vegetation to water deficit. Glob Chang Biol. 2016;22:1677–89.

131. Montúfar R, Anthelme F, Pintaud JC, Balslev H. Disturbance and Resilience in Tropical American Palm Populations and Communities. Bot Rev. 2011;77:426–61.

132. Moris J V., Vacchiano G, Ascoli D, Motta R. Alternative stable states in mountain forest ecosystems: the case of European larch (Larix decidua) forests in the western Alps. J Mt Sci. 2017;14:811–22.

133. Nitschke CR, Innes JL. A tree and climate assessment tool for modelling ecosystem response to climate change. Ecol Modell. 2008;210:263–77.

134. Pardini R, de Bueno AA, Gardner TA, Prado PI, Metzger JP. Beyond the fragmentation threshold hypothesis: Regime shifts in biodiversity across fragmented landscapes. PLoS One. 2010;5.

135. Ponce Campos GE, Moran MS, Huete A, Zhang Y, Bresloff C, Huxman TE, et al. Ecosystem resilience despite large-scale altered hydroclimatic conditions. Nature [Internet]. Nature Publishing Group; 2013;494:349–52. Available from: http://dx.doi.org/10.1038/nature11836

136. Reyes G, Kneeshaw D. Ecological Resilience: Is It Ready for operationalisation in forest management? In: Daniels JA, editor. Adv Environ Res. New York, USA: Nova Science Publishers, Inc.; 2014. p. 195–212.

137. Broncano MJ, Retana J, Rodrigo A. Predicting the recovery of Pinus halepensis and Quercus ilex forests after a large wildfire in northeastern Spain. Plant Ecol. 2005;180:47–56.

138. Sakschewski B, Von Bloh W, Boit A, Poorter L, Peña-Claros M, Heinke J, et al. Resilience of Amazon forests emerges from plant trait diversity. Nat Clim Chang. 2016;6:1032–6.

139. Salamon-Albert É, Abaligeti G, Ortmann-Ajkai A. Functional response trait analysis improves climate sensitivity estimation in beech forests at a trailing edge. Forests. 2017;8.

140. Sánchez-Pinillos M, Coll L, De Cáceres M, Ameztegui A. Assessing the persistence capacity of communities facing natural disturbances on the basis of species response traits. Ecol Indic [Internet]. Elsevier Ltd; 2016;66:76–85. Available from: http://dx.doi.org/10.1016/j.ecolind.2016.01.024

141. Sánchez-Salguero R, Camarero JJ, Rozas V, Génova M, Olano JM, Arzac A, et al. Resist, recover or both? Growth plasticity in response to drought is geographically structured and linked to intraspecific variability in Pinus pinaster. J Biogeogr. 2018;45:1126–39.

142. Scheffer M, Carpenter S, Foley JA, Folke C, Walker B. Catastrophic shifts in ecosystems. Nature. 2001;413:591–6.

143. Schirpke U, Kohler M, Leitinger G, Fontana V, Tasser E, Tappeiner U. Future impacts of changing land-use and climate on ecosystem services of mountain grassland and their

resilience. Ecosyst Serv [Internet]. The Authors; 2017;26:79–94. Available from: http://dx.doi.org/10.1016/j.ecoser.2017.06.008

144. Seidl R, Rammer W, Spies TA. Disturbance legacies increase the resilience of forest ecosystem structure, composition, and functioning. Ecol Appl. 2014;24:2063–77.

145. Sharma A, Goyal MK. Assessment of ecosystem resilience to hydroclimatic disturbances in India. Glob Chang Biol [Internet]. Elsevier; 2018;24:e432–41. Available from: https://doi.org/10.1016/j.jhydrol.2018.07.079

146. Spasojevic MJ, Bahlai CA, Bradley BA, Butterfield BJ, Tuanmu MN, Sistla S, et al. Scaling up the diversity-resilience relationship with trait databases and remote sensing data: The recovery of productivity after wildfire. Glob Chang Biol. 2016;22:1421–32.

147. Stampoulis D, Andreadis KM, Granger SL, Fisher JB, Turk FJ, Behrangi A, et al. Assessing hydro-ecological vulnerability using microwave radiometric measurements from WindSat. Remote Sens Environ [Internet]. Elsevier Inc.; 2016;184:58–72. Available from: http://dx.doi.org/10.1016/j.rse.2016.06.007

148. Bruelheide H, Luginbühl U. Peeking at Ecosystem Stability : Making Use of a Natural Disturbance Experiment to Analyze Resistance and Resilience Author (s): Helge Bruelheide and Ute Luginbühl Peeking at ecosystem experiment use of a natural disturbance stability : making to resist. Ecology. 2009;90:1314–25.

149. Tambosi LR, Martensen AC, Ribeiro MC, Metzger JP. A framework to optimize biodiversity restoration efforts based on habitat amount and landscape connectivity. Restor Ecol. 2014;22:169–77.

150. Torrico JC, Janssens MJJ. Rapid assessment methods of resilience for natural and agricultural systems. An Acad Bras Cienc. 2010;82:1095–105.

151. Van De Leemput IA, Van Nes EH, Scheffer M. Resilience of alternative states in spatially extended ecosystems. PLoS One. 2015;10:1–17.

152. Viglizzo EF, Nosetto MD, Jobbágy EG, Ricard MF, Frank FC. The ecohydrology of ecosystem transitions: A meta-analysis. Ecohydrology. 2015;8:911–21.

153. Walker XJ, Mack MC, Johnstone JF. Predicting Ecosystem Resilience to Fire from Tree Ring Analysis in Black Spruce Forests. Ecosystems. Springer US; 2017;20:1137–50.

154. Wallem PK, Anderson CB, Martínez-Pastur G, Lencinas MV. Using assembly rules to measure the resilience of riparian plant communities to beaver invasion in subantarctic forests. Biol Invasions. 2010;12:325–35.

155. Waltz AEM, Stoddard MT, Kalies EL, Springer JD, Huffman DW, Meador AS. Effectiveness of fuel reduction treatments: Assessing metrics of forest resiliency and wildfire severity after the Wallow Fire, AZ. For Ecol Manage [Internet]. Elsevier B.V.; 2014;334:43–52. Available from: http://dx.doi.org/10.1016/j.foreco.2014.08.026

156. Wittkuhn RS, McCaw L, Wills AJ, Robinson R, Andersen AN, Van Heurck P, et al. Variation in fire interval sequences has minimal effects on species richness and composition in fire-prone landscapes of south-west Western Australia. For Ecol Manage [Internet]. Elsevier B.V.; 2011;261:965–78. Available from: http://dx.doi.org/10.1016/j.foreco.2010.10.037

157. Wu T, Kim YS. Pricing ecosystem resilience in frequent-fire ponderosa pine forests. For Policy Econ [Internet]. Elsevier B.V.; 2013;27:8–12. Available from:

http://dx.doi.org/10.1016/j.forpol.2012.11.002

158. Xu C, Liu H, Anenkhonov OA, Korolyuk AY, Sandanov D V., Balsanova LD, et al. Long-term forest resilience to climate change indicated by mortality, regeneration, and growth in semiarid southern Siberia. Glob Chang Biol. 2017;23:2370–82.

159. Buma B, Wessman CA. Forest resilience, climate change, and opportunities for adaptation: A specific case of a general problem. For Ecol Manage [Internet]. Elsevier B.V.; 2013;306:216–25. Available from: http://dx.doi.org/10.1016/j.foreco.2013.06.044

160. Zenner EK, Dickinson YL, Peck JE. Recovery of forest structure and composition to harvesting in different strata of mixed even-aged central Appalachian hardwoods. Ann For Sci. 2013;70:151–9.

161. Akamani K. A community resilience model for understanding and assessing the sustainability of forest-dependent communities. Hum Ecol Rev [Internet]. 2012;19:99–109. Available from: http://opensiuc.lib.siu.edu/for_articles/1/

162. Akamani K, Hall TE. Determinants of the process and outcomes of household participation in collaborative forest management in Ghana: A quantitative test of a community resilience model. J Environ Manage. 2015;147:1–11.

163. Akamani K, Wilson PI, Hall TE. Barriers to collaborative forest management and implications for building the resilience of forest-dependent communities in the Ashanti region of Ghana. J Environ Manage. 2015;151:11–21.

164. Ballard HL, Belsky JM. Participatory action research and environmental learning: Implications for resilient forests and communities. Environ Educ Res. 2010;16:611–27.

165. Beeton TA, Galvin KA. Wood-based bioenergy in western Montana: The importance of understanding path dependence and local context for resilience. Ecol Soc. 2017;22.

166. Bernetti I, Ciampi C, Fagarazzi C, Sacchelli S. The evaluation of forest crop damages due to climate change. An application of Dempster-Shafer method. J For Econ [Internet]. Elsevier GmbH.; 2011;17:285–97. Available from: http://dx.doi.org/10.1016/j.jfe.2011.04.005

167. Bowditch EAD, McMorran R, Bryce R, Smith M. Perception and partnership: Developing forest resilience on private estates. For Policy Econ [Internet]. Elsevier; 2019;99:110–22. Available from: https://doi.org/10.1016/j.forpol.2017.12.004

168. Brown HCP, Sonwa DJ. Diversity within village institutions and its implication for resilience in the context of climate change in Cameroon. Clim Dev. Taylor & Francis; 2018;10:448–57.

169. Chapin FS, Peterson G, Berkes F, Callaghan T V., Angelstam P, Apps M, et al. Resilience and Vulnerability of Northern Regions to Social and Environmental Change. AMBIO A J Hum Environ [Internet]. 2004;33. Available from: https://www.researchgate.net/publication/8618949%0AMitigation

170. Calderon-Aguilera LE, Rivera-Monroy VH, Porter-Bolland L, Martínez-Yrízar A, Ladah LB, Martínez-Ramos M, et al. An assessment of natural and human disturbance effects on Mexican ecosystems: Current trends and research gaps. Biodivers Conserv. 2012;21:589–617.

171. Chapin FS, Lovecraft AL, Zavaleta ES, Nelson J, Robards MD, Kofinas GP, et al. Policy strategies to address sustainability of Alaskan boreal forests in response to a directionally changing climate. Proc Natl Acad Sci [Internet]. 2006;103:16637–43. Available from:

http://www.pnas.org/cgi/doi/10.1073/pnas.0606955103

172. Chapin FS, McGuire AD, Ruess RW, Hollingsworth TN, Mack MC, Johnstone JF, et al. Resilience of Alaska’s boreal forest to climatic changeThis article is one of a selection of papers from The Dynamics of Change in Alaska’s Boreal Forests: Resilience and Vulnerability in Response to Climate Warming. Can J For Res [Internet]. 2010;40:1360–70. Available from: http://www.nrcresearchpress.com/doi/abs/10.1139/X10-074

173. Daniels JM. Assessing socioeconomic resiliency in Washington counties. Gen. Tech. Rep. - Pacific Northwest Res. Station. USDA For. Serv. Portland, Oregon; 2004.

174. DasGupta R, Shaw R. An indicator based approach to assess coastal communities’ resilience against climate related disasters in Indian Sundarbans. J Child Fam Stud. 2015;24:85–101.

175. Dessalegn M. Threatened common property resource system and factors for resilience: Lessons drawn from serege-commons in Muhur, Ethiopia. Ecol Soc. 2016;21.

176. Doughty CA. Building climate change resilience through local cooperation: a Peruvian Andes case study. Reg Environ Chang. Springer Berlin Heidelberg; 2016;16:2187–97.

177. Dymond CC, Tedder S, Spittlehouse DL, Raymer B, Hopkins K, McCallion K, et al. Diversifying managed forests to increase resilience. Can J For Res [Internet]. 2014;44:1196–205. Available from: http://www.nrcresearchpress.com/doi/10.1139/cjfr-2014-0146

178. Dymond CC, Spittlehouse DL, Tedder S, Hopkins K, McCallion K, Sandland J. Applying resilience concepts in forest management: A retrospective simulation approach. Forests. 2015;6:4421–38.

179. Fuller L, Quine CP. Resilience and tree health: A basis for implementation in sustainable forest management. Forestry. 2016;89:7–19.

180. Hale JD, Pugh TAM, Sadler JP, Boyko CT, Brown J, Caputo S, et al. Delivering a multi-functional and resilient urban forest. Sustain. 2015;7:4600–24.

181. Candan F, Broquen P. Aggregate stability and related properties in NW Patagonian Andisols. Geoderma [Internet]. Elsevier B.V.; 2009;154:42–7. Available from: http://dx.doi.org/10.1016/j.geoderma.2009.09.010

182. Harris CC, McLaughlin W, Brown G, Becker DR. Rural communities in the inland Northwest: an assessment of small rural communities in the interior and upper Columbia River basins. [Internet]. Portland, Oregon; 2000. Available from: https://login.ezproxy.net.ucf.edu/login?auth=shibb&url=http://search.ebscohost.com/login.aspx?direct=true&db=cat00846a&AN=ucfl.024909820&site=eds-live&scope=site%5Cnhttp://purl.access.gpo.gov/GPO/LPS10938

183. Jarzebski MP, Tumilba V, Yamamoto H. Application of a tri-capital community resilience framework for assessing the social–ecological system sustainability of community-based forest management in the Philippines. Sustain Sci. Springer Japan; 2016;11:307–20.

184. Kelly C, Ferrara A, Wilson GA, Ripullone F, Nolè A, Harmer N, et al. Community resilience and land degradation in forest and shrubland socio-ecological systems: Evidence from Gorgoglione, Basilicata, Italy. Land use policy [Internet]. Elsevier Ltd; 2015;46:11–20. Available from: http://dx.doi.org/10.1016/j.landusepol.2015.01.026

185. Kim M, You S, Chon J, Lee J. Sustainable land-use planning to improve the coastal resilience of the social-ecological landscape. Sustain. 2017;9:1–21.

186. Knoot TG, Schulte L a, Tyndall JC, Palik BJ. The State of the System and Steps Toward Resilience of Disturbance- dependent Oak Forests. Ecol Soc. 2010;15:5.

187. Lyon C. Place Systems and Social Resilience: A Framework for Understanding Place in Social Adaptation, Resilience, and Transformation. Soc Nat Resour. 2014;27:1009–23.

188. Magis K. Community resilience: An indicator of social sustainability. Soc Nat Resour. 2010;23:401–16.

189. Moen J, Keskitalo ECH. Interlocking panarchies in multi-use boreal forests in Sweden. Ecol Soc. 2010;15.

190. Nightingale A, Sharma JR. Conflict resilience among community forestry user groups: Experiences in Nepal. Disasters. 2014;38:517–39.

191. Pinkerton EW, Benner J. Small sawmills persevere while the majors close: Evaluating resilience and desirable timber allocation in British Columbia, Canada. Ecol Soc. 2013;18.

192. Carnwath G, Nelson C. Effects of biotic and abiotic factors on resistance versus resilience of Douglas fir to drought. PLoS One. 2017;12:1–19.

193. Salvati L, De Angelis A, Bajocco S, Ferrara A, Barone PM. Desertification Risk, Long-Term Land-Use Changes and Environmental Resilience: A Case Study in Basilicata, Italy. Scottish Geogr J. 2013;129:85–99.

194. Sarkki S, Heikkinen H. The resilience of communities and nature-based livelihoods in northern Finland. In: Nuttall M, Tervo-Kankare K, Karjalainen T, editors. NGP Yearb 2012 Negot Resour Engag people Human-environment relations North. Oulu; 2012. p. 95–107.

195. Sarkki S, Ficko A, Wielgolaski F, Abraham E, Bratanova-Doncheva S, Grunewald K, et al. Assessing the resilient provision of ecosystem services by social-ecological systems: introduction and theory. Clim Res [Internet]. 2017;AdvanceVie:1–9. Available from: http://www.int-res.com/abstracts/cr/Resilience in SENSitive mountain FORest ecosystems under environmental change/av2/

196. Saxena A, Guneralp B, Bailis R, Yohe G, Oliver C. Evaluating the resilience of forest dependent communities in Central India by combining the sustainable livelihoods framework and the cross scale resilience analysis. Curr Sci. 2016;110:1195–207.

197. Schoennagel T, Balch JK, Brenkert-Smith H, Dennison PE, Harvey BJ, Krawchuk MA, et al. Adapt to more wildfire in western North American forests as climate changes. Proc Natl Acad Sci [Internet]. 2017;114:4582–90. Available from: http://www.pnas.org/lookup/doi/10.1073/pnas.1617464114

198. ● Seidl R, Spies TA, Peterson DL, Stephens SL, Jeffrey A. Searching for resilience : addressing the impacts of changing disturbance regimes on forest ecosystem services. J Appl Ecol. 2016;53:120–9. **This article studies how resilience can be used in forest management as a response to the changing disturbance regimes. It proposes pathways to manage forests for resilience and ensure the maintanence of the ecosystem service provision.**

199. Singer J, Hoang H, Ochiai C. Post-displacement community resilience: Considering the contribution of indigenous skills and cultural capital among ethnic minority Vietnamese. Asia Pac Viewp. 2015;56:208–22.

200. Smith JW, Moore RL, Anderson DH, Siderelis C. Community Resilience in Southern Appalachia: A Theoretical Framework and Three Case Studies. Hum Ecol. 2012;40:341–53.

201. Ticktin T, Quazi S, Dacks R, Tora M, Mcguigan A, Hastings Z, et al. Linkages between measures of biodiversity and community resilience in Pacific Island agroforests. Conserv Biol. 2018;0:1–11.

202. Toledo VM, Ortiz-Espejel B, Cortés L, Moguel P, Ordoñez M de J. The multiple use of tropical forests by indigenous peoples in Mexico: A case of adaptive management. Conserv Ecol [Internet]. 2003;7:9. Available from: http://www.consecol.org/vol7/iss3/art9

203. Chaer G, Fernandes M, Myrold D, Bottomley P. Comparative resistance and resilience of soil microbial communities and enzyme activities in adjacent native forest and agricultural soils. Microb Ecol. 2009;58:414–24.

204. Townsend PA, Masters KL. Lattice-work corridors for climate change: A conceptual framework for biodiversity conservation and social-ecological resilience in a tropical elevational gradient. Ecol Soc. 2015;20.

205. Bottero A, D'Amato AW, Palik BJ, Kern CC, Bradford JB, Scherer SS. Influence of Repeated Prescribed Fire on Tree Growth and Mortality in Pinus resinosa Forests, Northern Minnesota. For Sci [Internet]. 2017;63:94–100. Available from: http://www.ingentaconnect.com/content/10.5849/forsci.16-035

206. Stuart-Haëntjens E, De Boeck HJ, Lemoine NP, Mänd P, Kröel-Dulay G, Schmidt IK, et al. Mean annual precipitation predicts primary production resistance and resilience to extreme drought. Sci Total Environ. 2018;636:360–6.

207. Summerville KS. Forest lepidopteran communities are more resilient to shelterwood harvests compared to more intensive logging regimes. Ecol Appl. 2013;23:1101–12.

208. Moretti M, Legg C. Combining plant and animal traits to assess community functional responses to disturbance. Ecography (Cop). 2009;32:299–309.

209. Chergui B, Fahd S, Santos X. Quercus suber forest and Pinus plantations show different post-fire resilience in Mediterranean north-western Africa. Ann For Sci. Annals of Forest Science; 2018;75.

210. Chompuchan C, Lin CY. Assessment of forest recovery at Wu-Ling fire scars in Taiwan using multi-temporal Landsat imagery. Ecol Indic [Internet]. Elsevier; 2017;79:196–206. Available from: http://dx.doi.org/10.1016/j.ecolind.2017.04.038

211. Creed IF, Spargo AT, Jones JA, Buttle JM, Adams MB, Beall FD, et al. Changing forest water yields in response to climate warming: Results from long-term experimental watershed sites across North America. Glob Chang Biol. 2014;20:3191–208.

212. Curran TJ, Gersbach LN, Edwards W, Krockenberger AK. Wood density predicts plant damage and vegetative recovery rates caused by cyclone disturbance in tropical rainforest tree species of North Queensland, Australia. Austral Ecol. 2008;33:442–50.

213. Curzon MT, D'Amato AW, Palik BJ. Bioenergy harvest impacts to biodiversity and resilience vary across aspen-dominated forest ecosystems in the Lake States region, USA. Appl Veg Sci. 2016;19:667–78.

214. D'Amato AW, Bradford JB, Fraver S, Palik BJ. Effects of thinning on drought vulnerability and climate response in north temperate forest ecosystems. Ecol Appl. Wiley Online Library; 2013;23:1735–42.

215. Dănescu A, Kohnle U, Bauhus J, Sohn J, Albrecht AT. Stability of tree increment in relation to episodic drought in uneven-structured, mixed stands in southwestern Germany. For

Ecol Manage. 2018;415–416:148–59.

216. Danielson TM, Rivera-Monroy VH, Castañeda-Moya E, Briceño H, Travieso R, Marx BD, et al. Assessment of Everglades mangrove forest resilience: Implications for above-ground net primary productivity and carbon dynamics. For Ecol Manage [Internet]. Elsevier; 2017;404:115–25. Available from: http://dx.doi.org/10.1016/j.foreco.2017.08.009

217. Das P, Behera MD, Roy PS. Modeling precipitation dependent forest resilience in India. Int Arch Photogramm Remote Sens Spat Inf Sci - ISPRS Arch. 2018;42:263–6.

218. DeClerck F, Barbour M, Sawyer J. Species richness and stand stabilty in conifer forests of the Sierra Nevada. Ecology [Internet]. 2006;87:2787–99. Available from: https://doi.org/10.1890/0012-9658(2006)87[2787:SRASSI]2.0.CO%0Ahttp://0.0.0.2

219. Derroire G, Balvanera P, Castellanos-Castro C, Decocq G, Kennard DK, Lebrija-Trejos E, et al. Resilience of tropical dry forests – a meta-analysis of changes in species diversity and composition during secondary succession. Oikos. 2016;125:1386–97.

220. Di Mauro B, Fava F, Busetto L, Crosta GF, Colombo R. Post-fire resilience in the Alpine region estimated from MODIS satellite multispectral data. Int J Appl Earth Obs Geoinf [Internet]. Elsevier B.V.; 2014;32:163–72. Available from: http://linkinghub.elsevier.com/retrieve/pii/S0303243414000944

221. Diaconu D, Kahle HP, Spiecker H. Thinning increases drought tolerance of European beech: a case study on two forested slopes on opposite sides of a valley. Eur J For Res. Springer Berlin Heidelberg; 2017;136:319–28.

222. Díaz-Delgado R, Lloret F, Pons X, Terradas J. Satellite Evidence of Decreasing Resilience in Mediterranean Plant Communities After Recurrent Wildfires. Ecology [Internet]. 2002;83:2293–303. Available from: https://esajournals.onlinelibrary.wiley.com/doi/abs/10.1890/0012-9658(2002)083%5B2293:SEODRI%5D2.0.CO%3B2

223. Dörner J, Dec D, Zúñiga F, Sandoval P, Horn R. Effect of land use change on Andosol's pore functions and their functional resilience after mechanical and hydraulic stresses. Soil Tillage Res. 2011;115–116:71–9.

224. Duveneck MJ, Scheller RM. Measuring and managing resistance and resilience under climate change in northern Great Lake forests (USA). Landsc Ecol. Springer Netherlands; 2016;31:669–86.

225. Dynesius M, Hylander K, Nilsson C. High resilience of bryophyte assemblages in streamside compared to upland forests. Ecology. 2009;90:1042–54.

226. Fahey RT, Bialecki MB, Carter DR. Tree growth and resilience to extreme drought across an urban land-use gradient. Arboric Urban For. 2013;39:279–85.

227. Fahey RT, Fotis AT, Woods KD. Quantifying canopy complexity and effects on productivity and resilience in late- successional hemlock — hardwood forests. Ecol Appl. 2015;25:834–47.

228. Fernandez-Manso A, Quintano C, Roberts DA. Burn severity influence on post-fire vegetation cover resilience from Landsat MESMA fraction images time series in Mediterranean forest ecosystems. Remote Sens Environ [Internet]. Elsevier Inc.; 2016;184:112–23. Available from: http://dx.doi.org/10.1016/j.rse.2016.06.015

229. García-Romero A, Oropeza-Orozco O, Galicia-Sarmiento L. Land-use systems and

resilience of tropical rain forests in the Tehuantepec Isthmus, Mexico. Environ Manage. 2004;34:768–85.

230. Gazol A, Camarero JJ. Functional diversity enhances silver fir growth resilience to an extreme drought. J Ecol. 2016;104:1063–75.

231. George JP, Grabner M, Karanitsch-Ackerl S, Mayer K, Weißenbacher L, Schueler S. Genetic variation, phenotypic stability, and repeatability of drought response in European larch throughout 50 years in a common garden experiment. Tree Physiol. 2017;37:33–46.

232. González-De Vega S, De las Heras J, Moya D. Resilience of Mediterranean terrestrial ecosystems and fire severity in semiarid areas: Responses of Aleppo pine forests in the short, mid and long term. Sci Total Environ [Internet]. Elsevier B.V.; 2016;573:1171–7. Available from: http://dx.doi.org/10.1016/j.scitotenv.2016.03.115

233. Abella SR, Fornwalt PJ. Ten years of vegetation assembly after a North American mega fire. Glob Chang Biol. 2015;21:789–802.

234. Hancock MH, Legg CJ. Diversity and stability of ericaceous shrub cover during two disturbance experiments: one on heathland and one in forest. Plant Ecol Divers. 2012;5:275–87.

235. Heer K, Behringer D, Piermattei A, Bässler C, Brandl R, Fady B, et al. Linking dendroecology and association genetics in natural populations: Stress responses archived in tree rings associate with SNP genotypes in silver fir (Abies alba Mill.). Mol Ecol. 2018;27:1428–38.

236. Heinimann HR. A concept in adaptive ecosystem management-An engineering perspective. For Ecol Manage. 2010;259:848–56.

237. Helman D, Lensky IM, Yakir D, Osem Y. Forests growing under dry conditions have higher hydrological resilience to drought than do more humid forests. Glob Chang Biol. 2017;23:2801–17.

238. Herrero A, Zamora R. Plant responses to extreme climatic events: A field test of resilience capacity at the southern range edge. PLoS One. 2014;9:1–12.

239. Hirota M, Holmgren M, Van Nes EH, Scheffer M. Global Resilience of Tropical Forest. Science (80-) [Internet]. 2011;334:232–5. Available from: http://www.sciencemag.org/content/334/6053/232.short

240. Hoffmann N, Schall P, Ammer C, Leder B, Vor T. Drought sensitivity and stem growth variation of nine alien and native tree species on a productive forest site in Germany. Agric For Meteorol. 2018;256–257:431–44.

241. Huang W, Fonti P, Larsen JB, Ræbild A, Callesen I, Pedersen NB, et al. Projecting tree-growth responses into future climate: A study case from a Danish-wide common garden. Agric For Meteorol [Internet]. Elsevier; 2017;247:240–51. Available from: http://dx.doi.org/10.1016/j.agrformet.2017.07.016

242. Jacobs BF. Restoration of degraded transitional (piñon-juniper) woodland sites improves ecohydrologic condition and primes understory resilience to subsequent disturbance. Ecohydrology. 2015;8:1417–28.

243. Jacquet K, Prodon R. Measuring the postfire resilience of a bird-vegetation system: A 28-year study in a Mediterranean oak woodland. Oecologia. 2009;161:801–11.

244. Acuña V, Giorgi A, Muñoz I, Sabater F, Sabater S. Meteorological and riparian influences on organic matter dynamics in a forested Mediterranean stream. J North Am Benthol Soc. 2007;26:54–69.

245. Johnstone JF, McIntire EJB, Pedersen EJ, King G, Pisaric MJF. A sensitive slope: Estimating landscape patterns of forest resilience in a changing climate. Ecosphere. 2010;1.

246. Julio Camarero J, Gazol A, Sangüesa-Barreda G, Cantero A, Sánchez-Salguero R, Sánchez-Miranda A, et al. Forest Growth Responses to Drought at Short- and Long-Term Scales in Spain: Squeezing the Stress Memory from Tree Rings. Front Ecol Evol [Internet]. 2018;6:1–11. Available from: http://journal.frontiersin.org/article/10.3389/fevo.2018.00009/full

247. Karavani A, Boer MM, Baudena M, Colinas C, Díaz-Sierra R, Pemán J, et al. Fire-induced deforestation in drought-prone Mediterranean forests: drivers and unknowns from leaves to communities. Ecol Monogr. 2018;88:141–69.

248. Keyser TL, Brown PM. Drought response of upland oak (Quercus L.) species in Appalachian hardwood forests of the southeastern USA. Ann For Sci [Internet]. Annals of Forest Science; 2016;73:971–86. Available from: http://dx.doi.org/10.1007/s13595-016-0575-0

249. Kipfer T, Moser B, Egli S, Wohlgemuth T, Ghazoul J. Ectomycorrhiza succession patterns in Pinus sylvestris forests after stand-replacing fire in the Central Alps. Oecologia. 2011;167:219–28.

250. Kunz J, Löffler G, Bauhus J. Minor European broadleaved tree species are more drought-tolerant than Fagus sylvatica but not more tolerant than Quercus petraea. For Ecol Manage. 2018;414:15–27.

251. Larson AJ, Lutz JA, Gersonde RF, Franklin JF, Hietpas FF. Potential site productivity influences the rate of forest structural development. Ecol Appl. 2008;18:899–910.

252. Lawrence D, Radel C, Tully K, Schmook B, Schneider L. Untangling a decline in tropical forest resilience: Constraints on the sustainability of shifting cultivation across the globe. Biotropica. 2010;42:21–30.

253. Leão TCC, Lobo D, Scotson L. Economic and Biological Conditions Influence the Sustainability of Harvest of Wild Animals and Plants in Developing Countries. Ecol Econ. 2017;140:14–21.

254. Lebrija-trejos AE, Bongers F, Pérez-garcía EA, Meave JA, Lebrija-trejos E, Ciencias F De, et al. Successional Change and Resilience of a Very Dry Tropical Deciduous Forest following Shifting Agriculture Successional Change and Resilience of a Very Dry Tropical Deciduous Forest Following Shifting Agriculture. Biotropica. 2008;40:422–31.

255. Aikio S. The contribution of direct and indirect flows to the resilience of element cycles. Acta Oecologica. 2004;26:129–35.

256. Leite M de S, Tambosi LR, Romitelli I, Metzger JP. Landscape ecology perspective in restoration projects for biodiversity conservation: A review. Nat a Conserv. 2013;11:108–18.

257. Lin TC, Hamburg SP, Lin KC, Wang LJ, Chang C Te, Hsia YJ, et al. Typhoon Disturbance and Forest Dynamics: Lessons from a Northwest Pacific Subtropical Forest. Ecosystems. 2011;14:127–43.

258. Lloret F, Siscart D, Dalmases C. Canopy recovery after drought dieback in holm-oak

Mediterranean forests of Catalonia (NE Spain). Glob Chang Biol. 2004;10:2092–9.

259. Lloret F, Estevan H, Vayreda J, Terradas J. Fire regenerative syndromes of forest woody species across fire and climatic gradients. Oecologia. 2005;146:461–8.

260. Long JN, Windmuller-Campione M, De Rose RJ. Building resistance and resilience: Regeneration should not be left to chance. Forests. 2018;9:1–12.

261. Lopez-Toledo L, Anten NPR, Endress BA, Ackerly DD, Martínez-Ramos M. Resilience to chronic defoliation in a dioecious understorey tropical rain forest palm. J Ecol. 2012;100:1245–56.

262. Lucash MS, Scheller RM, J. Gustafson E, R. Sturtevant B. Spatial resilience of forested landscapes under climate change and management. Landsc Ecol. Springer Netherlands; 2017;32:953–69.

263. Madrigal-González J, Herrero A, Ruiz-Benito P, Zavala MA. Resilience to drought in a dry forest: Insights from demographic rates. For Ecol Manage. 2017;389:167–75.

264. Malinga GM, Valtonen A, Nyeko P, Roininen H. High resilience of galling insect communities to selective and clear-cut logging in a tropical rainforest. Int J Trop Insect Sci. 2014;34:277–86.

265. Marqués L, Camarero JJ, Gazol A, Zavala MA. Drought impacts on tree growth of two pine species along an altitudinal gradient and their use as early-warning signals of potential shifts in tree species distributions. For Ecol Manage. 2016;381:157–67.

266. Andivia E, Natalini F, Fernández M, Alejano R, Vázquez-Piqué J. Contrasting holm oak provenances show different field performance but similar resilience to drought events eight years after planting in a mediterranean environment. IForest. 2018;11:259–66.

267. Martínez-Yrízar A, Jaramillo VJ, Maass M, Búrquez A, Parker G, Álvarez-Yépiz JC, et al. Resilience of tropical dry forest productivity to two hurricanes of different intensity in western Mexico. For Ecol Manage. 2018;426:53–60.

268. Matusick G, Ruthrof KX, Fontaine JB, Hardy GESJ. Eucalyptus forest shows low structural resistance and resilience to climate change-type drought. J Veg Sci. 2016;27:493–503.

269. McLaren KP, McDonald MA. Coppice regrowth in a disturbed tropical dry limestone forest in Jamaica. For Ecol Manage. 2003;180:99–111.

270. Merlin M, Perot T, Perret S, Korboulewsky N, Vallet P. Effects of stand composition and tree size on resistance and resilience to drought in sessile oak and Scots pine. For Ecol Manage. 2015;339:22–33.

271. Moretti M, Duelli P, Obrist MK. Biodiversity and resilience of arthropod communities after fire disturbance in temperate forests. Oecologia. 2006;149:312–27.

272. Na-U-Dom T, Garcia M, Mo X. Ecosystem Resilience to Drought and Temperature Anomalies in the Mekong River Basin. IOP Conf Ser Earth Environ Sci. 2017;68:12012–7.

273. Navarro-Cerrillo RM, Rodriguez-Vallejo C, Silveiro E, Hortal A, Palacios-Rodríguez G, Duque-Lazo J, et al. Cumulative drought stress leads to a loss of growth resilience and explains higher mortality in planted than in naturally regenerated Pinus pinaster stands. Forests. 2018;9:1–18.

274. O'Brien MJ, Ong R, Reynolds G. Intra-annual plasticity of growth mediates drought

resilience over multiple years in tropical seedling communities. Glob Chang Biol. 2017;23:4235–44.

275. O'Hara KL. Multiaged forest stands for protection forests: concepts and applications. For Snow Landsc Res. 2006;80:45–55.

276. O'Hara KL, Ramage BS. Silviculture in an uncertain world: Utilizing multi-aged management systems to integrate disturbance. Forestry. 2013;86:401–10.

277. Andivia E, Madrigal-González J, Villar-Salvador P, Zavala MA. Do adult trees increase conspecific juvenile resilience to recurrent droughts? Implications for forest regeneration. Ecosphere [Internet]. 2018;9:e02282. Available from: http://doi.wiley.com/10.1002/ecs2.2282

278. Pérez-Ramos IM, Zavala MA, Marañón T, Díaz-Villa MD, Valladares F. Dynamics of understorey herbaceous plant diversity following shrub clearing of cork oak forests: A five-year study. For Ecol Manage. 2008;255:3242–53.

279. Pilaš I, Medved I, Medak J, Medak D. Response strategies of the main forest types to climatic anomalies across Croatian biogeographic regions inferred from FAPAR remote sensing data. For Ecol Manage. 2014;326:58–78.

280. Poorter L, Bongers F, Aide TM, Almeyda Zambrano AM, Balvanera P, Becknell JM, et al. Biomass resilience of Neotropical secondary forests. Nature [Internet]. Nature Publishing Group; 2016;530:211–4. Available from: http://dx.doi.org/10.1038/nature16512

281. Pretzsch H, Schütze G, Uhl E. Resistance of European tree species to drought stress in mixed versus pure forests: Evidence of stress release by inter-specific facilitation. Plant Biol. 2013;15:483–95.

282. Príncipe A, van der Maaten E, van der Maaten-Theunissen M, Struwe T, Wilmking M, Kreyling J. Low resistance but high resilience in growth of a major deciduous forest tree (Fagus sylvatica L.) in response to late spring frost in southern Germany. Trees - Struct Funct. 2017;31:743–51.

283. Proença V, Pereira HM, Vicente L. Resistance to wildfire and early regeneration in natural broadleaved forest and pine plantation. Acta Oecologica [Internet]. Elsevier Masson SAS; 2010;36:626–33. Available from: http://dx.doi.org/10.1016/j.actao.2010.09.008

284. Rais A, van de Kuilen JWG, Pretzsch H. Growth reaction patterns of tree height, diameter, and volume of Douglas-fir (Pseudotsuga menziesii [Mirb.] Franco) under acute drought stress in Southern Germany. Eur J For Res. 2014;133:1043–56.

285. Reiners WA, Driese KL, Fahey TJ, Gerow KG. Effects of Three Years of Regrowth Inhibition on the Resilience of a Clear-cut Northern Hardwood Forest. Ecosystems. 2012;15:1351–62.

286. Reis SM, de Oliveira EA, Elias F, Gomes L, Morandi PS, Marimon BS, et al. Resistance to fire and the resilience of the woody vegetation of the "Cerradão" in the "Cerrado"–Amazon transition zone. Rev Bras Bot. 2017;40:193–201.

287. Riva MJ, Liniger H, Valdecantos A, Schwilch G. Impacts of land management on the resilience of mediterranean dry forests to fire. Sustain. 2016;8.

288. Balint PJ, Stewart RE, Desai A, Walters LC. Wicked Environmental Problems. Washington DC, USA: Island Press; 2011.

289. Müller F, Bergmann M, Dannowski R, Dippner JW, Gnauck A, Haase P, et al. Assessing

resilience in long-term ecological data sets. Ecol Indic [Internet]. Elsevier Ltd; 2016;65:10–43. Available from: http://dx.doi.org/10.1016/j.ecolind.2015.10.066

290. Brand FS, Jax K. Focusing the meaning(s) of resilience: Resilience as a descriptive concept and a boundary object. Ecol Soc. 2007;12.

291. Weichselgartner J, Kelman I. Geographies of resilience: Challenges and opportunities of a descriptive concept. Prog Hum Geogr. 2015;39:249–67.

292. Brown K. Global environmental change I: A social turn for resilience? Prog Hum Geogr. 2014;38:107–17.

293. Cote M, Nightingale AJ. Resilience thinking meets social theory: Situating social change in socio-ecological systems (SES) research. Prog Hum Geogr. 2012;36:475–89.

294. Olsson L, Jerneck A, Thoren H, Persson J, O'Byrne D. Why resilience is unappealing to social science: Theoretical and empirical investigations of the scientific use of resilience. Sci Adv. 2015;1:1–12.

295. Steffen W, Rockström J, Richardson K, Lenton TM, Folke C, Liverman D, et al. Trajectories of the Earth System in the Anthropocene. Proc Natl Acad Sci U S A. 2018;115:8252–9.

296. Rist L, Felton A, Nyström M, Troell M, Sponseller RA, Bengtsson J, et al. Applying resilience thinking to production ecosystems. Ecosphere. 2014;5:1–11.

297. Folke C, Carpenter SR, Walker B, Scheffer M, Chapin T, Rockström J. Resilience thinking: Integrating resilience, adaptability and transformability. Ecol Soc. 2010;15.

298. Gunderson LH. ECOLOGICAL RESILIENCE-IN THEORY AND APPLICATION. Annu Rev Ecol Syst. 2000;31:425–39.

299. Verstraeten G, Vancampenhout K, Desie E, De Schrijver A, Hlava J, Schelfhout S, et al. Tree species effects are amplified by clay content in acidic soils. Soil Biol Biochem [Internet]. Elsevier; 2018;121:43–9. Available from: https://doi.org/10.1016/j.soilbio.2018.02.021

300. Scheffer M, Hirota M, Holmgren M, Van Nes EH, Chapin FS. Thresholds for boreal biome transitions. Proc Natl Acad Sci [Internet]. 2012;109:21384–9. Available from: http://www.pnas.org/cgi/doi/10.1073/pnas.1219844110

301. Hirota M, Holmgren M, Van Nes EH, Scheffer M. Global Resilience of Tropical Forest and Savanna to Critical Transitions. Science (80-) [Internet]. 2011;334:232 LP – 235. Available from: http://science.sciencemag.org/content/334/6053/232.abstract

302. Carpenter S, Walker B, Anderies JM, Abel N. From Metaphor to Measurement: Resilience of What to What? Ecosystems. 2001;4:765–81.

303. Wolfslehner B, Vacik H. Evaluating sustainable forest management strategies with the Analytic Network Process in a Pressure-State-Response framework. J Environ Manage. 2008;88:1–10.

304. Yousefpour R, Bredahl Jacobsen J, Thorsen BJ, Meilby H, Hanewinkel M, Oehler K. A review of decision-making approaches to handle uncertainty and risk in adaptive forest management under climate change. Ann For Sci. 2012;69:1–15.

305. ISO I. Risk management–Principles and guidelines. Int Organ Stand Geneva, Switz. 2009;

306. Hanewinkel M, Hummel S, Albrecht A. Assessing natural hazards in forestry for risk management: a review. Eur J For Res. 2011;130:329–51.

307. Park J, Seager TP, Rao PSC. Lessons in risk- versus resilience-based design and management. Integr Environ Assess Manag. 2011;7:396–9.

308. Messier C, Puettmann K, Chazdon R, Andersson KP, Angers VA, Brotons L, et al. From Management to Stewardship: Viewing Forests As Complex Adaptive Systems in an Uncertain World. Conserv Lett. 2015;8:368–77.

309. Biggs R, Schlüter M, Biggs D, Bohensky EL, BurnSilver SB, Cundill G, et al. Toward Principles for Enhancing the Resilience of Ecosystem Services. Ssrn. 2012;

310. Chapin FS, Carpenter SR, Kofinas GP, Folke C, Abel N, Clark WC, et al. Ecosystem stewardship: sustainability strategies for a rapidly changing planet. Trends Ecol Evol. 2010;25:241–9.

311. Hosseini S, Barker K, Ramirez-Marquez JE. A review of definitions and measures of system resilience. Reliab Eng Syst Saf. 2016;145:47–61.

312. Roostaie S, Nawari N, Kibert CJ. Sustainability and resilience: A review of definitions, relationships, and their integration into a combined building assessment framework. Build Environ [Internet]. Elsevier; 2019;154:132–44. Available from: https://doi.org/10.1016/j.buildenv.2019.02.042