FACULTY OF BIOSCIENCE ENGINEERING
DEPARTMENT OF EARTH AND ENVIRONMANTAL SCIENCES
DIVISION OF FOREST, NATURE AND LANDSCAPE
Celestijnenlaan 200E
B-3001 HEVERLEE, BELGIUM
tel. + 32 16 32 00800
laura.nikinmaa@kuleuven.be
www.kuleuven.be

Laura Nikinmaa

ENHANCING THE RESILIENCE OF EUROPEAN FORESTS
FROM CONCEPT TO FOREST MANAGEMENT APPLICATION

August 2022

KU LEUVEN

ARENBERG DOCTORAL SCHOOL
FACULTY OF BIOSCIENCE ENGINEERING

Enhancing the resilience of European forests

From concept to forest management application

Laura Nikinmaa

Supervisor(s):
Prof. Dr. ir. Bart. Muys, KU Leuven
Dr. Marcus Lindner, EFI

Dissertation presented in partial fulfilment of the requirements for the degree of Doctor in Bioscience Engineering
August 2022

ENHANCING THE RESILIENCE OF EUROPEAN FORESTS:
From concept to forest management application

Laura NIKINMAA

Supervisor:
Prof. Dr. ir. Bart. Muys, KU Leuven

Co-supervisor:
Dr. Marcus Lindner, EFI

Members of the Examination Committee:
Prof. Dr. ir. Johan Buyse (Chairman), KU Leuven
Prof. Dr. Constanza Parra Novoa, KU Leuven
Prof. Dr. ir. Rupert Seidl, TUM
Prof. Dr. ir. Anne Gobin, KU Leuven
Prof. Dr. Annikki Mäkelä, UH

Dissertation presented in partial fulfilment of the requirements for the degree of Doctor in Bioscience Engineering

August 2022

Doctoraatsproefschrift nr. 1799 aan de faculteit Bio-ingenieurswetenschappen van de KU Leuven

Uitgegeven in eigen beheer, Laura Nikinmaa, Joensuu, Finland

Acknowledgements

When my PhD journey started in June 2018, I could not imagine that in the next four years that I would face a pandemic with lockdowns, a war in Europe, a move back home and a joy of raising my own puppy. Now four years later I am at the end of my doctoral research journey. While I have been working hard, I would not have been able to come where I am now without the help and support of multiple people.

First and foremost, I would like to thank Marcus. I don't think you realise how meaningful and important it was for me to be able to join EFI Bonn in the spring of 2017 after the immense personal loss. I would not have been able to finish this quickly without you. During these five years you have continuously supported me and believed in me even when I myself was doubtful of my capacities. Thanks for all the discussions, both professional and private, for your interest in both my work and well-being and most of all for always championing for me. I could not have wished for a better supervisor.

I would also like to thank Bart for your support and encouragement during my PhD journey. You welcomed me to KU Leuven and made me feel that I belong there even if I could not be there often. You pushed me to aim high and reach for excellency without stressing me. Thank you for always making time for me when I was in the campus, for your advice, and for your kindness.

It takes a village to raise a child and it takes a community to make a doctor. My community has been EFI, and I'd like to thank the German Federal Ministry of Agriculture, the RESONATE and I-Maestro projects, and the Finnish Cultural Foundation for providing the funding for me to conduct my research there. I feel incredibly fortunate to have been able to work at EFI and befriend the staff during my PhD. While all the staff at EFI has been a great support, I would like to give a special thanks to the people at EFI Bonn with who became my surrogate family in Germany and with whom I have laughed until I cried, had the most amazing Christmas parties and other outings and the most heartfelt discussions, both professionally and personally. Thank you everyone! Special thanks to Gabriela for creating the figures in my chapter 3. I'd also like to give a special thanks to EFI HQ for welcoming me so warmly to Joensuu. I felt at home straight away!

To my colleagues in KU Leuven, thank you for always warmly welcoming me whenever I would come for a visit and all your help with the practicalities of the university administration. You have always been very kind to me even if I could not be there physically very often.

I owe a great thank you to all the co-authors without whom this thesis would not have been possible. Thank you for teaching me the ways of research and helping me on every step of the way. I'd especially like to thank Annemiek, from whom I learned a great deal about not only technical parts of the research but also about the mentality. You have supported me so much during these past years but also told me when I needed to step up in my efforts, which helped me to grow a lot as a researcher. I'm very grateful for that.

Besides work and research, many other people have supported me along the journey. Karen, thanks for the travels together and being my trusted translator! It has been a great pleasure to explore new regions with you and take a break from the PhD from time to time. Satulotta and Eeva, thank you for being there for me remotely when it was not physically possible and always supporting me with your encouragements. Anna, what is there to say, you are and have always been my pillar to lean on. You know how important you are to me. My girls from Tervalampi and high school, thanks for being my roots and the unwavering friendship through the years! To the clan Fontell, thank you for being the family I always want to come back to. Miika, Sakke, Reetta and Minna, thanks for the encouragement, the laughs, the support, and the intense Whatsapp debates! It's a blessing to be your sister. Rafael, Elja, and Linnea, I'm so proud to be your aunt! Thank you for always making my days brighter. Mom, I would not be here without you. Thank you for always putting up with my frustration and struggles, for supporting me, and for always being there for me. Finally, Rilla, Paavo, Taica, and Mimmi, thank you for giving me the joy and comfort only a pet can give.

Lastly, I want to thank my father Eero who passed away before I could start my PhD journey but who had set the seed for curiosity and passion for research in me from the start. I missed you very much during this journey and would have hoped for you to be there with me in person. But I could feel you were there in spirit in every step of this journey. This is for you. Thank you for everything.

Laura

Summary

Enhancing the resilience of the forests has become increasingly more important as climate changes and disturbances become more severe and frequent. Disturbances such as drought, bark beetle and fires are causing excessive tree mortality across Europe. Resilience is seen as an answer to improve the capacity of forests to persist despite disturbances and adapt to climate change. New policies demand measures to increase forest resilience to ensure the provision of crucial ecosystem services to facilitate the transition from fossil-based to bio-based economy. However, resilience is a debated concept with multiple definitions in science ranging from simple deterministic ones to more complex ones. The variety of definitions has led to a lack of common metrics for measurement. The ambiguity in how to define and measure resilience makes it difficult for forest owners and managers to implement the concept in their forest management. There is a dire need to make resilience more operationalised to help the forests to better cope with climate change and the increased disturbances.

In this research, we addressed the knowledge gap in how to operationalise resilience in forest management by providing for a frame for navigating the different definitions and giving examples on how they can be measured. To do this, we first reviewed how the concept is used in forest sciences in terms of definition and measurements. In the literature, three main resilience concepts dominate: engineering resilience ("recovery of a previous state"), ecological resilience ("remaining within the prevailing system domain through maintaining important ecosystem processes and functions") and social-ecological resilience ("the capacity to reorganize and adapt through multi-scale interactions between social and ecological components of the system). We examined how similar the three concepts were by analysing the types of research settings these three definitions were used, how they were assessed, and what indicators were used. Then we developed a Principle, Criteria, and Indicator -framework to help forest managers to identify how forest management objectives and trade-offs influence resilience and how the trade-offs could be balanced to achieve more resilient forest. In addition, we analysed the use of high-resolution dendrometers as a tool for monitoring tree stress and resilience to drought. Finally, we explored how the science-practice interphase in forest management could be improved to facilitate the transferring of the scientific knowledge on how to improve resilience to disturbances into practical forest management.

We found that the different definitions of resilience are not contrasting but rather complimentary to one another and form a nested hierarchy where engineering resilience is nested inside ecological resilience, which in turn is nested inside the social-ecological resilience. Their use depends on the complexity of the researched system with engineering resilience used for simple systems and ecological and social-ecological resilience for more complex ones. Therefore, instead of debating on the correct definition to use, forest managers should carefully determine of what part of the forest or forest

value chain, to what they need to increase the resilience to, and who are likely to be influenced by their decisions. We were furthermore able to show with the developed framework that the forest management goals influence the trade-offs in forest management and the level of resilience of forest and the surrounding society, indicating that the steps to achieve resilient forest differ depending on the management goal. In addition, the results showed that high-resolution dendrometers have the potential to inform forest managers on the stress and resilience of trees, however more research is still needed before the tool is useful in the practical management level. Lastly, we found that while the science-practice interphase is valued by the forest professionals, there is in some cases weak evidence for the effectiveness of the forest management measures proposed by forest professionals. Moreover, many forest professionals face considerable barriers in implementing resilience into forest management.

To conclude, the research we conducted provided remarkable advances on operationalising resilience into forest management. Our results showed that resilience can be implemented into forest management with a variety of forest management goals. The future research should focus on developing, together with practitioners, resilience indicators for forests under different management regimes across Europe. Moreover, efforts to study the impacts of different forest management measures on resilience to disturbances should be increased. However, forest-related policies and management practices should already proceed to incorporate measures to enhance resilience of forests to ensure the provisioning of ecosystem services.

Samenvatting

De veerkracht van bossen vergroten, is steeds belangrijker geworden naarmate de veranderingen en verstoringen van het klimaat ernstiger en frequenter worden. Verstoringen zoals droogte, letterzetters en branden veroorzaken uitzonderlijk hoge boomsterfte. Veerkracht wordt als antwoord gezien om het vermogen van bossen om stand te houden ondanks verstoringen en aan te passen aan klimaatsverandering, te verbeteren. Nieuw beleid vereist maatregelen om de veerkracht van bossen te vergroten en zo de levering van cruciale ecosysteemdiensten te garanderen. Bovendien kan zo ook de overgang van een fossiele economie naar een economie gebaseerd op biologische brandstoffen vereenvoudigd worden. Veerkracht is echter een omstreden begrip met tal van definities in de wetenschap. De verscheidenheid aan definities heeft geleid tot een gebrek aan algemene meetmethoden. De onduidelijkheid over hoe veerkracht gedefinieerd en gemeten moet worden, maakt het moeilijk voor boseigenaars en -beheerders om het concept in bosbeheer te implementeren. Er is dringend nood om het concept veerkracht in de praktijk te brengen om bossen te helpen om beter aan klimaatsverandering en verstoringen te weerstaan.

In dit onderzoek hebben we het gebrek aan kennis over het operationaliseren van veerkracht in bosbeheer aangepakt door een algemeen kader te scheppen. In dit kader worden de verschillende definities doorgrond en worden voorbeelden gegeven van hoe ze kunnen worden gemeten. Hiervoor hebben we eerst bekeken hoe het concept in bosonderzoek wordt gebruikt op het gebied van definities en metingen. In de literatuur overheersen drie belangrijke veerkrachtconcepten: engineering veerkracht ("herstel van een vorige toestand"), ecologische veerkracht ("binnen het heersende systeemdomein blijven door belangrijke ecosysteemprocessen en -functies te behouden") en socio-ecologische veerkracht ("het vermogen om te reorganiseren en zich aan te passen via multi-scale interacties tussen sociale en ecologische onderdelen van het systeem"). Wij hebben onderzocht in welke mate de drie concepten op elkaar lijken door te analyseren in welke soorten onderzoekssettings deze drie definities werden gebruikt, hoe ze werden beoordeeld en welke indicatoren werden gebruikt. Vervolgens hebben we een ‘Principle, Criteria, and Indicator’ -kader ontwikkeld om bosbeheerders te helpen met het evalueren hoe de veerkracht beïnvloed wordt door bosbeheerdoelstellingen en trade-offs. Bovendien kunnen ook de trade-offs worden afgewogen om veerkrachtigere bossen te realiseren. Verder hebben we het gebruik van hoge resolutie dendrometers geëvalueerd als een meetinstrument voor het monitoren van stress bij bomen en de weerbaarheid tegen droogte. Ten slotte hebben we onderzocht hoe de interactie tussen wetenschap en praktijk in bosbeheer kan worden verbeterd. Dit heeft als uiteindelijke doel om de overdracht van kennis, inzake het verhogen van veerkracht tegen verstoringen, naar het bosbeheer in de praktijk te vergemakkelijken.

We hebben vastgesteld dat de drie veelgebruikte veerkrachtconcepten elkaar niet tegenspreken, maar eerder complementair zijn en een geneste hiërarchie vormen waarin 'engineering' veerkracht in ecologische veerkracht genest is, wat op zijn beurt in socio-ecologische veerkracht genest is. Het gebruik hangt van de complexiteit van het onderzochte systeem af, waarbij 'engineering' veerkracht voor simpele systemen en ecologische en socio-ecologische veerkracht voor meer complexe gebruikt worden. In plaats van te discussiëren over welke definitie gebruikt moet worden, moeten bosbeheerders daarom zorgvuldig bepalen welk deel van het bos of de sector ze managen, waarvoor ze de veerkracht moeten vergroten, en wie waarschijnlijk door hun beslissingen zal worden beïnvloed. Bovendien konden we met het ontwikkelde framework vaststellen dat de afwegingen in het bosbeheer en het veerkrachtniveau van het bos en de maatschappij rondom door bosbeheerdoelstellingen beïnvloed worden. Dit toont aan dat de stappen die nodig zijn om een veerkrachtig bos te bereiken, verschillen op basis van het beheersdoel. Daarnaast tonen de resultaten dat dendrometers met hoge resolutie potentieel hebben om bosbeheerders te informeren over de stress en veerkracht van boven bij droge omstandigheden. Er is echter meer onderzoek nodig voor de tool in de praktijk gebruikt kan worden. Ten slotte hebben we vastgesteld dat, hoewel de interactie tussen wetenschap en praktijk door de bosbouwprofessionals wordt gewaardeerd, er in sommige gevallen weinig bewijs is voor de doeltreffendheid van de beheermaatregelen die door de bosbouwprofessionals voorgesteld worden. Bovendien ondervinden veel bosprofessionals aanzienlijke drempels bij het implementeren van veerkracht in bosbeheer.

Als conclusie kan worden gesteld dat het onderzoek dat we hebben uitgevoerd opmerkelijke vooruitgang heeft geboekt bij het operationaliseren van veerkracht in bosbeheer. Onze resultaten toonden aan dat veerkracht kan worden geïmplementeerd in bosbeheer met een verscheidenheid aan bosbeheerdoelstellingen en -strategieën. Toekomstig onderzoek moet zich toespitsen op de ontwikkeling, samen met praktijkmensen, van veerkrachtindicatoren voor bossen onder verschillende beheersregimes is heel Europa. Daarenboven moeten de inspanningen worden uitgebreid om de effecten van verschillende bosbeheersmaatregelen op de veerkracht tegen verstoringen te bestuderen. In het beleid en de beheerspraktijken met betrekking tot bossen moeten echter nu al maatregelen worden genomen om de veerkracht van bossen te vergroten, zodat de verlening van ecosysteemdiensten gegarandeerd blijft.

Contents

List of Abbreviations

AIC	Akaike Information Criterion
BMEL	German Federal Ministry of Food and Agriculture
E-OBS	A daily gridded observational dataset for precipitation, temperature, sea level pressure, relative humidity, wind speed and global radiation in Europe
EU	European Union
GLMM	Generalized Linear Mixed Effects Model
IPCC	International Panel for Climate Change
LULUCF	Land use, land-use change and forestry
NGO	Non-Governmental Organization
NMDS	Non-Metric Multidimensional Scaling
OECD	Organization for Economic Co-operation and Development
PCI	Principle, Criteria, and Indicators
PSR	Pressure-State-Response
SPEI	Standardized Precipitation Evapotranspiration Index
TWD	Tree Water Deficit
VPD	Vapour Pressure Deficit

List of Figures

Chapter 1

Chapter 2

Chapter 3

Chapter 4

Chapter 5

Appendix B

Appendix D

List of Tables

Chapter 2

Chapter 3

Chapter 4

Appendix B

Appendix C

Appendix D

1 Introduction

"You certainly usually find something, if you look, but it is not always quite the something you were after."

J.R.R Tolkien, The Hobbit, or There and Back Again

Forests are tectonic to the functioning of the biosphere and the society. They cover 31 % of the land globally (FAO and UNEP 2020) and more than one third in Europe (FOREST EUROPE 2020a). Forests are part of the planetary water and carbon regime (Bonan 2008), are the largest singular terrestrial habitat type (Jung et al. 2020), and provide multiple ecosystem services to the society, ranging from raw material to cultural experiences. However, the continuation of the forest functions is under threat (Trumbore et al. 2015). In the epoch of Anthropocene, human caused phenomena such as climate change and spread of invasive species to new areas are challenging the capacity of forests to continue to function as they have so far (Steffen et al. 2018). Simultaneously, forests have a key role in mitigating and adapting to climate change and loss of biodiversity (Thompson et al. 2009). Forests sequester carbon from the atmosphere, wood-based material can be used to replace fossil-based ones, and forests are the habitat for numerous endangered and declining species. According to several authors, maintaining and increasing the *resilience* of forests in the face of global changes is of utmost importance (Messier et al. 2021; Reyer et al. 2015a; Seidl, et al. 2016a). However, the exact meaning of resilience and how it can be brought into practice remains debated.

1.1 Resilience: evolution of the concept

Resilience is a popular concept without a single definition that is used in a large variety of research fields (Folke 2016). In the climate change policy context, resilience is often linked together with risk, hazards, vulnerability, exposure, and adaptive capacity and is considered to be a positive attribute of the coupled social-ecological system that maintains the capacity of a system to function, adapt and transform (IPCC 2022). In this context, resilience can be seen as an outcome of reducing the vulnerability and exposure of a system to hazards by adaptation and the consequent reduction of risks. In ecology, several definitions of the concept continue to coexist, causing conceptual ambiguity in the use of the concept. The cause of the ambiguity is partly in the history of resilience. The concept has its roots in research on ecosystem stability, with two different schools emerging more or less simultaneously: one focusing on systems close to equilibrium and one focusing on the non-equilibrium behaviour of systems and alternative basins of attraction (Van Meerbeek et al. 2021).

The underlying assumption for equilibrium systems is the capacity to return to the stable state after a perturbation (Pimm 1984). The stability of the ecosystems is in turn described with different properties, notably resistance (the degree to which a variable is changed, following a perturbation) and resilience (how fast variables return towards their equilibrium following a perturbation) (Boesch 1974; Pimm 1984). In this context, it was explicitly noted that resilience is not defined for non-equilibrium ecosystems. Later, this definition of resilience as the rate with which the system goes back to the pre-disturbance state was often referred to as engineering resilience.

The other school focusing on non-equilibrium systems criticizes the assumption of ecosystems being in an equilibrium state (Holling 1973). Instead, ecosystems are considered to be in constant transient state far from thermodynamic equilibrium and with multiple basins of attraction (Gunderson 2000; Holling 1973). A basin of attraction describes how locally stable a system is and has often been illustrated with the ball-and-cup metaphor (Lamothe et al. 2019) where the ball represents the current ecosystem state and the different cups represent the alternative stable states or basins of attraction. A disturbance can push a system from one basin to another. The harder it is to move the ball to another cup, the more locally stable the ecosystem is. In this context, resilience is defined as the capacity of a system to absorb external disturbance without moving to another basin, as well as the ability to self-organize and build adaptive capacity (Holling 1973). This definition is often referred to as ecological resilience. Other underlying concepts for this type of resilience research are the concepts of adaptive cycles (Fig. 1.1) and panarchy (Fig. 1.2).

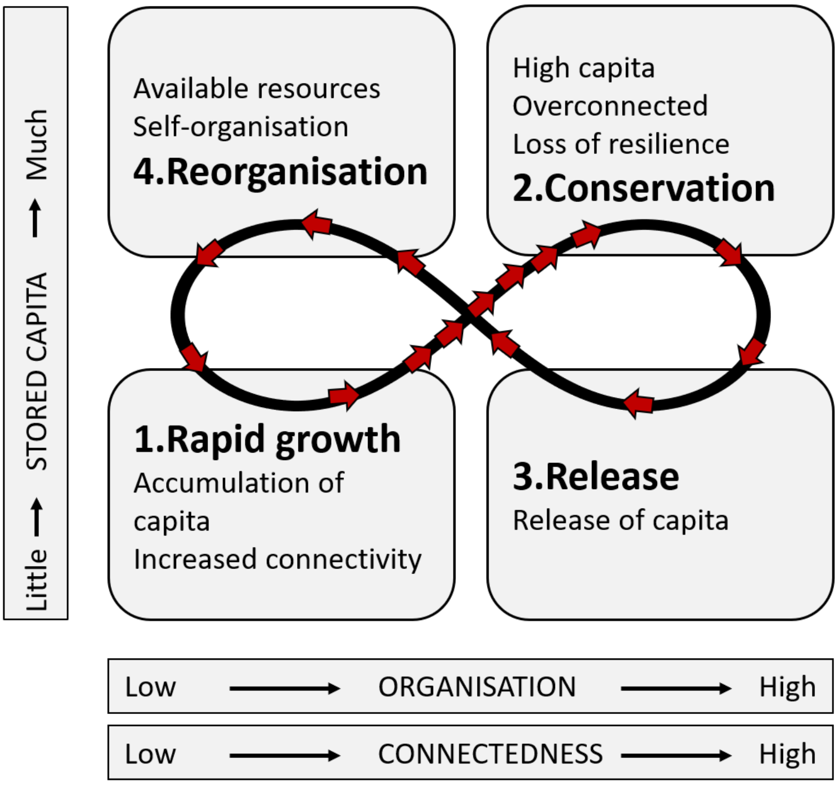


Figure 1.1. A simplified presentation of the adaptive cycle. The phases 1 and 2 represent the relatively predictable dynamics where material accumulates, and level of organisation and connectedness increases. The system becomes more rigid, which leads to loss of resilience. In phase 2, the system is fragile to large disturbances, which may enter the system to phase 3. The phases 3 and 4 are uncertain, novel phases where accumulated material is lost, and the system reorganizes itself. The x-axis shows the level of organization and connectedness whereas the y-axis shows the level of stored capita in the different phases. Modified from Holling (1986).

Adaptive cycles are nested transformative cycles with four phases: growth, conservation, release and reorganisation overlapping in a range of both temporal and spatial scales (Holling 1986). The phases of the adaptive cycles show how rapid growth and conservation accumulate capita and increase order and connectivity in a system leads to rigidity and over connectedness and therefore a loss of resilience, which is followed by release of capita and a phase of reorganisation and redistribution of resources (Holling 1986; Muys 2013).

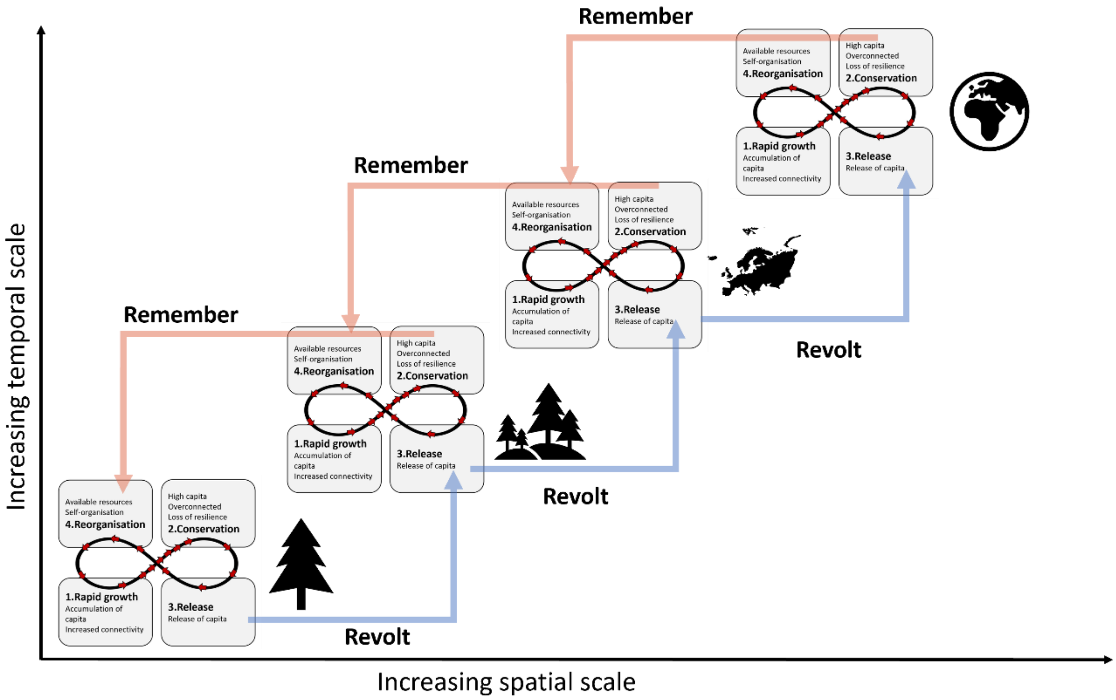


Figure 1.2. A simplified figure of panarchy, where the adaptive cycles in different temporal and spatial scales influence one another: cross-scale interactions influence the within scale phases of adaptive cycles. During the reorganisation (phase 4), the structures from higher scales may "remember" the system of the previous structures around which to reorganise rather than creating fully new structures. Similarly, the release at a given scale (phase 3) may influence the adaptive cycles of the higher scales, which some call "revolting" (Allen et al. 2014). The memory from higher scales keeps system stabile whereas revolting may lead to new, unpredictable system dynamics (Allen et al. 2014). Modified from Allen et al. (2014).

A panarchy is the hierarchical structure in which systems of nature and humans are interlinked in continuous adaptive cycles (Holling 2001). The hierarchies range from the cellular level to the biosphere in spatial scale and from seconds to millennia in temporal scales. The adaptive cycles influence one another across the scales and therefore changes in local and short-term scale may scale up to large scale disruptions and slow changes in the global scale may tribble down to the local scale in an abrupt manner (Holling 2001), leading to system tipping points (Scheffer, et al. 2012a). A tipping point is a phenomenon where a seemingly small change may lead to a runaway process causing big transitions in the system (van Nes et al. 2016), and therefore overcoming its resilience. The concept of tipping points is used often in research on the resilience of ecosystems to climate change (Albrich et al. 2020; Hirota et al. 2011; Staal et al. 2020). Tipping points may also cause the system to show hysteresis: the system will not return to its precedent state even if the conditions go back to the pre-tipping point values (Albrich et al. 2020). From the conceptualization of ecosystems as non-equilibrium systems in panarchy, research on ecosystem tipping points and *social-ecological resilience* has evolved (Van Meerbeek et al. 2021).

Yet another resilience concept is the social-ecological resilience, which evolved from the ecological resilience, and which has been increasingly more researched from the late 1990s and early 2000 when the research on resilience expanded from adaptive management of ecosystems to governing complex social-ecological systems (Folke 2016). The foundation of social-ecological resilience is a social-ecological system. Social-ecological systems are systems consisting of two equally important interacting biological and social subsystems (Cherkasskii 1988; Folke and Berkes 1998). The concept of social-ecological system emphasizes that people and their society is embedded in the biosphere where they shape ecosystems in all spatial and temporal scales (Folke 2016), meaning that the long-term prosperity of people is dependent on the stability of the biosphere. Social-ecological resilience emphasizes the capacity of social-ecological systems to transform with change in addition to absorbing or adapting to it (Reyers et al. 2018). It is defined as "the ability of people, communities, societies, or cultures to live and develop with change and with ever-changing environments. Social-ecological resilience is about cultivating the capacity to continue to develop in the face of change, incremental and abrupt, expected and surprising" (Folke 2016). The concept of social-ecological resilience is less of a system property to be measured and more a philosophy on how social-ecological systems should be managed and governed. It is often referred to as resilience thinking to distinguish from the research approaches aiming at quantifying resilience. This concept is often seen as a more suitable concept to respond to the challenges caused by the Anthropocene (Folke et al. 2021; Reyers et al. 2018).

1.2 Forest resilience: from trees to ecosystems to societies

While the exact meaning of resilience remains debated, the need to foster and increase resilience to forest disturbances is more agreed upon, as forests are under pressure from climate change and the increased disturbance severity and frequency (Seidl, et al. 2014a). Furthermore, a common understanding on the properties that underline the resilience of a system is developing. These so-called resilience mechanisms are functions that maintain ecosystem functioning and facilitate its resistance, recovery, and persistence. Recovery is defined as the process of the variable returning, after a disturbance, to the values of the reference state or dynamics (Weise et al. 2020). Persistence refers to the existence of a system through time as an identifiable unit (Holling 1973; Weise et al. 2020). By influencing resistance, recovery and persistence, the resilience mechanisms contribute to the resilience of the whole social-ecological system (Biggs et al. 2012; Oliver et al. 2015). This section expands on the impacts of changing forest disturbance regimes, the resilience mechanisms behind forest resilience, what they are and how they are present in the forests.

1.2.1 Changing forest disturbance regimes

The average global temperature has risen approximately 1°C since the pre-industrial times (IPCC 2018). The alteration of the global temperatures has significant effects on weather and subsequently impacts on forest disturbance regimes. Warm and dry conditions increase the probability of drought and forest fires whereas warm and wet conditions increase the probability of wind and pathogen damage (Seidl, et al. 2017a). Changes in disturbance regimes as well as land use change and other environmental drivers are pushing forests into younger and shorter stands (McDowell et al. 2020). Forest disturbances may catalyse the adaptation of the forests to the future environmental conditions, but this process may take up to hundreds of years (Thom et al. 2017). In Europe, the increase of drought periods is of particular concern. The occurrence of normal and hot droughts is likely to increase across Europe with climate change (Manning et al. 2019; Spinoni et al. 2018). Severe droughts can lead to years of reduced growth and incomplete recovery (Anderegg et al. 2015), reduction in trees' defence against biotic pests (Stephenson et al. 2019), increase in fire susceptibility (Whitman et al. 2019), and eventually tree mortality (Allen et al. 2010). It is therefore of utmost importance to increase the resilience of forests to drought.

1.2.2 Biodiversity

Forest biological diversity is defined as "the variability among forest living organisms and the ecological processes of which they are part; this includes diversity in forests within species, between species and of ecosystems and landscapes." (Convention on Biological Diversity 2022). Biodiversity is a large overarching concept that covers several resilience mechanisms, notably redundancy, heterogeneity, and diversity. The importance of diversity for ecosystem stability has been recognised already in the 1960s (Lewontin 1969; Pimentel 1961) and currently the importance of biodiversity for resilience is well-established (Aquilué et al. 2020; Sakschewski et al. 2016; Thompson et al. 2009).

Biodiversity supports ecosystem resilience in many ways. Functional groups, i.e., assemblages of species performing similar functional roles within an ecosystem, such as pollination, production, or decomposition (Thompson et al. 2009), are crucial for ecosystem resilience as they provide redundancy in the ecosystem by having overlaps in the species' ecological roles as well as functional response diversity to factors of change (Aquilué et al. 2020; Mori et al. 2013). Heterogeneity in species composition, their functional diversity and ecosystem structures provides the ecosystem with wider range of potential responses to different factors of change and ensures the provision of ecosystem services (Isbell et al. 2011; Levine et al. 2016; Messier et al. 2021; Mori et al. 2021).

1.2.3 Adaptive capacity of forests

Adaptive capacity of forests describes the ability of forests to respond to changing disturbance regimes and climate change, while at the same time continue to provide essential ecosystem services to society (Puettmann 2014). Trees and forest ecosystems have inherent adaptive capacity that encompass evolutionary mechanisms and processes that permit them to adjust to new environmental conditions (Aitken et al. 2008). At the individual level the adaptation happens via epigenetic responses and acclimation, at the population level via natural selection, at the species level via gene flow and colonization of new sites, and at the community level via the competition and facilitation between the tree species (Lindner et al. 2010). Adaptive capacity is a key component in ensuring that forests will be able to provide the crucial ecosystem services also in the uncertain future (Messier et al. 2015).

The key feature of adaptive capacity in plant populations are the functional traits that reflect the genetic diversity and acclimatization (Bussotti et al. 2015). Functional traits influence the adjustment of plants on the morphological and physiological level, i.e., they enable the phenotypic plasticity of plants (Bussotti et al. 2015). Phenotypic plasticity is "the ability of an individual organism to alter its phenotype in response to changes in environmental conditions" (Garland and Kelly 2006). At the ecosystem level, local adaptation takes place by having new genotypes of the same species that are better suited for the new environmental conditions (Bussotti et al. 2015). If local adaptation is not possible, species may migrate to new, more suitable areas. Species using wind for seed dispersal may be able to move fast enough with the changes in climatic biomes, but for species relaying on animals dispersing their seeds this might not be the case (Bussotti et al. 2015). Finally, if adaptation is not possible, species may die and go locally extinct.

1.2.4 Connectivity

In recent years, emphasis on the importance of connectivity on forest resilience has become stronger (Aquilué et al. 2020; Messier et al. 2019; Mina et al. 2020). Connectivity is "the way and degree to which resources, species, or social actors disperse, migrate, or interact across ecological and social landscapes" (Biggs et al. 2012). Connectivity influences resilience by affecting the spread of a disturbance and species across the landscape (Biggs et al. 2012; Nyström and Folke 2001). However, as shown in the adaptive cycles, over connectedness reduces resilience as it makes system more vulnerable to shock disturbances (Holling 1986; Muys 2013). Resilient systems are connected to one another for efficient spread of information but not so connected that any shocks in the system cause disproportionate damage (Walker and Salt 2012).

Connectivity can be modelled with a network analysis (Biggs et al. 2012; Messier et al. 2019). In a landscape, forest stands create the nodes of the network that are connected to another by their seed dispersal and tree establishment capacity (Messier et al. 2019). The network of forest stands are characterised by clusters of closely connected stands that are loosely connected to other clusters, creating a modular landscape that can buffer against the spread of disturbances (Aquilué et al. 2020).

1.3 Adopting resilience in forest management

Traditional forest management has been ill-equipped to deal with the challenges caused by the Anthropocene (Rist and Moen 2013). There are increasing demands from policy to make forests more resilient to global change (DEFRA 2018; European Commission 2021). Resilience is a useful concept in bridging science, policy and practice together as a boundary concept that allows for different interpretations while still connecting different disciplines together (Brand and Jax 2007). The benefits of multidisciplinary research are apparent for proper management of the ecosystems (Moser et al. 2019). However, the application of the concept in practical natural resource management situations remains difficult (Timberlake and Schultz 2017). The use of different definitions or not specifying the used definitions in forest policies cause challenges in designing management paradigm focused on forest resilience (Bone et al. 2016). Furthermore, the lack of uniformity in how forest science uses the concepts of resilience makes it challenging for forest managers to implement and communicate the management decisions to the wider public (Greiner et al. 2020; Timberlake and Schultz 2017), as there are unclear or contradictory messages to policy and practice on what resilience is and how it can be achieved (Moser et al. 2019).

Another possible barrier for implementing resilience in practice is the lack of measurable metrics and examples on successful cases (Greiner et al. 2020; Moser et al. 2019; Standish et al. 2014). Having a singular indicator for resilience in complex ecosystems and societies cannot be done (Allen et al. 2011), and therefore there has been many attempts and explorations to measure resilience in research (e.g., Lloret et al. 2011, Standish et al. 2014, Bowditch et al. 2019, Bryant et al. 2019) to try to capture the multiple resilience mechanism and that way to make it an easier concept to be applied in practice. A commonly agreed starting point for resilience assessments is to define the resilience of what to what (Carpenter et al. 2001). This approach emphasizes the context dependency of resilience and the need to identify the system boundaries and the disturbance or stress affecting the system, and the temporal and spatial scales of interest to facilitate quantifying resilience. However, there may be various understandings on the system boundaries and the disturbance in question, which in turn might lead to different interpretations of the resilience of the system (Greiner et al. 2020). It is therefore important to advance on research to reconcile the differences and similarities of the various meanings of resilience, and to transfer the resulting insights into more actionable and operationalised ways for practitioners to implement in their management (Moser et al. 2019).

1.4 Objectives and the outline of the thesis

The overall aim of this research was to advance the operationalisation of resilience in forest management. Many studies have been published on forest resilience and how management may influence it (e.g., Bryant et al. 2019; DeRose and Long 2014; Seidl, et al. 2016a). However, less attention has been given to explaining how resilience has been understood and what have been the implications of the adopted definition to the outcomes. This thesis therefore aims at addressing the knowledge-gap between science and practice by providing insights on how resilience can be applied in different forest management contexts. The hypothesis of the thesis is that resilience can be made into an operationalised concept in the practical forest management.

The thesis is structured around the following research questions:

1. How is the concept of resilience used in the scientific literature and how can resilience be quantified?
2. How can forest resilience to forest disturbance be enhanced in management?
3. How forest management needs to deal with climate change induced challenges?

To respond to these research questions, this thesis is structured in six chapters (Fig. 1.3). The chapters 2, 3, 4, and 5 are written as stand-alone articles, enabling reading them according to one's interest.

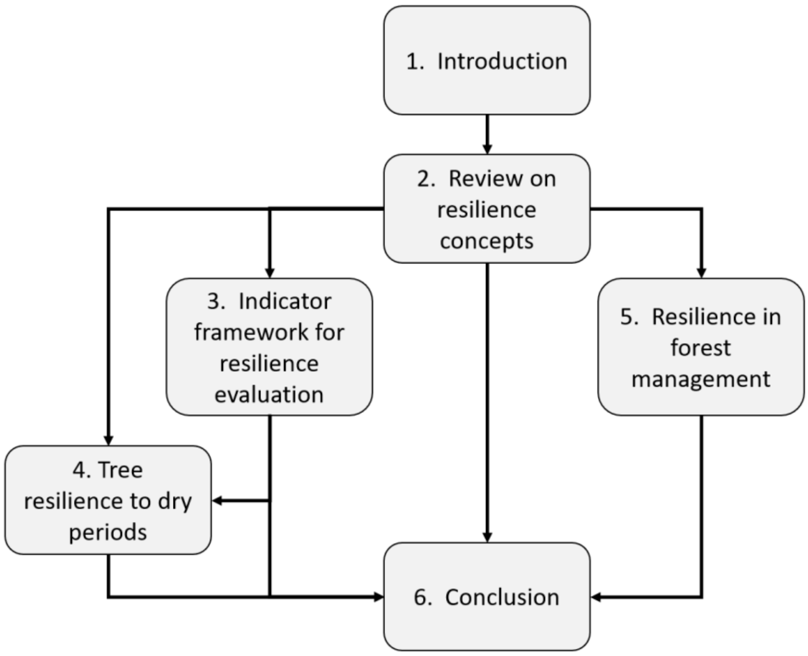


Figure 1.3. The graphical illustration of the thesis structure and how the different chapters relate to one another.

The objective of **Chapter 2** was to review how the concepts of resilience are used and assessed in forest sciences. A systematic review on 255 scientific articles was conducted and the use of the concepts of engineering, ecological and social-ecological resilience was assessed. More specifically, the area of interest was the systems the concepts were used in, the disturbance the concepts were used with, and the method that was used to assess the concepts.

The objective of **Chapter 3** was to develop a hierarchical Principles, Criteria and Indicator framework that explicitly recognises trade-offs to assess the social-ecological resilience in forest management context. Resilience mechanisms that are prevalent in both the ecosystems and the society to describe the social-ecological resilience were selected and principles, criteria and example indicators for each one were developed. The chapter highlighted how resilience depends on the forest management context and management goal.

The objective of **Chapter 4** was to develop a method for quantifying a measure of engineering resilience to reoccurring dry periods. High resolution dendrometer time series from 681 trees from 127 different sites from 14 different countries were used to analyse if the replenishment time of the stem water reserves, i.e., recovery time, increases with the increasing number of dry periods in summer season. The information could be used to monitor tree resilience to drought.

The objective of **Chapter 5** was to analyse how organisations guiding forest management in large areas (e.g., forest extension services, public forest authorities) acquire and apply knowledge on forest disturbance management to enhance forest resilience. Interviews in Finland, France, Germany, Poland, and Spain were conducted to explore the European-wide situation of forest management guidelines and identify the future research needs from the practitioners.

The **Chapter 6** summarises the main findings and discusses the relevance of the results to forest management as well as the potential limitations of the research. It, furthermore, outlines future research directions.

2 Understanding how resilience is used in forest sciences

Based on: Nikinmaa, Laura, Marcus Lindner, Elena Cantarello, Alistair S. Jump, Rupert Seidl, Georg Winkel, and Bart Muys. "Reviewing the use of resilience concepts in forest sciences." *Current Forestry Reports* 6, no. 2 (2020): 61-80.

2.1 Introduction

Global change causes shifts in forest disturbance regimes (Seidl et al. 2017a; Turner 2010) that can potentially reduce the capacity of forests to provide ecosystem services (Thom and Seidl 2016). The change may furthermore alter the distribution of species (Lindner et al. 2010; Thuiller 2004) including forest-dependent species that, if not able to migrate as their habitat shifts, can face extinction (Thomas et al. 2004). Interacting disturbances can alter forest development pathways (Johnstone et al. 2016), and an increased disturbance frequency can erode the capacity of forests to recover (Lloret et al. 2011; Seidl, et al. 2017b). 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 (Grassi et al. 2017) or the development of a wood-based bioeconomy (Philp 2015). 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 (Messier et al. 2013; Puettmann et al. 2009).

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 (Chambers et al. 2016; DEFRA 2018; Spears et al. 2015). However, resilience is a difficult concept to define, as demonstrated by the numerous definitions and approaches available in the literature (Brand and Jax 2007; Moser et al. 2019). 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 (Moser et al. 2019). In the literature on social-ecological systems, three broad conceptualisations of the term resilience have emerged: engineering, ecological and social-ecological resilience (Bone et al. 2016). Engineering resilience is often cited as first defined by Pimm (Pimm 1984). 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 (1973), 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 (Boeing 2016). 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 (Folke et al. 2002). Social-ecological resilience considers the maintenance of the current regime and the adaptive capacity of a coupled human-natural system (Folke 2016). Several variants of social-ecological resilience exist but all focus on the adaptive capacity of the social-ecological system as a whole (Quinlan et al. 2016). 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"* (Holling and Gunderson 2002; Walker et al. 2004).

While resilience is widely considered in forest ecology, the resilience concept has not been implemented widely in the daily practice of forest management (Reyer et al. 2015b). 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 (Brown and Williams 2015; Xu et al. 2015) and forest management in particular (Newton and Cantarello 2015) 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 (Moser et al. 2019; Rist and Moen 2013). 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.

2.2 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 (Folke 2016), 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. (Olson et al. 2001). 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. 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 (OECD 1993). We further organised the indicators into larger groups. 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 (Team 2018). 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” (Oksanen et al. 2019) in R (Team 2018). Figures were created with the package “ggplot2” (Wickham 2016).

2.3 Results

The initial search resulted in 2,629 peer-reviewed studies that were all screened (published online material ESM1). The abstracts that fulfilled the first three selection criteria were chosen for further analysis, narrowing the set down to 625 studies (published online material ESM2). Of these a final set of 255 studies also fulfilled the selection criteria 4 and 5 (Appendix A). 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.

2.3.1 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. 2.1). 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.

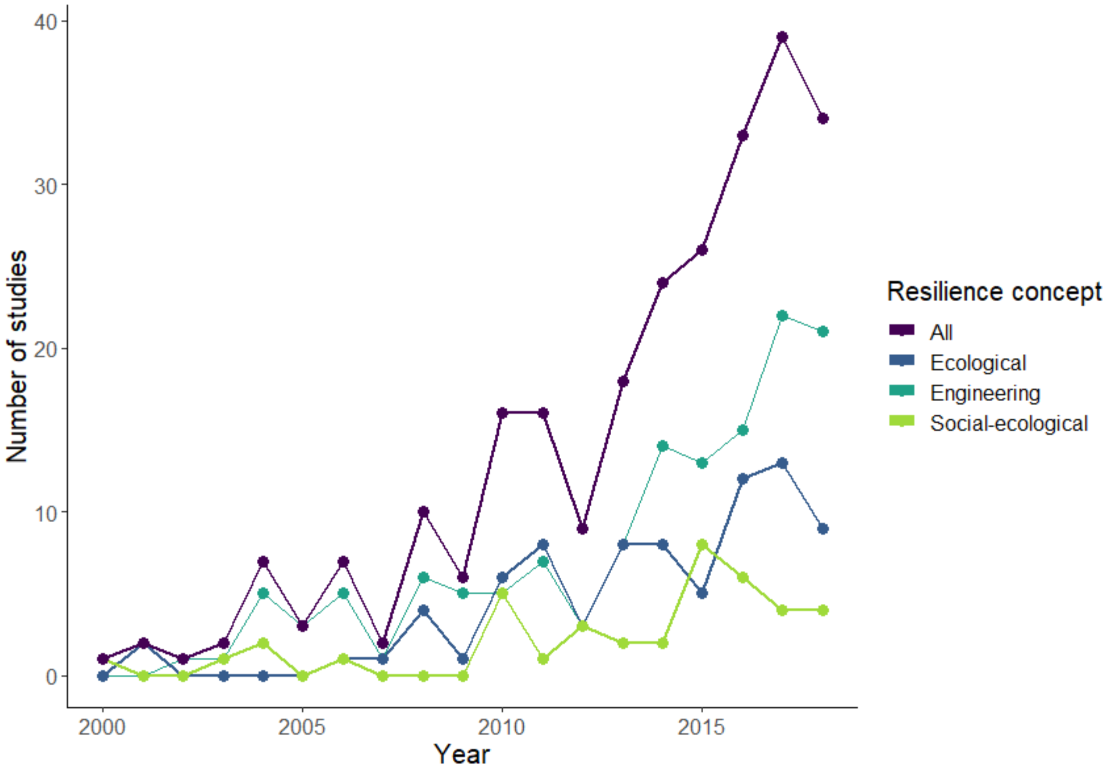


Figure 2.1. The development of the use of the three resilience concepts in forest resilience studies from 2000 to 2018. The figure shows the number of studies using engineering, ecological or social-ecological resilience concepts and the total number of forest resilience studies published per year. The cut-off date for the review was in mid-August 2018, and therefore not all studies published in 2018 were included in the review.

2.3.2 Geographical spread of resilience concept applications

Our review contained studies from 11 different biomes (Fig. 2.2.). 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 %).

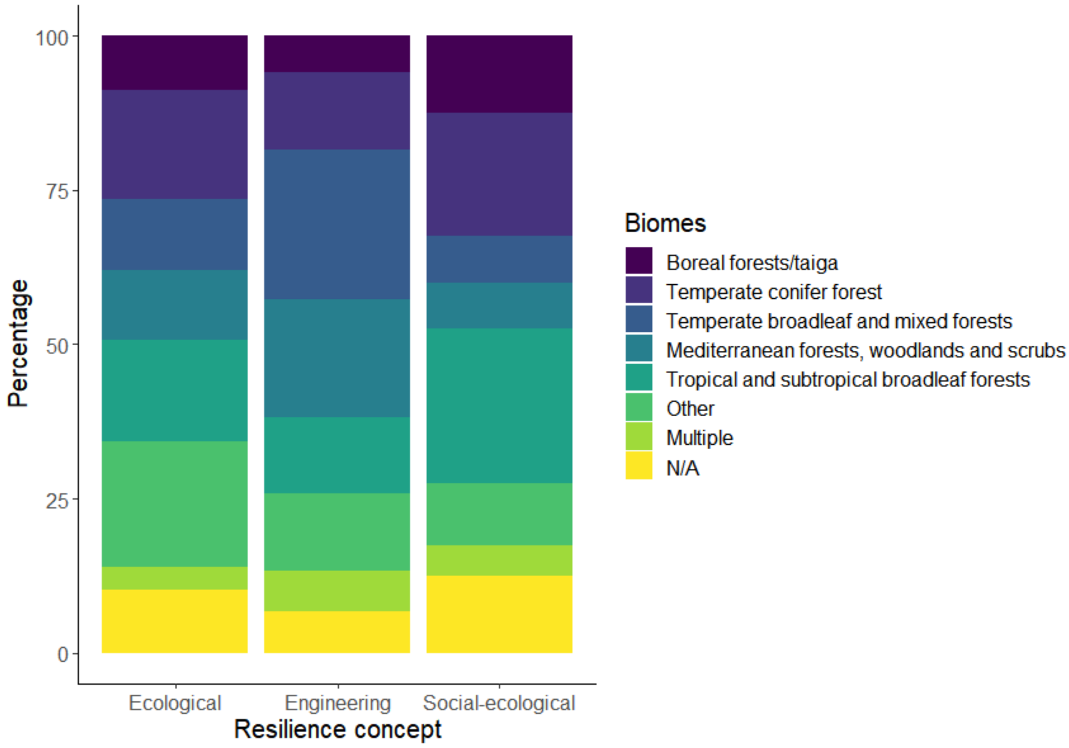


Figure 2.2. The use of the resilience concepts by forest biome. The figure shows the share of the biomes studied for each of the three resilience concepts. N/A means that no biome was mentioned in a study.

2.3.3 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 2.1).

Table 2.1. 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 %).

2.3.4 Indicators used to assess resilience

The most used indicators for each resilience concept are shown in Table 2.2. 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 2.2. 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 font expresses the type of indicator according to the classification of

OECD's environmental indicators (OECD 1993). Italicized entries are Pressure-type indicators, bold entries are State-type indicators and bold-italics 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 %)**	*Agricultural practices (10.0 %)*	***Socio-economic diversity (4.7 %)***
		Disturbance severity (8.9 %)	*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 %)	

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. 2.3). 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.

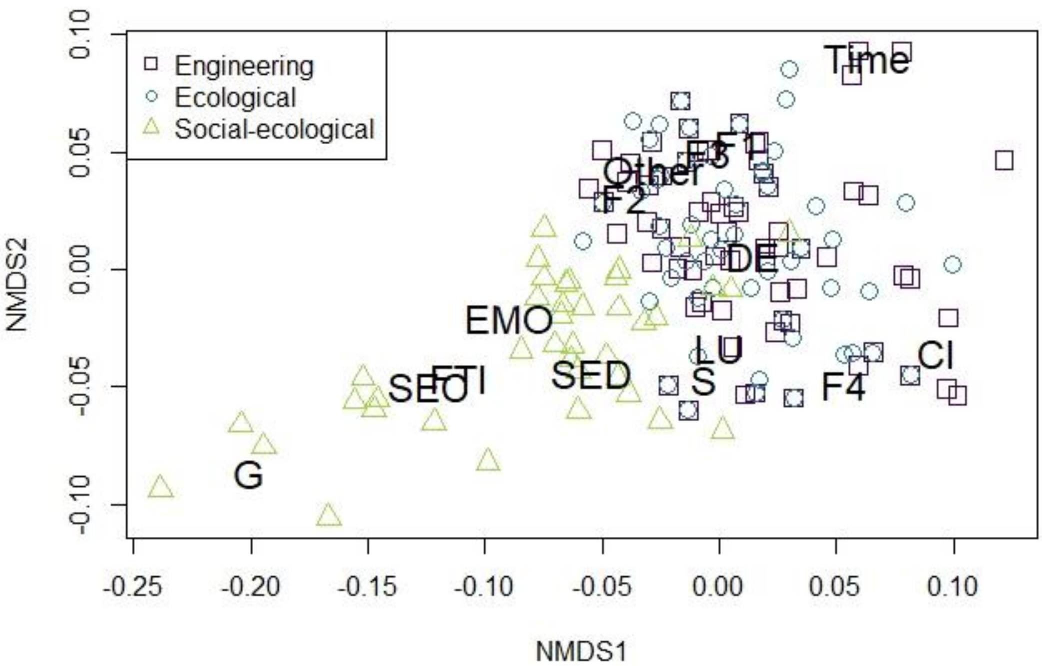


Figure 2.3. The indicator groups used to assess resilience, ordinated in two dimensions based on the NMDS analysis. The NMDS gives a representation of the relationship between objects (studies) and descriptors (indicator groups) in a reduced number of dimensions. The x- and y-axes are the first two axes 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 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. 2.4). Assessments of social-ecological resilience use on average more indicators than assessments of ecological or engineering resilience (7 indicators vs. 4 and 3, respectively).

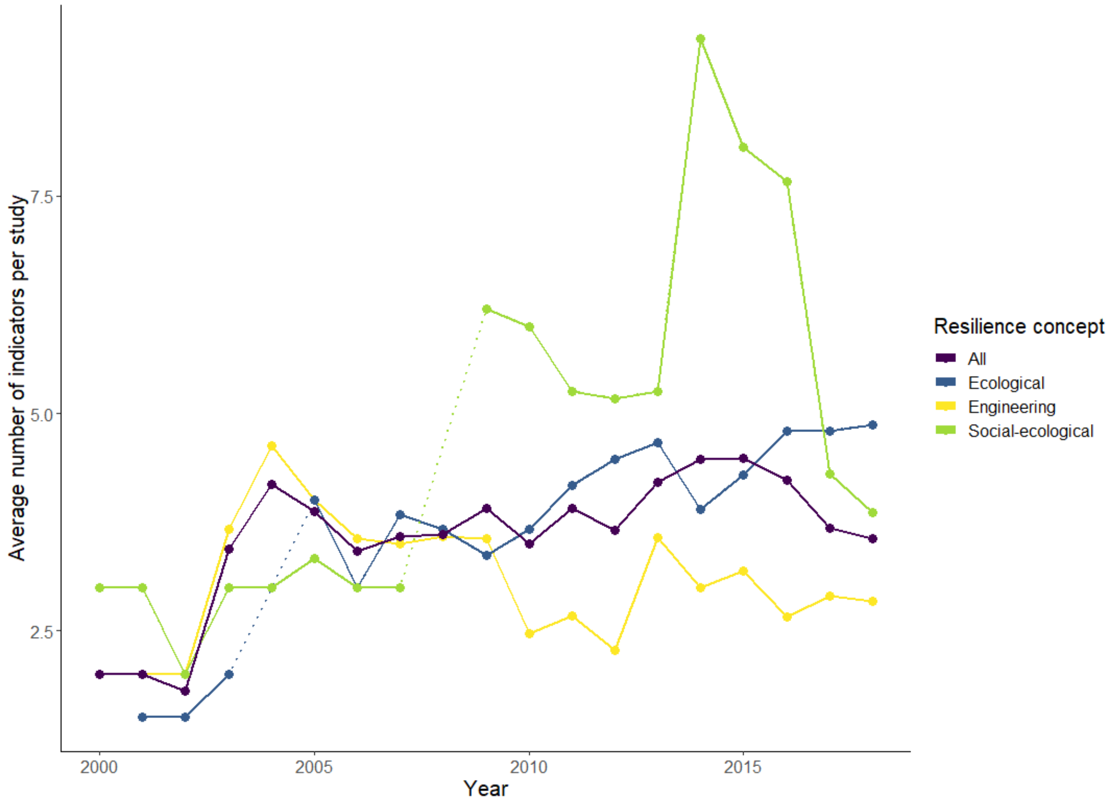


Figure 2.4. The moving average of number of indicators per study. The averages are calculated for three-year periods except for 2000 and 2018, which were calculated for two-year periods. The dashed lines show the interpolation over the years where there were no studies published with that resilience concept.

2.4 Discussion

2.4.1 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 (Balint et al. 2011). 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 (Müller et al. 2016). 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. (Lloret et al. 2011) 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 (Brand and Jax 2007).

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 (Moser et al. 2019), supports this interpretation. Furthermore, resilience receives considerable criticism from the social sciences (Brown 2014; Cote and Nightingale 2012; Weichselgartner and Kelman 2015) 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 (Olsson et al. 2015). 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 (Brand and Jax 2007). 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 (Akamani 2012; Bowditch et al. 2019) and quantitative (DasGupta and Shaw 2015) ways.

The use of engineering resilience also has clear limitations. As the concept assumes the existence of only one stable state (Pimm 1984) 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 (Steffen et al. 2018). 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 (Rist et al. 2014). 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.

2.4.2 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. 2.3). 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 (Moser et al. 2019). 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 (Moser et al. 2019). 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 (Folke et al. 2010; Moser et al. 2019).

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 (Gunderson 2000). 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 (Gunderson 2000). Social-ecological resilience assumes the existence of multiple basins of attractions as well (Folke et al. 2010), 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 2.2 and Fig. 2.3).

Our results reflect this conceptual background. For example, drought resilience of trees was the most 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. (2011), 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 (Hirota et al. 2011; Scheffer et al. 2012b; Verstraeten et al. 2018), some scientists see the evidence as limited (Newton and Cantarello 2015) 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 (Seidl et al. 2014b; Seidl et al. 2016a; Seidl et al. 2017b), underlining the importance of precisely defining the term in each instance of its use (Carpenter et al. 2001), 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 (Moser et al. 2019).

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 (Folke et al. 2010). 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 (DeRose and Long 2014; Moretti and Legg 2009; Rivest et al. 2015). Some scientists argue for separating resistance, resilience and adaptive capacity into their own concepts for conceptual clarity and better operationalisation of resilience (DeRose and Long 2014; Müller et al. 2016). 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 (Folke et al. 2010).

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 (Walker et al. 2004). According to this hierarchy, engineering resilience is nested inside ecological resilience, which in turn is nested inside social-ecological resilience (Fig. 2.5). Moving from one concept to another either adds or removes different dimensions from the system under study and changes the system boundaries. The interest in a certain property together with the disturbance of concern therefore 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.

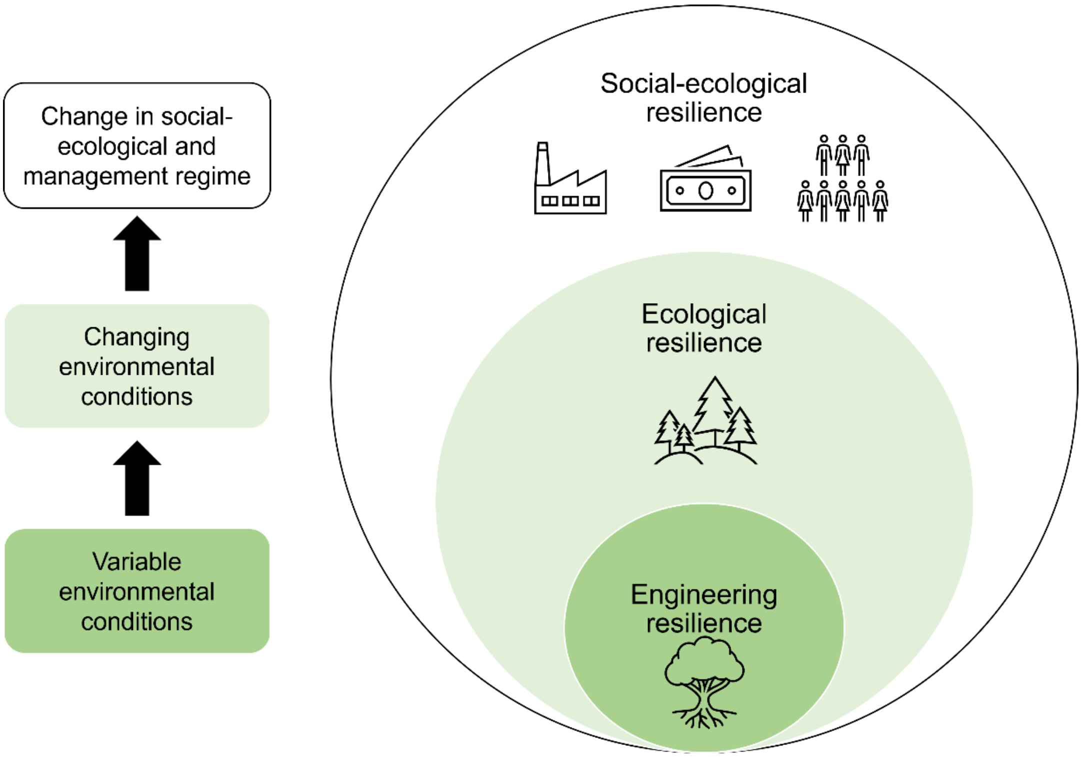


Figure 2.5. The hierarchy of resilience concepts and assumptions behind each concept. The circles on the right show how resilience concepts are related to one another. The boxes on the left indicate increasing complexity in the systems that are studied by the respective resilience concepts. Variable environmental conditions mean conditions where the conditions vary but remain in the historical range of variation. Changing environmental conditions mean that the conditions are no longer within the range of historical variation of the environment.

2.4.3 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 (Brand and Jax 2007), 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 (Cantarello et al. 2017; DeRose and Long 2014; Newton and Cantarello 2015; Seidl et al. 2016a), 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 to 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 (Wolfslehner and Vacik 2008). 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 (Yousefpour et al. 2012). Risk is by definition the effect of uncertainty on objectives (ISO 2009), frequently expressed quantitatively in probabilistic terms (Hanewinkel et al. 2011), and risk-based management strategies are most effective when hazard probabilities are known (Park et al. 2011). However, the impacts of changes in disturbance regimes as well as of shocks caused by political and societal changes are currently unknown (Messier et al. 2015), which can cause risk management approaches to fail (Park et al. 2011). In contrast, resilience prepares for minimizing the damage caused by unknown, novel risks (Park et al. 2011), 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 (Carpenter et al. 2001). 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 (Müller et al. 2016). If alternative states for the system are known, e.g. forests transforming into savannah (Hirota et al. 2011), 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 (Carpenter et al. 2001). 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 (Folke et al. 2010).

3. *Identify the temporal scale of interest.* Engineering resilience can be appropriately used for assessing resilience on a short temporal scale (Müller et al. 2016). 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 (Biggs et al. 2012; Chapin et al. 2010; Müller et al. 2016). 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 2.2) 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 (Müller et al. 2016).

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 (Hosseini et al. 2016; Moser et al. 2019; Roostaie et al. 2019). 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.

2.5 Conclusion

In our rapidly changing world, resilience has gained wide popularity in forest management, but operationalising the concept still lags. 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.

3 Creating an operational framework to implement resilience to forest management

Based on Nikinmaa, L., Lindner, M., Cantarello, E., Gardiner, B., Jacobsen, J.B., Jump, A.S., Parra, C., Plieninger, T., Schuck, A., Seidl, R., Timberlake, T.J., Waring, K., Winkel, G., and Muys, B. "Indicator framework for social-ecological resilience of forests: a balancing act". Under revision.

3.1 Introduction

Forests are complex social-ecological systems, providing essential ecosystem services (Brockerhoff et al. 2017) that are in increasingly high demand (Böttcher et al. 2012). Simultaneously, forests face multiple disturbances linked to global environmental change (McDowell et al. 2020; Trumbore et al. 2015). To ensure a stable provision of forest ecosystem services, policy makers and scientists advocate for increased forest resilience (European Commission 2021; Messier et al. 2013). However, operationalizing forest resilience remains difficult (Nikinmaa et al. 2020), as forests have specific resilience challenges due to the long time-spans of ecological cycles that clash with the time-span of economic cycles, and the vulnerability in the face of climate change.

Implementing the concept of resilience in forest management faces numerous challenges due to the ambiguity of the concept as well as the lack of appropriate indicators and best practice examples (Greiner et al. 2020). Furthermore, resilience is itself a heavily debated concept and has many definitions (Brand and Jax 2007; Moser et al. 2019; Van Meerbeek et al. 2021). In the literature, three main resilience concepts dominate: engineering resilience ("recovery of a previous state"), ecological resilience ("remaining within the prevailing system domain through maintaining important ecosystem processes and functions") and social-ecological resilience ("the capacity to reorganize and adapt through multi-scale interactions between social and ecological components of the system") (Nikinmaa et al. 2020; Seidl et al. 2016a). In social-ecological systems, a multitude of ecosystem functions and services need to be assessed at multiple scales while considering the assemblage of public demands and expectations (Messier et al. 2019). To examine the resilience of forests and their multiple use, we adopt the social-ecological resilience concept in this paper and refer to it when using the term "resilience". We furthermore consider resilience from a normative perspective to be a desired property of a system.

Resilience can be assessed for the overall social-ecological system of a forest with its socio-economic links, for the ecological and social subsystem separately, or for the flows of different ecosystem services from the ecological to the social subsystem (Biggs et al. 2012). However, assessing resilience for subsystems and flows separately without accounting for their interconnections may lead to biased conclusions regarding the overall resilience of the social-ecological system. For example, diversity in forest ownership structure can create a more diverse landscape if forest owners have diverse management objectives. This diversity can generate a mosaic of varying forest structures (Rammer and Seidl 2015; Schaich and Plieninger 2013), yet the presence of many small owners in an area could also constrain integrated landscape-scale management and thus result in a lack of coordinated action in for example disturbance management. This example illustrates that there is a need to balance the trade-offs between different facets of resilience, and to consider their interrelations, necessitating guidance of transparency and consequences of trade-offs, when forest managers wish to implement resilience in practice. We would like to point out that with balancing we do not mean to aim at achieving the balance of nature (Jelinski 2005; Wu and Loucks 1995) but rather to navigate between resilience facets of ecological and social subsystems, including between the different stakeholder demands and preferences. Here we propose a framework for how social-ecological resilience of a forest system could be assessed and balanced in support of specific, predefined forest management goals.

In a context of sustainable forest management, Lammerts van Bueren and Blom (1997) have argued that a rigorous and consistent indicator framework should be built hierarchically on *principles* (fundamental laws or rules, serving as a basis for reasoning and action), *criteria* (states of the dynamic ecosystem processes or the interacting social system, which should be in place as a result of adherence to a principle), and *indicators* (a qualitative or quantitative variable that can be assessed to check compliance with a criterion). This PCI approach has been widely adopted, e.g., to allow intercomparison between forest sustainability standards (Holvoet and Muys 2004; Salas-Garita and Soliño 2021), or for assessing the sustainability of agricultural systems (Van Cauwenbergh et al. 2007) and LULUCF-projects (Madlener et al. 2006). To include trade-offs and stakeholder preferences in the framework, PCI can be combined with elements from multi-criteria decision making, namely active stakeholder involvement and weighting indicators according to their importance for stakeholders. In this paper, our aim is to build an indicator framework that provides guidance for understanding the resilience trade-offs in practice and to use a hypothetical case study to demonstrate its utility. Specifically, the objectives of this paper are to (1) explore the trade-offs in forest management which affect resilience; (2) present a PCI framework for balancing resilience trade-offs in the context of strategic forest management planning; and (3) demonstrate the applicability of the proposed resilience framework under different forest management contexts.

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

3.2 Developing the framework

3.2.1 Resilience mechanisms, trade-offs and balancing

Social-ecological systems are open systems with interlinked social and ecological subsystems (Berkes and Folke 1998). The subsystems are linked through the ecosystem services provided by the ecological system and their contribution to human well-being in one direction; and by the feedbacks of the social subsystem in terms of intentional ecosystem management that optimizes the flow of services or unintentional human impacts on the ecosystem in the other direction (Muys 2013; Thonicke et al. 2020) (Fig. 3.1.).

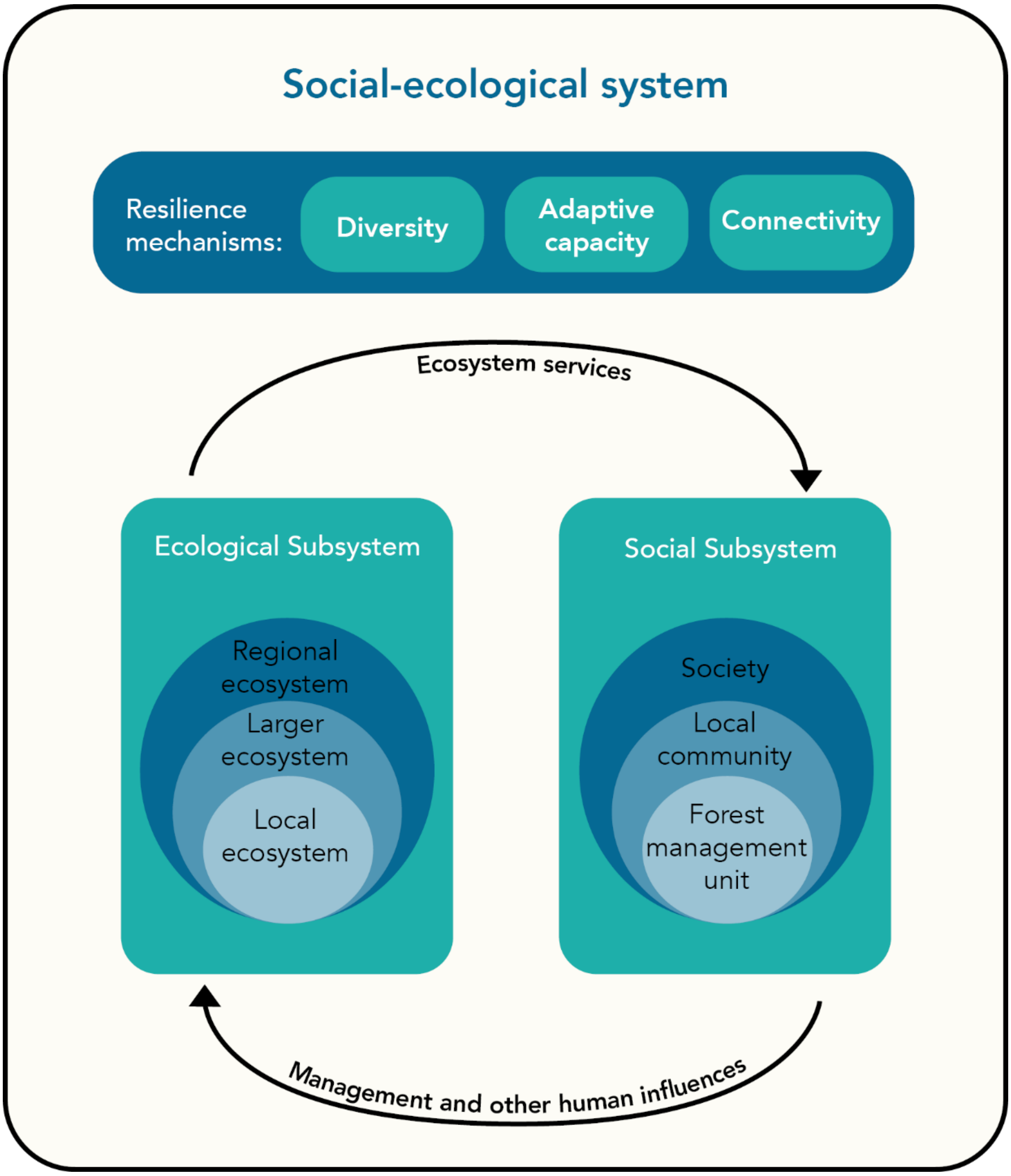


Figure 3.1. Social-ecological resilience concept applied in this study. The arrows represent the flows that connect the social and ecological subsystems of a forest social-ecological system whereas the coloured boxes on top represent the three resilience mechanisms relevant for both subsystems and all hierarchical levels. Adapted from Colding and Barthel (2019).

There is increasing interest in managing the mechanisms that support the resilience of ecosystem services (Biggs et al. 2012; Sarkki et al. 2017; Weise et al. 2020). Resilience mechanisms are system properties or functions that facilitate the resilience of the system (Weise et al. 2020). Various resilience mechanisms have been described in the literature, including redundancy, heterogeneity, diversity, modularity, adaptive capacity, memory, learning capacity, and connectivity (Kay 2000). Similarly to Bernhardt and Leslie (2013), we chose to focus on the key resilience mechanisms diversity, connectivity, and adaptive capacity (Fig. 3.1) to explore the balancing of these resilience mechanisms within and between the ecological and social subsystems, as these three mechanisms are considered essential for resilience (Angeler et al. 2019; Bernhardt and Leslie 2013; Cumming 2011). Diversity of the ecological system may be exhibited by living organisms, their assemblages and biotic communities (DeLong 1996), while diversity in the social system may be expressed by social actors and their interactions at different levels (Walker et al. 2006). Diversity increases the chances that at least some elements persist after a disturbance. Furthermore, diversity in responses to a disturbance facilitates recovery (Sousa-Silva et al. 2018a). Connectivity (sometimes also referred to as connectedness) is the manner and the extent to which available resources, species, or social actors interact, disperse, or migrate across ecological and social landscapes (Bodin and Prell 2011). Connectivity enables the movement of species and therefore contributes to the self-organisation of the ecological system. It also spreads knowledge, boosts innovation and increases well-being in the social system (Berkman and Glass 2000; Egerer et al. 2020). However, high connectivity may also decrease resilience (Holling 1973) as systems become sensitive to spreading disturbances, e.g., pathogens or invasive species. Adaptive capacity enables systems to tolerate stress, acclimate to changing situations and reorganise into something new (Bernhardt and Leslie 2013). In a climate change context, for example, adaptive capacity is defined as the ability of a system to adjust to climate change, to moderate potential damages, to take advantage of opportunities, or to cope with the consequences (IPCC 2007, 2022).

In a complex system, enhancing resilience of different subsystems at multiple temporal and spatial scales can also lead to conflicting situations, where measures to increase resilience of one subsystem can have detrimental effects on another (Cumming 2011). Such trade-offs are not limited to human-nature interactions, but occur also in natural systems without human presence, e.g., between plant species' adaptation strategies to drought (Lu et al. 2021). The existing trade-offs and their effect on the management of forests need to be identified, understood, and managed. Several types of trade-offs exist in social-ecological systems: trade-offs within resilience mechanisms, trade-offs between ecosystem services (Rodríguez et al. 2006), trade-offs between different temporal and spatial scales (Guerrero et al. 2013), and trade-offs between ecological and social subsystems (Armitage et al. 2012). These trade-offs need to be managed to achieve resilience in the context of given management goals and objectives. The trade-off types are described in Table 3.1.

Table 3.1. Description of the types of trade-offs existing in a social-ecological system, illustrated with examples.

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

The described trade-offs need to be balanced to achieve a resilient social-ecological system. Balancing is an exercise where in the limits of minimum levels of the variables creating trade-offs, a balance is determined for the contrasting variables. For example, to balance the vulnerability caused by highly connected social-ecological systems, processes enhancing modularity (e.g., limiting entrance of introduced species) may be increased.

Balancing should be performed within and across the resilience mechanisms, between subsystems of the social-ecological system, between ecosystem services, and between scales to achieve resilient system (Table 3.3). Minimum levels for variables are set to avoid the temptation to increase some variable values in hopes that high resilience in parts of the social-ecological system will compensate for other parts of the system. Setting minimum levels will not replace the need for balancing as there likely remain multiple management options possible. The most suitable balance depends on the goal of the management: some outcomes are more favourable to a management goal than others.

3.2.2 A framework to assess the resilience of forest management

3.2.2.1 Description of the framework

We developed a PCI framework with 7 principles and 20 criteria addressing resilience mechanisms and balancing of trade-offs at landscape level, which is the relevant spatial scale level for considering socio-ecological resilience (Keane et al. 2018). The first three principles and nine criteria (Table 3.2) address the resilience mechanisms of the ecological and social subsystems in isolation whereas the last four principles and 12 criteria (Table 3.3) address the resilience trade-offs within the system more holistically by balancing the resilience within and between mechanisms and subsystems. While the principles and criteria can be universally used for any forest related social-ecological system, the indicators and their response curves are context dependent and should therefore be selected in participatory manner according to the management context. The principles and criteria are built on the resilience mechanisms, which are qualitative and do not have a single quantitative definition. Therefore, the principles and criteria are expressed with quantitative indicators to facilitate monitoring of resilience. The criteria may need more than one indicator for validation.

Table 3.2. Resilience Principles, Criteria and Indicators framework. For every criterion, one or more indicators can be selected. The table shows example indicators for a forest management decision-making context. Depending on the context, other indicators can be developed.

Principle	Criterion	Example Indicator	Why this example indicator is important for resilience	References
1.System diversity should be	1.1. Ecological diversity is maintained or enhanced	1.1.1. Stand Structural Complexity Index (SSC-index)	Structural complexity strongly affects biodiversity and	Bauhus et al. 2017; Ehbrecht et al.

developed and fostered			ecosystem functions. Higher index values indicate higher structural complexity, enabling diverse habitat conditions for species with contrasting physiological traits.	2017; 2021
	1.2. Socio-economic diversity is maintained or enhanced	1.2.1. Number of marketed timber products	Diversifying marketed products leads to income spreading and market risk mitigation.	Knoke et al. 2017
	1.3. Social-ecological diversity is maintained or enhanced	1.3.1. Number of small-scale forest owners with different management strategies in a landscape	Forest owners have different objectives and management strategies, which result in more varied forest landscapes.	Bieling 2004; Schaich and Plieninger 2013
2. System connectivity should be developed and fostered	2.1. Ecological connectivity is maintained or enhanced	2.1.1. The percentage of forest edge area relative to total forest area	Fragmentation of forests can reduce fitness of forest dwelling species and limit the adaptive capacity of forest ecosystems. It can also affect ecosystem functions and climate regulation.	Carranza et al. 2015; Ruete et al. 2016; Svensson et al. 2019
	2.2. Socio-economic connectivity is	2.2.1. The degree of forest association	Forest associations provide and	Glück et al. 2010; Kronholm

	maintained or enhanced	membership of forest owners	disseminate new knowledge and information. Furthermore, they represent the interests of private forest owners in policy discussions.	2015; Weiss et al. 2019
	2.3. Social-ecological connectivity is maintained or enhanced	2.3.1. The degree of involvement of all landscape actors in management decision making	Involving the broad diversity of landscape actors may lead to a holistic decision-making process resulting in forest management for multiple societal demands.	Cumming 2011; Beller et al. 2019; Plieninger et al. 2020
3. System adaptive capacity should be developed and fostered	3.1. Ecological adaptive capacity is maintained or enhanced	3.1.1. Evenness in representation of life stages of species and successional stages of communities, including old-growth features and natural regeneration	The presence of different life stages and successional stages ensures the stability and enhances the adaptive capacity of the forest ecosystem.	Thijs et al. 2014
	3.2. Socio-economic adaptive capacity is maintained or enhanced	3.2.1. Option value of the stand (the difference in stand value between making a management decision and waiting to make that decision)	Option value describes the possibility to wait until decision needs to be taken maintaining the economic flexibility.	Jacobsen and Thorsen 2003; Jacobsen 2007; Strange et al. 2019
	3.3. Social-ecological adaptive	3.3.1. Number of technical possibilities for	Technical possibilities, e.g., availability of tree	Lefèvre et al. 2014;

	capacity is maintained or enhanced	forest management	breeding programs, increase the capacities of forest managers and potential to increase the adaptive capacity of forests.	Fremout et al. 2021

Table 3.3. Balancing Principles, Criteria and Indicators. The principles and criteria show where in the social-ecological system balancing is required, whereas the examples show which concrete resilience indicators could be balanced. These examples are context dependent, and others can be used depending on the forest management context.

Principles	Criteria	Examples for balancing resilience indicators	Why these indicators need to be balanced	Reference
4. Balancing within and across mechanisms should be addressed	4.1. There is a balance within resilience mechanisms	Example for adaptive capacity: Balance between 'Genetic diversity from natural regeneration' and 'Planting of more adapted non-local species or provenances'.	Adaptation to climate change may be achieved through local evolution that requires genetic diversity. However, if the expected changes are big, assisted migration of new species or planting of non-local provenances might be needed.	Bussotti et al. 2015
	4.2. There is a balance across resilience mechanisms.	Example for balancing diversity and adaptive capacity: 'Species richness' and 'Share of non-native tree species'.	Non-native tree species may be better suited for future climate and outperform native tree species. However, non-native tree species	Oxbrough et al. 2016; Castro-Díez et al. 2019

			might have negative effects on local species diversity and therefore reduce resilience of the forest.	
5. Balancing between subsystems should be addressed	5.1. Diversity of ecosystem and social subsystem are balanced	Example for balancing between indicators ‘Stand Structural Complexity Index’ and ‘Number of marketed timber products’	Structurally diverse forest can provide a variety of timber products that decrease economic risk. Very diverse forest structure might however lead to economically unfeasible provision of each product.	Jacobsen and Helles 2006
	5.2. Connectivity of ecosystem and social subsystem are balanced	Example for balancing between indicators ‘Percentage of forest edge area relative to total forest area’ and ‘Degree of forest association membership of forest owners’	Members of forest associations can coordinate the management actions to create bigger patches of forests with similar types.	van Noordwijk 2020
	5.3. Adaptive capacity of ecosystem and social subsystem are balanced	Example for balancing between indicators ‘Number of tree species in a stand’ and ‘Option value of the stand’	Having multiple tree species present in a stand increases the option value of the stand as it allows to post-pone decision making. As time goes on, more	Jacobsen and Thorsen 2003

			information on species fitness has been gathered and better decisions on management can be made.	
6. Balancing between ecosystem services should be addressed	6.1. Provisioning and cultural services are balanced	Example for balancing between provisioning indicator ‘Timber production (in m3/ha/year)’ and cultural service indicator ‘Recreational value (number of visitors per day) of the forest’	Intensive timber production (e.g., clearcuts) decrease the recreational values of the forest.	Eggers et al. 2019
	6.2. Provisioning and regulating services are balanced	Example for balancing between provisioning indicator ‘Timber production (in m3/ha/year)’ and regulating indicator ‘Avalanche protection (percentage of forest area managed for avalanche protection)’	Avalanche protection limits the amount of timber that can be harvested as well as affects the type of forest management that can be practised.	Lafond et al. 2017
	6.3. Regulating and cultural services are balanced	Example for balancing between regulating indicator ‘Biodiversity conservation (percentage of strictly protected areas)’ and	Heavy recreational activities may cause harm to sensitive ecosystems by e.g. trampling, littering and disturbing the	De Groot et al. 2010

		cultural service indicator 'Recreation activities (number of visitors per day)'	local flora and fauna.	
7. Balancing between scales should be addressed	7.1. Resilience mechanisms are balanced between time scale levels	Example for balancing between indicators 'Short-term resilience to wind disturbance' and 'Long-term resilience to wind disturbance'	Long-term resilience of Norway spruce forest to wind requires thinning that can make the forest less resilient to wind in the short-term.	Gardiner et al. 2013
	7.2. Resilience mechanisms are balanced between spatial scale levels	Example for balancing indicator 'Structural diversity' between stand and forest management unit level	Having high structural diversity at stand level (uneven-aged, same species), but managing all the stands in the same way creates a homogeneous landscape. Creating diversity at both scales (uneven aged at stand level and stands of different species) creates diversity at landscape level.	Schall et al. 2018
	7.3. Resilience mechanisms are balanced between hierarchical scales	Example for balancing between indicators 'The degree of forest association membership of forest owners' and	Adaptation and resilience require coordinated responses across multiple levels of government to prevent	Araos et al. 2017; Phuong et al. 2018

		'Presence of forest owners associations in the national decision-making'	fragmented and maladaptive actions.	

The first part of the framework (Table 3.2) addresses the need to enhance resilience in all parts of the social-ecological system. The second part (Table 3.3) addresses the emerging trade-offs and how they are balanced. In forest management, trade-offs may be differently perceived and have varying importance for stakeholders involved in the decision-making. The choice of the management strategy achieving the most resilient outcome, i.e., the most resilient social-ecological system, for the management goal is subjective and stakeholder dependent. Stakeholders' preferences on indicators and trade-offs can be considered by using one of the available multicriteria decision making methods where indicators are weighted (Ananda and Herath 2009). The outcomes of stakeholder preference analysis can be used to balance different stakeholder perceptions of the trade-offs to achieve the most resilient outcome for a specific forest management goal.

In our framework, we consider that indicator values may not have a linear effect on the resilience of a system. In other words, the indicators have response curves. Indicator response curves are functions that show the effect of an indicator value on resilience. Resilience can change and evolve (Cabell and Oelofse 2012). Consequently, the same indicator value can have a different effect on resilience of the social-ecological system depending on the context and temporal scale of the assessment. Resilience might also not linearly increase with an increasing indicator value but plateau or even decrease. Indicators' response curves represent this behaviour (Fig. 3.2). The weights assigned to indicators by the stakeholders are expressed by the size of the response curves: weighting is done by multiplying each point on the response curve with the weight factor. Balancing of trade-offs is done by identifying the indicator values of the future offering the highest possible level of resilience considering the weighting, as obtained from using e.g., simulation models. Based on the changes in the level of resilience for the indicators over time, an average resilience score at a certain time in the future can be calculated by combining the level of resilience of all the measured indicators.

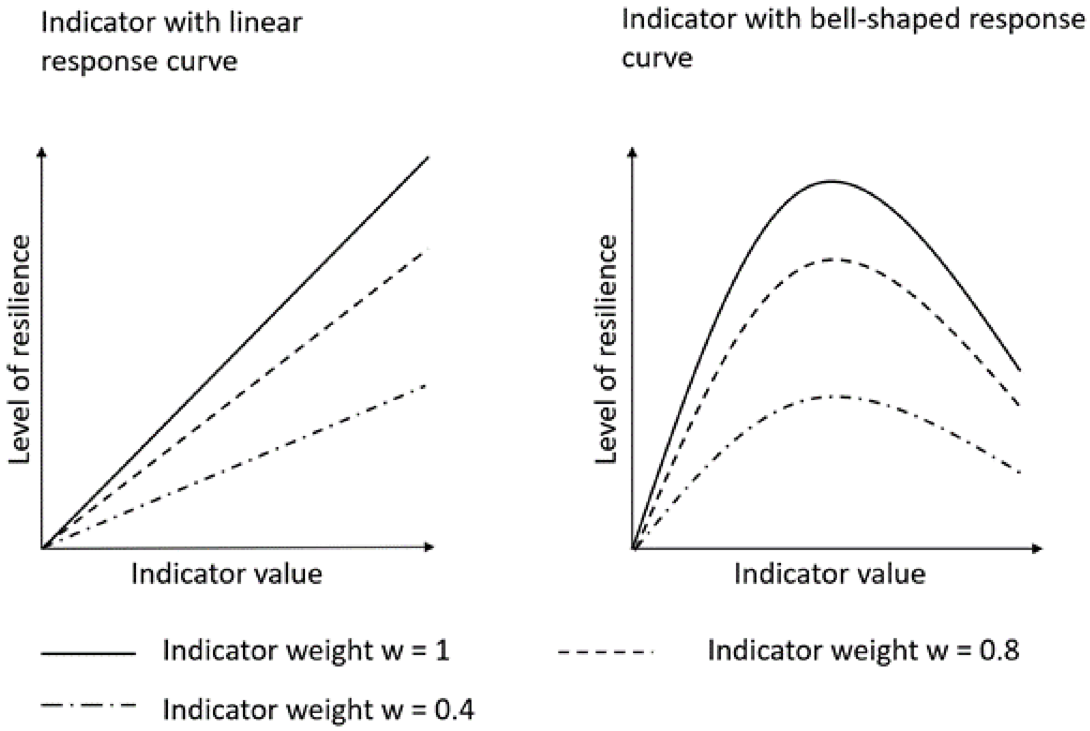


Figure 3.2. Two examples of resilience indicator response curves. For each response curve weighting of the indicators affects the height of the curve.

3.2.2.2 Application of the framework

We developed ten steps to apply the framework into practice. The steps are designed to include all the different phases from determining the resilience indicators and their response curves to evaluating different management strategies and objectives. The steps are: i) establish a stakeholder panel; ii) identify the system and its boundaries at the landscape level; iii) define management goals and main trade-offs; iv) identify indicators, their response curves, and their weights; v) project future scenarios for each management goal; vi) evaluate projected management outcomes; vii) revise the management strategy if needed; viii) perform resilience assessment; ix) revise the resilience assessment; and x) agree on accepted management strategy (Fig. 3.3). The framework process can be repeated periodically to support adaptive management.

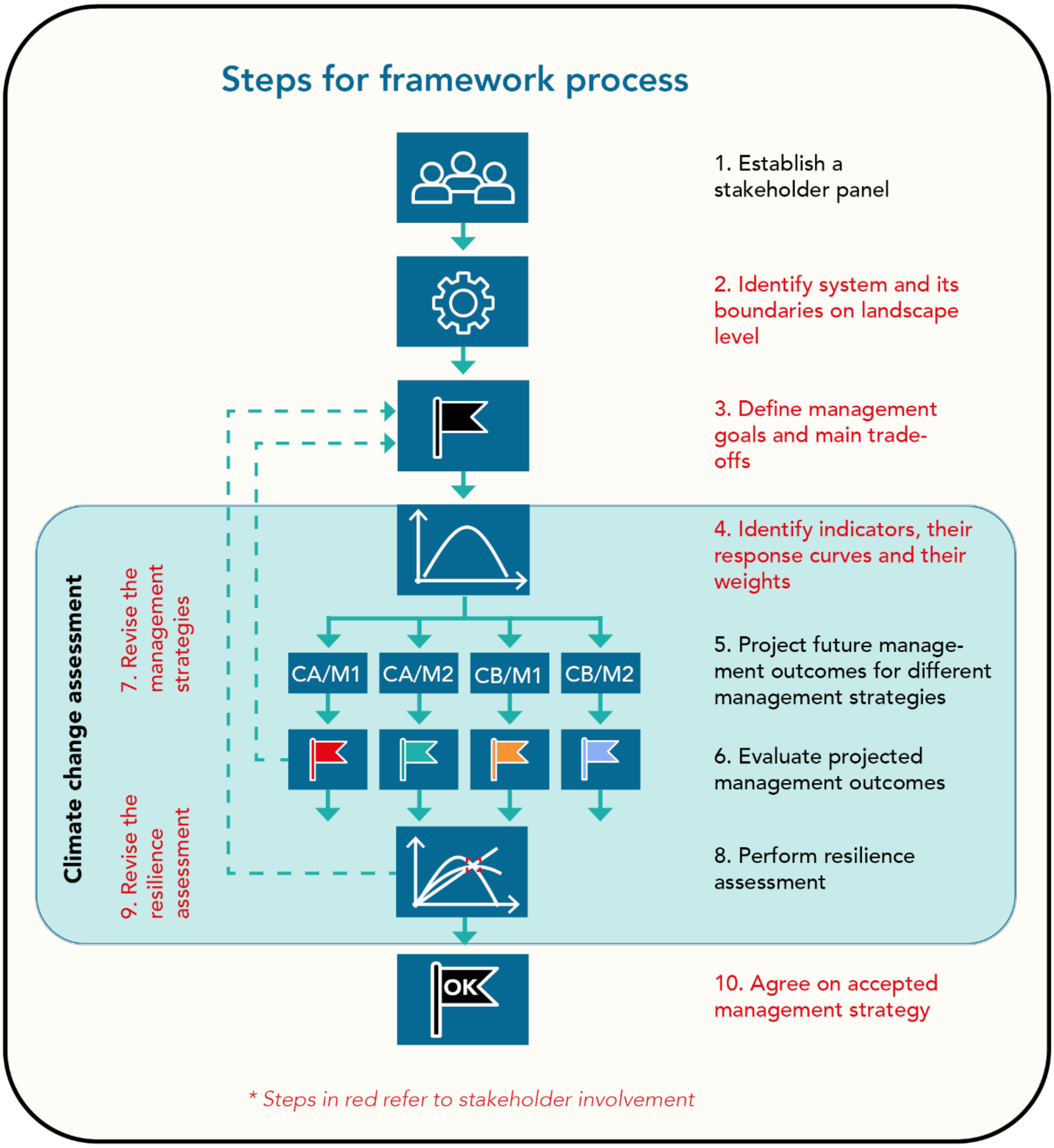


Figure 3.3. Process map describing the different steps of the framework. Stakeholder engagement takes place in steps 2, 3, 4, 7, 9 and 10. CA, CB, M1 and M2 refer to different climate and management scenarios, the flags of different colours refer to different management outcomes.

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

Step 1: Establish a stakeholder panel

The proposed framework requires a deeper understanding of both the ecological and social subsystems being analysed and therefore the stakeholders, e.g., forest owners and managers, forest enterprises, forest and nature conservation administration, local NGOs, and experts, should be heavily involved. Stakeholder involvement is an integral part of any framework assessing social-ecological resilience to define the system boundaries and establishing important attributes of the system (Walker et al. 2002).

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

Step 2: Identify system and its boundaries on landscape level

System boundaries need to be defined to identify the factors affecting the capacity to reorganize or adapt. The system boundaries may be defined by identifying homogeneous biophysical and socio-economic variables in a landscape to form landscapes and socio-economic units that create the social-ecological system (Martín-López et al. 2017), e.g., a forest management unit. Identifying the major disturbances affecting the social-ecological system is important as systems may be robust to some disturbances at the expense of system performance under other disturbances (Schoon and Cox 2012). Remote sensing can be increasingly used to identify the prevailing disturbance regimes (Senf and Seidl 2021a). In addition, it is necessary to define the desired spatial, temporal, and hierarchical scales and to recognise the trade-offs in resilience that might occur between the defined system boundaries and the scales outside the defined boundaries (Armitage et al. 2012).

In our example, we look at the management of 100 ha forested landscape dominated by Norway spruce over the time span of 30 years until 2050. Norway spruce is a tree species with a high ecological and economic importance in Europe (Jansson et al. 2013). Its wood is used for multiple purposes, ranging from solid wood products to pulp and paper (Spiecker et al. 2004). However, the species is increasingly vulnerable to disturbances such as windthrow (Gardiner et al. 2013; Jansson et al. 2013), drought (Zang et al. 2014), and bark beetles (Hlásny et al. 2021a; Seidl et al. 2016b). These disturbances have been projected to increase significantly with climate change, especially outside the natural range of Norway spruce (Seidl et al. 2014a). Therefore, we look at how the resilience of the Norway spruce dominated landscape (resilience of what) can be enhanced to climate change induced changes in the disturbance regime (resilience to what) in the next 30 years (temporal scale).

Step 3: Define management goals, management strategies and main trade-offs
The management goals and possible strategies to reach them should be defined together with the stakeholders. This process usually starts from the current business-as-usual management but can include historic management approaches as well as potential future management alternatives (Seidl et al. 2018). Defining management objectives and outcomes is required to identify the main trade-offs created by the management goal, which are affecting the resilience of the forest-related social-ecological system.

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

The identified main trade-offs are different for each management goal. For management targeting multiple ecosystem services, the provisioning of several ecosystem services automatically causes trade-offs between services that can affect resilience e.g., by causing disputes between stakeholders. For management targeting timber production, a main trade-off could be between short- and long-term resilience where measures to increase long-term resilience decrease the short-term resilience, e.g., thinning to increase storm and drought resistance. For management targeting biodiversity conservation, a main trade-off could be between social and ecological parts of the system, for example when storm-felled trees are left unsalvaged in the forest to increase biodiversity which decreases the economic and recreational value of a forest and may cause social conflicts. The management goals, related strategies, and trade-offs are described in Table 3.4.

Table 3.4. Description of management objectives and strategies: main goal, management strategy 1, management strategy 2, and the main trade-offs relevant for managing resilience.

Management goal	Management for multiple ecosystem services	Management for timber production	Management for biodiversity conservation
Example management objective	Maintain or enhance the resilience of multiple ecosystem services for a great variety of stakeholders.	Earn the highest possible profit from sustained timber production.	Protect and increase the biodiversity of the forest.

Management strategy 1	Perform group cutting to open the canopy to improve light conditions on the ground. Retain all the regenerating species. Retain large and iconic trees. Plant oak in the gaps.	Convert forest into a mixed beech-spruce continuous cover forest by opening canopy and planting beech.	No further active forest management, spruces are left as they are in the forest. Natural disturbances acting as main drivers for regeneration and modification of structural diversity.
Management strategy 2	Perform single tree cuttings to develop structural diversity to convert to continuous cover forest. Promote structural diversity by removing trees of different heights.	Spruce is maintained with intensive forest management with reduced rotation periods and little to no thinning before clearcut. Regeneration is done by planting improved spruce seedling material.	Active restoration. Gap and single tree cutting conducted to create dead wood and increase the light conditions. Broadleaved species (e.g., maple, aspen, birch) are planted.
Main trade-offs	Trade-offs between ecosystem services.	Trade-off between short- and long-term resilience.	Trade-off between social and ecological parts of the social-ecological system.

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

This step requires that stakeholders jointly determine the indicators they deem important for the resilience of the forest system (resilience of what) to a certain disturbance (resilience to what, sensu Carpenter et al. 2001). In real life, the stakeholders would need to determine the response curve of the indicator (how the indicator values affect the level of resilience). Based on literature and our expertise, we identified common response curves to each indicator, out of which we show two examples here: indicators ‘Genetic diversity from natural regeneration’ and ‘Planting of more adapted non-local species and provenances’. An overview of all the response curves is given in Appendix B (Appendix B Table 8.1 and Table 8.2). It is important to note that these curves are an interpretation of how resilience responds for different indicators in specific circumstances, and they might take other forms depending on the social-ecological context and the identified trade-off. The response curves reflect the selected spatial and temporal scale of the management and therefore may take forms that would not necessarily be realistic in a long-term analysis of natural ecosystems. Furthermore, the stakeholders should decide on the minimum threshold values for each indicator before the indicator weighting to ensure that none of the indicators has extremely low values even if their influence on the resilience would be low in the stakeholder opinion.

Once all indicators have been decided on, the stakeholders should assign weights for each of them in accordance with their importance for reaching the management objectives. Here we decided on the weights of the two indicators for each management goal. For management targeting multiple ecosystem services, ‘Genetic diversity from natural regeneration’ receives high importance (w = 1), while ‘Planting of more adapted non-local species and provenances’ receives medium importance (w = 0.8). In the gap areas, oaks that are adapted to local site conditions are planted, whereas Norway spruce is naturally regenerated. For management targeting timber production, ‘Genetic diversity from natural regeneration’ receives medium importance (w = 0.8), while ‘Planting of more adapted non-local species and provenances’ receives high importance (w = 1). Improved seedling material from southern provenances may perform better than natural regeneration if maintaining spruce forest is desired. For management targeting biodiversity conservation, ‘Genetic diversity from natural regeneration’ receives high importance (w = 1), while ‘Planting of more adapted non-local species and provenances’ receives low importance (w = 0.4). Enabling natural regeneration of the species naturally present in the landscape may be more beneficial for biodiversity than planting more adapted non-local species.

Step 5: Project future scenarios for each management goal

Projecting the future indicator values for the defined management strategy based on climate change and socio-economic change helps to visualise possible future outcomes of management. The projection of future scenarios is needed as a static snapshot of the system ignores the temporal dynamics of the system and therefore the information on indicators describing processes or outcomes might be misleading to interpret (i.e., the behaviour of the system cannot be determined from short time periods; Müller et al. 2016). Future changes in the environmental conditions should be assessed and analysed, for instance in relation to the question of how species viability is affected. Similarly, scenarios for future changes in policies and demands related to forests should be assessed. Both could result in different scenarios that can be used for simulation of future management outcomes.

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

Step 6: Evaluate projected management outcomes

The projected outcomes of the management strategies should be evaluated. The management strategy outcomes should be evaluated against the achievement of the management goals. The outcome of the hypothetical examples would refer to the level of different ecosystem services provided (management targeting multiple ecosystem services), the income received from timber production (management targeting timber production), and the number and abundance of different species (management targeting biodiversity conservation). If the management strategy results in an undesirable average resilience score for the forest-related social-ecological system, the management strategy should be revisited with the stakeholders (Step 7). If the outcomes are desirable, the resilience assessment can be done (Step 8).

Step 7: Revise the management strategy if needed

The management strategy and objectives defined in the Step 4 should be reassessed in the light of the projected management strategy outcomes. The strategy and objectives should be modified to project more promising outcomes to fulfil the management goal. In case that the outcomes of the management strategies are not desirable (e.g., the level of provided ecosystem services is projected to be too low), the management strategy would need to be revised and changed.

Step 8: Perform resilience assessment

Once the projected management strategy outcomes are deemed acceptable, the resilience of the forest-related social-ecological system under different management strategies should be assessed. To assess the resilience of a management strategy indicators representing all the principles and criteria from Table 3.2 and 3.3 should be included. Based on the evaluation of the current situation and projected development of the landscape, indicator values and their movement on the indicator response curves can be determined (Fig. 3.4) and evaluated. Balancing takes place after the individual values for the considered time period are known by examining the results with the stakeholders. In the balancing phase questions to consider are e.g., whether the low level of resilience indicated by certain indicators are acceptable if other indicators indicate high levels of resilience, whether the indicators should show similar levels of resilience, or whether the resilience increases fast enough for the stakeholders. For example, having indicator values at extreme ends might result in a medium average resilience score but many low resilience indicator values might indicate weak points of the system and even start to erode the average resilience in time. Balancing might result in leaving some of the proposed management strategies out of the resilience assessment if they are considered by stakeholders as not suitable. If the balancing exercise results in a disagreement, the management strategies might need to be revised.

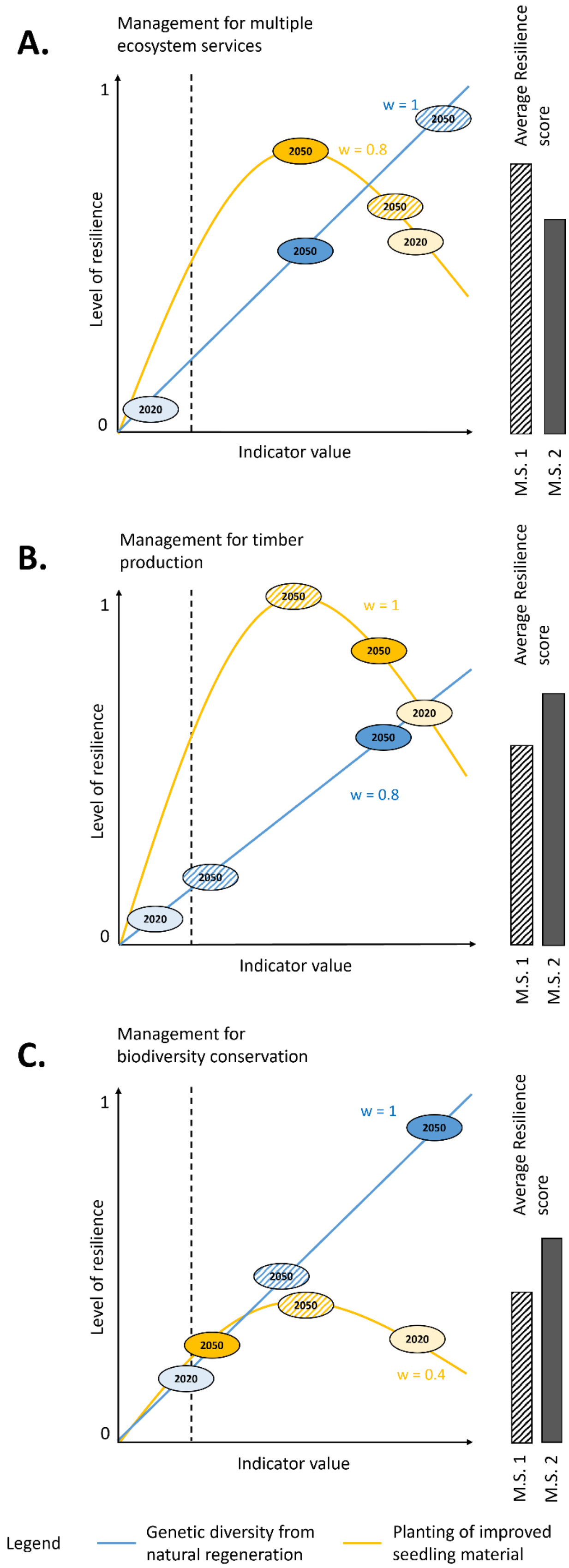

A.
Management for multiple ecosystem services
1
0
Level of resilience
Indicator value
w = 1
w = 0.8
2050
2050
2050
2050
2020
2020
Average Resilience score
M.S. 1
M.S. 2
B.
Management for timber production
1
0
Level of resilience
Indicator value
w = 1
w = 0.8
2050
2050
2020
2050
2050
2020
Average Resilience score
M.S. 1
M.S. 2
C.
Management for biodiversity conservation
1
0
Level of resilience
Indicator value
w = 1
w = 0.4
2050
2050
2050
2020
2050
2020
Average Resilience score
M.S. 1
M.S. 2
Legend
Genetic diversity from natural regeneration
Planting of improved seedling material

Figure 3.4. Illustration of how weighting of indicators and different management scenarios affect the resilience outcome of two indicators. The indicator values presented are in accordance with the management scenarios described in Table 3.4, with (A) management targeting multiple ecosystem services, (B) timber production, (C) biodiversity conservation. The solid lines represent the indicator response curves, the height of the solid line represents the weight the indicator has for the management goal, the slashed and filled bubbles represent the indicator value in time for the two management scenarios and the slashed and solid bars show the average resilience score of the indicators for the two management scenarios (M.S. 1 and M.S. 2).

Once the balancing is done and the selection of the management strategies is clear, the resilience assessment is done by calculating the average resilience score of the indicators for each management strategy (Fig. 3.5). The multiple indicators and the potential emerging trade-offs between the indicator values can be dealt with involving multi-criteria decision-making tools (Borges et al. 2017; Kangas and Kangas 2005; Wolfslehner et al. 2012). The multi-criteria decision-making tools enable the incorporation of the stakeholders' preferences into the decision-making process and therefore support the exploration of alternative solutions and preferences in transparent manner (Borges et al. 2017; Wolfslehner et al. 2012). Each management strategy involves a different set of interventions with different timings and therefore the temporal development of the average resilience score might change with time. Therefore, the resilience assessment should be done for regular timesteps, e.g., every 5 or 10 years. The use of multi-criteria decision-making tools may facilitate the reassessment of resilience as the information behind the tool models can be updated (Borges et al. 2017). Depending on the resilience assessment outcome, the management strategy can be either accepted or it should be revised again if the assessment results fail to find a resilient system.

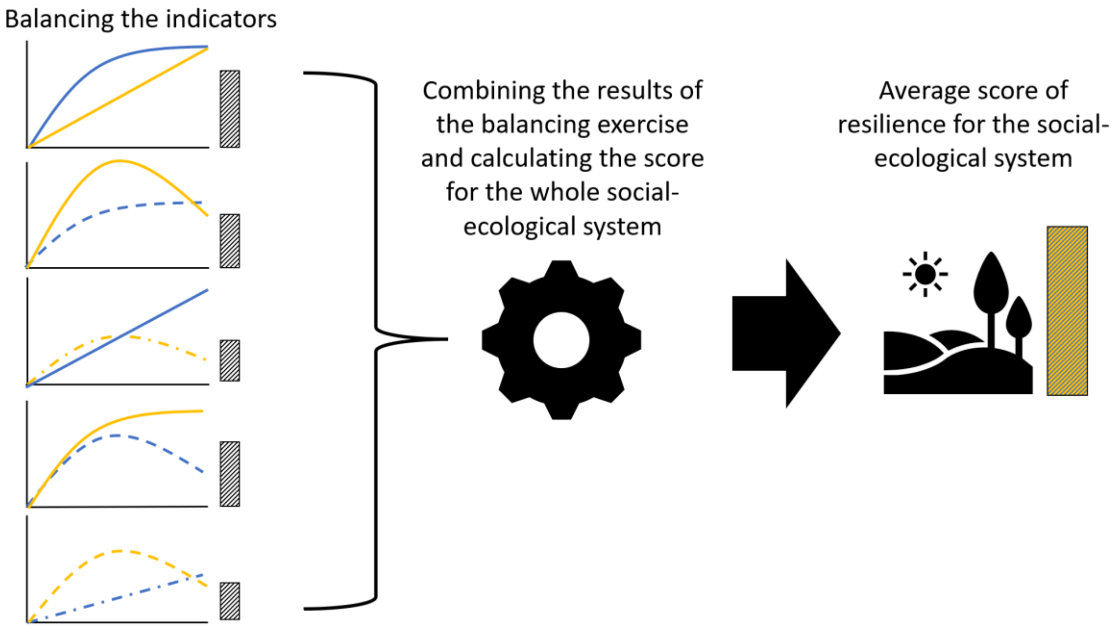


Figure 3.5. The process of calculating the average resilience score. First, all the identified indicators are balanced and the average score of social-ecological resilience is calculated. Then all the individual balancing exercises are combined with the help of multi-criteria decision-making tools and the average score of social-ecological resilience is calculated for the whole social-ecological system.

Step 9: Revise the resilience assessment

If the stakeholders are content with the results of the balancing exercise, the management strategy can be accepted. If in the previous step results are unsatisfactory, the management strategy should be revised again with the stakeholders with attention paid to the vulnerable parts of the system where the indicator values showed low levels of resilience. The resilience impacts of the newly defined strategy should then be reanalysed following the previous steps.

Step 10: Agree on accepted management strategy

If the stakeholders agree that the level of resilience achieved with a specific management goal is enough, they may choose that management goal and related strategy to be implemented.

3.3 Discussion

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

3.3.1 Foundations of the framework

The first objective of this study was to explore the trade-offs in the social-ecological system. While many possible resilience mechanisms could have been considered (Weise et al. 2020), our focus was on those considered most relevant in the literature for social-ecological systems as forests, namely diversity, adaptive capacity, and connectivity (Bernhardt and Leslie 2013). In the forest management context, diversity may represent the range of resources at the manager's disposal, connectivity the ability and possibility to coordinate action, and adaptive capacity the capacity and ability to act. If any of them are weak, it could hamper the resilience of the system. The complexity of forest-related social-ecological systems leads to several possible trade-offs that affect the resilience of the system (Allen et al. 2018). We identified four classes of trade-offs that have strong effects on resilience in the forest management context: trade-offs between resilience mechanisms, trade-offs between ecosystem services, trade-offs between the ecological and social subsystems, and trade-offs between spatial and temporal scales (Table 3.1). Some of the trade-offs are better known than others. For example, trade-offs between ecosystem services are well-studied (Rodríguez et al. 2006; Turkelboom et al. 2018) whereas trade-offs between resilience mechanisms are less studied and harder to analyse (Weise et al. 2020).

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

3.3.2 Applying the framework to management

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

Mincey 2020). Therefore, an approach which can be tailored to fit these external constraints is beneficial.

Our framework highlights the importance of involving stakeholders when assessing resilience, as that is the start for identifying the system, its management goals and resilience indicators. Initially, we started to look for a way where forest owners could assess the social-ecological resilience of forests without consulting many stakeholders as this process may be challenging to conduct without satisfactory results (Sheppard and Meitner 2005). However, it became apparent that to adequately capture the complexity of the situation, knowledge of and experience from different parts of the social-ecological system is needed. Local stakeholders with the support of experts hold the key information of the system in their knowledge and mental models (Walker et al. 2002) and could therefore provide a more accurate view and projections of resilience than what a single decision-maker is able to do. Furthermore, the involvement of the stakeholders underlines the need to discuss the agency of resilience: for whom, for what purpose and by whom the resilience of a social-ecological system is decided (Keck and Sakdapolrak 2013). As the power may be differently distributed in the communities and the actors may have unequal chances to participate in the decision-making, addressing the winners and losers of the changed management practices to increase resilience is needed (Keck and Sakdapolrak 2013). A purposeful stakeholder involvement is needed if any legitimate visions on resilience are to be created (Larsen et al. 2011). In many instances the stakeholder involvement may require that forest managers consider more the attributes that increase the social resilience ("the way in which individuals, communities and societies adapt, transform, and potentially become stronger when faced with environmental, social, economic or political challenges" (Cuthill et al. 2008)) of the communities in the managed landscape, even if this normally considered to be out of the scope for managers (Maclean et al. 2014). However, acknowledging that management influences the social resilience and considering people and environment mutually may lead to more legitimate and resilient outcomes (Maclean et al. 2014). A holistic view of the analysed system is particularly important while defining the indicator response curves as different stakeholders may perceive the effects of indicators differently or they may have different priorities in enhancing resilience, e.g., focusing more on service provisioning than forest ecosystem resilience. Jointly determining the indicator response curves may incorporate the potential conflicts of individual objectives tighter to the resilience assessment. Nevertheless, the framework can provide food for thought even to managers that are unable to engage in the full stakeholder process. The framework represents a helpful tool that ensures each of the key indicators are considered and the implications of any actions or any choices are considered.

While our framework is flexible to be applied in various situations, it does require defining the temporal and spatial scale in which resilience is considered. The framework also needs information on how the indicator values would change in the future. As resilience is a dynamic property of a system that changes over time (Cabell and Oelofse 2012), the temporal and spatial scales can change the target indicator values. Furthermore, forest managers operate simultaneously at multiple nested scales and hierarchies from local stands to global forest policies, and affect and, in turn, are affected by outside influences (Fischer 2018). The results of the initial determination of the resilience indicators and their response curves should be revised regularly by the stakeholder panel to account for possible changes in the system or surrounding conditions (Fischer et al. 2009) as well as to check if the predicted indicator values are taking place. For example, pulse (e.g., a storm) and press (e.g., climate change) types of forest disturbances can have different effects on forests and their resilience (Cantarello et al. 2017) that might also change both the major trade-offs and the response curves of the resilience indicators of the balancing framework. Furthermore, disturbances can lead to varying management responses depending on the management goal. If importance is laid on reducing disturbance impact, more attention is paid to measures that increase short-term resilience (or resistance sensu Bryant et al. 2019), e.g., to more frequent thinning and centralized emergency response. If importance is laid on a system being resilient far into the future, attention is paid to measures that increase long-term resilience, with e.g., measures that ensure regeneration of the system (Xu et al. 2017). Our example clearly shows that the average resilience score for each management goal is dependent on the selected indicators and the weights assigned for them. While the example was made to illustrate the use of the framework, it also shows that no single management goal was always more resilient than the others. Therefore, the definition of the indicator response curves and regularly reviewing them is a crucial step in the application of the framework.

3.3.3 Future pathways of research

To advance the operationalization of a resilience assessment framework as presented in this paper, future research should aim at carrying out regional case studies (as in Nagel et al. 2017) with participatory stakeholder engagement. Such research would require an initial assessment of the forest management goals and the social context as well as an outlook on the future social-ecological pathways. The research should involve simulation of the future forest conditions and market development as well as explore the development of social demands on forests. Against such an analysis, relevant indicators need to be selected and context specific response curves for these resilience indicators determined. Here the framework could be combined with other promising methods to assess resilience, for example the functional response traits and network analysis (Aquilué et al. 2020; Mina et al. 2020), to identify relevant indicators. With developing experience from diverse regional case studies, common stakeholder preferences related to the indicator selection and weighting can be expected, which should reduce the required implementation efforts and facilitate the uptake of such assessment methods. Furthermore, climate change impact assessments using forest simulation modelling should be expanded with quantification and evaluation of resilience indicators, which would also support the operationalization of the approach.

3.4 Conclusion

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

4 The resilience of trees to tree water deficit across Europe

Based on Nikinmaa, L., Stegehuis, A.I., Lindner, M., Zweifel, R., Teuling, A.J., von Arx, G., Van Meerbeek, K., Muys, B., and the DenDrought2018 consortium. "The recovery of trees from tree water deficit across Europe". To be submitted.

4.1 Introduction

Climate change has increased the occurrence of drought and other disturbances in forest ecosystems worldwide (Seidl et al. 2017a) leading to a global increase in drought-induced tree mortality (McDowell et al. 2022). Normal and hot droughts are likely to become more frequent in Europe (Manning et al. 2019; Spinoni et al. 2018), causing augmented drought stress to trees. Drought stress could lower tree productivity (Kannenberg et al. 2019), defence against pests (Stephenson et al. 2019), and increase the susceptibility to fires (Whitman et al. 2019). In addition to the extreme droughts, the increased occurrence of mild but chronic drought stress can significantly reduce growth and carbon assimilation of forests (Brzostek et al. 2014). The lowered yield and increased susceptibility to disturbances may cause significant economic losses to forest industry, and a general reduction of ecosystem services (Thom and Seidl 2016).

While the effects of single drought events have been actively investigated (e.g., Camarero et al. 2015, Gazol et al. 2017, Sturm et al. 2022), the effects of repeated or persistent drought periods on trees are relatively little studied, with the exception of some long-term drought experiments (e.g., Barbeta et al. 2015, Grams et al. 2021). These studies found that persistent drier conditions exacerbate the effects of more severe droughts (Barbeta et al. 2015), and significantly reduce stem growth in the season (Grams et al. 2021). In both cases, the experiments were conducted in a small number of plots with weekly or seasonal measurements. Studies analysing long-term tree behaviour on a European scale are scarce due to the lack of harmonized datasets (but see Salomón et al. (2022)). Many of the studies on tree responses to drought stress use tree-ring width data (Camarero et al. 2018; Lloret et al. 2011), which only have a yearly resolution, making observing the seasonal behaviour of trees and detecting early warning signs in tree decline challenging.

Tree responses to drought stress depend, amongst other features, on their hydraulic architecture and wood type. Tree stems have tissues for static support and water transport, with distinct levels of differentiation: gymnosperms (e.g., conifers) have xylem consisting of tracheids for stability and vertical conductance of water, whereas angiosperms have xylem composed of fibres for stability and vessels for water transport (Pfautsch 2016). Angiosperm trees can be further categorized into diffuse-porous and ring-porous species. The diffuse-porous species have vessels with fairly constant diameter in the radial direction from earlywood to latewood, whereas the ring-porous wood shows an abrupt change between very wide earlywood vessels and much narrower latewood vessels (Panshin and De Zeeuw 1980 in McCulloh et al. 2010). Water is stored in symplastic (place inside plasma membrane of plant cells) and apoplastic (place outside plasma membrane of plant cells) spaces in sapwood and inner bark. In angiosperms, wood rays, which are thin-walled parenchyma cells that interconnect by plasmodesmata, play an important role in the bidirectional transportation of water between the sapwood and inner bark (Pfautsch et al. 2015). The different wood types as well as the leaf phenology influence the diameter growth rhythm, which implies that the times when tree growth is the most sensitive to climate varies (D'Orangeville et al. 2022). Therefore, the stress reaction patterns and consequences for the different wood types may vary even under similar environmental conditions.

Tree water deficit (TWD) is proposed as a good indicator of water stress in trees (Dietrich et al. 2018; Hinckley et al. 1978; Zweifel et al. 2005), as it is proportional to the water content of the living tissues in the stem (Herzog et al. 1995), and primarily determined by the evaporative demand on the one hand, and the soil water conditions on the other (Brito et al. 2017; Zweifel et al. 2005). In addition, it has the advantage of providing information on the stress reaction of the individual trees and can therefore improve the mechanistic understanding of the impacts of stress on trees. TWD can be calculated from the diurnal changes in stem diameter measurements after detrending for growth (Zweifel et al. 2016). TWD occurs when the diameter of the stem falls below the preceding maximum daily value. There are two physiological processes behind the changes in stem diameter: irreversible stem expansion caused by tree growth on the one hand and swelling and shrinking of the stem caused by hydration and dehydration mainly of the bark on the other hand. This shrinking is referred to as TWD (Zweifel 2016). During times of stem shrinkage, very little growth or no growth is possible (Zweifel et al. 2016). Automated dendrometers enable a feasible way to observe stem diameter changes in high temporal resolution (in µm), calculate TWD, identify the phases of stem water depletion and replenishment (Zweifel and Häsler 2001), and thus observe tree stress status on a sub-daily scale.

Tree stems shrink every day due to transpiration rates that are larger than the water uptake by the roots at the same time. Consequently, TWD increases every day (De Schepper et al. 2012; Zweifel et al. 2001), however, trees are often capable to refill their stem water reserves and reduce the TWD back to zero when vapour pressure deficit (VPD) decreases during night (Zweifel et al. 2021). When evaporative demand increases or soil water content decreases, trees are no longer able to fully replenish their stem water reserves and TWD remains higher than zero. TWD can remain high for a few days, weeks or even months. In this study, we defined dry periods as the times when TWD had stayed above zero for at least five consecutive days.

Tree species have different stem phenology and lengths of the growing season (Etzold et al. 2022) and growth rates vary between species (Cuny et al. 2012). In contrast, while the absolute TWD values differ between tree species, the relative values and the seasonal course of the TWD are more uniform between species (Brinkmann et al. 2016; Zweifel et al. 2005, 2007). However, the response to the changes in TWD differs significantly between species in relation to other physiological responses, e.g., stomatal opening and closure, and sap flow (Brinkmann et al. 2016; Zweifel et al. 2007). The time of occurrence and the duration of the dry periods might therefore have significantly different consequences between different species and wood types.

In this study, we focused on tree behaviour during stress and the resilience of trees to water stress on short time scales of days and weeks. We assessed resilience as the capacity of trees to maintain the time that it took for trees to reduce TWD to zero, i.e., the replenishment time (engineering resilience sensu Pimm (1984)) for consecutive dry periods. We further analysed whether the replenishment time remains constant for multiple consecutive dry periods in a season. To our knowledge, this has not been done before on a large scale. We hypothesized that the replenishment time of the stem water reserves increases as the stress of trees accumulates with the consecutive dry periods and the magnitude of TWD in a summer season, the wood type of the tree, and the climatic conditions influence the magnitude of the increase. We analysed how consecutive stress periods affect the replenishment time of the tree stem water reserves for different wood types. We expected to see the replenishment time to increase towards the end of the season as the soil water conditions dry further.

4.2 Material and methods

4.2.1 Data collection and processing

We used tree-specific point and band dendrometer measurements with a temporal resolution of 15 to 60 min, which were compiled from 127 monitoring plots across Europe (Fig. 4.1), consisting of measurements of 681 trees (Table 4.1). The length of the measurement periods varied between sites with the longest being from 2003 to 2018 and the shortest being only in 2018 (Table 4.1). The data originate from the DenDrought2018 initiative (Salomón et al. 2022). Full data on the sites are available in the Appendix (Appendix C Table 8.3). From each site, we used the raw dendrometer measurement time series, the information on the type of dendrometer used, the species and wood type of the measured trees (Fig. 4.1), site coordinates, temperature data with a 0.1 degree grid from the E-OBS dataset (Cornes et al. 2018) and Standardized Precipitation Evapotranspiration Index (SPEI) calculated with one month timestep from the SPEIbase (Beguería et al. 2010, 2014; Vicente-Serrano et al. 2010). We standardised temperatures derived from the E-OBS dataset, re-gridded to sites, and corrected for the elevation by calculating the difference between the E-OBS and actual site elevation, multiplying it with a fixed temperature gradient of 0.65° per 100m (Stone and Carlson 1979), and adding it to the E-OBS temperature.

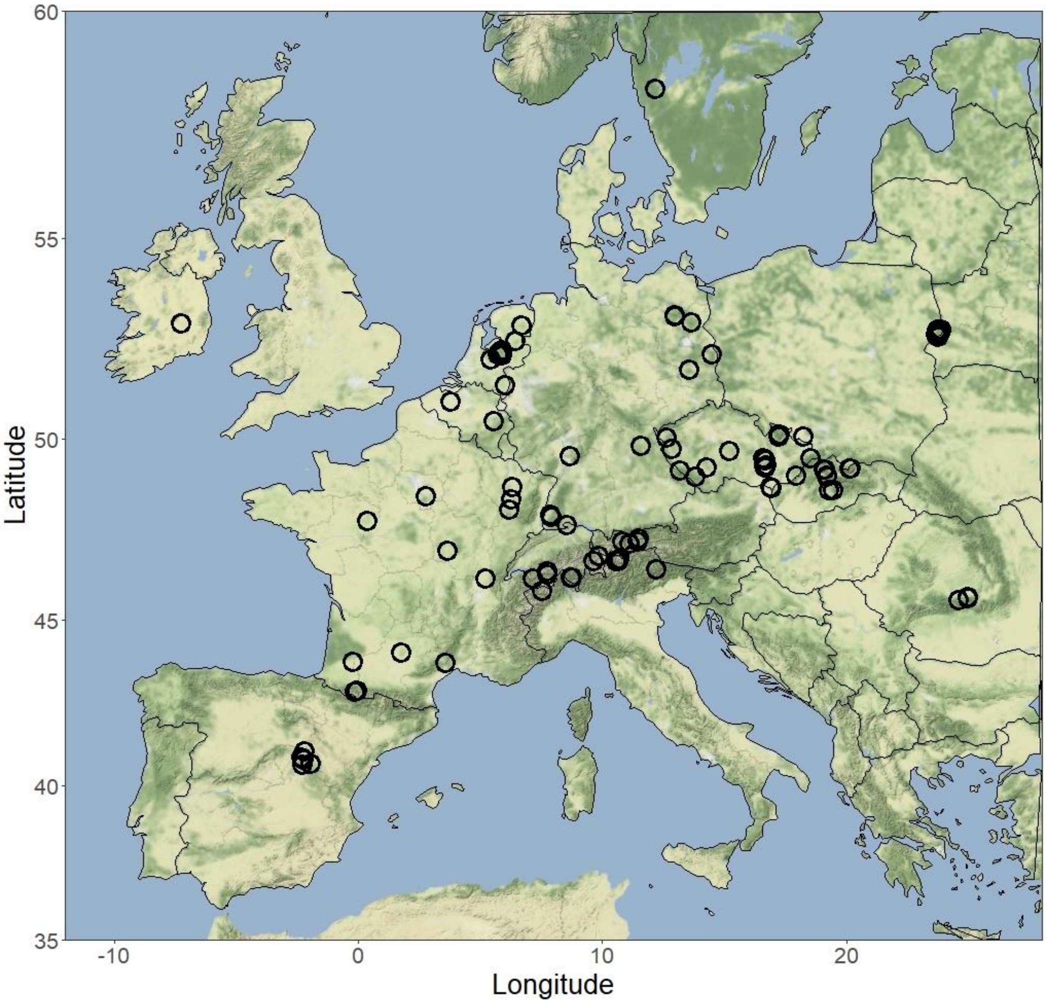


Figure 4.1. The location of sites in Europe.

Table 4.1. Metadata of the study including the length of the measurement period, number of sites, number of trees, number of trees for different wood types and the number of different species the trees present indicated in brackets. The second row shows all the data, and the following rows are divided according to the length of measurement period.

Length of the measurement periods in years	Number of sites	Number of trees	Number of coniferous trees (#species)	Number of diffuse-porous trees (#species)	Number of ring-porous trees (#species)
Number of years \ Total number of sites and trees	**127**	**681**	**404 (10)**	**105 (9)**	**172 (9)**
1	22	112	76 (7)	12 (1)	24 (3)

2	17	96	31 (3)	16 (3)	49 (2)
3	16	87	39 (3)	3 (1)	45 (3)
4	24	89	32 (4)	41 (4)	16 (4)
5	14	74	49 (2)	20 (1)	5 (2)
6	9	56	37 (4)	1 (1)	18 (3)
7	5	33	28 (4)	5 (1)	0 (0)
8	0	0	0 (0)	0 (0)	0 (0)
9	6	28	26 (3)	2 (1)	0 (0)
10	4	17	13 (2)	0 (0)	4 (1)
11	6	23	18 (3)	5 (1)	0 (0)
12	7	55	55 (2)	0 (0)	0 (0)
13	0	0	0 (0)	0 (0)	0 (0)
14	0	0	0 (0)	0 (0)	0 (0)
15	0	0	0 (0)	0 (0)	0 (0)
16	1	11	0 (0)	0 (0)	11 (1)

The raw data of stem diameter measurements were quality-checked and homogenized with the treenetproc R package version 0.1.4 (Haeni et al. 2020; Knüsel et al. 2021; Wickham et al. 2019), which also computes a growth- and a water-related component (TWD), following the zero-growth concept of Zweifel et al. (2016). Afterwards, all the dendrometer time series were visually checked for remaining errors. Time series with errors were excluded. Tree species vary in their timing of growth with some peaking already in April and some in June (Etzold et al. 2022). To make sure that our data reflect only active trees and TWD caused by dryness-related water stress and not e.g., freezing-thawing cycles, we limited the analysis to the summer months (June, July, and August). For the drought periods that started in late August and extended into September we only included the days in August.

We kept the 90% quantile of the calculated TWD values to remove outliers. We furthermore removed the years with negative stem diameter increments as these were likely caused by a measurement error or unhealthy and dying trees. We standardized TWD for each tree (mean = 0 and standard deviation = 1). We also assigned each species to their respective wood type based on literature (Appendix C Table 8.4). To select periods with drought stress, we defined dry periods when TWD remained above zero for a minimum of five consecutive days. Replenishment time was defined as the length of a dry period i.e., as the length that it takes for the TWD to return back to zero. We then aggregated the data for each identified dry period and calculated the minimum and maximum temperature, minimum and maximum SPEI, and the highest and lowest minimum TWD values for each dry period. We compared trees that experienced the same number of the dry periods in a year to explore the differences between years with few and many dry periods (Table 4.2).

Table 4.2. The number of trees included in the comparison of the replenishment time for the years with different number of dry periods.

Number of experienced dry periods	Total number of trees	Coniferous trees	Diffuse-porous trees	Ring-porous trees
2	290	159	60	71
3	378	229	64	85
4	357	224	44	89
5	279	183	29	67
6	175	133	17	25
7	78	68	0	10

4.2.2 Statistical analysis

We employed individual tree-based analyses to investigate how the consecutive dry periods, minimum TWD during dry period, maximum temperature during dry period, monthly SPEI and the wood anatomy group influence the replenishment time. We applied Poisson generalised linear mixed effects models (GLMM) by maximum likelihood estimation (Laplace approximation) using the lme4 package (Bates et al. 2015) in R (R Core Team 2018). We tested which TWD measurement would explain most of the variation in the data: the highest, the average, and the lowest minimum TWD measured during the dry period. Vapour pressure deficit had a high correlation with temperature (Spearman $r > 0.82$) and was not included in the model. Based on our hypotheses, the replenishment time was modelled using the log link function with fixed effects of (1) highest minimum TWD (a continuous variable), (2) maximum temperature (a continuous variable), (3) minimum SPEI (a continuous variable), (4) wood type (a categorical variable), and (5) the consecutive number of the dry period (a categorical variable), and the interactions amongst SPEI and temperature. We included a nested random effect for the individual trees within the measurement site and a random effect for the measurement year to account for spatial variation between sites and tree individuals, as well as for the variation between years respectively.

We assessed the temporal autocorrelation of residuals, homoscedasticity and normality of the residuals, and overdispersion using the DHARMa package (Hartig 2021). As the model showed overdispersion, we fitted three extra models with the same fixed effect structure: (1) a model with Poisson distribution and an additional random effect for observations to adjust for overdispersion (Harrison et al. 2018), (2) a model with zero-inflated Poisson distribution and the additional random effect for observations (Harrison et al. 2018), and (3) a model with negative binomial distribution, with the glmmTMB package (Brooks et al. 2017). We compared the model fit by using the Akaike Information Criteria (AIC) for the three models (Appendix C Table 8.5). As the model with Poisson distribution and an additional random effect for the observations had the lowest AIC, we chose it for the analysis.

4.3 Results

4.3.1 Model outcomes

The replenishment time was best explained by the highest minimum TWD value, the maximum temperature, and the interaction between the maximum temperature and the minimum SPEI value during the dry period, the wood type, and the number of the dry periods in the season (Table 4.3). The replenishment time increased with higher minimum TWD values (1.349 ± 0.008, $p < 0.001$) and higher maximum temperatures (1.36 ± 0.01, $p < 0.001$). The minimum SPEI value during the dry period increased the replenishment time slightly (1.025 ± 0.009, $p < 0.01$). The intercept of the replenishment time for conifers was 7.26 (± 0.30, $p < 0.001$), whereas for ring-porous broadleaved species the replenishment time was 0.86 days shorter ($p < 0.01$) and for diffuse-porous broadleaved species the replenishment time was 0.81 days shorter when compared to conifers ($p < 0.001$). The increased number of dry periods and the interaction between the maximum temperature and SPEI decreased the replenishment time slightly (0.988 ± 0.004 and 0.926 ± 0.006 respectively, $p < 0.001$ for both). The fixed factors explained 46.6 % and the full model explained 86.5 % of the variation in the data.

Table 4.3. Replenishment time explained by a Generalized Linear Mixed Effects Model (GLMM).

Variable	Estimate	Confidence interval	p-values
Intercept	7.26	6.96 – 7.57	< 2e-16
Min_twd_stan_max	1.35	1.34 – 1.36	< 2e-16
Temp_max	1.36	1.35 – 1.37	< 2e-16
Spei_min	1.02	1.02 – 1.03	0.006236
Wood_anatomyDiffuse	-0.81	-0.84 – (-)0.78	1.39e-07
Wood_anatomyRing	-0.86	-0.90 – (-)0.82	0.001458
Period_number	-0.99	-0.99 – (-)0.98	0.000696
Temp_max * spei_min	-0.93	-0.93 – (-)0.92	< 2e-16

The maximum replenishment time per site also varied for different years, however the comparison is slightly challenging due to measurement periods with different lengths. We compared trees with measurements starting in 2015, another dry year in Europe, and finishing in 2018 (Fig. 4.2). The maximum replenishment time was on average higher in

2018 than in any other previous year. SPEI values had the lowest mean in 2015. Low SPEI values indicate drier periods than the average whereas high SPEI values indicate wetter periods than the average. In 2018, the spread of SPEI values was much higher, indicating that the drought of 2018 was more heterogenous in severity and timing than the drought in 2015, which hit the subset of measured sites more uniformly over Europe.

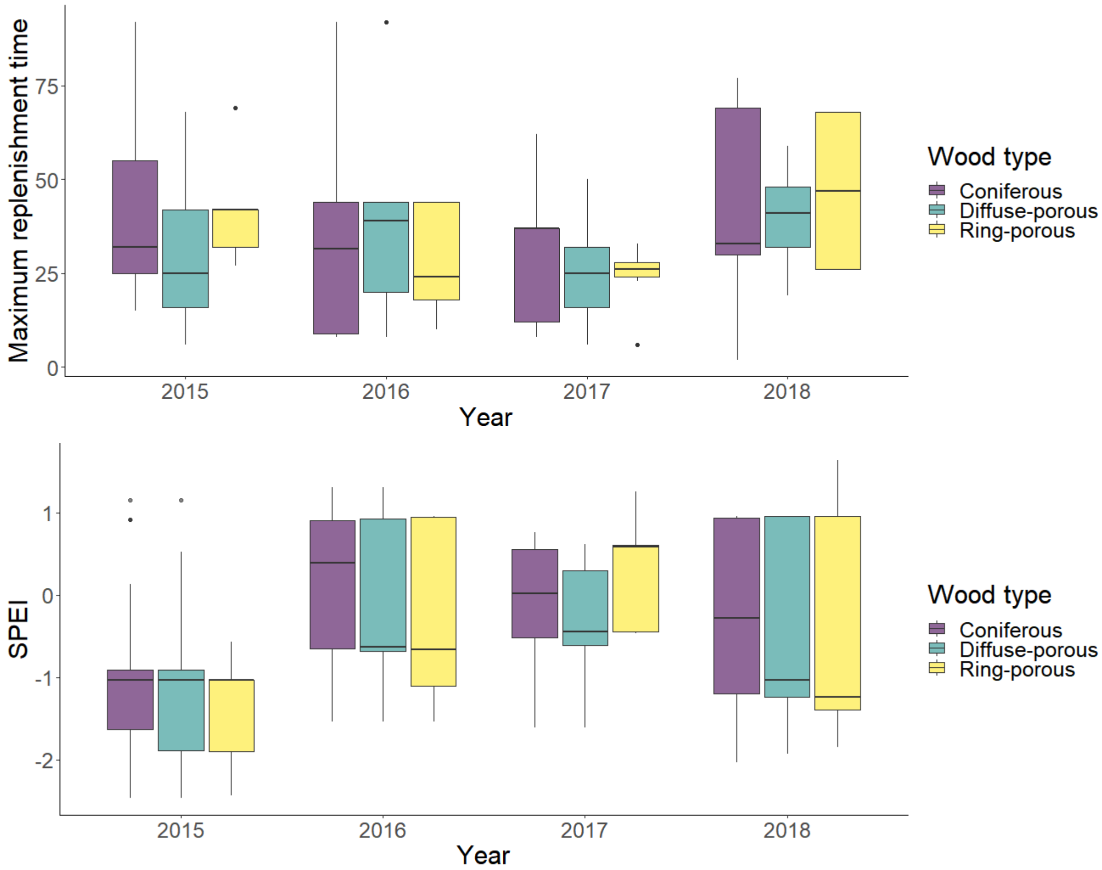


Figure 4.2. The maximum replenishment time and SPEI values per site from 2015 to 2018.

In 2018, the SPEI values were especially low in Central Europe. However, the low SPEI values were not directly reflected by the measured maximum replenishment time as some sites had relatively short replenishment time even if the SPEI values were very low (Fig. 4.3).

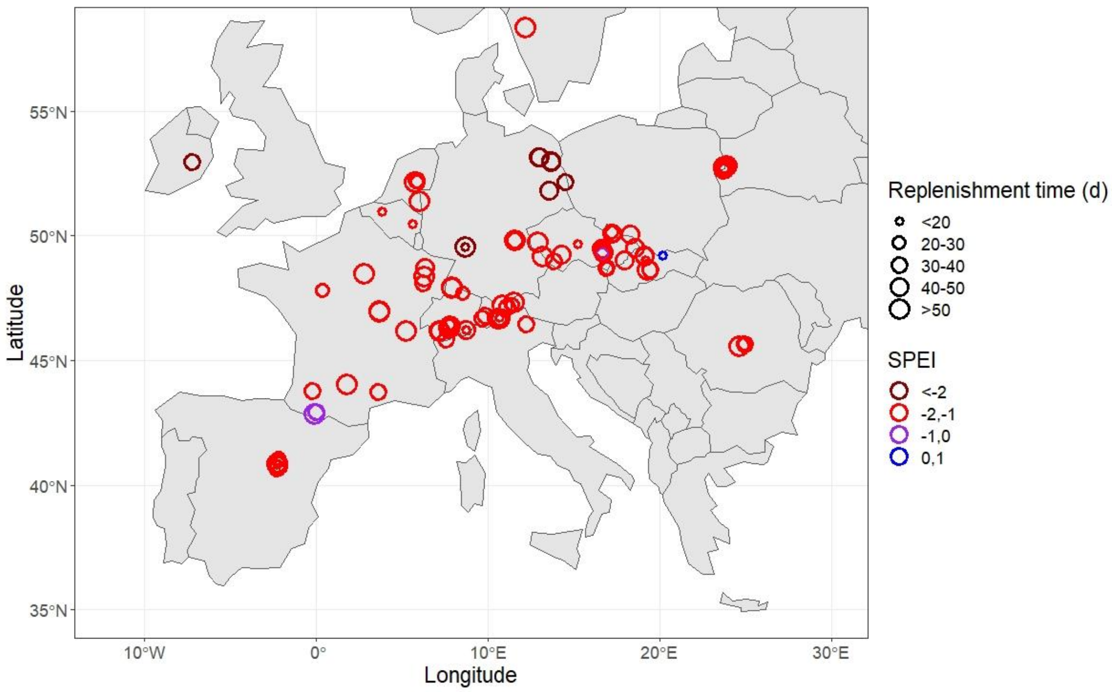


Figure 4.3. The maximum replenishment time and SPEI values in 2018 for the different sites. Both the maximum replenishment time and the SPEI values were divided into five groups with equal number of observations. The size of the circles indicates the replenishment time with smaller circles for short periods and larger circles for longer periods, and the colours indicate the SPEI values (with negative values indicating drier conditions and positive values wetter conditions than on average).

4.3.2 The behaviour of TWD over multiple stress periods

We compared the replenishment time for trees that experienced 2-7 dry periods in a year. For the trees that experienced only two dry periods in a year, only the ring-porous trees had a significantly longer replenishment time for the second dry period ($p < 0.001$). For the trees that experienced three, four, or five periods in a year, the replenishment time of the last period was significantly higher compared to first period for coniferous and ring-porous trees ($p < 0.001$) (Fig. 4.4). For the diffuse-porous trees, only for the trees that experienced three dry periods in a year, the last period had significantly longer replenishment time than the first period ($p < 0.001$). For the trees that experience either six or seven dry periods, only coniferous trees had a longer replenishment time in the last period compared to the first period ($p < 0.001$).

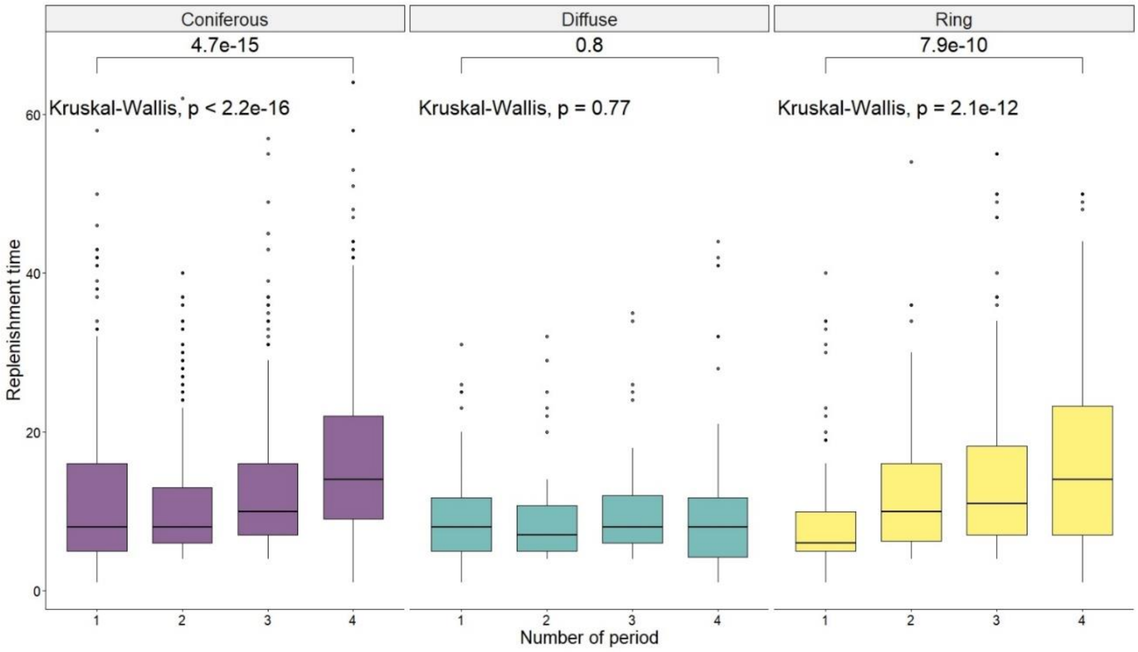


Figure 4.4. The replenishment time during four consecutive dry periods for coniferous, diffuse-, and ring-porous trees. The horizontal black line shows the median values, the boxes show the interquartile range. Only trees that experienced four dry periods in a year were selected for this analysis.

The difference in the average replenishment time of the different dry periods between coniferous and ring-porous trees was not significant except for the 2nd and 3rd period of the year when ring-porous trees had slightly longer replenishment time than conifers (Fig. 4.4.). However, the diffuse-porous trees had in general always shorter replenishment time than coniferous or ring-porous trees except for the 3rd period when the difference between the length of the dry period for coniferous and diffuse-porous trees was not significant.

As 2018 was an exceptionally hot and dry year in many areas in Europe, notably the north Atlantic and Central European regions (Drouard et al. 2019) where many of the sites are located (Fig 4.1), we also compared the minimum TWD values from time period 2004-2017 to the values of 2018 for trees that experienced an equal number of dry periods in a year (Fig. 4.5). In 2018, the minimum TWD values were higher compared to the average from the period of 2004 to 2017, except for the years that experienced two or seven dry periods. The spread of the values between different periods was higher, especially for diffuse- and ring-porous trees.

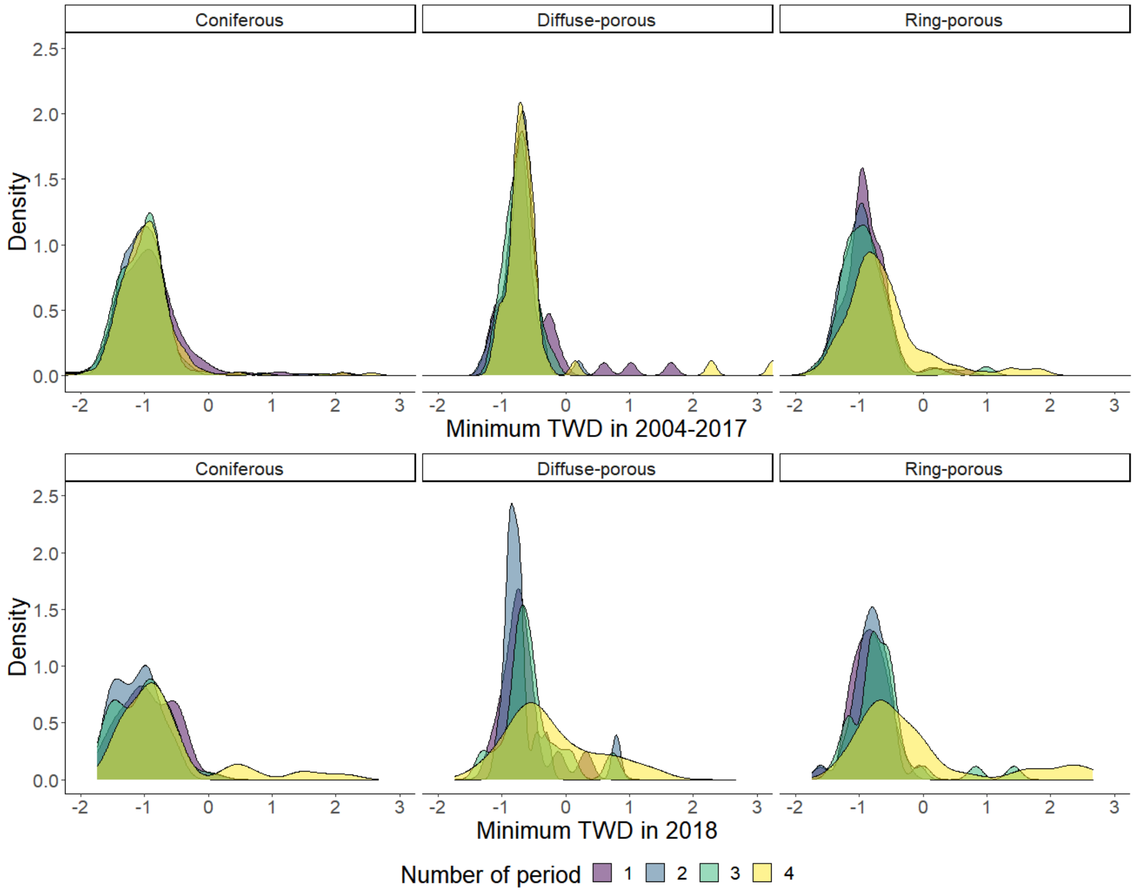


Figure 4.5. The density distribution of the minimum TWD for trees that only experienced four dry periods in all years (2004-2017) (upper pane) and in 2018 (lower pane). The x-axis shows the scaled minimum TWD values with negative values meaning lower than average values whereas positive values mean higher than average values. The y-axis shows the probability density function values. Colours refer to the number of periods.

4.4 Discussion

We analysed how resilient trees are to reoccurring dry periods, expressed as the times trees experience TWD for more than five days, by measuring the replenishment time, i.e., the time it took for tree stem water reserve to replenish. We explored how temperature, SPEI, highest minimum TWD, wood type and period number affected the replenishment time, using a generalized linear mixed effects model. We hypothesized that stress of trees builds up over consecutive dry periods and that this is expressed by increased replenishment time. We also hypothesized that the reactions to stress would be different for the different wood types.

4.4.1 The effects of consecutive dry periods on the different wood types

The results indicate that the coniferous and the ring-porous trees start to lose their resilience of maintaining their stem water reserves along the season, whereas the diffuse-porous species are able to maintain their resilience throughout the season. The results also show the effects of the exceptional year of 2018, when the replenishment times were on average higher than during the previous years (Fig. 4.2), indicating a high level of stress. While the model results showed a trend where the replenishment time decreased with their increased occurrence, focusing on years with trees that experienced an equal number of dry periods in the season, we can confirm our hypothesis for coniferous and ring-porous trees (Fig. 4.4), with both having significantly longer replenishment time at the end of the season than in the beginning when there were more than two drought periods in a year. Moreover, diffuse-porous trees had consistently shorter replenishment times than coniferous or ring-porous trees while the average replenishment time did not differ between the coniferous and ring-porous trees except for the 2nd and 3rd dry period of the year when ring-porous trees had longer replenishment time. Coniferous species had the most trees with very long replenishment times (more than 50 days), indicating a low capacity to replenish their stem water reserves during the season.

In addition to the replenishment time, the minimum TWD values between the different dry periods had higher range in 2018 than in the long-term average, especially for the diffuse-porous trees (Fig. 4.5), which in the long-term average were very concentrated around the same TWD values. In the period of 2004-2017, the trees had very similar minimum TWD values between the different dry periods whereas in 2018, the minimum TWD values of especially the last dry period of the year had higher range, indicating a stronger drought stress reaction. High minimum TWD values indicate large stem shrinkage, and therefore trees would need more time or water to replenish their stem water reserves. High evaporative demand in summer months may increase the TWD values while the long periods of daylight leave less time for recovery and replenishment of the stem water reserves (Vieira et al. 2013). Furthermore, TWD is very sensitive to the changes in VPD (Zweifel et al. 2021), and even a slight decrease in VPD might enable an improved refilling of the stem water reserves and therefore end the dry period (Zweifel et al. 2005). It is likely that years with many dry periods have had more spread-out summer precipitation that has decreased VPD and therefore have been less stressful for the trees than the years with less but longer dry periods. The difference in the replenishment time and minimum TWD values between 2018 and the average of the previous years could indicate that the observed and predicted increase of hotter droughts may overwhelm the resilience of the trees with all wood types (Hammond et al. 2022).

The difference between the responses of the wood types to consecutive dry periods could partly be due to the better stomatal conductance capacity of the coniferous and ring-porous trees at low leaf water potentials (to which TWD can be used as an indicator

(Dietrich et al. 2018)) in comparison to the diffuse-porous trees (Klein 2014), which enables the continuation of the metabolic activities even in drier conditions. However, it should be noted that the difference in stomatal conductivity between coniferous and diffuse-porous trees is not very large. The increased length of the dry periods by the end of the seasons for the ring-porous species could also be due to their highly conductive vessel cells losing functionality along the season, as moisture decreases (Klein 2014). Coniferous trees are more water conservative due to lethal consequences of the loss of leaf hydraulic conductance (Brodribb and Cochard 2009) and have higher vertical resistance in the stem water flow and leaf water potential, leading to faster depletion of the stem water (Evert 2006), which may explain the long replenishment times.

The long replenishment times are an indicator of tree stress, but the consequences and the damage of the dry periods depend on the timing of their occurrence, mainly whether they occur at the time of wood formation (Lempereur et al. 2015). Tree diameter growth takes place in a relatively short time window (Rossi et al. 2008) and is highly sensitive to water deficit (Lempereur et al. 2015, Zweifel et al. 2016). Therefore, long dry periods can stop the annual growth in the worst case. However, if the adverse environmental conditions take place after growth has peaked, the consequences on tree growth are not necessarily severe, at least in the same growing season. For example, the 2018 drought was not as detrimental to tree growth, as feared, because it took place after trees had peaked their growth (Salomón et al. 2022). Wood types influence the timing for stem growth and have therefore different vulnerability to dry periods taking place in spring or summer season: coniferous and ring-porous species were shown to have a longer growth period than diffuse-porous species, but their growth peak takes place up to a month earlier than diffuse-porous species, making them more vulnerable to spring drought whereas diffuse-porous species are more vulnerable to summer droughts (D’Orangeville et al. 2022). Therefore, the diffuse-porous trees might have longer lasting consequences if the dry periods occurred at the time of the radial growth. It is however important to note that in addition to the wood type, there are many other factors influencing tree drought stress responses (e.g., stomatal regulation, resistance to embolism or rooting depth (D’Orangeville et al. 2022; Nardini et al. 2016)), and that species belonging to the same wood type may have very different response to water stress (Güney et al. 2020), making it difficult to predict drought response based on the wood type alone. Therefore, the results of this study do not indicate that diffuse-porous species are in general more resilient to drought stress than coniferous or ring-porous species. Indeed, there is evidence that *Quercus petraea*, a ring-porous species is more drought tolerant than *Fagus sylvatica*, a diffuse-porous species (Kunz et al. 2018).

4.4.2 The impact of climate on the replenishment time and TWD

Increase in the maximum temperature measured during the dry period resulted in the highest increase in the replenishment time when compared with the other explanatory variables. This result is in line with previous studies, where TWD was shown to depend on both the soil water content and evaporative demand (Zweifel et al. 2005), which in turn is positively correlated with temperature (D'Orangeville et al. 2016). It should be noted that while we observed similar patterns in TWD response for the different wood types, plant characteristics and local climate may induce a different response in the plants water conservation strategy with gymnosperms and vegetation in boreal climate being more water conservative (i.e., closing the stomata) than angiosperms and vegetation in temperate climate (Massmann et al. 2019). Closing of the stomata and decreasing evapotranspiration increases the sensible heat in the forest, which may further exacerbate the effects of heatwaves (Lansu et al. 2020), as hot temperatures can cause leaf damages and photosynthetic impairment (Ruehr et al. 2019). Long stomatal closure periods may also lead to nutrient deficit and imbalance (Salazar-Tortosa et al. 2018) as well as carbon starvation (McDowell et al. 2022). Therefore, to use TWD as indicator for tree resilience to drought stress, future studies should investigate the link between TWD and stomatal closure rates to better understand the full tree response to water deficit. An example for beech can be found in Walthert et al (2021).

We used SPEI values to determine the dryness of the sites. While less significant than temperature, increase in SPEI also caused an increased the replenishment time (Table 4.3, Fig. 4.3). The lower significance could be due to the difference in temporal and spatial resolution of the data: while temperature and tree-derived data was measured daily and sub-daily, SPEI has a monthly temporal resolution, making it much coarser. Furthermore, the study sites mostly include a small number of trees within meters from one another whereas the grid used to derive SPEI values was approximately 10 km * 10 km. Therefore, the calculated minimum SPEI for the dry period might not be able to capture the exact local conditions and the maximum replenishment time could be lower than expected from the SPEI values (Fig. 4.3).

4.4.3 Outlook for further research

The high-resolution observations of tree growth and diameter fluctuations are rapidly increasing in both length of the time series and spatial density of the observations. They furthermore cover more species and site conditions than before. This constitutes a fascinating evidence base on tree responses to the changing climate and disturbances. Such data is continuously more valuable for contributing to the analysis of species responses to climate change. In the case of this study, the data set posed some limitations to our analysis. As the data was acquired from several contributors, the length, location, and species included in the time series analysis varied significantly. The number of diffuse-porous trees was low in comparison to conifers and ring-porous trees and therefore interpretations of the results should be made cautiously. Furthermore, the lack of more detailed site information, e.g., forest composition, climate data and other environmental variables such as topography, limited the number of variables we could include in our analysis. For example, high competition between trees reduces resistance to drought (Castagneri et al. 2021), whereas understory vegetation increases tree water deficit in trees and may therefore increase the stress they are experiencing (Giuggiola et al. 2018). Furthermore, information on the site topography and soil characteristics would have likely improved the model, as the topography and soil type of the site (e.g., slope, aspect, soil texture) may affect the access trees have to soil water (Cartwright et al. 2020). Nevertheless, the data enables a large-scale analysis of tree behaviour during drought stress that deepens our understanding on the consequences of consecutive stress periods during the summer season.

While TWD is a good indicator of stress, it is difficult to derive the severity of the stress only from TWD timeseries (Brinkmann et al. 2016). Therefore, future research should concentrate on analysing TWD values together with other drought stress mechanisms such as sapflow and stomatal conductance monitoring on the European scale to better understand the relationship between the experienced drought stress and the environmental conditions. The research should also investigate the long-term effects of intense droughts and to assess if the high-resolution dendrometer data could be used to detect early indications of growth decline.

4.5 Conclusions

We used high resolution dendrometer data to analyse how trees respond to consecutive dry periods on the European scale. We hypothesized that trees would accumulate stress over multiple dry periods, and this would be demonstrated by the increased replenishment time, indicating a loss of resilience. We used generalized linear mixed effects models to analyse how the replenishment time is influenced by minimum tree water deficit values, wood type, the number of tree water deficit periods in a season and climatic conditions. The results showed that the replenishment time increased towards the end of the season for coniferous and ring-porous trees, indicating that the resilience to drought stress decreases with the consecutive dry periods and proving our hypothesis correct for the two wood types. Similar trend was not seen for diffuse-porous trees. Our results prove that the wood type influences the response of trees to drought stress, with higher temperatures increasing the experienced stress. Our results indicate that while high resolution dendrometers are a valuable tool to monitor and study tree stress, large data sets should be processed to avoid the bias created by specific site conditions. To use dendrometer measurements as an indicator of tree resilience to drought, it would be desirable to continue measurements beyond the extreme stress events and where possible to combine them with other variables expressing tree health. Following research should furthermore investigate whether short-term responses in stem diameter can indicate a long-term decline in tree growth.

5 Perceptions of forest professionals on managing disturbances to enhance forest resilience

Based on Nikinmaa, L., de Koning, J., Derks, J., Grabska-Szwagrzyk, E., Konczal, A., Lindner, M., Socha, J., and Muys, B. "Perceptions of forest professionals on managing forest disturbance to enhance forest resilience". To be submitted.

5.1 Introduction

Climate change is changing the operational environment of forest management. Forest disturbances are increasing in occurrence and intensity (Seidl et al. 2017a), i.e., record-braking heatwaves (Salomón et al. 2022), unprecedented insect outbreaks (Hlásny et al. 2021b), increased wildfire occurrences (de Rigo et al. 2017) and intensified storm damages (Senf and Seidl 2021b). Simultaneously, the demand for forest ecosystem services is increasing: the need for wood use to substitute fossil based materials (Verkerk et al. 2020) carbon sequestration , recreational activities (Derks et al. 2020), and forest set aside to protect biodiversity (European Commission 2021) are all growing. The recognised importance of forests to society and their vulnerability to changing disturbance regimes has resulted in policies demanding for enhanced forest resilience (Greiner et al. 2020).

Forest disturbances are part of natural ecosystem dynamics but they tend to have a negative impact on the forest sector by constituting an increased risk of loss of income (Kirilenko and Sedjo 2007) and crucial ecosystem services (Thom and Seidl 2016). With the witnessed higher frequency (Senf and Seidl 2021a) and severity of disturbances (Hlásny et al. 2021a; McDowell et al. 2020; Seidl et al. 2017a), forest productivity is decreasing (Reyer et al. 2017). Therefore, there is urgency to modify forest management to increase forest resilience to disturbances. Resilience is a debated concept in research with many different definitions (Moser et al. 2019; Nikinmaa et al. 2020). The vagueness of the concept is emphasized by the scarcity of metrics for properly measuring resilience (Greiner et al. 2020; Standish et al. 2014). In this study, we understand resilience as the social-ecological resilience (Folke et al. 2010), i.e., as the ability of the social-ecological system to absorb and adapt to disturbances and still maintain its identity. We particularly focus on how management may influence forests' capacity to resist and recover from disturbances. There are several suggestions for new forest management paradigms that embrace the complexity of forest ecosystems to increase resilience, e.g., closer to nature forestry (Larsen et al. 2022) or natural disturbance based forest management (Kuuluvainen et al. 2021). However, these approaches are yet to be mainstreamed in forest management guidance.

Forest management can reduce the vulnerability of forests to disturbances by e.g., aiming at preventing or controlling the different disturbance agents (O'Hara and Ramage 2013) and increasing diversity to enhance the ecosystem stability (Biggs et al. 2020). For example, by reducing the dominance of vulnerable species, e.g., Norway spruce, management can reduce the direct impact of spruce-specific disturbances, such as bark beetles (Wohlgemuth et al. 2002). Recovery after disturbance can be facilitated by ensuring the presence of regenerating trees (Keenan 2015) and increasing the species diversity in the stand (Sousa-Silva et al. 2018a). However, while forest managers tend to have a high awareness of climate change and changed disturbance regimes especially in areas with recent disturbances, the awareness is seldom leading to changes in forest management (Blennow et al. 2012; Seidl et al. 2016c; Sousa-Silva et al. 2016). Lack of knowledge and useful, i.e., salient, technical information is considered as a barrier for implementing changes to forest management (Bissonnette et al. 2017; Blades et al. 2016; Sousa-Silva et al. 2018c), which may hinder the resilience of the organisation as information and knowledge are among the key attributes of the resilience of social systems (Maclean et al. 2014). Salience is the perception of whether the knowledge is relevant to the needs of decision-makers (Cash et al. 2003). Nonetheless, forest management is facing pressure to modify management to better respond to the multitude of challenges and demands from society with the current available information. The individual actors often lack the capacity and time to assess how the management can be changed to have an efficient and effective impact (Blades et al. 2016). Therefore, to guide practical forest management decision making, a profound understanding of the effects and effectiveness of forest management measures to disturbances and the transfer of this knowledge to practice is needed.

Forest management guidelines can be considered a part of a science-practice interphase, as they provide practical guidance based on scientific evidence developed by institutes with extensive knowledge and experience in forest management, e.g., forest extension services or forest administrations. The earlier guidelines, such as the ones established in Germany in the 18th and 19th centuries with the focus on sustainable yield, i.e., harvesting in the limits of the growth capacity of forests (Vehkamäki 2005). The newer generation of guidelines for sustainable forest management were established decades ago for the pan-European level (MCPFE 1998) with the aim of helping to create national and regional guidance for forest owners and managers to broaden the management from purely timber production and manage their forests sustainably and considering the economic, ecological and social values of forests. These guidelines pan-European guidelines were adapted by countries to fit the national or regional environmental and legislative conditions, showing movement towards more multilevel governance (Art and Visseren-Hamdkers 2012).. Forest extension services provided the adapted guidelines to forest owners and managers. State forest enterprises and industry forest owners could follow the adapted guidelines or have their own equivalent (Yrjölä 2002). However, the rapid changes in climate and disturbance regimes are challenging forest management based on the guidelines as they often lack advice on how to counteract increasing disturbance impacts based on the latest research findings. In some cases, the recommendations remain ineffective and can even have adverse effects on forests (Maher et al., 2018). A new generation of forest management guidelines, which in addition to previous elements of sustainability also include advice on adapting forests to climate change and making them more resilient, is needed.

European forest legislation and traditions, forest use, ownership structures, biogeographical conditions, and tree species compositions vary greatly, which influences the adaptation of pan-European guidelines to the local conditions. Furthermore, forest management objectives and the possible trade-offs they cause influence the selection of management measures, and therefore multiple approaches are needed (Eggers et al. 2020; Ontl et al. 2018). In this study, we were interested in the evidence-base of the proposed forest management measures to reduce disturbance impacts and how the changes in disturbance regimes and the need to enhance resilience are currently reflected in the forest management guidelines and perceived by the forest professionals. Our objective was to better understand the science-practice interphase in forest management and how resilience to disturbances is implemented. As forest management guidelines are one interphase between science and practice, we examined how they are being adapted to the climate change induced change in the disturbance regimes. Furthermore, we aimed to improve understanding of how forest professionals acquire knowledge on forest disturbance management and what are the perceived barriers in translating scientific knowledge into salient information for the forest management guidelines. Identifying the barriers may help to understand how research results reach forest professionals, why some evidence is not adopted to guide decision-making, and why some guidance is adopted despite contrasting evidence. Exploration of this process may help to bridge the gap between science and practice by pointing out barriers in implementing adaptive forest management and possible ways around them. Therefore, our research questions were 1) how the perception of the current management practices to increase resilience to forest disturbances in Europe reflects scientific evidence; 2) how forest professionals working on the science-practice interphase perceive the need to adapt forest management guidelines; and 3) what are the perceived barriers in adapting forest management in practice?

To answer our questions, we combined a literature review with two different sets of in-depth interviews sets with forest professionals. The literature review was done to understand the propositions of the scientists by analysing the current scientific evidence and of the different forest management measures used to mitigate forest disturbance impacts, whereas the interviews were conducted to understand the type of measures forest professionals currently suggest for increasing resilience to disturbances. The results were analysed together. The interviews were carried out under two different projects: the project "Integrated Forest Management Learning Architecture" (INFORMAR) supported and funded by the German Federal Ministry for Food and Agriculture (BMEL) and the project "Innovative Forest Management Strategies for a Resilient Bioeconomy Under Climate Change and Disturbances" (I-Maestro) supported under the umbrella of ForestValue ERA-NET co-fund by the National Science Centre, Poland and French Ministry of Agriculture, Agrifood, and Forestry; French Ministry of Higher Education, Research and Innovation, German Federal Ministry of Food and Agriculture (BMEL).

5.2 Materials and methods

5.2.1 Literature review

In the literature review, we focused on how forest management can mitigate disturbance impacts on provisional ecosystem services. Provisional ecosystem services are services the society directly consume, e.g., wood and food (Rodríguez et al. 2006). While the focus of this study is on Europe, we purposefully chose to include all studies conducted in similar environmental conditions in other continents as we recognise that forest management can also be informed through scientific evidence from similar forest systems.

We conducted a review on the Scopus-database with three alternative search strings for five different disturbance terms: *fire, wind, storm, pest, and biotic,* and screened all the upcoming abstracts. The search strings used were:

- "forest*" AND "manage*" AND "**prevent***" AND "*disturbance term"* AND "damage"
- "forest*" AND "manage*" AND "**reduce**" AND "*disturbance term"* AND "damage"
- "forest*" AND "manage*" AND "**mitigate**" AND "*disturbance term"* AND "damage"

To be included in our analysis, articles had to meet the following requirements : they 1) were published in English in a peer-reviewed journal; 2) have a boreal, temperate, or Mediterranean biome scope as described in Trimble and van Aarde, (2012); 3) identify management practices mitigating damage to provisional ecosystem services; and 4) propose management practices that are performed in the forest, affecting forest characteristics. No studies published after the 10th of August 2021 were included. The literature search resulted in 619 abstracts, out of which 234 articles complying with the first two selection criteria were screened and finally 134 articles complying also with the last two selection criteria were accepted to the review.

5.2.2 Interviews

In the first set of in-depth interviews, we asked the interviewees which, in their opinion, were the most important management measures to increase resilience to forest disturbances. We interviewed altogether 42 forest professionals in nine European countries (Austria, Belgium, Denmark, France, Germany, Poland, Spain, Switzerland, and Sweden) in 2018 and 2019. The interviews consisted of a standardized survey and open questions using an interview methodology explained in detail in Konczal et al. (submitted). All interviews were conducted by members of the research team (Konczal, Derks, de Koning). When possible, interviews in the respondent's native language were preferred in order to elicit more spontaneous answers (cf. Caldwell-Harris, 2014). Consequently, interviews were conducted in Dutch, English, French, German, Polish, and Spanish respectively. Interviews were conducted with two groups of forest professionals: i) 28 interviews with forest managers (on the enterprise level) and ii) 14 interviews with national experts on forest management and forest conservation. The respondents included both experts who managed forests themselves and those who did not. Most interviews were conducted in person. In case a personal meeting was not possible, interviews were performed online. The interview recordings were fully transcribed in the source language. Subsequently, the guideline-based open-question part of the transcribed interviews (excluding the standardised survey) was summarised in English. The open interview questions and the resulting summaries were then analysed inductively, with a coding system based on the outcomes of the interviews, using MAXQDA software.

In the second set of in-depth interviews, we asked the interviewees how forest management guidelines are adapted to increase the resilience to disturbances, and what they perceive as barriers for implementing the guidelines in practice. We interviewed seven forest professionals involved in the science-practice interphase by developing evidence-based forest management guidelines in five different European countries (Finland, France, Germany, Poland, and Spain) in 2021 and 2022. The interviews were conducted online. The selection of the interviewees aimed at covering different biogeographic regions in Europe with diverging forest management contexts. The interviewees presented forest extension services (2) and state or regional forest services (5). All interviews were conducted by the research team (Nikinmaa, Grabska-Szwagrzyk, Socha) and if possible, in the native language of the interviewee, in this study Finnish, French, and Polish, respectively. When conducting the interview in the native language of the interviewee was not possible, the interview was conducted in English. The interview recordings were fully transcribed and kept in the original language except in the case of Polish transcriptions that were translated to English. We used descriptive analysis of the answers as the sample size was small. We described the perceived state of the forest management guidelines, the main trade-offs in forest management identified by the forest professionals as well as the barriers the forest professional face in applying forest management guidelines to practice. The interview questions were analysed inductively by using MAXQDA software.

5.2.3 Comparing the literature review and the interview results

From the literature review and the first set of interviews, we identified the unique management measures. One study could have more than one analysed measure. Similar management measures were grouped together to facilitate the comparison between the literature review results and the interviews. The grouping was done by the technique or main principle the measures used. For example, all the measures proposing some forms of thinning were combined under “Change to suitable harvesting and thinning regime to avoid disturbances”, and all the measures proposing increasing species diversity were combined under “Convert to and increase mixed-species management”. We then compared the frequency in which the group of measures was mentioned by the literature and interviews to analyse the abundance of the group of measures in the two data sets.

5.3 Results

5.3.1 Identified measures to mitigate the effects of forest disturbances

The studies included in the literature review were published between 1997 and 2021 with steady increase in the number of studies published per year (from 1 per year in 1997 to 14 in 2021). They were mostly conducted in either North America (43%) or Europe (34%). In Europe, the countries with the most conducted studies were Sweden (19%), Spain (17%), Finland (13%), and France (11%). It is notable that only 15 European countries were presented in the results as locations of research, the countries being Austria, Estonia, Finland, France, Greece, Italy, Latvia, Poland, Portugal, Slovakia, Slovenia, Spain, Sweden, Switzerland, and the United Kingdom. We grouped them according to the EuroVoc classification to four regions: Central and Eastern Europe, Northern Europe, Southern Europe, and Western Europe (Publications Office of the European Union 2022). The most studied disturbances were the disturbances caused by different pest insects and fire (Fig. 5.1). High presentation of pest insects is due to the number of different insects present in this category. It should also be noted that pests are often the secondary disturbance that affect weakened trees and therefore primary disturbances causing stress, for example drought, might be masked under the pest insect category.

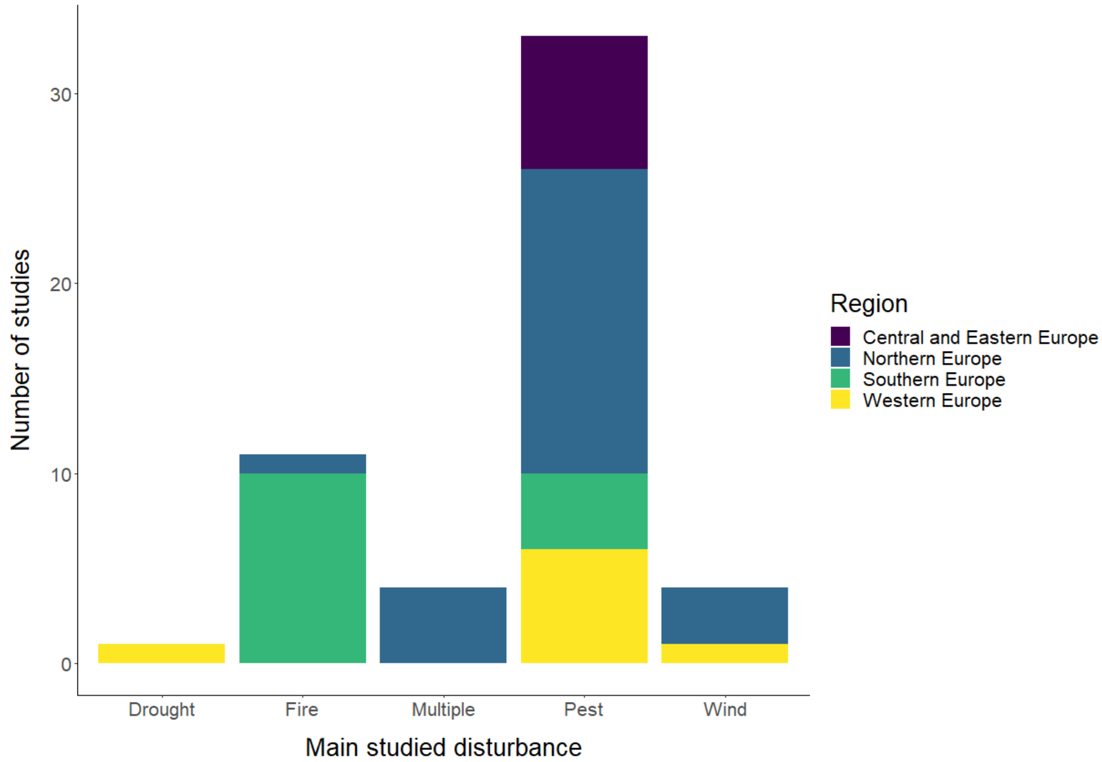


Figure 5.1. The most studied forest disturbances in Europe according to the literature review for the four European regions. Pest-category involves all the studies involving insects or other herbivores. Multiple-category involves studies that researched several disturbances in the same study.

In the first set of interviews, the respondents were asked to identify the three most important measures to increase resilience. However, they were not asked to specify to which disturbance the forests should be made more resilient to. Out of the 42 respondents, only two said that there were no measures taken to improve resilience in their district while one was unsure. The remaining 39 respondents stated that measures were taken to improve resilience to disturbances. The described measures from both the literature and the interviews ranged from very detailed (e.g., description of a biological control of an insect) to very broad (e.g., uneven-aged mixed species management). The full set of identified measures (Appendix D Table 8.6) and to which disturbances they were studied for (Appendix D Figure 8.16) are provided in the appendix. The literature review resulted in 62 identified management measures whereas the interviews resulted in 47 identified measures. We grouped the measures under 14 broad categories based on the measure and the disturbance it was aimed to mitigate. In the figure 5.2, we show the difference between the percentage of measures mentioned by the interviews and the studies. The most mentioned measure in the interviews was by far converting to and increasing mixed species management (79% of respondents), whereas in the literature different measures to manage insect and pathogen outbreaks were the most studied (31% of the reviewed studies). In general, the measures mentioned in the interviews tended to be broad (e.g., increase share of broadleaves, increase structural heterogeneity, avoid monocultures), whereas the measures mentioned in the studies were often very specific (e.g., what type of fuel management is the most effective, what type of thinning regime is the most effective). While the categories were determined to be exclusive in the sense that a management measure could be classified in only one of them, it should be recognised that some management measures may inherently include other management measures and therefore mask them in other categories. For example, in mixed-species management native tree species are often used in the mixtures without it being explicitly highlighted.

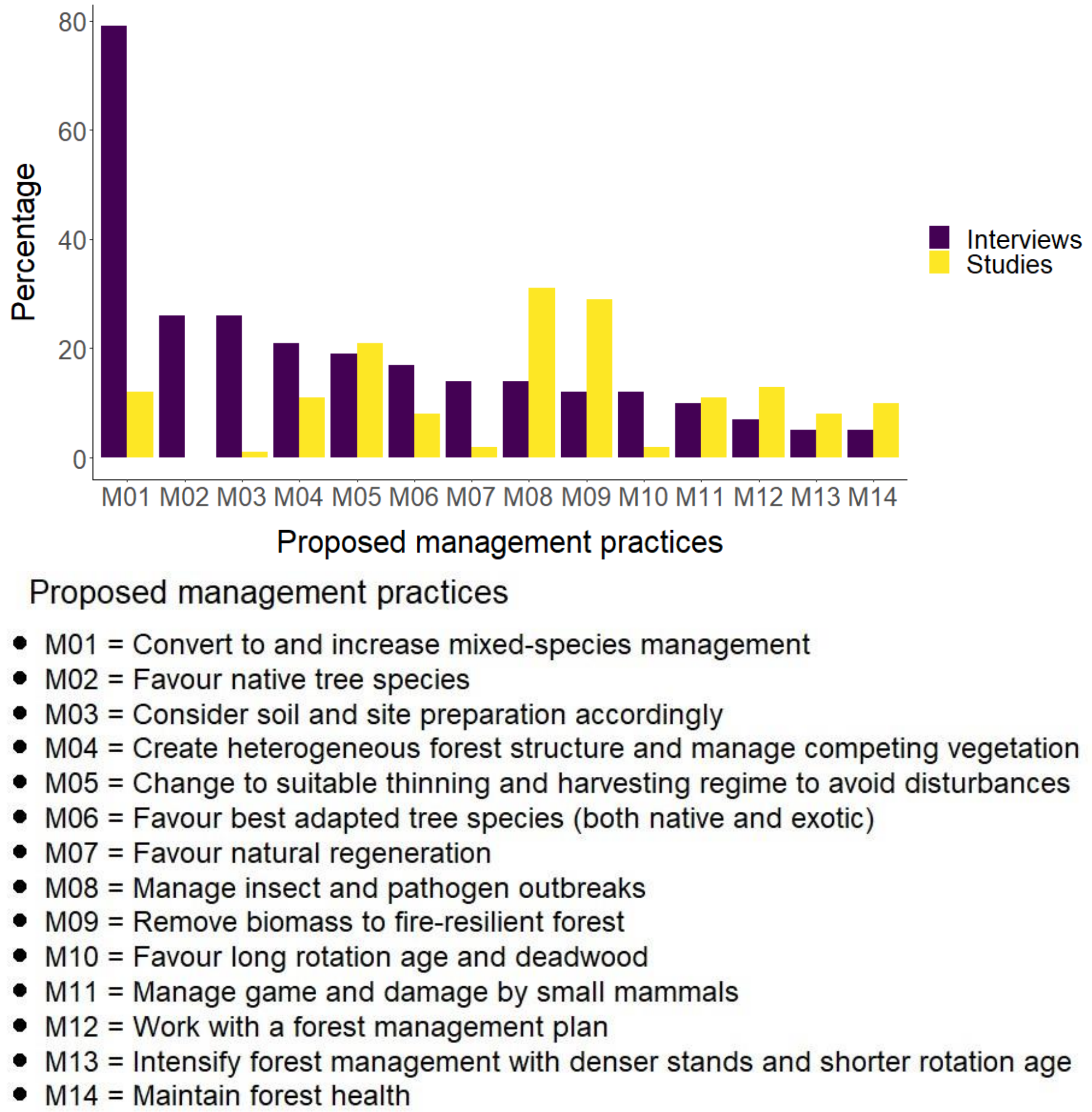


Figure 5.2. The percentage of measures mentioned by the interviews and by the studies.

5.3.2 Adapting forest management guidelines to increase the resilience to disturbances

In general, the respondents were concerned about climate change and the related uncertainty of the future conditions. In the first set of interviews, 23 out of 42 respondents mentioned concern for climate change and the following uncertainty in species' performance and disturbances even when they were not directly asked about it. In the second set of interviews all the respondents were concerned about climate change and the consequent uncertainty in the future environmental conditions. In the second set of interviews, the respondents were asked if their organisation has defined the term 'resilience'. In several of them resilience is not explicitly defined but the respondents gave examples on how they understand it. Some of the respondents understood resilience as the state of non-vulnerability to adverse actors, for some it was the ability of a system to mitigate disturbances and increase the forest functions, i.e., essentially to adapt to the new environmental conditions. The respondents also mentioned that the topic of resilience has become widely discussed in the recent years due to the perceived increase of forest disturbances. The respondents had experienced wide-spread insect outbreaks (FR, DE, PL, ES), increased drought occurrences (PL), extraordinary storm events (FR, DE, PL), or a high number of forest fires (ES). In one country, the disturbances have not dramatically increased but the trend seen in Central Europe has prompted to prepare for future damages (FI). Norway spruce forest was mentioned to be especially affected by disturbances (FI, FR, DE, PL):

"On my area I have a valley which specifically is mainly composed of Norway spruce plantations, and they are getting clearcuts because everything is dying." (FR_1)

The respondents were also worried about the increased interactions of different disturbances and the consequent augmenting damage on forests:

"Kyrill uprooted or snapped about 25 million trees, mainly spruce. 11 years later we had hurricane Friederike, and this storm caused an estimated damage of 1.9 million cubic meter of wood in the forest followed by the bark beetle calamity. This is coming on top due to the drought of the recent years from 2018 to 2020." (DE_1)

"There are more small-scale disturbances, and their linkage (to other disturbances) has a significant role currently. Even small-scale disturbances can cause epidemies in the property of a forest owner." (FI_1)

The concern about the changed climate and increased disturbances has contributed to the need of the organisations to start updating and adapting their forest management guidelines to better respond to challenges posed by climate change. Some of the respondents mentioned that the pressure to adapt management guidelines came directly from a national policy level (FI, FR). Other reasons to start updating forest management guidelines were e.g., changes in forest legislation or merging two regional forest extension services into one. Out of the seven interviewed organisations in the second set of interviews, two had already updated their forest management guidelines and the rest were in the process of updating them.

The process of updating the management guidelines differs for the different organisations regarding who is involved in the process. In one organisation the revision and updating of the forest management guidelines is done by the staff: each staff member developed the guidelines for their area of expertise. These draft guidelines were then compiled and shared for open consultation online, however with a very low engagement. In two organisations, the regional forest universities were involved in developing the guidelines together with the state or regional forest enterprises with the option to use the expertise of other fields (e.g., climatology) if needed. In two other organisations, an extensive number of stakeholders from research, forest enterprises, nature conservation organisations and other focus groups were consulted, in a process lasting several years, to create consensus on the new forest management guidelines. In the latter processes, the national research institutes were involved and produced for example reports on climate change and its implication to forest management. The intensive involvement of the stakeholders was seen as demanding but ultimately leading to wider acceptance of the developed management guidelines.

5.3.3 Identified challenges in implementing forest management guidelines in practice

Several barriers to implement more resilient forest management in practice could be identified from the interviews (Fig. 5.3). It should be noted that the respondents stressed different barriers and this figure gives a summarized overview.

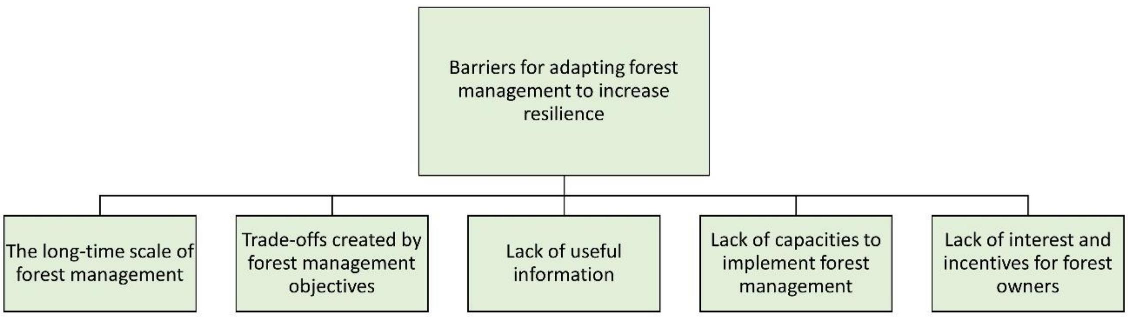


Figure 5.3. The barriers for adapting forest management to increase resilience identified by the respondents.

The long-time scale of forest management was seen as a two-dimensional problem: on the one hand the climate was perceived to change so rapidly that the adaptation measures for forest management are already late, on the other hand the results of changes in management and how successful they are could only be seen after years or decades. The latter was especially seen as an issue when contrasting to the current fast-paced changes in policy objectives.

"It is the problem that everything takes long time. You can have a good idea now, but you see the effects much later and often the political scenarios and possibilities, they change earlier. And this is sometimes a problem, because the good ideas you have implemented on the forest stocks, you can only see the results after several years." (DE_1)

Trade-offs between forest management objectives were seen generally as challenge in forest management. Almost all the respondents of both interview sets mentioned that they, or the organisations they represent, have multiple objectives, with timber production, recreation, and nature conservation as the most mentioned ones. The respondents recognised that combining the different objectives in the same area often creates challenges as multiple trade-offs between the different uses emerge. The trade-off between timber production and both nature conservation and recreation were seen especially challenging as it creates a lot of tension between forest management and the public.

"My area is a very touristic area. We have more and more recreational activities and there are quite a lot of places where we have conflicts between timber production and recreational activities. It's a bit tricky to manage to balance these two." (FR_1)

"We have a lot of political partners and stakeholders, and we have lot of political tension with different parties. Currently the biggest area of compromise seems to be between the highly commercialized maximum profit-oriented forestry and on the other hand the demand of the greatest possible protection area of forest for climate change, biodiversity, and common goals." (DE_1)

Lack of salient or useful information was considered to be a major barrier by the forest professionals. Many of the respondents felt that they were overwhelmed with the amount of information available, but they could not say how relevant and therefore useful it was for their needs to create forest management guidelines. The respondents felt that they need more precise information on the regional and local future environmental conditions and tree species performance. Some felt that they could not recommend a certain evidence-based forest management measure unless it had been proven to be beneficial in their region. While some wished to have a better access to peer-reviewed journals, many wished that scientists would make the information more relevant for them with e.g., publicly accessible webinars, workshops, videos, or smartphone applications:

“The people need workshops to show them how to change the practices and how it works in the field. Less and less people need books. Indeed, paper is going a little bit out of fashion.” (PL_1)

“An exercise with a smartphone application in the forest would be much more efficient (in increasing understanding) than all the guides published on a paper.” (FR_2)

The lack of both financial and personnel capacity was also seen as an issue. Some of the respondents worried that there is not enough proper seed material or experienced forest specialists to implement the adapted management guidelines. One respondent mentioned that in their area they had approximately 20 000 forest owners for them to provide guidance and a staff of 70 people, making it impossible to properly guide all of them. In addition, the tendency of forest industry to specialise in the use of only a few coniferous species and to value quantity over quality and therefore the lack of revenues from potentially better adapted or native species was seen as a barrier for forest management to diversify its species portfolio. Some of the respondents mentioned that they would like to see a better valorisation of broadleaved and native trees:

“Our sawmills in the department [French administrative region] are all for Norway spruce, silver fir, or larch. We have quite a lot of oak and beech, but they're only for burning. We do not value it in the industry.” (FR_1)

Finally, both the lack of interest of forest owners on improving resilience and the lack of incentives to improve resilience was seen as a barrier in implementing the adapted forest management guidelines in practice. Many of the respondents mentioned that in their region or country, the private forest owners were not obliged to follow the forest management guidelines, only the forest legislation (e.g., DE, FI, FR). Therefore, it is up to the forest owners if they want to implement the forest management guidelines in their forests. Notable exceptions were in Galicia, Spain, and Poland. In Galicia, to get a cutting permit the owners needed to prove that they comply with the guidelines provided. In Poland, the surveillance of forest management is the responsibility of local government, who often employ foresters to assess, to what extent the forest management guidelines are followed. Some of the respondents mentioned that the non-compulsory nature of forest management guidelines and the perceived increase in forest management costs has led some forest owners to give up completely on forest management while others continue with the same forest management as they have before. It was also perceived by some of the respondents that the increased disturbance damages and the subsidies for forest management, which have decreased or are not corresponding to the actual need, are making the adaptation of forest management challenging and expensive:

"Right now, we allocate about 5-6 million euros per year to pest and disease prevention and treatments. And I would say five years ago the budget would not be over 2-3 million euros per year. The number of pest disease are higher every year." (SP_1)

"We are less and less [staff] every year and the special subsidies that the state gives to forest owners are not really adapted to the true reality of forest property and the small areas that we have here. So we know that we will have a very big problem in the next 10 years when we have diebacks and we will probably not have enough money and people to replant them and to adapt them." (FR_1)

5.4 Discussion

Our results show that while the value of science-practice interphase is appreciated and working to some extent, there are still barriers for fluent transfer of scientific knowledge into practical management. Analysing how the perception of the current management practices to increase resilience reflects scientific evidence by comparing the results from the literature review and the interviews showed that there is a noticeable divide between the measures studied by the literature and proposed by the interviews. For example, most of the respondents mentioned mixed-species management as one of the most important ways to increase resilience, whereas only a few studies tested whether mixed-species management decreases the damage caused by disturbances. Similar results on the positive perception of the mixed-species management have been found previously (Carnol et al. 2014; Hengst-Ehrhart 2019; Sousa-Silva et al. 2016), however this perception was in contrast to the less conclusive evidence from research (Carnol et al. 2014). In general, it is also well-known in research that a diverse species portfolio has many advantages to monocultures in risk mitigation and provisioning of ecosystem services (Bolte et al. 2009; Kolström et al. 2011), however, the strength of the evidence is lower when it comes to the capacity of mixed-species to reduce the susceptibility to drought, fire and storms when compared to monocultures (Messier et al. 2021). Partly this could be due to the long time it takes to gather experimental evidence on the effects of species mixture in comparison to other types of forest management measures, e.g., fire prevention or insect management with pesticides. It could also be due to increased demands to increase the share of mixed species forests in EU policy levels (European Commission 2021), which may influence a change in the national and therefore regional forest management guidance. However, it should be noted that the review of practices proposed in the scientific literature to increase resilience to forest disturbances in Europe missed many countries and had relatively low number of studies filling the search criteria, which might mean that there is more evidence available. The low number of retrieved studies could indicate that the forest management measures to reduce disturbance impacts are not much researched, which is unlikely. Indeed, disturbance impacts have been studied widely (e.g., Reyer et al. 2017; Senf and Seidl 2021a), but almost exclusively in retrospective analysis, after occurrence of disturbances. In Europe, disturbances were up to the early 21st century not considered to be important drivers of forest dynamics, until the noticeable increase in the forest area affected by disturbances (Schelhaas et al. 2003; Seidl et al. 2014a). Since then, the importance of the disturbances as drivers of forest resource development has been recognised by both practice, as proven by our interviews, and science (e.g., Danneyrolles et al. 2019; Kuuluvainen et al. 2021). However, as it will take time until research evidence becomes available from dedicated experiments, establishment of a European wide network of research sites with alternative forest management would be needed for analysing the effects of forest management on the impacts of changing disturbance regime. It should be also noted that disturbances, especially the frequent small-scale ones, can also provide an opportunity to change management and become more resilient (Thom et al., 2017).

Another potential reason for the limited number of studies in the review could be the language. The requirement to have the studies published in English rules out any national publications where studies focusing on practical forest management in countries with other native languages may be published. Even if the national publications would have research published in English as is the case with the Polish Leśne Prace Badawcze and Sylwan, the articles may not come as search results in the journal databases as the databases have not indexed these journals (as is the case with the Scopus database). The lack of international publications on the topic makes synthesising disturbance management measures used in Europe challenging and may lead to duplication of efforts while hindering the wider adaptation of good practices. Researchers and practitioners should be encouraged to share their studies for a wider international audience and interact across the language barriers, whereas the journal databases should make the national journals more prominently available.

Another case of the mismatch between the perception of the effectiveness of a measure to decrease disturbance damage and the scientific evidence behind it was the use of native tree species to increase resilience to disturbances. This measure was often proposed by the respondents, but it did not come up in the results of the review at all. These results are in accordance with the previous surveys on how forest management is being adapted to climate change in different European countries (FOREST EUROPE 2020b), while at the same time science behind the recommendation is inconclusive. Some researchers argue that we cannot solely rely on native species anymore and should consider planting more resilient species (Fares et al. 2015), whereas some argue that planting exotic species would further deteriorate the biodiversity decline in forests (Newton 2016). The exotic species have many benefits, e.g., fast growth and potential resistance to native pests and pathogens (Bottollier-Curtet et al. 2013; Kawaletz et al. 2013; Martin et al. 2010; Pötzelsberger et al. 2020). Their share of the commercial timber is high in some countries, e.g., the United Kingdom (Cavers and Cottrell 2015) and e.g., in selection of urban trees it has been said that exotic trees cannot be afforded to leave out (Sjöman et al. 2016). However, the exotic species pose risks of invading non-intended areas as well as spreading invasive pests and pathogens that may cause tremendous harm for the native species (Ennos 2015; Pötzelsberger et al. 2020). This risk of potential harmful consequences of exotic species might cause forest professionals to favour native species even if the evidence on their resilience to disturbances in comparison to exotic trees might be lacking.

The interviews with the forest professionals showed that there are challenges for adapting forest management on both ends of the science-practice spectrum. The lack of changes in the practical management has been linked to the lack of awareness, however, the interviewed professionals working closely with forests were aware and concerned about climate change and the uncertainty in the future environmental conditions, a result that is in line with some previous studies on the topic (Ontl et al. 2018; Seidl et al. 2016c; Sousa-Silva et al. 2016; Sousa-Silva et al. 2018b). The forest professional recognised the need to adapt and change management and mentioned how resilience has become a widely discussed topic in the last years due to increasing occurrence of severe forest disturbances. In contrast to the research done on the level of climate change adaptation in forests management (Hengst-Ehrhart 2019; Sousa-Silva et al. 2018b), who found that a relatively small share of forest owners and forest managers had modified their management, our results show that most of the respondents think that measures to increase resilience to disturbances have been made. The results may reflect to some extent the exceptional drought of 2018 and the need to urgently adapt to future disturbances. It should however be noted that part of the respondents were in charge of updating the forest management guidelines and therefore they should be optimistic that the management practices can be changed. It does not imply that the practice will directly follow these guidelines unless they are legally forced to do so. Indeed, there is some evidence that people tend to be more willing to change forest management when they do not need to implement the change themselves (Seidl et al. 2016c), which may result in overly optimistic views on how much of the forest management has actually changed. Furthermore, the mentioned studies asked about adapting management to climate change whereas we more specifically addressed increasing resilience to disturbances. The uncertainty related to climate change and how it might affect the forest ecosystem may lead to ignoring it in decision-making and therefore no changes in management are implemented (Blades et al. 2016), whereas disturbance management has a long history in forest management and is therefore potentially easier to act on.

The respondents identified several barriers for why the scientific advances have not reached the practical management level. These barriers can be examined through the theory on social resilience of the forest managers and the institutes and organisations they work in to understand, how the barriers influence the attributes of social resilience: knowledge and learning, diverse and innovative economy, and engaged governance (Maclean et al. 2014). One of the most mentioned barriers was the ambiguity of the information and the lack of local relevance. Ambiguity and uncertainty of the received information and consequent lack of usefulness of the information has been recognised as a common hindrance for forest management (Hengst-Ehrhart 2019; Sousa-Silva et al. 2018b; Timberlake and Schultz 2017), and the respondents also commented how there is a lack of capacity and resources to identify how singular study results relate to the wider body of research and whether they are applicable in the regional context, making their work at developing new management guidelines challenging. Knowledge and capacity to learn new ways of operating are essential for adapting to change (Keck and Sakdapolrak 2013), and therefore the lack of them may lead to maladaptation or no adaptation at all. To facilitate the interactions of the science-policy interphase, there is a clear need for making the scientific knowledge more useful for practitioners and to strengthen the networks between practitioners and researchers. However, there the choices made by individuals are deeply influenced by institutions and the setting they create through rules and values (Art and Visseren-Hamdkers 2012). Therefore, for change to happen the institutions need to create openness and possibility for staff to critically reflect the current practices and adopt new ones. Institutes can facilitate the uptake of new forest management practices by emphasising on the necessity of life-long education of forestry professionals and by providing resources for the staff to increase their knowledge and skills. This adaptation and increased openness for new ideas often benefits from generational changes, i.e., retirement of older foresters, and otherwise constitutes a major barrier to enhancing resilience in practice.

The lack of financial resources and incentives can be seen to undermine the attributes of a diverse and innovative economy and engaged governance. The focus of the forest industry on coniferous trees limits the options of the forest owners and forest managers to diversify their timber product portfolio, which in turn makes them more vulnerable to market disruptions and natural disturbances (Pinkerton and Benner 2013). In addition to that, the decrease in financial support for planting and forest management operations (Art and Visseren-Hamdkers 2012) may indicate the influence of disengaged governance that does not support the adaption efforts. The case of mixed-species management is an example where the three social resilience attributes are shown to influence the adaptation in different ways. In case of knowledge and learning, it shows both the capacity to change views and adapt forest management when information considered useful is adopted in forest management whereas the information considered not useful is disregarded. Even if the evidence on the effects of mixed-species management to reduce disturbance impact is contrasting (Pretzsch et al. 2017), there is consensus that in general mixed-species forests have multiple benefits in comparison to monocultures (Huuskonen et al. 2021; Messier et al. 2021). In other words, there is enough certainty to base decisions on. Nevertheless, the uncertainty of the future profitability of alternative species may reduce the willingness of some forest owners to change their management (Lodin et al. 2017), indicating that the economic diversity and innovation remains lacking. Furthermore, forest owners tend to be reluctant to change their management without knowing successful alternative management strategies (Lawrence and Marzano 2014; Thomas et al. 2022), which was also reflected by some of the respondents. The lack of economic incentives may excavate the unwillingness to change the management either by the absolute lack of money to implement management or by having to shoulder individual economic risks. A disengaged government, expressed by the lack of financial support for forest management may excavate the unwillingness to change the management either by the absolute lack of money to implement management or by having to shoulder individual economic risks.

There are positive experiences to meet this need to have more useful information for providing guidelines with workshops between scientists and managers on understanding the effects of climate change on regional scale and what are the information needs of managers for decision-making (Blades et al. 2016). The involved researchers should not be limited to silvicultural or climatological background, but also include researchers from social sciences, as adapting management involves different levels of governance and institutional practices that need to be also addressed. The benefits of the interactions became already apparent when the respondents were asked about how information could be made more useful for the managers to increase the resilience of forests to disturbances. They believed that the digitalisation of the research results into user friendly smart-phone applications, diagnosing forest disturbances with drones, and videos tutorials on how adaptive management measures can be applied, would motivate, and help the forest owners and managers in decision-making. The potential of digitalisation in climate change adaptation has been recognised in cities (Balogun et al. 2020) and wood supply chain (Makkonen 2018; Müller et al. 2019), but more research should be done on how and which forms of digitalisation would bring added value to forest owners. Another way of producing more useful information to increase resilience to disturbances is involving stakeholders in the decision-making process (Timberlake et al. 2020). This was also apparent in the process of how forest management guidelines were updated in the different countries. One main difference between the processes was in the involvement of external experts and other stakeholders. The involvement of stakeholders in the process of environmental management can enhance the quality of the decision-making and can lead to better outcomes than if the stakeholders are excluded from the management (Reed 2008). Furthermore, carefully planned stakeholder involvement has the potential to deal with the challenges caused by the trade-offs between forest management objectives, as it can increase the general agreement on how the multiple management objectives are to be achieved (Sheppard and Meitner 2005). However, the success of the process involving stakeholders may be low and lead to disappointment for the involved parties if it is not well-planned (Reed 2008). Moreover, intense involvement of the stakeholders requires resources that the organisations may not have available. Some of the professionals also questioned to what extend the public opinion, that may not be informed, should be incorporated into forest management. However, it is increasingly recognized that for successful climate change adaptation, stakeholder involvement that increases mutual learning and acceptance is needed for holistic multifunctional climate change adaptation (Döll and Romero-Lankao 2017; Luís et al. 2018; Terzi et al. 2019).

5.5 Conclusion

In this article, we investigated how forest management measures to increase resilience to forest disturbances suggested by forest professionals in Europe reflect the scientific evidence. We performed a literature review and interviewed in total 49 experts. The interviews were carried out after the recent wave of intensive disturbance damages in most of the studied regions and results showed that there was a strong awareness of climate change, and that awareness has translated into action to increase resilience to forest management disturbances and adaptation of national and regional forest management guidelines. To answer our first research question on how the perception of the current management practices to increase resilience to forest disturbances in Europe reflects scientific evidence, we compared the results of the literature review and the interviews. Our results showed striking differences between the management measures suggested by forest professionals and the management measures most studied by researchers, showing that some of the measures suggested by the forest professionals do not have strong evidence. The low evidence for some management measures may be influenced by the long time it takes to gather experimental evidence on slow changes in forest composition. To answer our second question on how forest professional working on the science-practice interphase perceive the need to forest management guidelines, we interviewed forest professionals responsible for developing forest management guidelines. The results showed that the professionals perceived a great need to adapt the guidelines to better cope with climate change, and the organisations represented by the interviewed forest professional were either currently updating their guidelines or had recently done it. To answer our third question on the perceived barriers in adapting forest management in practice, we further analysed the interviews. Several barriers for adapting forest management were identified, notably the lack of salient information that would facilitate the practical application, and the lack of professional and financial capacity. The role of the research is to facilitate the uptake of scientific knowledge where possible by for example developing new tools for forest management decision making. Based on the results, we recommend to 1) establish more designed experiments to explore the effectiveness of less researched measures to prevent and mitigate disturbances, 2) increase the availability of practical knowledge across the language barriers by for example creating tutorial videos that can be translated, 3) increase participatory stakeholder engagement in forest management planning with joint workshops to address trade-offs between management objectives and consider them in the selection of resilience enhancing measures, and 4) to improve the continuous education and capacity building to update knowledge in practice.

6 Conclusions

“I wish it need not have happened in my time," said Frodo.
"So do I," said Gandalf, "and so do all who live to see such times. But that is not for them to decide. All we have to decide is what to do with the time that is given us.”
J.R.R Tolkien, Fellowship of the Ring

6.1 Resilience in forest sciences

Since the beginning of this thesis, the world has experienced shocks that most thought unimaginable. The COVID-19 pandemic profoundly changed the everyday life and shook the sense of security of many. Then the start of the Ukrainian war marked an end to the post-Cold War relationships and pushed especially Europe to a new era. At the same time, forests have experienced unprecedented disturbances in many parts of Europe. I started this thesis in the beginning of the 2018 heatwave that was followed by three years amongst the hottest five years on record (Copernicus Climate Change Services 2022). During these years, the highest rates of tree canopy mortality have been observed (Senf et al. 2021), caused by drought induced tree diebacks (Obladen et al. 2021; Senf et al. 2020) and bark beetle outbreaks (Hlásny et al. 2021a). The Ukrainian war has also direct consequences to European forests, as all the parties of the war are timber exporters (Prins 2022). The decrease of imported wood and the simultaneous need to detach from the energy exported from Russia creates pressure to harvest more wood in other European countries. At the same time, the COVID-19 pandemic showed how important forests are to people and increased the visits in close-by forests (Derks et al. 2020), creating pressure to keep forests for mainly recreational purposes. The pandemic was furthermore influenced by the loss of intact habitats and increased human-nature interactions that expose humanity novel emerging diseases (Chin et al. 2020). Therefore, forests face multiple and sometimes contrasting demands from society while being increasingly vulnerable. The recent shocks and disturbances have shown how important enhancing the resilience of both forests and the society that depends on it is.

The aim of this thesis was to advance the operationalisation of resilience in forest management.
We hypothesised that resilience can be made into an operationalised concept in practical forest management. To answer our research questions,

1. How is the concept of resilience used in the scientific literature and how can resilience be quantified?
2. How can forest resilience to forest disturbance be enhanced in management?
3. How forest management needs to deal with climate change induced challenges?

I will briefly summarize the findings of each chapter, show the contribution of the thesis to the scientific literature, explore the future avenues of research, and conclude with some guidance for practice.

To consciously increase something, we first need to know what it is. In **Chapter 2**, we reviewed how resilience, notably the concepts of engineering ("recovery of a previous state"), ecological ("remaining within the prevailing system domain through maintaining important ecosystem processes and functions"), and social-ecological resilience ("the capacity to reorganize and adapt through multi-scale interactions between social and ecological components of the system") are used in forest sciences. As many have argued that the vagueness of the meaning of resilience hinders its application in forest management (Greiner et al. 2020; Moser et al. 2019), understanding how the concepts are used, what they study and how they assess resilience was crucial to clarify the differences and similarities between the three concepts. The results showed that in the 255 reviewed articles, the engineering resilience was the most used concept, followed by ecological and social-ecological resilience with increased number of indicators used for more complex concepts and systems. The two most important indicators for engineering resilience were basal area increment and vegetation cover, for ecological resilience vegetation cover and density or number of trees, and for social-ecological resilience socio-economic diversity and biodiversity.

The key message of the research was that these adopted resilience concepts are not contradictory to one another but rather complementary, with engineering resilience being suitable to describe simple systems on short time scale, ecological resilience being suitable for more complex systems, e.g., populations or ecosystems, and social-ecological resilience being suitable for any situation where the ecosystems and society interact. However, the searched system under evaluation, the temporal and spatial scale and the stress or disturbance the system should be resilient to need to be clearly defined. Defining the resilience of what to what (sensu Carpenter et al. (2001)) and to whom (sensu Lebel et al. (2006)) helps to better explicitly understand the challenges the system is facing and what exactly needs to be improved. Defining the system also shows, which resilience concept would be the most suitable for the system in question.

In **Chapter** 3 we addressed the question on how resilience could be applied in practice. Shifting the focus from resilience per se to the mechanisms that build it in the system enables more precise determination of what exactly should be resilient, and may guide concrete steps to achieve increased resilience (Biggs et al. 2012; Weise et al. 2020). Forests are complex social-ecological systems, where ecosystems are managed to produce the desired services and therefore a multitude of ecosystem functions and services need to be assessed at multiple scales while considering the assemblage of public demands and expectations (Messier et al. 2019). Multiple demands, ecosystem services and scales create trade-offs (Cumming 2011; Turkelboom et al. 2018), where increasing resilience of one part of the system at certain scale for a specific resilience mechanism may decrease the resilience of another part of the system. These trade-offs need to be balanced; however, this exercise may be challenging for forest management, which is influenced by e.g., legislation, and ownership, and therefore there may be legislative, financial, or personal constraints on how forests can be managed.

To help to overcome this challenge, we created a Principles, Criteria, and Indicators (PCI) framework for balancing the resilience trade-offs where we focused on the resilience mechanisms of diversity, adaptive capacity, and connectivity, and showed how it could be applied in three different forest management contexts. We determined seven principles, 20 criteria and an example indicator for each criterion, resulting in 20 indicators. Due to the dynamic nature of resilience (Cabell and Oelofse 2012), an increase in the indicator value may not have a constant effect on resilience. These indicators show a resilience response curve that depends on the context of forest management. Determining the shape of the response curves and their importance for achieving the management goal requires involvement of stakeholders in the decision-making process, as stakeholders are essential for bringing in the local knowledge of the system and increasing the acceptability of forest management (Walker et al. 2002; Xu et al. 2015).

The key message of the research was that the resilience of forest management depends on the context created by the forest management goal. Stakeholder involvement is needed because without it the trade-offs in forest management cannot be understood properly, and context dependent decision-making motives are easily disregarded or overlooked. However, with wider adoption of the framework, a common set of most crucial indicators may evolve, and the context dependency of response curves will get clearer. This will continuously decrease the time required for stakeholder engagement, facilitating the wider uptake of the framework by the wider forest management community to increase the resilience of forests.

In **Chapter 4**, we studied the potential of continuous high-resolution dendrometer measurements to be used as a mean to assess tree resilience to consecutive drought stress. Determining indicators to measure tree resilience to drought stress is important as droughts cause both direct damage and mortality (McDowell et al. 2022) and indirect threats by weakening the trees and making them more susceptible to other disturbances (Seidl et al. 2017a). As droughts are predicted to become more frequent and severe with climate change (IPCC 2018), understanding how tree drought stress varies for different species on European scale and how it can be monitored is important. Especially the effect of consecutive drought stress periods on trees has been less studied.

We analysed the dendrometer time series of 681 trees from 127 sites across Europe. We looked at how the length of the periods where trees experience water deficit, a measure of tree stress, changes across the summer season. We found that some trees experience very long periods with tree water deficit that may last the entirety of the season. For the coniferous and ring-porous broadleaved trees that experienced many dry periods, the length of the periods increased towards the end of the season. This indicates that coniferous and ring-porous species have limited capacity to maintain the resilience of their water status with the increased number of water deficit periods. However, due to the limited sample size of diffuse-porous trees, more reference data would be needed to make a conclusive analysis on the drought tolerance of the three wood types.

This research contributes to the operationalisation of the scientific analysis of high-resolution data on tree resilience to drought. Our results support findings from previous research on the usefulness of dendrometer measurements as a way to measure tree stress efficiently and still receive reliable information on the tree stress (e.g., Dietrich et al. 2018; Salomón et al. 2022). With improved understanding on how tree water deficit is affected by other physiological functions, the dendrometer measurements may evolve into a widely adopted procedure for determining tree resilience to drought with high-resolution. Once the relationships are better understood, it will require more scientific analysis to gather substantial evidence to establish reference data reflecting species specific and site dependent response patterns. The reference data will help to interpret the continuous observations of tree responses and incorporate the improved understanding in forest management decision-making.

In **Chapter 5**, we studied the gap between science and practice and analysed which measures to increase resilience to forest disturbances are suggested by forest experts from different European countries, and to what extend there is evidence for the effectiveness of these measures. Researchers may provide a wide range of frameworks and indicators for resilience; however, they will not lead to changes in forest management unless the people implementing management adopt them. Gaps between scientific evidence and actions in practice remains strong in forest related fields (e.g., Messier et al. 2021; Pretzsch 2009). The first requirement to change action is to be aware of the issue. The awareness about climate change has increased amongst the European forest managers and many see the need to adapt forest management (Hengst-Ehrhart 2019; Seidl et al. 2016c; Sousa-Silva et al. 2018b). However, there is a lot of uncertainty amongst the forest managers on how resilience could be increased (Blades et al. 2016; Sousa-Silva et al. 2016). Despite the uncertainty, actions to enhance forest resilience by changing management are taken in many countries. Involving measures to increase resilience in the sustainable forest management guidelines would be one step further to implement resilience into forest management.

We analysed the barriers for adapting forest management to better cope with climate change. We reviewed 134 articles and interviewed 49 forest experts from ten European countries. Our results showed that there is a difference between the measures suggested by the forest experts and the measures that are most studied by researchers, showing that there exists a clear gap between science and practice. The interviewed forest experts identified several barriers for adapting forest management, notably the lack of salient information as well as the lack of financial and personal capacity. Therefore, to better adapt to the challenges caused by global change, forest management needs to have more resources, relevant information and willingness of the managers to change their practices.

While some of the barriers are out of the control of researchers, the lack of salient information is something researchers should aim to address with their work. In conservation sciences, there has been a call for having so called evidence bridges, i.e., persons or organisations, who would identify research topics based on the management priorities, synthesize the existing evidence in an accessible and user-friendly manner as well as develop and maintain networks of connections with researchers and practitioners (Kadykalo et al. 2021). The mutual learning experiences and workshops between researchers and practitioners have been seen as useful ways to increase the reception of scientific evidence and to incorporate it to the management plans of the natural resource managers (Blades et al. 2016). To increase the operationalisation of resilience in forest management, plain language summary reports on effective measures for doing it should be higher on the agenda of researchers and publishers.

6.2 Contribution to operationalising forest resilience

The aim of this thesis was to advance the operationalisation of resilience into forest management. Increasing forest resilience is of crucial importance for ensuring the provision of future ecosystem services. While many definitions have hindered both the research on resilience as well as the practical application of the concept, clear advances in making the concept more useful have been made. In the following paragraphs we discuss how this thesis contributed to that work and brought more clarity to how resilience is defined in forest sciences, how it could be applied and what are the main barriers for managing forests for resilience.

The results of Chapter 2 show that the ongoing debate about which resilience definition is the correct one may not be very useful or fertile, as the adopted definition very much depends on the context of the performed research. The debate on whether “resilience” is a boundary or a scientific concept (Brand and Jax 2007; Nüchter et al. 2021) and which definition is the correct one to use in forest management increases the vagueness of the concept, and makes it harder for practitioners to implement (Greiner et al. 2020). Therefore, instead of first determining which resilience concept should be used, the affected system and its boundaries, the disturbances affecting it as well as the affected actors should be properly defined as also recommended in the early literature on resilience (Carpenter et al. 2001; Lebel et al. 2006).

In Chapter 3, we provide an innovative proposal on how to adopt the concept of resilience in a participatory setting with relevant stakeholders. Here we show how the definition of the system boundaries, the major affecting disturbance, and the actors affected depend on the forest management goals. To our knowledge, it is the first framework that explicitly shows how the trade-offs in forest management and the forest management goal affect the optimal resilience indicator values and how these may change with time. This framework can now be filled with case study examples to consolidate indicators and response curves, which will facilitate the uptake of the framework in the future.

Chapters 4 and 5 demonstrate that moving scientific knowledge into practical action takes several steps from 1) observing to 2) understanding what happens in the forest and 3) what exactly can be done to influence forest responses to 4) identifying proper management measures and 5) implementing them in practice. Applying an operational forest resilience framework requires proper information to guide decision-making. Chapters 4 and 5 contributed on this end to help bridge the science-practice divide by providing a better understanding of how tree-level dendrometer measurements could be interpreted and pointing out the barriers that the forest management faces when adapting the management practices.

On the whole, the research conducted in this thesis highlighted that despite the difficulties of implementing resilience, which is a multiscalar and multidimensional concept, into practical management decisions, advances can be made simultaneously in several fronts of research and management. Therefore, the hypothesis of the thesis, stating that resilience can be made into an operationalised concept in the practical forest management, can be confirmed. The research showed that while we still need to further increase our understanding on tree and ecosystem responses to climate change and disturbances, it is important to look for solutions to increase forest resilience through the perspective of the forest managers, as their goals and capacities ultimately determine, how resilience is implemented in forest management. However, even if it might help forest managers, we should not concentrate on finding one single way to measure resilience at the expense of the complexity of the concept. The power in the concept of resilience is that it fosters communication and interdisciplinary research (Baggio et al. 2015), which is needed to face the challenges caused by climate change. To further increase the operationalisation of resilience, we should move towards transdisciplinary research and increase the involvement of forest managers.

6.3 Limitations and future avenues of research

One of the main limitations of this doctoral research was the time and budget constraints that did not allow carrying out a case study to test the practical application of the framework presented in Chapter 3. Having a real-life example would likely have improved especially the parts of the framework that involve stakeholder engagement, as successful stakeholder involvement requires careful planning and testing (Reed 2008). A case study with stakeholders could also have improved our understanding of the challenges faced by forest management and produced more useful information on how the framework could be developed to facilitate its future adoption (Timberlake et al.

2020). Future research should thus involve testing the application of the framework in practice.

Another limitation of especially Chapter 4 was uneven sampling of the data on measurements of tree responses to drought stress which led to a clear majority of coniferous trees over deciduous diffuse-porous and ring-porous trees. To further analyse the resilience of European forests to drought, it is important to expand the time series of observations beyond the unprecedented drought of 2018 and analyse their resistance and recovery during the following years. In addition, the geographic spread of the tree types was not uniform, which made geographical comparison not possible. Similarly, most of the sites had only one species, which made it not possible to compare the responses of trees with different wood types to exactly the same conditions on a larger scale. The data was also heavily concentrated on central and western Europe, leaving especially northern, but also southern and eastern Europe less covered. Further effort should therefore be made to establish more sites in these regions and preferably with trees of more than one species. Fortunately, many more sites have been recently established to expand the observational network. Efforts should be directed towards feeding more data sets into the European compilation to enable more comparative research.
For the Chapter 5, one of the limitations was the need to translate the questionnaire into different languages, and while carefully done, the meanings of some words might have been altered in the process and therefore the translation to native language of the respondents could have impeded comparability of the answers to some extent. On the other side, not all interviews were possible to be conducted in the native language of the respondents, which might have had an effect on the impulsiveness and spontaneity of the answers.

Overall, future research on resilience and forest management should involve engagement with the practitioners to determine what are the information needs in the practice and how science could provide for them. The lack of transdisciplinary research in resilience research is prominent, but it could have a transformative power in management (Nüchter et al. 2021). Researchers should develop resilience-specific study designs that facilitate and mainstream the participation of practitioners and other stakeholders.

6.4 Recommendations for practice

This thesis started from the observation that forest resilience was not yet an operational concept that could be easily implemented in forest management. Through the research conducted, we made significant contributions to propose how the concept can be made more operational and identified recommendations for improving forest resilience in practice.

The first recommendation is to be very precise when planning interventions to increase forest resilience. One should ask, what exactly do they want to make more resilient. E.g., increasing resilience of a certain tree species might require completely different actions than increasing provisioning of a specific ecosystem service. Once the system of interest has been defined, one should ask, to what it needs to be resilient to. As a system cannot be resilient to all shocks and disturbances simultaneously, one should identify the most concerning disturbance. Finally, one should question at which scale do they want the system to be resilient. Increasing resilience in short-term may decrease the resilience in the long-term and vice versa.

The second recommendation is to involve relevant stakeholders in the decision-making even in privately owned forests. The involvement of stakeholders may help to better recognise the trade-offs emerging in forest management which aids in optimising the forest management. Furthermore, the stakeholders may have information unavailable to the forest managers which may influence the assessment of forest resilience. Lastly, involvement of the stakeholders may lead to better acceptance of forest management and decrease the risk of social conflict over management decisions.

The third recommendation is to collaborate with researchers whenever possible. The active interaction between practitioners and researchers may lead to better recognition of the gaps of knowledge that is needed by practitioners. This recognition may lead to the production of more relevant and locally adaptable knowledge for adapting forest management to climate change.

Following these recommendations could provide forest managers with a broadened understanding of how climate change and disturbances are affecting the managed forests and the type of demands the society has on forests. Such understanding will hopefully help them to adapt their forest management and be better prepared for the uncertain future.

7 References

Aitken, S. N., Yeaman, S., Holliday, J. A., Wang, T., & Curtis-McLane, S. (2008). Adaptation, migration or extirpation: climate change outcomes for tree populations. *Evolutionary Applications*, *1*(1), 95–111. https://doi.org/10.1111/j.1752-4571.2007.00013.x

Akamani, K. (2012). A community resilience model for understanding and assessing the sustainability of forest-dependent communities. *Human Ecology Review*, *19*(2), 99–109. http://opensiuc.lib.siu.edu/for_articles/1/

Albrich, K., Rammer, W., & Seidl, R. (2020). Climate change causes critical transitions and irreversible alterations of mountain forests. *Global Change Biology*, *26*(7), 4013–4027. https://doi.org/10.1111/gcb.15118

Allen, C. D., Macalady, A. K., Chenchouni, H., Bachelet, D., McDowell, N. G., Vennetier, M., et al. (2010). A global overview of drought and heat-induced tree mortality reveals emerging climate change risks for forests. *Forest Ecology and Management*, *259*(4), 660–684. https://doi.org/10.1016/j.foreco.2009.09.001

Allen, C. R., Angeler, D. G., Garmestani, A. S., Gunderson, L. H., & Holling, C. S. (2014). Panarchy: Theory and Application. *Ecosystems*, *17*(4), 578–589. https://doi.org/10.1007/s10021-013-9744-2

Allen, C. R., Birgé, H., Angeler, D. G., Arnold, C. A., Chaffin, B. C., DeCaro, D., et al. (2018). Quantifying uncertainty and trade-offs in resilience assessments. *Ecology and Society*, *23*(1), 243–268. https://doi.org/10.1007/978-3-319-72472-0_15

Allen, C. R., Cumming, G. S., Garmestani, A. S., Taylor, P. D., & Walker, B. H. (2011). Managing for resilience. *Wildlife Biology*, *17*(4), 337–349. https://doi.org/10.2981/10-084

Ananda, J., & Herath, G. (2009). A critical review of multi-criteria decision making methods with special reference to forest management and planning. *Ecological Economics*, *68*(10), 2535–2548. https://doi.org/10.1016/j.ecolecon.2009.05.010

Anderegg, W. R. L., Schwalm, C., Biondi, F., Camarero, J. J., Koch, G., Litvak, M., et al. (2015). Pervasive drought legacies in forest ecosystems and their implications for carbon cycle models. *Science*, *349*(6247), 528–532. https://doi.org/10.1126/science.aab1833

Angeler, D. G., Fried-Petersen, H. B., Allen, C. R., Garmestani, A. S., Twidwell, D., Chuang, W.-C., et al. (2019). Adaptive capacity in ecosystems. In *Advances in Ecological Research* (Vol. 60, pp. 1–24). https://doi.org/10.1016/bs.aecr.2019.02.001

Aquilué, N., Filotas, É., Craven, D., Fortin, M. J., Brotons, L., & Messier, C. (2020). Evaluating forest resilience to global threats using functional response traits and network properties. *Ecological Applications*, *30*(5), 0–1. https://doi.org/10.1002/eap.2095

Araos, M., Ford, J., Berrang-Ford, L., Biesbroek, R., & Moser, S. (2017). Climate change adaptation planning for Global South megacities: the case of Dhaka. *Journal of Environmental Policy and Planning*, *19*(6), 682–696. https://doi.org/10.1080/1523908X.2016.1264873

Armitage, D., Béné, C., Charles, A. T., Johnson, D., & Allison, E. H. (2012). The interplay of well-being and resilience in applying a social- ecological perspective. *Ecology and Society*, *17*(4). https://doi.org/10.5751/ES-04940-170415

Art, B., & Visseren-Hamdkers, I. (2012). Forest governance: a state of the art review. In *Forest-people interfaces* (pp. 241–257). Wageningen: Wageningen Academic Publishers. https://doi.org/10.3920/978-90-8686-749-3_15

Baggio, J. A., Brown, K., & Hellebrandt, D. (2015). Boundary object or bridging concept? A citation network analysis of resilience. *Ecology and Society*, *20*(2). https://doi.org/10.5751/ES-07484-200202

Balint, P. J., Stewart, R. E., Desai, A., & Walters, L. C. (2011). *Wicked Environmental Problems*. Washington DC, USA: Island Press.

Balogun, A. L., Marks, D., Sharma, R., Shekhar, H., Balmes, C., Maheng, D., et al. (2020). Assessing the Potentials of Digitalization as a Tool for Climate Change Adaptation and Sustainable Development in Urban Centres. *Sustainable Cities and Society*, *53*(November 2019), 101888. https://doi.org/10.1016/j.scs.2019.101888

Barbeta, A., Mejía-Chang, M., Ogaya, R., Voltas, J., Dawson, T. E., & Peñuelas, J. (2015). The combined effects of a long-term experimental drought and an extreme drought on the use of plant-water sources in a Mediterranean forest. *Global Change Biology*, *21*(3), 1213–1225. https://doi.org/10.1111/gcb.12785

Bates, D., Mächler, M., Bolker, B., & Walker, S. (2015). Fitting Linear Mixed-Effects Models Using lme4. *Journal of Statistical Software*, *67*(1). https://doi.org/10.18637/jss.v067.i01

Bauhus, J., Forrester, D. I., Gardiner, B., Jactel, H., Vallejo, R., & Pretzsch, H. (2017). Ecological Stability of Mixed-Species Forests. In H. Pretzsch, D. I. Forrester, & J. Bauhus (Eds.), *Mixed-Species Forests: Ecology and Management* (pp. 1–653). Springer Berlin Heidelberg. https://doi.org/10.1007/978-3-662-54553-9

Beguería, S., Vicente-Serrano, S. M., & Angulo-Martínez, M. (2010). A Multiscalar Global Drought Dataset: The SPEIbase: A New Gridded Product for the Analysis of Drought Variability and Impacts. *Bulletin of the American Meteorological Society*, *91*(10), 1351–1356. https://doi.org/10.1175/2010BAMS2988.1

Beguería, S., Vicente-Serrano, S. M., Reig, F., & Latorre, B. (2014). Standardized precipitation evapotranspiration index (SPEI) revisited: parameter fitting, evapotranspiration models, tools, datasets and drought monitoring. *International Journal of Climatology*, *34*(10), 3001–3023. https://doi.org/10.1002/joc.3887

Beller, E. E., Spotswood, E. N., Robinson, A. H., Anderson, M. G., Higgs, E. S., Hobbs, R. J., et al. (2019). Building Ecological Resilience in Highly Modified Landscapes. *BioScience*, *69*(1), 80–92. https://doi.org/10.1093/biosci/biy117

Berkes, F., & Folke, C. (1998). Linking social and ecological systems for resilience and sustainability. *Beijer Discussion Paper Series*, *52*, 459.

Berkman, L. F., & Glass, T. (2000). Social integration, social networks, social support, and health. *Social epidemiology*, *1*(6), 137–173.

Bernhardt, J. R., & Leslie, H. M. (2013). Resilience to climate chnge in coastal marine ecosystems. *Annual Review of Marine Science*, *5*, 371–392. https://doi.org/10.1146/annurev-marine-121211-172411

Bianchi, E., Bugmann, H., & Bigler, C. (2021). Light availability predicts mortality probability of conifer saplings in Swiss mountain forests better than radial growth and tree size. *Forest Ecology and Management*, *479*(June 2020), 118607. https://doi.org/10.1016/j.foreco.2020.118607

Bieling, C. (2004). Non-industrial private-forest owners: Possibilities for increasing adoption of close-to-nature forest management. *European Journal of Forest Research*, *123*(4), 293–303. https://doi.org/10.1007/s10342-004-0042-6

Biggs, C. R., Yeager, L. A., Bolser, D. G., Bonsell, C., Dichiera, A. M., Hou, Z., et al. (2020). Does functional redundancy affect ecological stability and resilience? A review and meta-analysis. *Ecosphere*, *11*(7). https://doi.org/10.1002/ecs2.3184

Biggs, R., Schlüter, M., Biggs, D., Bohensky, E. L., BurnSilver, S. B., Cundill, G., et al. (2012). Toward Principles for Enhancing the Resilience of Ecosystem Services. *Annual Review of Environment and Resources*, *37*, 421–48. https://doi.org/10.1146/annurev-environ-051211-123836

Bissonnette, J. F., Dupras, J., Doyon, F., Chion, C., & Tardif, J. (2017). Perceptions of Small Private Forest Owner's Vulnerability and Adaptive Capacity to

Environmental Disturbances and Climate Change: Views from a Heterogeneous Population in Southern Quebec, Canada. *Small-scale Forestry*, *16*(3), 367–393. https://doi.org/10.1007/s11842-016-9361-y

Blades, J. J., Klos, P. Z., Kemp, K. B., Hall, T. E., Force, J. E., Morgan, P., & Tinkham, W. T. (2016). Forest managers' response to climate change science: Evaluating the constructs of boundary objects and organizations. *Forest Ecology and Management*, *360*, 376–387. https://doi.org/10.1016/j.foreco.2015.07.020

Blennow, K., Persson, J., Tomé, M., & Hanewinkel, M. (2012). Climate Change: Believing and Seeing Implies Adapting. *PLoS ONE*, *7*(11), e50182. https://doi.org/10.1371/journal.pone.0050182

Bodin, Ö., & Prell, C. (Eds.). (2011). *Social networks and natural resource management: uncovering the social fabric of environmental governance*. Cambridge University Press.

Boeing, G. (2016). Visual Analysis of Nonlinear Dynamical Systems : Chaos , Fractals , Self-Similarity and the Limits. *Systems*, *4*(37). https://doi.org/10.3390/systems4040037

Boesch, D. F. (1974). Proceedings of the First International Congress of Ecology The Hague The Netherlands September 8-14 , 1974. In W. H. van Dobben & R. H. Lowe-McConnell (Eds.), *Unifying concepts in ecology: Report of the plenary sessions of the First international congress of ecology, The Hague, the Netherlands* (pp. 109–114). Dordrecht: Springer, Dordrecht.

Bolte, A., Ammer, C., Löf, M., Madsen, P., Nabuurs, G. J., Schall, P., et al. (2009). Adaptive forest management in central Europe: Climate change impacts, strategies and integrative concept. *Scandinavian Journal of Forest Research, 24*(6), 473–482. https://doi.org/10.1080/02827580903418224

Bonan, G. B. (2008). Forests and Climate Change: Forcings, Feedbacks, and the Climate Benefits of Forests. *Science*, *320*(1444). https://doi.org/10.1126/science.1155121

Bone, C., Moseley, C., Vinyeta, K., & Bixler, R. P. (2016). Employing resilience in the United States Forest Service. *Land Use Policy*, *52*, 430–438. https://doi.org/10.1016/j.landusepol.2016.01.003

Borges, J. G., Marques, S., Garcia-Gonzalo, J., Rahman, A. U., Bushenkov, V., Sottomayor, M., et al. (2017). A multiple criteria approach for negotiating ecosystem services supply targets and forest owners' programs. *Forest Science, 63*(1), 49–61. https://doi.org/10.5849/FS-2016-035

Böttcher, H., Verkerk, P. J., Gusti, M., Havlík, P., & Grassi, G. (2012). Projection of the future EU forest CO2 sink as affected by recent bioenergy policies using two advanced forest management models. *GCB Bioenergy*, *4*(6), 773–783. https://doi.org/10.1111/j.1757-1707.2011.01152.x

Bottollier-Curtet, M., Planty-Tabacchi, A. M., & Tabacchi, E. (2013). Competition between young exotic invasive and native dominant plant species: Implications for invasions within riparian areas. *Journal of Vegetation Science*, *24*(6), 1033–1042. https://doi.org/10.1111/jvs.12034

Bowditch, E. A. D., McMorran, R., Bryce, R., & Smith, M. (2019). Perception and partnership: Developing forest resilience on private estates. *Forest Policy and Economics*, *99*(March 2017), 110–122. https://doi.org/10.1016/j.forpol.2017.12.004

Brand, F. S., & Jax, K. (2007). Focusing the meaning(s) of resilience: Resilience as a descriptive concept and a boundary object. *Ecology and Society*, *12*(1), art23. https://doi.org/10.5751/ES-02029-120123

Brinkmann, N., Eugster, W., Zweifel, R., Buchmann, N., & Kahmen, A. (2016). Temperate tree species show identical response in tree water deficit but different sensitivities in sap flow to summer soil drying. *Tree Physiology*, *36*(12), 1508–1519. https://doi.org/10.1093/treephys/tpw062

Brito, P., Wieser, G., Oberhuber, W., Gruber, A., Lorenzo, J. R., González-Rodríguez, M., & Jiménez, M. S. (2017). Water availability drives stem growth and stem water deficit of Pinus canariensis in a drought-induced treeline in Tenerife. *Plant Ecology*, *218*(3), 277–290. https://doi.org/10.1007/s11258-016-0686-6

Brockerhoff, E. G., Barbaro, L., Castagneyrol, B., Forrester, D. I., Gardiner, B., González-Olabarria, J. R., et al. (2017). Forest biodiversity, ecosystem functioning and the provision of ecosystem services. *Biodiversity and Conservation*, *26*(13), 3005–3035. https://doi.org/10.1007/s10531-017-1453-2

Brodribb, T. J., & Cochard, H. (2009). Hydraulic failure defines the recovery and point of death in water-stressed conifers. *Plant Physiology*, *149*(1), 575–584. https://doi.org/10.1104/pp.108.129783

Brooks, M. E., Kristensen, K., van Benthem, K. J., Magnusson, A., Berg, C. W., Nielsen, A., et al. (2017). glmmTMB balances speed and flexibility among packages for zero-inflated generalized linear mixed modeling. *R Journal*, *9*(2), 378–400. https://doi.org/10.32614/rj-2017-066

Brown, E. D., & Williams, B. K. (2015). Resilience and Resource Management. *Environmental Management*, *56*(6), 1416–1427. https://doi.org/10.1007/s00267-

015-0582-1

Brown, K. (2014). Global environmental change I: A social turn for resilience? *Progress in Human Geography*, *38*(1), 107–117. https://doi.org/10.1177/0309132513498837

Bryant, T., Waring, K., Sánchez Meador, A., & Bradford, J. B. (2019). A Framework for Quantifying Resilience to Forest Disturbance. *Frontiers in Forests and Global Change*, *2*(September), 1–14. https://doi.org/10.3389/ffgc.2019.00056

Brzostek, E. R., Dragoni, D., Schmid, H. P., Rahman, A. F., Sims, D., Wayson, C. A., et al. (2014). Chronic water stress reduces tree growth and the carbon sink of deciduous hardwood forests. *Global Change Biology*, *20*(8), 2531–2539. https://doi.org/10.1111/gcb.12528

Bussotti, F., Pollastrini, M., Holland, V., & Brüggemann, W. (2015). Functional traits and adaptive capacity of European forests to climate change. *Environmental and Experimental Botany*, *111*, 91–113. https://doi.org/10.1016/j.envexpbot.2014.11.006

Cabell, J. F., & Oelofse, M. (2012). An indicator framework for assessing agroecosystem resilience. *Ecology and Society*, *17*(1). https://doi.org/10.5751/ES-04666-170118

Caldwell-Harris, C. L. (2014). Emotionality differences between a native and foreign language: Theoretical implications. *Frontiers in psychology*, *5*, 1055.

Camarero, J. J., Gazol, A., Sangüesa-Barreda, G., Cantero, A., Sánchez-Salguero, R., Sánchez-Miranda, A., et al. (2018). Forest Growth Responses to Drought at Short- and Long-Term Scales in Spain: Squeezing the Stress Memory from Tree Rings. *Frontiers in Ecology and Evolution*, *6*(February), 1–11. https://doi.org/10.3389/fevo.2018.00009

Camarero, J. J., Gazol, A., Sangüesa-Barreda, G., Oliva, J., & Vicente-Serrano, S. M. (2015). To die or not to die: Early warnings of tree dieback in response to a severe drought. *Journal of Ecology*, *103*(1), 44–57. https://doi.org/10.1111/1365-2745.12295

Cantarello, E., Newton, A. C., Martin, P. A., Evans, P. M., Gosal, A., & Lucash, M. S. (2017). Quantifying resilience of multiple ecosystem services and biodiversity in a temperate forest landscape. *Ecology and Evolution*, *7*(22), 9661–9675. https://doi.org/10.1002/ece3.3491

Carnol, M., Baeten, L., Branquart, E., Grégoire, J. C., Heughebaert, A., Muys, B., et al. (2014). Ecosystem services of mixed species forest stands and monocultures: Comparing practitioners and scientists perceptions with formal scientific knowledge. *Forestry*, *87*(5), 639–653. https://doi.org/10.1093/forestry/cpu024

Carpenter, S., Walker, B. H., Anderies, J. M., & Abel, N. (2001). From Metaphor to Measurement: Resilience of What to What? *Ecosystems*, *4*(8), 765–781. https://doi.org/10.1007/s10021-001-0045-9

Carranza, M. L., Hoyos, L., Frate, L., Acosta, A. T. R., & Cabido, M. (2015). Measuring forest fragmentation using multitemporal forest cover maps: Forest loss and spatial pattern analysis in the Gran Chaco, central Argentina. *Landscape and Urban Planning*, *143*, 238–247. https://doi.org/10.1016/j.landurbplan.2015.08.006

Cartwright, J. M., Littlefield, C. E., Michalak, J. L., Lawler, J. J., & Dobrowski, S. Z. (2020). Topographic, soil, and climate drivers of drought sensitivity in forests and shrublands of the Pacific Northwest, USA. *Scientific Reports*, *10*(1), 1–13. https://doi.org/10.1038/s41598-020-75273-5

Cash, D. W., Clark, W. C., Alcock, F., Dickson, N. M., Eckley, N., Guston, D. H., et al. (2003). Knowledge systems for sustainable development. *Proceedings of the National Academy of Sciences of the United States of America*, *100*(14), 8086–8091. https://doi.org/10.1073/pnas.1231332100

Castagneri, D., Vacchiano, G., Hacket-Pain, A., DeRose, R. J., Klein, T., & Bottero, A. (2021). Meta-analysis Reveals Different Competition Effects on Tree Growth Resistance and Resilience to Drought. *Ecosystems*. https://doi.org/10.1007/s10021-021-00638-4

Castro-Díez, P., Vaz, A. S., Silva, J. S., van Loo, M., Alonso, Á., Aponte, C., et al. (2019). Global effects of non-native tree species on multiple ecosystem services. *Biological Reviews*, *94*(4), 1477–1501. https://doi.org/10.1111/brv.12511

Cavers, S., & Cottrell, J. E. (2015). The basis of resilience in forest tree species and its use in adaptive forest management in Britain. *Forestry*, *88*(1), 13–26. https://doi.org/10.1093/forestry/cpu027

Chambers, J. C., Beck, J. L., Campbell, S., Carlson, J., Christiansen, T. J., Clause, K. J., et al. (2016). 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. *General Technical Report.*, *RMRS-GTR-3*(December), 143. https://www.fs.usda.gov/treesearch/pubs/53201

Chapin, F. S., Carpenter, S. R., Kofinas, G. P., Folke, C., Abel, N., Clark, W. C., et al. (2010). Ecosystem stewardship: sustainability strategies for a rapidly changing planet. *Trends in Ecology and Evolution*, *25*(4), 241–249. https://doi.org/10.1016/j.tree.2009.10.008

Chapin, F. S., Walker, L. R., Fastie, C. L., & Sharman, L. C. (1994). Mechanisms of Primary Succession Following Deglaciation at Glacier Bay , Alaska. *Ecological Monographs, 64*(2), 149–175.

Cherkasskii, B. L. (1988). The system of the epidemic process. *Journal of Hygiene Epidemology Microbiology and Immunology*, *32*(3), 321–328.

Chin, A., Simon, G. L., Anthamatten, P., Kelsey, K. C., Crawford, B. R., & Weaver, A. J. (2020). Pandemics and the future of human-landscape interactions. *Anthropocene*, *31*, 100256. https://doi.org/10.1016/j.ancene.2020.100256

Colding, J., & Barthel, S. (2019). Exploring the social-ecological systems discourse 20 years later. *Ecology and Society*, *24*(1). https://doi.org/10.5751/ES-10598-240102

Convention on Biological Diversity. (2022). Definitions. https://www.cbd.int/forest/definitions.shtml

Copernicus Climate Change Services. (2022). Copernicus: Globally, the seven hottest years on record were the last seven; carbon dioxide and methane concentrations continue to rise. https://climate.copernicus.eu/copernicus-globally-seven-hottest-years-record-were-last-seven. Accessed 9 May 2022

Cornes, R. C., van der Schrier, G., van den Besselaar, E. J. M., & Jones, P. D. (2018). An Ensemble Version of the E-OBS Temperature and Precipitation Data Sets. *Journal of Geophysical Research: Atmospheres*, *123*(17), 9391–9409. https://doi.org/10.1029/2017JD028200

Cote, M., & Nightingale, A. J. (2012). Resilience thinking meets social theory: Situating social change in socio-ecological systems (SES) research. *Progress in Human Geography*, *36*(4), 475–489. https://doi.org/10.1177/0309132511425708

Cumming, G. S. (2011). Spatial resilience: Integrating landscape ecology, resilience, and sustainability. *Landscape Ecology*, *26*(7), 899–909. https://doi.org/10.1007/s10980-011-9623-1

Cuny, H. E., Rathgeber, C. B. K., Lebourgeois, F., Fortin, M., & Fournier, M. (2012). Life strategies in intra-annual dynamics of wood formation: Example of three conifer species in a temperate forest in north-east France. *Tree Physiology, 32*(5), 612–625. https://doi.org/10.1093/treephys/tps039

Cuthill, M., Ross, H., Maclean, K., Owens, K., Witt, B., & King, C. (2008). Reporting Social Outcomes of Development: An Analysis of Diverse Approaches. *The International Journal of Interdisciplinary Social Sciences: Annual Review*, *3*(6), 145–158. https://doi.org/10.18848/1833-1882/CGP/v03i06/52646

D'Orangeville, L., Duchesne, L., Houle, D., Kneeshaw, D., Côté, B., & Pederson, N. (2016). Northeastern North America as a potential refugium for boreal forests in a warming climate. *Science*, *352*(6292), 1452–1455. https://doi.org/10.1126/science.aaf4951

D'Orangeville, L., Itter, M., Kneeshaw, D., Munger, J. W., Richardson, A. D., Dyer, J. M., et al. (2022). Peak radial growth of diffuse-porous species occurs during periods of lower water availability than for ring-porous and coniferous trees. *Tree Physiology*, *42*(2), 304–316. https://doi.org/10.1093/treephys/tpab101

Danneyrolles, V., Dupuis, S., Fortin, G., Leroyer, M., de Römer, A., Terrail, R., et al. (2019). Stronger influence of anthropogenic disturbance than climate change on century-scale compositional changes in northern forests. *Nature Communications*, *10*(1), 1–7. https://doi.org/10.1038/s41467-019-09265-z

DasGupta, R., & Shaw, R. (2015). An indicator based approach to assess coastal communities' resilience against climate related disasters in Indian Sundarbans. *Journal of Child and Family Studies*, *24*(3), 85–101. https://doi.org/10.1007/s11852-014-0369-1

De Groot, R. S., Alkemade, R., Braat, L., Hein, L., & Willemen, L. (2010). Challenges in integrating the concept of ecosystem services and values in landscape planning, management and decision making. *Ecological complexity*, *7*(3), 260–272. https://doi.org/10.1016/j.ecocom.2009.10.006

de Rigo, D., Libertà, G., Houston Durrant, T., Artés Vivancos, T., & San-Miguel-Ayanz, J. (2017). *Forest fire danger extremes in Europe under climate change : variability and uncertainty*. Luxembourg. https://doi.org/10.2760/13180

De Schepper, V., Van Dusschoten, D., Copini, P., Jahnke, S., & Steppe, K. (2012). MRI links stem water content to stem diameter variations in transpiring trees. *Journal of Experimental Botany*, *63*(7), 2645–2653. https://doi.org/10.1093/jxb/err445

DEFRA. (2018). *The National Adaptation Programme and the Third Strategy for Climate Adaptation Reporting*.

DeLong, D. C. (1996). Defining biodiversity. *Wildlife Society Bulletin*, *24*(4), 738–749. https://doi.org/10.1016/s1460-1567(02)80010-1

Derks, J., Giessen, L., & Winkel, G. (2020). COVID-19-induced visitor boom reveals the importance of forests as critical infrastructure. *Forest Policy and Economics*, *118*(April), 102253. https://doi.org/10.1016/j.forpol.2020.102253

DeRose, R. J., & Long, J. N. (2014). Resistance and Resilience: A Conceptual Framework for Silviculture. *Forest Science*, *60*(6), 1205–1212. https://doi.org/10.5849/forsci.13-507

Deutscher Wetterdienst. (2022). German Climate Atlas. https://www.dwd.de/EN/climate_environment/climateatlas/climateatlas_node.html;jsessionid=4D7091CA28984288C1BB1D896DB9B680.live31091

Dietrich, L., Zweifel, R., & Kahmen, A. (2018). Daily stem diameter variations can predict the canopy water status of mature temperate trees. *Tree Physiology*, *38*(7), 941–952. https://doi.org/10.1093/treephys/tpy023

Döll, P., & Romero-Lankao, P. (2017). How to embrace uncertainty in participatory climate change risk management-A roadmap. *Earth's Future*, *5*(1), 18–36. https://doi.org/10.1002/2016EF000411

Drouard, M., Kornhuber, K., & Woollings, T. (2019). Disentangling Dynamic Contributions to Summer 2018 Anomalous Weather Over Europe. *Geophysical Research Letters*, *46*(21), 12537–12546. https://doi.org/10.1029/2019GL084601

Egerer, M., Fouch, N., Anderson, E. C., & Clarke, M. (2020). Socio-ecological connectivity differs in magnitude and direction across urban landscapes. *Scientific Reports*, *10*(1), 1–16. https://doi.org/10.1038/s41598-020-61230-9

Eggers, J., Holmgren, S., Nordström, E. M., Lämås, T., Lind, T., & Öhman, K. (2019). Balancing different forest values: Evaluation of forest management scenarios in a multi-criteria decision analysis framework. *Forest Policy and Economics*, *103*(July), 55–69. https://doi.org/10.1016/j.forpol.2017.07.002

Eggers, J., Räty, M., Öhman, K., & Snäll, T. (2020). How well do stakeholder-defined forest management scenarios balance economic and ecological forest values? *Forests*, *11*(1). https://doi.org/10.3390/f11010086

Ehbrecht, M., Schall, P., Ammer, C., & Seidel, D. (2017). Quantifying stand structural complexity and its relationship with forest management, tree species diversity and microclimate. *Agricultural and Forest Meteorology*, *242*(April), 1–9. https://doi.org/10.1016/j.agrformet.2017.04.012

Ehbrecht, M., Seidel, D., Annighöfer, P., Kreft, H., Köhler, M., Zemp, D. C., et al. (2021). Global patterns and climatic controls of forest structural complexity. *Nature Communications*, *12*(1), 1–12. https://doi.org/10.1038/s41467-020-20767-z

Ennos, R. A. (2015). Resilience of forests to pathogens: An evolutionary ecology perspective. *Forestry*, *88*(1), 41–52. https://doi.org/10.1093/forestry/cpu048

Etzold, S., Sterck, F., Bose, A. K., Braun, S., Buchmann, N., Eugster, W., et al. (2022).

Number of growth days and not length of the growth period determines radial stem growth of temperate trees. *Ecology Letters*, *25*(2), 427–439. https://doi.org/10.1111/ele.13933

European Commission. New EU Forest Strategy for 2030. , COMMUNICATION FROM THE COMMISSION TO THE EUROPEAN PARLIAMENT, THE COUNCIL, THE EUROPEAN ECONOMIC AND SOCIAL COMMITTEE AND THE COMMITTEE OF THE REGIONS (2021). https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:52021DC0572. Accessed 12 December 2021

Evert, R. F. (2006). *Esau's plant anatomy: meristems, cells, and tissues of the plant body: their structure, function, and development*. John Wiley & Sons.

FAO, & UNEP. (2020). *The State of the World's Forests 2020. Forests, Biodiversity and People*. Rome: FAO and UNEP. https://doi.org/10.4060/ca8642en

Fares, S., Mugnozza, G. S., Corona, P., & Palahí, M. (2015). Sustainability: Five steps for managing Europe's forests. *Nature*, *519*(7544), 407–409. https://doi.org/10.1038/519407a

Fischer, A. P. (2018). Forest landscapes as social-ecological systems and implications for management. *Landscape and Urban Planning*, *177*(May), 138–147. https://doi.org/10.1016/j.landurbplan.2018.05.001

Fischer, J., Peterson, G. D., Gardner, T. A., Gordon, L. J., Fazey, I., Elmqvist, T., et al. (2009). Integrating resilience thinking and optimisation for conservation. *Trends in Ecology and Evolution*, *24*(10), 549–554. https://doi.org/10.1016/j.tree.2009.03.020

Folke, C. (2016). Resilience. In *Oxford Research Encyclopedia of Environmental Science* (Vol. 1, pp. 1–63). Oxford University Press. https://doi.org/10.1093/acrefore/9780199389414.013.8

Folke, C., & Berkes, F. (1998). *Understanding dynamics of ecosystem-institution linkages for building resilience*. *Beijer Discussion Paper No. 112*. Stockholm: The Beijer Institute of Ecological Economics, Royal Academy of Sciences.

Folke, C., Carpenter, S. R., Elmqvist, T., Gunderson, L. H., & Walker, B. H. (2002). Resilience and Sustainable Development : Building Adaptive Capacity in a World of Transformations, *31*(5), 437–440. https://doi.org/10.1579/0044-7447-31.5.437

Folke, C., Carpenter, S. R., Walker, B. H., Scheffer, M., Chapin, T., & Rockström, J. (2010). Resilience thinking: Integrating resilience, adaptability and transformability. *Ecology and Society*, *15*(4). https://doi.org/10.5751/ES-03610-150420

Folke, C., Polasky, S., Rockström, J., Galaz, V., Westley, F., Lamont, M., et al. (2021).

Our future in the Anthropocene biosphere. *Ambio* (Vol. 50). https://doi.org/10.1007/s13280-021-01544-8

FOREST EUROPE. (2020a). *State of Europe's Forests 2020*.

FOREST EUROPE. (2020b). *Adaptation to Climate Change in Sustainable Forest Management in Eu*. Zvolen. https://www.taylorfrancis.com/books/9781351297950/chapters/10.4324/9781351297967-18

Fremout, T., Thomas, E., Bocanegra-González, K. T., Aguirre-Morales, C. A., Morillo-Paz, A. T., Atkinson, R., et al. (2021). Dynamic seed zones to guide climate-smart seed sourcing for tropical dry forest restoration in Colombia. *Forest Ecology and Management*, *490*(February). https://doi.org/10.1016/j.foreco.2021.119127

Gardiner, B., Schuck, A., Schelhaas, M.-J., Orazio, C., Blennow, K., & Nicoll, B. (2013). *Living with storm damage to forests*. (L. Hetemäki & M. Korhonen, Eds.). Joensuu: European Forest Institute. https://doi.org/10.13140/2.1.1730.2400

Garland, T., & Kelly, S. A. (2006). Phenotypic plasticity and experimental evolution. *Journal of Experimental Biology*, *209*(12), 2344–2361. https://doi.org/10.1242/jeb.02244

Gazol, A., Camarero, J. J., Anderegg, W. R. L., & Vicente-Serrano, S. M. (2017). Impacts of droughts on the growth resilience of Northern Hemisphere forests. *Global Ecology and Biogeography*, *26*(2), 166–176. https://doi.org/10.1111/geb.12526

Gilliams, S., Raymaekers, D., Muys, B., & Van Orshoven, J. (2005). Comparing multiple criteria decision methods to extend a geographical information system on afforestation. *Computers and Electronics in Agriculture*, *49*(1), 142–158. https://doi.org/10.1016/J.COMPAG.2005.02.011

Giuggiola, A., Zweifel, R., Feichtinger, L. M., Vollenweider, P., Bugmann, H., Haeni, M., & Rigling, A. (2018). Competition for water in a xeric forest ecosystem – Effects of understory removal on soil micro-climate, growth and physiology of dominant Scots pine trees. *Forest Ecology and Management*, *409*(February), 241–249. https://doi.org/10.1016/j.foreco.2017.11.002

Glück, P., Avdibegović, M., Čabaravdić, A., Nonić, D., Petrović, N., Posavec, S., & Stojanovska, M. (2010). The preconditions for the formation of private forest owners' interest associations in the Western Balkan Region. *Forest Policy and Economics*, *12*(4), 250–263. https://doi.org/10.1016/j.forpol.2010.02.001

Grams, T. E. E., Hesse, B. D., Gebhardt, T., Weikl, F., Rötzer, T., Kovacs, B., et al.

(2021). The Kroof experiment: realization and efficacy of a recurrent drought experiment plus recovery in a beech/spruce forest. *Ecosphere*, *12*(3). https://doi.org/10.1002/ecs2.3399

Grassi, G., House, J., Dentener, F., Federici, S., Den Elzen, M., & Penman, J. (2017). The key role of forests in meeting climate targets requires science for credible mitigation. *Nature Climate Change*, *7*(3), 220–226. https://doi.org/10.1038/nclimate3227

Greiner, S. M., Grimm, K. E., & Waltz, A. E. M. (2020). Managing for Resilience? Examining Management Implications of Resilience in Southwestern National Forests. *Journal of Forestry*, (March). https://doi.org/10.1093/jofore/fvaa006

Guerrero, A. M., McAllister, R. R. J., Corcoran, J., & Wilson, K. A. (2013). Scale Mismatches, Conservation Planning, and the Value of Social-Network Analyses. *Conservation Biology*, *27*(1), 35–44. https://doi.org/10.1111/j.1523-1739.2012.01964.x

Gunderson, L. H. (2000). Ecological Resilience - in Theory and Application. *Annual Review of Ecology and Systematics*, *69*(1), 473–439. https://doi.org/10.1146/annurev.ecolsys.31.1.425

Güney, A., Zweifel, R., Türkan, S., Zimmermann, R., Wachendorf, M., & Güney, C. O. (2020). Drought responses and their effects on radial stem growth of two co-occurring conifer species in the Mediterranean mountain range. *Annals of Forest Science*, *77*(4). https://doi.org/10.1007/s13595-020-01007-2

Haeni, M., Knüsel, S., Wilhelm, M., Peters, R. L., & Zweifel, R. (2020). Clean, process and visualise dendrometer data. https://github.com/treenet/treenetproc

Halofsky, J. E., Peterson, D. L., & Harvey, B. J. (2020). Changing wildfire, changing forests: the effects of climate change on fire regimes and vegetation in the Pacific Northwest, USA. *Fire Ecology*, *16*(1). https://doi.org/10.1186/s42408-019-0062-8

Hammond, W. M., Williams, A. P., Abatzoglou, J. T., Adams, H. D., Klein, T., López, R., et al. (2022). Global field observations of tree die-off reveal hotter-drought fingerprint for Earth's forests. *Nature Communications*, *13*(1), 1761. https://doi.org/10.1038/s41467-022-29289-2

Hanewinkel, M., Hummel, S., & Albrecht, A. T. (2011). Assessing natural hazards in forestry for risk management : a review. *European Journal of Forest Research*, *130*, 329–351. https://doi.org/10.1007/510342-01 0-0392- 1

Harrison, X. A., Donaldson, L., Correa-Cano, M. E., Evans, J., Fisher, D. N., Goodwin, C. E. D., et al. (2018). A brief introduction to mixed effects modelling and multimodel inference in ecology. *PeerJ*, *2018*(5), 1–32. https://doi.org/10.7717/peerj.4794

Hartig, F. (2021). DHARMa: Residual Diagnostics for Hierarchical (Multi-Level / Mixed) Regression Models. https://cran.r-project.org/package=DHARMa

Hengst-Ehrhart, Y. (2019). Knowing is not enough: exploring the missing link between climate change knowledge and action of German forest owners and managers. *Annals of Forest Science*, *76*(4). https://doi.org/10.1007/s13595-019-0878-z

Herzog, K. M., Häsler, R., & Thum, R. (1995). Diurnal changes in the radiues of a subalpine Norway spruce stem: their relation to the sap flow and their use to estimate transpiration. *Trees*, *10*, 94–101.

Hinckley, T. M., Lassoie, J. P., & Running, S. W. (1978). Temporal and spatial variations in the water status of forest trees. *Forest Science*, *24*(Supplement 20), 1–72. http://www.ingentaconnect.com/content/saf/fs/1978/00000024/A020s020/art00001

Hirota, M., Holmgren, M., Van Nes, E. H., & Scheffer, M. (2011). Global Resilience of Tropical Forest and Savanna to Critical Transitions. *Science*, *334*(6053), 232 LP – 235. http://science.sciencemag.org/content/334/6053/232.abstract

Hlásny, T., König, L., Krokene, P., Lindner, M., Montagné-Huck, C., Müller, J., et al. (2021a). Bark Beetle Outbreaks in Europe: State of Knowledge and Ways Forward for Management. *Current Forestry Reports*, *7*(3), 138–165. https://doi.org/10.1007/s40725-021-00142-x

Hlásny, T., Zimová, S., & Bentz, B. (2021b). Scientific response to intensifying bark beetle outbreaks in Europe and North America. *Forest Ecology and Management*, *499*(August), 119599. https://doi.org/10.1016/j.foreco.2021.119599

Holling, C. S. (1973). Resilience and Stability of Ecological Systems. *Annual Review of Ecology and Systematics*, *4*(1), 1–23. https://doi.org/10.1146/annurev.es.04.110173.000245

Holling, C. S. (1986). The resilience of terrestial ecosystems: local surprise and global change. In W. C. Clark & R. E. Munn (Eds.), *Sustainable development of the biosphere* (pp. 292–320). International Institute for Applied Systems Analysis (IIASA).

Holling, C. S. (2001). Understanding the Complexity of Economic, Ecological, and Social Systems. *Ecosystems*, *4*(5), 390–405. https://doi.org/10.1007/s10021-00

Holling, C. S., & Gunderson, L. H. (2002). *Panarchy: understanding transformations in human and natural systems*. Island Press.

Holvoet, B., & Muys, B. (2004). Sustainable forest management worldwide: a comparative assessment of standards. *International Forestry Review*, *6*(2), 99–122. https://doi.org/10.1505/ifor.6.2.99.38388

Honkaniemi, J., Rammer, W., & Seidl, R. (2020). Norway spruce at the trailing edge: the effect of landscape configuration and composition on climate resilience. *Landscape Ecology*, *35*(3), 591–606. https://doi.org/10.1007/s10980-019-00964-y

Hosseini, S., Barker, K., & Ramirez-Marquez, J. E. (2016). A review of definitions and measures of system resilience. *Reliability Engineering and System Safety*, *145*, 47–61. https://doi.org/10.1016/j.ress.2015.08.006

Huuskonen, S., Domisch, T., Finér, L., Hantula, J., Hynynen, J., Matala, J., et al. (2021). What is the potential for replacing monocultures with mixed-species stands to enhance ecosystem services in boreal forests in Fennoscandia? *Forest Ecology and Management*, *479*(August 2020), 118558. https://doi.org/10.1016/j.foreco.2020.118558

IPCC. (2007). *Climate Change 2007: Impacts, Adaptation, and Vulnerability, Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*. (J. J. McCarthy, O. . Canziani, N. A. Leary, D. J. Dokken, & K. S. White, Eds.). Cambridge: Cambridge University Press.

IPCC. (2018). *Global warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change,*. (V. Masson-Delmotte, P. Zhai, H.-O. Pörtner, D. Roberts, J. Skea, P. R. Shukla, et al., Eds.).

IPCC. (2022). *IPCC WGII Sixt Assessment Report - Summary for Policymakers*.

Isbell, F., Calcagno, V., Hector, A., Connolly, J., Harpole, W. S., Reich, P. B., et al. (2011). High plant diversity is needed to maintain ecosystem services. *Nature*, *477*(7363), 199–202. https://doi.org/10.1038/nature10282

Ishii, H., & Ford, E. D. (2002). Persistence of Pseudotsuga menziesii (Douglas-fir) in temperate coniferous forests of the Pacific Northwest Coast, USA. *Folia Geobotanica*, *37*(1), 63–69. https://doi.org/10.1007/BF02803191

ISO, I. (2009). Risk management–Principles and guidelines. *International Organization for Standardization, Geneva, Switzerland*.

Jacobsen, J. B. (2007). The regeneration decision: A sequential two-option approach. *Canadian Journal of Forest Research*, *37*(2), 439–448. https://doi.org/10.1139/X06-

Jacobsen, J. B., & Helles, F. (2006). Adaptive and nonadaptive harvesting in uneven-aged beech forest with stochastic prices. *Forest Policy and Economics*, *8*(3), 223–238. https://eurekamag.com/research/004/394/004394670.php

Jacobsen, J. B., & Thorsen, B. J. (2003). A Danish example of optimal thinning strategies in mixed-species forest under changing growth conditions caused by climate change. *Forest Ecology and Management*, *180*(1–3), 375–388. https://doi.org/10.1016/S0378-1127(02)00652-7

Jansson, G., Danusevičius, D., Grotehusman, H., Kowalczyk, J., Krajmerova, D., Skrøppa, T., & Wolf, H. (2013). Norway Spruce (Picea abies (L.) H.Karst.). In L. E. Pâques (Ed.), *Forest Tree Breeding in Europe: Current State-of-the-Art and Perspectives* (pp. 123–176). Springer, Dordrecht. https://doi.org/10.1007/978-94-007-6146-9

Jelinski, D. E. (2005). There is no Mother Nature - There is no balance of nature: Culture, ecology and conservation. *Human Ecology*, *33*(2), 271–288. https://doi.org/10.1007/s10745-005-2435-7

Johnstone, J. F., Allen, C. D., Franklin, J. F., Frelich, L. E., Harvey, B. J., Higuera, P. E., et al. (2016). Changing disturbance regimes, ecological memory, and forest resilience. *Frontiers in Ecology and the Environment*, *14*(7), 369–378. https://doi.org/10.1002/fee.1311

Jung, M., Dahal, P. R., Butchart, S. H. M., Donald, P. F., De Lamo, X., Lesiv, M., et al. (2020). A global map of terrestrial habitat types. *Scientific Data*, *7*(1), 1–8. https://doi.org/10.1038/s41597-020-00599-8

Kadykalo, A. N., Buxton, R. T., Morrison, P., Anderson, C. M., Bickerton, H., Francis, C. M., et al. (2021). Bridging research and practice in conservation. *Conservation Biology*, *35*(6), 1725–1737. https://doi.org/10.1111/cobi.13732

Kangas, J., & Kangas, A. (2005). Multiple criteria decision support in forest management - The approach, methods applied, and experiences gained. *Forest Ecology and Management*, *207*(1-2 SPEC. ISS.), 133–143. https://doi.org/10.1016/j.foreco.2004.10.023

Kannenberg, S. A., Novick, K. A., Alexander, M. R., Maxwell, J. T., Moore, D. J. P., Phillips, R. P., & Anderegg, W. R. L. (2019). Linking drought legacy effects across scales: From leaves to tree rings to ecosystems. *Global Change Biology*, *25*(9), 2978–2992. https://doi.org/10.1111/gcb.14710

Kawaletz, H., Mölder, I., Zerbe, S., Annighöfer, P., Terwei, A., & Ammer, C. (2013). Exotic tree seedlings are much more competitive than natives but show underyielding when growing together. *Journal of Plant Ecology*, *6*(4), 305–315. https://doi.org/10.1093/jpe/rts044

Kay, J. J. (2000). II. 1.2 Ecosystems as Self-organising Holarchic Open Systems: Narratives and the Second Law of Thermodynamics. *Handbook of ecosystem theories and management*, 135.

Keane, R. E., Loehman, R. A., Holsinger, L. M., Falk, D. A., Higuera, P. E., Hood, S. M., & Hessburg, P. F. (2018). Use of landscape simulation modeling to quantify resilience for ecological applications. *Ecosphere*, *9*(9). https://doi.org/10.1002/ecs2.2414

Keck, M., & Sakdapolrak, P. (2013). What is social resilience? lessons learned and ways forward. *Erdkunde*, *67*(1), 5–19. https://doi.org/10.3112/erdkunde.2013.01.02

Keenan, R. J. (2015). Climate change impacts and adaptation in forest management: a review. *Annals of Forest Science*, *72*(2), 145–167. https://doi.org/10.1007/s13595-014-0446-5

Kirilenko, A. P., & Sedjo, R. A. (2007). Climate change impacts on forestry. *Proceedings of the National Academy of Sciences of the United States of America*, *104*(50), 19697–19702. https://doi.org/10.1073/pnas.0701424104

Klein, T. (2014). The variability of stomatal sensitivity to leaf water potential across tree species indicates a continuum between isohydric and anisohydric behaviours. *Functional Ecology*, *28*(6), 1313–1320. https://doi.org/10.1111/1365-2435.12289

Knoke, T., Messerer, K., & Paul, C. (2017). The Role of Economic Diversification in Forest Ecosystem Management. *Current Forestry Reports*, *3*(2), 93–106. https://doi.org/10.1007/s40725-017-0054-3

Knüsel, S., De Boni, A., Conedera, M., Schleppi, P., Thormann, J. J., Frehner, M., & Wunder, J. (2017). Shade tolerance of Ailanthus altissima revisited: novel insights from southern Switzerland. *Biological Invasions*, *19*(2), 455–461. https://doi.org/10.1007/s10530-016-1301-4

Knüsel, S., Peters, R. L., Haeni, M., Wilhelm, M., & Zweifel, R. (2021). Processing and Extraction of Seasonal Tree Physiological Parameters from Stem Radius Time Series. *Forests*, *12*(6), 765. https://doi.org/10.3390/f12060765

Kolström, M., Lindner, M., Vilén, T., Maroschek, M., Seidl, R., Lexer, M. J., et al. (2011). Reviewing the science and implementation of climate change adaptation measures in European forestry. *Forests*, *2*(4), 961–982. https://doi.org/10.3390/f2040961

Kouba, Y., Martínez-García, F., De Frutos, Á., & Alados, C. L. (2015). Effects of previous land-use on plant species composition and diversity in Mediterranean forests. *PLoS ONE*, *10*(9), 1–15. https://doi.org/10.1371/journal.pone.0139031

Kronholm, T. (2015). Forest Owners' Associations in a Changing Society. *Acta Universitatis agriculturae Sueciae 2015:102*

Kunstler, G., Curt, T., & Lepart, J. (2004). Spatial pattern of beech (Fagus sylvatica L.) and oak (Quercus pubescens Mill.) seedlings in natural pine (Pinus sylvestris L.) woodlands. *European Journal of Forest Research*, *123*(4), 331–337. https://doi.org/10.1007/s10342-004-0048-0

Kunz, J., Löffler, G., & Bauhus, J. (2018). Minor European broadleaved tree species are more drought-tolerant than Fagus sylvatica but not more tolerant than Quercus petraea. *Forest Ecology and Management*, *414*(July 2017), 15–27. https://doi.org/10.1016/j.foreco.2018.02.016

Kuuluvainen, T., Angelstam, P., Frelich, L., Jõgiste, K., Koivula, M., Kubota, Y., et al. (2021). Natural Disturbance-Based Forest Management: Moving Beyond Retention and Continuous-Cover Forestry. *Frontiers in Forests and Global Change*, *4*. https://doi.org/10.3389/ffgc.2021.629020

Lafond, V., Cordonnier, T., Mao, Z., & Courbaud, B. (2017). Trade-offs and synergies between ecosystem services in uneven-aged mountain forests: evidences using Pareto fronts. *European Journal of Forest Research*, *136*(5–6), 997–1012. https://doi.org/10.1007/s10342-016-1022-3

Lammerts van Bueren, E. M., & Blom, E. M. (1997). *Hierarchical framework for the formulation of sustainable forest management standards.* The Tropenbos Foundation. http://library1.nida.ac.th/termpaper6/sd/2554/19755.pdf

Lamothe, K. A., Somers, K. M., & Jackson, D. A. (2019). Linking the ball-and-cup analogy and ordination trajectories to describe ecosystem stability, resistance, and resilience. *Ecosphere*, *10*(3), e02629. https://doi.org/10.1002/ecs2.2629

Lansu, E. M., van Heerwaarden, C. C., Stegehuis, A. I., & Teuling, A. J. (2020). Atmospheric Aridity and Apparent Soil Moisture Drought in European Forest During Heat Waves. *Geophysical Research Letters*, *47*(6). https://doi.org/10.1029/2020GL087091

Larsen, J. B., Angelstam, P., Bauhus, J., Carvalho, J. F., Diaci, J., Dobrowolska, D., et al. (2022). *Closer-to-Nature Forest Management. From Science to Policy 12*.

https://doi.org/10.36333/fs12

Larsen, R. K., Calgaro, E., & Thomalla, F. (2011). Governing resilience building in Thailand's tourism-dependent coastal communities: Conceptualising stakeholder agency in social–ecological systems. *Global Environmental Change*, *21*(2), 481–491. https://doi.org/10.1016/j.gloenvcha.2010.12.009

Lawrence, A., & Marzano, M. (2014). Is the private forest sector adapting to climate change? A study of forest managers in north Wales. *Annals of Forest Science*, *71*(2), 291–300. https://doi.org/10.1007/s13595-013-0326-4

Lebel, L., Anderies, J. M., Campbell, B., Folke, C., Hatfield-Dodds, S., Hughes, T. P., & Wilson, J. (2006). Governance and the Capacity to Manage Resilience in Regional Social-Ecological Systems. *Ecology and Society*, *11*(1). https://doi.org/10.5751/es-01606-110119

Lefèvre, F., Boivin, T., Bontemps, A., Courbet, F., Davi, H., Durand-Gillmann, M., et al. (2014). Considering evolutionary processes in adaptive forestry. *Annals of Forest Science*, *71*(7), 723–739. https://doi.org/10.1007/s13595-013-0272-1

Lempereur, M., Martin-Stpaul, N. K., Damesin, C., Joffre, R., Ourcival, J. M., Rocheteau, A., & Rambal, S. (2015). Growth duration is a better predictor of stem increment than carbon supply in a Mediterranean oak forest: Implications for assessing forest productivity under climate change. *New Phytologist*, *207*(3), 579–590. https://doi.org/10.1111/nph.13400

Levine, N. M., Zhang, K., Longo, M., Baccini, A., Phillips, O. L., Lewis, S. L., et al. (2016). Ecosystem heterogeneity determines the ecological resilience of the Amazon to climate change. *Proceedings of the National Academy of Sciences*, *113*(3), 793–797. https://doi.org/10.1073/pnas.1511344112

Lewontin, R. C. (1969). The meaning of stability. In *Brookhaven symposia in biology* (Vol. 22, pp. 13–24).

Lindner, M., Maroschek, M., Netherer, S., Kremer, A., Barbati, A., Garcia-Gonzalo, J., et al. (2010). Climate change impacts, adaptive capacity, and vulnerability of European forest ecosystems. *Forest Ecology and Management*, *259*(4), 698–709. https://doi.org/10.1016/j.foreco.2009.09.023

Lloret, F., Keeling, E. G., & Sala, A. (2011). Components of tree resilience: Effects of successive low-growth episodes in old ponderosa pine forests. *Oikos*, *120*(12), 1909–1920. https://doi.org/10.1111/j.1600-0706.2011.19372.x

Lodin, I., Brukas, V., & Wallin, I. (2017). Spruce or not? Contextual and attitudinal drivers behind the choice of tree species in southern Sweden. *Forest Policy and Economics*, *83*, 191–198. https://doi.org/10.1016/j.forpol.2016.11.010

Lu, N., Liu, L., Yu, D., & Fu, B. (2021). Navigating trade-offs in the social-ecological systems. *Current Opinion in Environmental Sustainability*, *48*, 77–84.

Luís, S., Lima, M. L., Roseta-Palma, C., Rodrigues, N., Sousa, L. P., Freitas, F., et al. (2018). Psychosocial drivers for change: Understanding and promoting stakeholder engagement in local adaptation to climate change in three European Mediterranean case studies. *Journal of Environmental Management*, *223*(August 2017), 165–174. https://doi.org/10.1016/j.jenvman.2018.06.020

Maclean, K., Cuthill, M., & Ross, H. (2014). Six attributes of social resilience. *Journal of Environmental Planning and Management*, *57*(1), 144–156. https://doi.org/10.1080/09640568.2013.763774

Madlener, R., Robledo, C., Muys, B., & Freja, J. T. B. (2006). A sustainability framework for enhancing the long-term success of lulucf projects. *Climatic Change*, *75*(1–2), 241–271. https://doi.org/10.1007/s10584-005-9023-0

Makkonen, M. (2018). Stakeholder Perspectives on the Business Potential of Digitalization in the Wood Products Industry. *BioProducts Buisness*, *6*(3), 63–80.

Manning, C., Widmann, M., Bevacqua, E., Van Loon, A. F., Maraun, D., & Vrac, M. (2019). Increased probability of compound long-duration dry and hot events in Europe during summer (1950-2013). *Environmental Research Letters*, *14*(9). https://doi.org/10.1088/1748-9326/ab23bf

Martín-López, B., Palomo, I., García-Llorente, M., Iniesta-Arandia, I., Castro, A. J., García Del Amo, D., et al. (2017). Delineating boundaries of social-ecological systems for landscape planning: A comprehensive spatial approach. *Land Use Policy*, *66*(April), 90–104. https://doi.org/10.1016/j.landusepol.2017.04.040

Martin, P. H., Canham, C. D., & Kobe, R. K. (2010). Divergence from the growth-survival trade-off and extreme high growth rates drive patterns of exotic tree invasions in closed-canopy forests. *Journal of Ecology*, *98*(4), 778–789. https://doi.org/10.1111/j.1365-2745.2010.01666.x

Massmann, A., Gentine, P., & Lin, C. (2019). When Does Vapor Pressure Deficit Drive or Reduce Evapotranspiration? *Journal of Advances in Modeling Earth Systems*, *11*(10), 3305–3320. https://doi.org/10.1029/2019MS001790

McCulloh, K., Sperry, J. S., Lachenbruch, B., Meinzer, F. C., Reich, P. B., & Voelker, S. (2010). Moving water well: Comparing hydraulic efficiency in twigs and trunks of coniferous, ring-porous, and diffuseporous saplings from temperate and tropical forests. *New Phytologist*, *186*(2), 439–450. https://doi.org/10.1111/j.1469-8137.2010.03181.x

McDowell, N. G., Allen, C. D., Anderson-Teixeira, K. J., Aukema, B. H., Bond-Lamberty, B., Chini, L., et al. (2020). Pervasive shifts in forest dynamics in a changing world. *Science*, *368*(6494). https://doi.org/10.1126/science.aaz9463

McDowell, N. G., Sapes, G., Pivovaroff, A., Adams, H. D., Allen, C. D., Anderegg, W. R. L., et al. (2022). Mechanisms of woody-plant mortality under rising drought, CO2 and vapour pressure deficit. *Nature Reviews Earth & Environment*, *3*, 103–111. https://doi.org/10.1038/s43017-022-00272-1

MCPFE. (1998). *Resolution L2 Pan-European Criteria, Indicators and Operational Level Guidelines for Sustainable Forest Management - Third Ministerial Conference on the Protection of Forests in Europe 2-4 June 1998, Lisbon/Portugal*.

Messier, C., Bauhus, J., Doyon, F., Maure, F., Sousa-Silva, R., Nolet, P., et al. (2019). The functional complex network approach to foster forest resilience to global changes. *Forest Ecosystems*, *6*(1), 21. https://doi.org/10.1186/s40663-019-0166-2

Messier, C., Bauhus, J., Sousa-Silva, R., Auge, H., Baeten, L., Barsoum, N., et al. (2021). For the sake of resilience and multifunctionality, let's diversify planted forests! *Conservation Letters*, (January), 1–8. https://doi.org/10.1111/conl.12829

Messier, C., Puettmann, K., Chazdon, R., Andersson, K. P., Angers, V. A., Brotons, L., et al. (2015). From Management to Stewardship: Viewing Forests As Complex Adaptive Systems in an Uncertain World. *Conservation Letters*, *8*(5), 368–377. https://doi.org/10.1111/conl.12156

Messier, C., Puettmann, K. J., & Coates, K. D. (2013). *Managing Forests as Complex Adaptive Systems - Building Resilience to the Challenge of Global Change*. (C. Messier, K. J. Puettmann, & K. D. Coates, Eds.) (1st ed.). London: Routledge.

Mina, M., Messier, C., Duveneck, M., Fortin, M. J., & Aquilué, N. (2020). Network analysis can guide resilience-based management in forest landscapes under global change. *Ecological Applications*, *0*(0), 1–18. https://doi.org/10.1002/eap.2221

Moretti, M., & Legg, C. (2009). Combining plant and animal traits to assess community functional responses to disturbance. *Ecography*, *32*(2), 299–309. https://doi.org/10.1111/j.1600-0587.2008.05524.x

Mori, A. S., Dee, L. E., Gonzalez, A., Ohashi, H., Cowles, J., Wright, A. J., et al. (2021). Biodiversity–productivity relationships are key to nature-based climate solutions.

Nature Climate Change, *11*(6), 543–550. https://doi.org/10.1038/s41558-021-01062-1

Mori, A. S., Furukawa, T., & Sasaki, T. (2013). Response diversity determines the resilience of ecosystems to environmental change. *Biological Reviews*, *88*(2), 349–364. https://doi.org/10.1111/brv.12004

Moser, S., Meerow, S., Arnott, J., & Jack-Scott, E. (2019). The turbulent world of resilience: interpretations and themes for transdisciplinary dialogue. *Climatic Change*, *153*(1–2), 21–40. https://doi.org/10.1007/s10584-018-2358-0

Müller, F., Bergmann, M., Dannowski, R., Dippner, J. W., Gnauck, A., Haase, P., et al. (2016). Assessing resilience in long-term ecological data sets. *Ecological Indicators*, *65*, 10–43. https://doi.org/10.1016/j.ecolind.2015.10.066

Müller, Fabian, Jaeger, D., & Hanewinkel, M. (2019). Digitization in wood supply – A review on how Industry 4.0 will change the forest value chain. *Computers and Electronics in Agriculture*, *162*(January), 206–218. https://doi.org/10.1016/j.compag.2019.04.002

Muys, B. (2013). Sustainable Development within Planetary Boundaries: A Functional Revision of the Definition Based on the Thermodynamics of Complex Social-Ecological Systems. *Challenges in Sustainability*, *1*(1). https://doi.org/10.12924/cis2013.01010041

Nagel, L. M., Palik, B. J., Battaglia, M. A., D'Amato, A. W., Guldin, J. M., Swanston, C. W., et al. (2017). Adaptive Silviculture for Climate Change: A National Experiment in Manager-Scientist Partnerships to Apply an Adaptation Framework. *Journal of Forestry*, *115*(3), 167–178. https://doi.org/10.5849/jof.16-039

Nardini, A., Casolo, V., Dal Borgo, A., Savi, T., Stenni, B., Bertoncin, P., et al. (2016). Rooting depth, water relations and non-structural carbohydrate dynamics in three woody angiosperms differentially affected by an extreme summer drought. *Plant Cell and Environment*, *39*(3), 618–627. https://doi.org/10.1111/pce.12646

Newton, A. C. (2016). Biodiversity Risks of Adopting Resilience as a Policy Goal. *Conservation Letters*, *9*(5), 369–376. https://doi.org/10.1111/conl.12227

Newton, A. C., & Cantarello, E. (2015). Restoration of forest resilience: An achievable goal? *New Forests*, *46*(5–6), 645–668. https://doi.org/10.1007/s11056-015-9489-1

Nikinmaa, L., Lindner, M., Cantarello, E., Jump, A. S., Seidl, R., Winkel, G., & Muys, B. (2020). Reviewing the Use of Resilience Concepts in Forest Sciences. *Current Forestry Reports*, *6*(2), 61–80. https://doi.org/10.1007/s40725-020-00110-x

Nüchter, V., Abson, D. J., von Wehrden, H., & Engler, J. O. (2021). The concept of resilience in recent sustainability research. *Sustainability (Switzerland)*, *13*(5), 1–21. https://doi.org/10.3390/su13052735

Nyström, M., & Folke, C. (2001). Spatial resilience of coral reefs. *Ecosystems*, *4*(5), 406–417. https://doi.org/10.1007/s10021-001-0019-y

O'Hara, K. L., & Ramage, B. S. (2013). Silviculture in an uncertain world: Utilizing multi-aged management systems to integrate disturbance. *Forestry*, *86*(4), 401–410. https://doi.org/10.1093/forestry/cpt012

Obladen, N., Dechering, P., Skiadaresis, G., Tegel, W., Keßler, J., Höllerl, S., et al. (2021). Tree mortality of European beech and Norway spruce induced by 2018-2019 hot droughts in central Germany. *Agricultural and Forest Meteorology*, *307*(February). https://doi.org/10.1016/j.agrformet.2021.108482

OECD. (1993). *Environment Monographs 83 - OECD Core Set of Indicators for Environmental Performance Reviews*. Paris.

Oksanen, J., Blanchet, F. G., Friendly, M., Kindt, R., Legendre, P., McGlinn, D., et al. (2019). vegan: Community Ecology Package. R package version 2.5-4. https://cran.r-project.org/package=vegan

Oliver, T. H., Heard, M. S., Isaac, N. J. B. B., Roy, D. B., Procter, D., Eigenbord, F., et al. (2015). Biodiversity and Resilience of Ecosystem Functions. *Trends in Ecology and Evolution*, *30*(11), 673–684. https://doi.org/10.1016/j.tree.2015.08.009

Olson, D. M., Dinerstein, E., Wikramanayake, E. D., Burgess, N. D., Powell, G. V. N., Underwood, E. C., et al. (2001). Terrestrial Ecoregions of the World: A New Map of Life on Earth. *BioScience*, *51*(11), 933–938.

Olsson, L., Jerneck, A., Thoren, H., Persson, J., & O'Byrne, D. (2015). Why resilience is unappealing to social science: Theoretical and empirical investigations of the scientific use of resilience. *Science Advances*, *1*(4), 1–12. https://doi.org/10.1126/sciadv.1400217

Ontl, T. A., Swanston, C., Brandt, L. A., Butler, P. R., D'Amato, A. W., Handler, S. D., et al. (2018). Adaptation pathways: ecoregion and land ownership influences on climate adaptation decision-making in forest management. *Climatic Change*, *146*(1–2), 75–88. https://doi.org/10.1007/s10584-017-1983-3

Owens, S. (2010). Learning across levels of governance: Expert advice and the adoption of carbon dioxide emissions reduction targets in the UK. *Global Environmental Change*, *20*(3), 394–401. https://doi.org/10.1016/j.gloenvcha.2009.11.001

Oxbrough, A., García-Tejero, S., Spence, J., & O'Halloran, J. (2016). Can mixed stands of native and non-native tree species enhance diversity of epigaeic arthropods in plantation forests? *Forest Ecology and Management*, *367*, 21–29. https://doi.org/10.1016/j.foreco.2016.02.023

Paluch, J. G., & Jastrzebski, R. (2013). Natural regeneration of shade-tolerant Abies alba Mill. in gradients of stand species compositions: Limitation by seed availability or safe microsites? *Forest Ecology and Management*, *307*, 322–332. https://doi.org/10.1016/j.foreco.2013.06.035

Panshin, A. J., & De Zeeuw, C. (1980). *Textbook of wood technology*. New York, NY, USA: McGraw-Hill.

Park, J., Seager, T. P., & Rao, P. S. C. (2011). Lessons in risk- versus resilience-based design and management. *Integrated Environmental Assessment and Management*, *7*(3), 396–399. https://doi.org/10.1002/ieam.228

Peters, E. B., McFadden, J. P., & Montgomery, R. A. (2010). Biological and environmental controls on tree transpiration in a suburban landscape. *Journal of Geophysical Research: Biogeosciences*, *115*(4), 1–13. https://doi.org/10.1029/2009JG001266

Petritan, A. M., Von Lüpke, B., & Petritan, I. C. (2007). Effects of shade on growth and mortality of maple (Acer pseudoplatanus), ash (Fraxinus excelsior) and beech (Fagus sylvatica) saplings. *Forestry*, *80*(4), 397–412. https://doi.org/10.1093/forestry/cpm030

Petrokas, R., Baliuckas, V., & Manton, M. (2020). Successional categorization of european hemi-boreal forest tree species. *Plants*, *9*(10), 1–13. https://doi.org/10.3390/plants9101381

Pfautsch, S. (2016). Hydraulic Anatomy and Function of Trees—Basics and Critical Developments. *Current Forestry Reports*, *2*(4), 236–248. https://doi.org/10.1007/s40725-016-0046-8

Pfautsch, S., Hölttä, T., & Mencuccini, M. (2015). Hydraulic functioning of tree stems - Fusing ray anatomy, radial transfer and capacitance. *Tree Physiology*, *35*(7), 706–722. https://doi.org/10.1093/treephys/tpv058

Philp, J. (2015). Balancing the bioeconomy: supporting biofuels and bio-based materials in public policy. *Energy Environ. Sci.*, *8*(11), 3063–3068. https://doi.org/10.1039/C5EE01864A

Phuong, L. T. H., Biesbroek, G. R., & Wals, A. E. J. (2018). Barriers and enablers to climate change adaptation in hierarchical governance systems: the case of Vietnam. *Journal of Environmental Policy and Planning*, *20*(4), 518–532. https://doi.org/10.1080/1523908X.2018.1447366

Pimentel, D. (1961). Species diversity and insect population outbreaks. *Annals of the entomological society of America*, *54*(1), 76–86.

Pimm, S. L. (1984). The complexity and stability of ecosystems. *Nature*, *307*(5949), 321–326. https://doi.org/10.1038/307321a0

Pinkerton, E. W., & Benner, J. (2013). Small sawmills persevere while the majors close: Evaluating resilience and desirable timber allocation in British Columbia, Canada. *Ecology and Society*, *18*(2). https://doi.org/10.5751/ES-05515-180234

Plieninger, T., Muñoz-Rojas, J., Buck, L. E., & Scherr, S. J. (2020). Agroforestry for sustainable landscape management. *Sustainability Science*, *15*(5), 1255–1266. https://doi.org/10.1007/s11625-020-00836-4

Pötzelsberger, E., Spiecker, H., Neophytou, C., Mohren, F., Gazda, A., & Hasenauer, H. (2020). Growing Non-native Trees in European Forests Brings Benefits and Opportunities but Also Has Its Risks and Limits. *Current Forestry Reports*, 339–353. https://doi.org/10.1007/s40725-020-00129-0

Pretzsch, H. (2009). *Forest Dynamics, Growth and Yield*. *Forest Dynamics, Growth and Yield*. Berlin, Heidelberg: Springer Berlin Heidelberg. https://doi.org/10.1007/978-3-540-88307-4

Pretzsch, H., Forrester, D. I., & Bauhus, J. (2017). *Mixed-species forests: Ecology and management*. *Mixed-Species Forests: Ecology and Management*. https://doi.org/10.1007/978-3-662-54553-9

Prins, K. (2022). War in Ukraine, and extensive forest damage in central Europe: Supplementary challenges for forests and timber or the beginning of a new era? *Forest Policy and Economics*, *140*, 102736. https://doi.org/10.1016/j.forpol.2022.102736

Publications Office of the European Union. (2022). 7206 Europe. *EuroVoc*.

Puettmann, K. J. (2014). Restoring the Adaptive Capacity of Forest Ecosystems. *Journal of Sustainable Forestry*, *33*(SUP1), 15–27. https://doi.org/10.1080/10549811.2014.884000

Puettmann, K. J., Coates, K. D., & Messier, C. (2009). *A Critique of Silviculture - Managing for Complexity*. Washington DC, USA: Island Press.

Quinlan, A. E., Berbés-Blázquez, M., Haider, L. J., & Peterson, G. D. (2016). Measuring and assessing resilience: broadening understanding through multiple disciplinary perspectives. *Journal of Applied Ecology*, *53*(3), 677–687. https://doi.org/10.1111/1365-2664.12550

Rammer, W., & Seidl, R. (2015). Coupling human and natural systems: Simulating adaptive management agents in dynamically changing forest landscapes. *Global Environmental Change*, *35*, 475–485. https://doi.org/10.1016/j.gloenvcha.2015.10.003

Reed, M. S. (2008). Stakeholder participation for environmental management: A literature review. *Biological Conservation*, *141*(10), 2417–2431. https://doi.org/10.1016/j.biocon.2008.07.014

Reyer, C. P. O., Bathgate, S., Blennow, K., Borges, J. G., Bugmann, H., Delzon, S., et al. (2017). Are forest disturbances amplifying or canceling out climate change-induced productivity changes in European forests? *Environmental Research Letters*, *12*(3). https://doi.org/10.1088/1748-9326/aa5ef1

Reyer, C. P. O., Brouwers, N., Rammig, A., Brook, B. W., Epila, J., Grant, R. F., et al. (2015b). Forest resilience and tipping points at different spatio-temporal scales: Approaches and challenges. *Journal of Ecology*, *103*(1), 5–15. https://doi.org/10.1111/1365-2745.12337

Reyer, C. P. O., Rammig, A., Brouwers, N., & Langerwisch, F. (2015a). Forest resilience, tipping points and global change processes. *Journal of Ecology*, *103*(1), 1–4. https://doi.org/10.1111/1365-2745.12342

Reyers, B., Folke, C., Moore, M. L., Biggs, R., & Galaz, V. (2018). Social-ecological systems insights for navigating the dynamics of the anthropocene. *Annual Review of Environment and Resources*, *43*, 267–289. https://doi.org/10.1146/annurev-environ-110615-085349

Rist, L., Felton, A., Nyström, M., Troell, M., Sponseller, R. A., Bengtsson, J., et al. (2014). Applying resilience thinking to production ecosystems. *Ecosphere*, *5*(6), 1–11. https://doi.org/10.1890/ES13-00330.1

Rist, L., & Moen, J. (2013). Sustainability in forest management and a new role for resilience thinking. *Forest Ecology and Management*, *310*, 416–427. https://doi.org/10.1016/j.foreco.2013.08.033

Rivest, D., Paquette, A., Shipley, B., Reich, P. B., & Messier, C. (2015). Tree communities rapidly alter soil microbial resistance and resilience to drought. *Functional Ecology*, *29*(4), 570–578. https://doi.org/10.1111/1365-2435.12364

Rodríguez, J. P., Beard, T. D., Bennett, E. M., Cumming, G. S., Cork, S. J., Agard, J., et al. (2006). Trade-offs across space, time, and ecosystem services. *Ecology and Society*, *11*(1). https://doi.org/10.5751/ES-01667-110128

Roostaie, S., Nawari, N., & Kibert, C. J. (2019). Sustainability and resilience: A review of definitions, relationships, and their integration into a combined building assessment framework. *Building and Environment*, *154*(November 2018), 132–144. https://doi.org/10.1016/j.buildenv.2019.02.042

Rossi, S., Deslauriers, A., Anfodillo, T., & Carrer, M. (2008). Age-dependent xylogenesis in timberline conifers. *New Phytologist*, *177*(1), 199–208. https://doi.org/10.1111/j.1469-8137.2007.02235.x

Ruehr, N. K., Grote, R., Mayr, S., & Arneth, A. (2019). Beyond the extreme: recovery of carbon and water relations in woody plants following heat and drought stress. *Tree physiology*, *39*(8), 1285–1299. https://doi.org/10.1093/treephys/tpz032

Ruete, A., Snäll, T., & Jönsson, M. (2016). Dynamic anthropogenic edge effects on the distribution and diversity of fungi in fragmented old-growth forests. *Ecological Applications*, *26*(5), 1475–1485. https://doi.org/10.1890/15-1271

Sakschewski, B., Von Bloh, W., Boit, A., Poorter, L., Peña-Claros, M., Heinke, J., et al. (2016). Resilience of Amazon forests emerges from plant trait diversity. *Nature Climate Change*, *6*(11), 1032–1036. https://doi.org/10.1038/nclimate3109

Salas-Garita, C., & Soliño, M. (2021). Set of reference indicators for the evaluation of sustainable management of natural forests in Costa Rica: The relevance of the institutional dimension. *Ecological Indicators*, *121*. https://doi.org/10.1016/j.ecolind.2020.106979

Salazar-Tortosa, D., Castro, J., Villar-Salvador, P., Viñegla, B., Matías, L., Michelsen, A., et al. (2018). The "isohydric trap": A proposed feedback between water shortage, stomatal regulation, and nutrient acquisition drives differential growth and survival of European pines under climatic dryness. *Global Change Biology*, *24*(9), 4069–4083. https://doi.org/10.1111/gcb.14311

Salomón, R. L., Peters, R. L., Zweifel, R., Sass-Klaassen, U. G. W., Stegehuis, A. I., Smiljanic, M., et al. (2022). The 2018 European heatwave led to stem dehydration but not to consistent growth reductions in forests. *Nature Communications*, *13*(1), 1–11. https://doi.org/10.1038/s41467-021-27579-9

Sarkki, S., Ficko, A., Wielgolaski, F. E., Abraham, E. M., Bratanova-Doncheva, S., Grunewald, K., et al. (2017). Assessing the resilient provision of ecosystem services by social-ecological systems: introduction and theory. *Climate Research*, *AdvanceVie*(February), 1–9. https://doi.org/10.3354/cr01437

Schaich, H., & Plieninger, T. (2013). Land ownership drives stand structure and carbon storage of deciduous temperate forests. *Forest Ecology and Management*, *305*, 146–157. https://doi.org/10.1016/j.foreco.2013.05.013

Schall, P., Gossner, M. M., Heinrichs, S., Fischer, M., Boch, S., Prati, D., et al. (2018). The impact of even-aged and uneven-aged forest management on regional biodiversity of multiple taxa in European beech forests. *Journal of Applied Ecology*, *55*(1), 267–278. https://doi.org/10.1111/1365-2664.12950

Scheffer, M., Carpenter, S. R., Lenton, T. M., Bascompte, J., Brock, W., Dakos, V., et al. (2012). Anticipating critical transitions. *Science*, *338*(6105), 344–348. https://doi.org/10.1126/science.1225244

Scheffer, M., Hirota, M., Holmgren, M., Van Nes, E. H., & Chapin, F. S. (2012). Thresholds for boreal biome transitions. *Proceedings of the National Academy of Sciences*, *109*(52), 21384–21389. https://doi.org/10.1073/pnas.1219844110

Schelhaas, M.-J., Nabuurs, G.-J., & Schuck, A. (2003). Natural disturbances in the European forests in the 19th and 20th centuries. *Global Change Biology*, *9*(11), 1620–1633. https://doi.org/10.1046/j.1365-2486.2003.00684.x

Schmitt-Harsh, M. L., & Mincey, S. K. (2020). Operationalizing the social-ecological system framework to assess residential forest structure: A case study in Bloomington, Indiana. *Ecology and Society*, *25*(2), 1–17. https://doi.org/10.5751/ES-11564-250214

Schoon, M. L., & Cox, M. E. (2012). Understanding disturbances and responses in social-ecological systems. *Society and Natural Resources*, *25*(2), 141–155. https://doi.org/10.1080/08941920.2010.549933

Schulze, E. D., Mischì, G., Asche, G., & Börner, A. (2007). Land-use history and succession of Larix decidua in the Southern Alps of Italy-An essay based on a cultural history study of Roswitha Asche. *Flora: Morphology, Distribution, Functional Ecology of Plants*, *202*(8), 705–713. https://doi.org/10.1016/j.flora.2007.05.003

Seidl, R., Aggestam, F., Rammer, W., Blennow, K., & Wolfslehner, B. (2016c). The sensitivity of current and future forest managers to climate-induced changes in ecological processes. *Ambio*, *45*(4), 430–441. https://doi.org/10.1007/s13280-015-0737-6

Seidl, R., Albrich, K., Thom, D., & Rammer, W. (2018). Harnessing landscape heterogeneity for managing future disturbance risks in forest ecosystems. *Journal of Environmental Management*, *209*, 46–56. https://doi.org/10.1016/j.jenvman.2017.12.014

Seidl, R., Müller, J., Hothorn, T., Bässler, C., Heurich, M., & Kautz, M. (2016b). Small beetle, large-scale drivers: how regional and landscape factors affect outbreaks of the European spruce bark beetle. *Journal of Applied Ecology*, *53*(2), 530–540. https://doi.org/10.1111/1365-2664.12540

Seidl, R., Rammer, W., & Spies, T. A. (2014b). Disturbance legacies increase the resilience of forest ecosystem structure, composition, and functioning. *Ecological Applications*, *24*(8), 2063–2077. https://doi.org/10.1890/14-0255.1

Seidl, R., Schelhaas, M.-J., Rammer, W., & Verkerk, P. J. (2014a). Increasing forest disturbances in Europe and their impact on carbon storage. *Nature Climate Change*, *4*(9), 806–810. https://doi.org/10.1038/nclimate2318

Seidl, R., Spies, T. A., Peterson, D. L., Stephens, S. L., & Hicke, J. A. (2016a). Searching for resilience: addressing the impacts of changing disturbance regimes on forest ecosystem services. *Journal of Applied Ecology*, *53*(1), 120–129. https://doi.org/10.1111/1365-2664.12511

Seidl, R., Thom, D., Kautz, M., Martin-Benito, D., Peltoniemi, M., Vacchiano, G., et al. (2017a). Forest disturbances under climate change. *Nature Climate Change*, *7*(6), 395–402. https://doi.org/10.1038/nclimate3303

Seidl, R., Vigl, F., Rössler, G., Neumann, M., & Rammer, W. (2017b). Assessing the resilience of Norway spruce forests through a model-based reanalysis of thinning trials. *Forest Ecology and Management*, *388*, 3–12. https://doi.org/10.1016/j.foreco.2016.11.030

Selva, N., Chylarecki, P., Jonsson, B. G., & Ibisch, P. L. (2020). Misguided forest action in EU Biodiversity Strategy. *Science*, *368*(6498), 1438–1439.

Senf, C., Buras, A., Zang, C. S., Rammig, A., & Seidl, R. (2020). Excess forest mortality is consistently linked to drought across Europe. *Nature Communications*, *11*(1), 1–8. https://doi.org/10.1038/s41467-020-19924-1

Senf, C., Sebald, J., & Seidl, R. (2021). Increasing canopy mortality affects the future demographic structure of Europe's forests. *One Earth*, *4*(5), 749–755. https://doi.org/10.1016/j.oneear.2021.04.008

Senf, C., & Seidl, R. (2021a). Mapping the forest disturbance regimes of Europe. *Nature Sustainability*, *4*(1), 63–70. https://doi.org/10.1038/s41893-020-00609-y

Senf, C., & Seidl, R. (2021b). Storm and fire disturbances in Europe: Distribution and trends. *Global Change Biology*, *27*(15), 3605–3619. https://doi.org/10.1111/gcb.15679

Sheppard, S. R. J., & Meitner, M. (2005). Using multi-criteria analysis and visualisation for sustainable forest management planning with stakeholder groups. *Forest Ecology and Management*, *207*(1-2 SPEC. ISS.), 171–187. https://doi.org/10.1016/j.foreco.2004.10.032

Sjöman, H., Morgenroth, J., Sjöman, J. D., Sæbø, A., & Kowarik, I. (2016). Diversification of the urban forest—Can we afford to exclude exotic tree species? *Urban Forestry and Urban Greening*, *18*, 237–241. https://doi.org/10.1016/j.ufug.2016.06.011

Sousa-Silva, R., Ponette, Q., Verheyen, K., Van Herzele, A., & Muys, B. (2016). Adaptation of forest management to climate change as perceived by forest owners and managers in Belgium. *Forest Ecosystems*, *3*(1). https://doi.org/10.1186/s40663-016-0082-7

Sousa-Silva, R., Verbist, B., Lomba, Â., Valent, P., Suškevičs, M., Picard, O., et al. (2018). Adapting forest management to climate change in Europe: Linking perceptions to adaptive responses. *Forest Policy and Economics*, *90*(February), 22–30. https://doi.org/10.1016/j.forpol.2018.01.004

Sousa-Silva, R., Verheyen, K., Ponette, Q., Bay, E., Sioen, G., Titeux, H., et al. (2018). Tree diversity mitigates defoliation after a drought-induced tipping point. *Global Change Biology*, *24*(9), 4304–4315. https://doi.org/10.1111/gcb.14326

Spears, B. M., Ives, S. C., Angeler, D. G., Allen, C. R., Birk, S., Carvalho, L., et al. (2015). Effective management of ecological resilience - are we there yet? *Journal of Applied Ecology*, *52*(5), 1311–1315. https://doi.org/10.1111/1365-2664.12497

Spiecker, H., Hansen, J., Klimo, E., Skovsgaard, J. P., Sterba, H., & von Teuffel, K. (2004). *Norway Spruce Conversion - Options and Consequences*. Leiden, Boston, Köln. https://doi.org/ISBN 90 04 13728 9

Spinoni, J., Vogt, J. V., Naumann, G., Barbosa, P., & Dosio, A. (2018). Will drought events become more frequent and severe in Europe? *International Journal of Climatology*, *38*(4), 1718–1736. https://doi.org/10.1002/joc.5291

Staal, A., Fetzer, I., Wang-Erlandsson, L., Bosmans, J. H. C., Dekker, S. C., van Nes, E. H., et al. (2020). Hysteresis of tropical forests in the 21st century. *Nature Communications*, *11*(1), 1–8. https://doi.org/10.1038/s41467-020-18728-7

Standish, R. J., Hobbs, R. J., Mayfield, M. M., Bestelmeyer, B. T., Suding, K. N., Battaglia, L. L., et al. (2014). Resilience in ecology: Abstraction, distraction, or where the action is? *Biological Conservation*, *177,* 43–51. https://doi.org/10.1016/j.biocon.2014.06.008

Steffen, W., Rockström, J., Richardson, K., Lenton, T. M., Folke, C., Liverman, D., et al. (2018). Trajectories of the Earth System in the Anthropocene. *Proceedings of the National Academy of Sciences of the United States of America*, *115*(33), 8252–8259. https://doi.org/10.1073/pnas.1810141115

Stephenson, N. L., Das, A. J., Ampersee, N. J., Bulaon, B. M., & Yee, J. L. (2019). Which trees die during drought? The key role of insect host-tree selection. *Journal of Ecology*, *107*(5), 2383–2401. https://doi.org/10.1111/1365-2745.13176

Stone, P. H., & Carlson, J. H. (1979). Atmospheric Lapse Rate Regimes and Their Parameterization. *Journal of The Atmospheric Sciences*, *36*(March), 415–423.

Stræde, S., & Treue, T. (2006). Beyond buffer zone protection: A comparative study of park and buffer zone products' importance to villagers living inside Royal Chitwan National Park and to villagers living in its buffer zone. *Journal of Environmental Management*, *78*(3), 251–267. https://doi.org/10.1016/j.jenvman.2005.03.017

Strange, N., Jacobsen, J. B., & Thorsen, B. J. (2019). Afforestation as a real option with joint production of environmental services. *Forest Policy and Economics*, *104*(October 2018), 146–156. https://doi.org/10.1016/j.forpol.2019.04.015

Sturm, J., Santos, M. J., Schmid, B., & Damm, A. (2022). Satellite data reveal differential responses of Swiss forests to unprecedented 2018 drought. *Global Change Biology*, (February), 2956–2978. https://doi.org/10.1111/gcb.16136

Svensson, J., Andersson, J., Sandström, P., Mikusiński, G., & Jonsson, B. G. (2019). Landscape trajectory of natural boreal forest loss as an impediment to green infrastructure. *Conservation Biology*, *33*(1), 152–163. https://doi.org/10.1111/cobi.13148

Team, R. C. (2018). R: A language and environment for statistical computing. Vienna, Austria: R Foundation for Statistical Computing. https://www.r-project.org/

Terzi, S., Torresan, S., Schneiderbauer, S., Critto, A., Zebisch, M., & Marcomini, A. (2019). Multi-risk assessment in mountain regions: A review of modelling approaches for climate change adaptation. *Journal of Environmental Management*, *232*(November 2018), 759–771. https://doi.org/10.1016/j.jenvman.2018.11.100

Thijs, K. W., Aerts, R., Musila, W., Siljander, M., Matthysen, E., Lens, L., et al. (2014).

Potential tree species extinction, colonization and recruitment in Afromontane forest relicts. *Basic and Applied Ecology*, *15*(4), 288–296. https://doi.org/10.1016/j.baae.2014.05.004

Thom, D., Rammer, W., & Seidl, R. (2017). Disturbances catalyze the adaptation of forest ecosystems to changing climate conditions. *Global Change Biology*, *23*(1), 269–282. https://doi.org/10.1111/gcb.13506

Thom, D., & Seidl, R. (2016). Natural disturbance impacts on ecosystem services and biodiversity in temperate and boreal forests. *Biological reviews of the Cambridge Philosophical Society*, *91*(3), 760–781. https://doi.org/10.1111/brv.12193

Thomas, C. D., Cameron, A., Green, R. E., Bakkenes, M., Beaumont, L. J., Collingham, Y. C., et al. (2004). Extinction risk from climate change. *Nature*, *427*, 145–148.

Thomas, J., Brunette, M., & Leblois, A. (2022). The determinants of adapting forest management practices to climate change: Lessons from a survey of French private forest owners. *Forest Policy and Economics*, *135*(November 2021), 102662. https://doi.org/10.1016/j.forpol.2021.102662

Thompson, I., Mackey, B., McNulty, S., & Mosseler, A. (2009). *Forest Resilience, Biodiversity, and Climate Change. A synthesis of the biodiversity/resilience/stability in forest ecosystems.* (Technical.). Montreal: Secretariat of the Convention on Biological Diversity. https://www.fs.usda.gov/treesearch/pubs/36775

Thonicke, K., Bahn, M., Lavorel, S., Bardgett, R. D., Erb, K., Giamberini, M., et al. (2020). Advancing the Understanding of Adaptive Capacity of Social-Ecological Systems to Absorb Climate Extremes. *Earth's Future*, *8*(2), 1–13. https://doi.org/10.1029/2019ef001221

Thuiller, W. (2004). Patterns and uncertainties of species' range shifts under climate change. *Global Change Biology*, *10*(12), 2020–2027. https://doi.org/10.1111/j.1365-2486.2004.00859.x

Timberlake, T. J., & Schultz, C. A. (2017). Policy, practice, and partnerships for climate change adaptation on US national forests. *Climatic Change*, *144*(2), 257–269. https://doi.org/10.1007/s10584-017-2031-z

Timberlake, T. J., Schultz, C. A., Evans, A., & Abrams, J. B. (2020). Working on institutions while planning for forest resilience: a case study of public land management in the United States. *Journal of Environmental Planning and Management*, *0*(0), 1–21. https://doi.org/10.1080/09640568.2020.1817730

Toïgo, M., Perot, T., Courbaud, B., Castagneyrol, B., Gégout, J. C., Longuetaud, F., et al.

(2018). Difference in shade tolerance drives the mixture effect on oak productivity. *Journal of Ecology*, *106*(3), 1073–1082. https://doi.org/10.1111/1365-2745.12811

Trimble, M. J., & van Aarde, R. J. (2012). Geographical and taxonomic biases in research on biodiversity in human-modified landscapes. *Ecosphere*, *3*(12), art119. https://doi.org/10.1890/es12-00299.1

Trumbore, S., Brando, P., & Hartmann, H. (2015). Forest health and global change. *Science*, *349*(6250), 814–818. https://doi.org/10.1126/science.aac6759

Turkelboom, F., Leone, M., Jacobs, S., Kelemen, E., García-Llorente, M., Baró, F., et al. (2018). When we cannot have it all: Ecosystem services trade-offs in the context of spatial planning. *Ecosystem Services*, *29*(October 2017), 566–578. https://doi.org/10.1016/j.ecoser.2017.10.011

Turner, M. G. (2010). Disturbance and landscape dynamics in a changing world. *Ecology*, *91*(10), 2833–2849.

Van Cauwenbergh, N., Biala, K., Bielders, C., Brouckaert, V., Franchois, L., Garcia Cidad, V., et al. (2007). SAFE-A hierarchical framework for assessing the sustainability of agricultural systems. *Agriculture, Ecosystems and Environment*, *120*(2–4), 229–242. https://doi.org/10.1016/j.agee.2006.09.006

Van Meerbeek, K., Jucker, T., & Svenning, J. C. (2021). Unifying the concepts of stability and resilience in ecology. *Journal of Ecology*, *109*(9), 3114–3132. https://doi.org/10.1111/1365-2745.13651

van Nes, E. H., Arani, B. M. S., Staal, A., van der Bolt, B., Flores, B. M., Bathiany, S., & Scheffer, M. (2016). What Do You Mean, 'Tipping Point'? *Trends in Ecology and Evolution*, *31*(12), 902–904. https://doi.org/10.1016/j.tree.2016.09.011

van Noordwijk, M. (2020). Prophets, Profits, Prove It: Social Forestry under Pressure. *One Earth*, *2*(5), 394–397. https://doi.org/10.1016/j.oneear.2020.05.008

Vayreda, J., Gracia, M., Martinez-Vilalta, J., & Retana, J. (2013). Patterns and drivers of regeneration of tree species in forests of peninsular Spain. *Journal of Biogeography*, *40*(7), 1252–1265. https://doi.org/10.1111/jbi.12105

Vehkamäki, S. (2005). The concept of sustainability in modern times. In A. Jalkanen & P. Nygren (Eds.), *Sustainable use of renewable natural resources: from principles to practices. Helsingin yliopiston metsäekologian laitoksen julkaisuja, no. 34* (p. 312). Helsinki: University of Helsinki, Department of Forest Ecology.

Verkerk, P. J., Costanza, R., Hetemäki, L., Kubiszewski, I., Leskinen, P., Nabuurs, G. J., et al. (2020). Climate-Smart Forestry: the missing link. *Forest Policy and*

Economics, *115*(April). https://doi.org/10.1016/j.forpol.2020.102164

Verstraeten, G., Vancampenhout, K., Desie, E., De Schrijver, A., Hlava, J., Schelfhout, S., et al. (2018). Tree species effects are amplified by clay content in acidic soils. *Soil Biology and Biochemistry*, *121*(April), 43–49. https://doi.org/10.1016/j.soilbio.2018.02.021

Vicente-Serrano, S. M., Beguería, S., López-Moreno, J. I., Angulo, M., & El Kenawy, A. (2010). A New Global 0.5° Gridded Dataset (1901–2006) of a Multiscalar Drought Index: Comparison with Current Drought Index Datasets Based on the Palmer Drought Severity Index. *Journal of Hydrometeorology*, *11*(4), 1033–1043. https://doi.org/10.1175/2010JHM1224.1

Vieira, J., Rossi, S., Campelo, F., Freitas, H., & Nabais, C. (2013). Seasonal and daily cycles of stem radial variation of Pinus pinaster in a drought-prone environment. *Agricultural and Forest Meteorology*, *180*, 173–181. https://doi.org/10.1016/j.agrformet.2013.06.009

Walker, B. H., Carpenter, S. R., Anderies, J. M., Abel, N., Cumming, G. S., Janssen, M., et al. (2002). Resilience management in social-ecological systems: a working\nhypothesis for a participatory approach. *Conservation Ecology*, *6*(1), 14. https://doi.org/14

Walker, B. H., Gunderson, L. H., Kinzig, A., Folke, C., Carpenter, S. R., & Schultz, L. (2006). A handful of heuristics and some propositions for understanding resilience in social-ecological systems. *Ecology and Society*, *11*(1). https://doi.org/10.5751/ES-01530-110113

Walker, B. H., Holling, C. S., Carpenter, S. R., & Kinzig, A. (2004). Resilience, Adaptability and Transformability in Social – ecological Systems. *Ecology and Society*, *9*(2), 5. https://doi.org/10.1103/PhysRevLett.95.258101

Walker, B. H., & Salt, D. (2012). *Resilience thinking: sustaining ecosystems and people in a changing world*. Island press.

Walthert, L., Ganthaler, A., Mayr, S., Saurer, M., Waldner, P., Walser, M., et al. (2021). From the comfort zone to crown dieback: Sequence of physiological stress thresholds in mature European beech trees across progressive drought. *Science of the Total Environment*, *753*, 141792. https://doi.org/10.1016/j.scitotenv.2020.141792

Weichselgartner, J., & Kelman, I. (2015). Geographies of resilience: Challenges and opportunities of a descriptive concept. *Progress in Human Geography*, *39*(3), 249–267. https://doi.org/10.1177/0309132513518834

Weise, H., Auge, H., Baessler, C., Bärlund, I., Bennett, E. M., Berger, U., et al. (2020). Resilience trinity: safeguarding ecosystem functioning and services across three different time horizons and decision contexts. *Oikos*, *129*(4), 445–456. https://doi.org/10.1111/oik.07213

Weiss, G., Lawrence, A., Hujala, T., Lidestav, G., Nichiforel, L., Nybakk, E., et al. (2019). Forest ownership changes in Europe: State of knowledge and conceptual foundations. *Forest Policy and Economics*, *99*(March 2017), 9–20. https://doi.org/10.1016/j.forpol.2018.03.003

Whitman, E., Parisien, M. A., Thompson, D. K., & Flannigan, M. D. (2019). Short-interval wildfire and drought overwhelm boreal forest resilience. *Scientific Reports*, *9*(1), 1–12. https://doi.org/10.1038/s41598-019-55036-7

Wickham, H. (2016). *ggplot2: Elegant Graphics for Data Analysis*. Springer-Verlag New York. https://ggplot2.tidyverse.org

Wickham, H., François, R., Henry, L., & Müller, K. (2019). dplyr: A Grammar of Data Manipulation. https://cran.r-project.org/package=dplyr

Wohlgemuth, T., Bürgi, M., Scheidegger, C., & Schütz, M. (2002). Dominance reduction of species through disturbance — a proposed management principle for central European forests. *Forest Ecology and Management*, *166*(1–3), 1–15. http://linkinghub.elsevier.com/retrieve/pii/S0378112701006624

Wolfslehner, B., Brüchert, F., Fischbach, J., Rammer, W., Becker, G., Lindner, M., & Lexer, M. J. (2012). Exploratory multi-criteria analysis in sustainability impact assessment of forest-wood chains: The example of a regional case study in Baden-Württemberg. *European Journal of Forest Research*, *131*(1), 47–56. https://doi.org/10.1007/s10342-011-0499-z

Wolfslehner, B., & Vacik, H. (2008). Evaluating sustainable forest management strategies with the Analytic Network Process in a Pressure-State-Response framework. *Journal of Environmental Management*, *88*(1), 1–10. https://doi.org/10.1016/j.jenvman.2007.01.027

Wu, J., & Loucks, O. L. (1995). From balance of nature to hierarchical patch dynamics: A paradigm shift in ecology. *Quarterly Review of Biology*, *70*(4), 439–466. https://doi.org/10.1086/419172

Xu, C., Liu, H., Anenkhonov, O. A., Korolyuk, A. Y., Sandanov, D. V., Balsanova, L. D., et al. (2017). Long-term forest resilience to climate change indicated by mortality, regeneration, and growth in semiarid southern Siberia. *Global Change Biology*, *23*(6), 2370–2382. https://doi.org/10.1111/gcb.13582

Xu, L., Marinova, D., & Guo, X. (2015). Resilience thinking: a renewed system approach for sustainability science. *Sustainability Science*, *10*(1), 123–138. https://doi.org/10.1007/s11625-014-0274-4

Yousefpour, R., Jacobsen, J. B., Thorsen, B. J., Meilby, H., Hanewinkel, M., & Oehler, K. (2012). A review of decision-making approaches to handle uncertainty and risk in adaptive forest management under climate change. *Annals of Forest Science*, *69*(1), 1–15. https://doi.org/10.1007/s13595-011-0153-4

Yrjölä, T. (2002). *Forest management guidelines and practices in Finland, Sweden and Norway*. *EFI Internal Report*.

Zang, C., Hartl-Meier, C., Dittmar, C., Rothe, A., & Menzel, A. (2014). Patterns of drought tolerance in major European temperate forest trees: Climatic drivers and levels of variability. *Global Change Biology*, *20*(12), 3767–3779. https://doi.org/10.1111/gcb.12637

Zweifel, R. (2016). Radial stem variations - a source of tree physiological information not fully exploited yet. *Plant, Cell and Environment*, *39*(2), 231–232. https://doi.org/10.1111/pce.12613

Zweifel, R., Haeni, M., Buchmann, N., & Eugster, W. (2016). Are trees able to grow in periods of stem shrinkage? *New Phytologist*, *211*(3), 839–849. https://doi.org/10.1111/nph.13995

Zweifel, R., & Häsler, R. (2001). Dynamics of water storage in mature subalpine Picea abies: Temporal and spatial patterns of change in stem radius. *Tree Physiology*, *21*(9), 561–569. https://doi.org/10.1093/treephys/21.9.561

Zweifel, R., Item, H., & Häsler, R. (2001). Link between diurnal stem radius changes and tree water relations. *Tree Physiology*, *21*(12–13), 869–877. https://doi.org/10.1093/treephys/21.12-13.869

Zweifel, R., Steppe, K., & Sterck, F. J. (2007). Stomatal regulation by microclimate and tree water relations: Interpreting ecophysiological field data with a hydraulic plant model. *Journal of Experimental Botany*, *58*(8), 2113–2131. https://doi.org/10.1093/jxb/erm050

Zweifel, R., Sterck, F., Braun, S., Buchmann, N., Eugster, W., Gessler, A., et al. (2021). Why trees grow at night. *New Phytologist*, *231*(6), 2174–2185. https://doi.org/10.1111/nph.17552

Zweifel, R., Zimmermann, L., & Newbery, D. M. (2005). Modeling tree water deficit from microclimate: An approach to quantifying drought stress. *Tree Physiology*, *25*(2), 147–156. https://doi.org/10.1093/treephys/25.2.147

8 Appendices

Appendix A

List of studies involved in the review

Abbott, I., & Le Maitre, D. (2010). Monitoring the impact of climate change on biodiversity: The challenge of megadiverse Mediterranean climate ecosystems. *Austral Ecology*, *35*(4), 406–422. https://doi.org/10.1111/j.1442-9993.2009.02053.x

Abella, S. R., & Fornwalt, P. J. (2015). Ten years of vegetation assembly after a North American mega fire. *Global Change Biology*, *21*(2), 789–802. https://doi.org/10.1111/gcb.12722

Acuña, V., Giorgi, A., Muñoz, I., Sabater, F., & Sabater, S. (2007). Meteorological and riparian influences on organic matter dynamics in a forested Mediterranean stream. *Journal of the North American Benthological Society*, *26*(1), 54–69. https://doi.org/10.1899/0887-3593(2007)26[54:MARIOO]2.0.CO;2

Aikio, S. (2004). The contribution of direct and indirect flows to the resilience of element cycles. *Acta Oecologica*, *26*(2), 129–135. https://doi.org/10.1016/j.actao.2004.03.012

Akamani, K. (2012). A community resilience model for understanding and assessing the sustainability of forest-dependent communities. *Human Ecology Review*, *19*(2), 99–109. http://opensiuc.lib.siu.edu/for_articles/1/

Akamani, K., & Hall, T. E. (2015). Determinants of the process and outcomes of household participation in collaborative forest management in Ghana: A quantitative test of a community resilience model. *Journal of Environmental Management*, *147*, 1–11. https://doi.org/10.1016/j.jenvman.2014.09.007

Akamani, K., Wilson, P. I., & Hall, T. E. (2015). Barriers to collaborative forest management and implications for building the resilience of forest-dependent communities in the Ashanti region of Ghana. *Journal of Environmental Management*, *151*, 11–21. https://doi.org/10.1016/j.jenvman.2014.12.006

Alongi, D. M. (2008). Mangrove forests: Resilience, protection from tsunamis, and responses to global climate change. *Estuarine, Coastal and Shelf Science*, *76*(1), 1–13. https://doi.org/10.1016/j.ecss.2007.08.024

Andivia, E., Natalini, F., Fernández, M., Alejano, R., & Vázquez-Piqué, J. (2018). Contrasting holm oak provenances show different field performance but similar resilience to drought events eight years after planting in a mediterranean environment. *IForest*, *11*(2), 259–266. https://doi.org/10.3832/ifor2573-011

Andivia, Enrique, Madrigal-González, J., Villar-Salvador, P., & Zavala, M. A. (2018). Do adult trees increase conspecific juvenile resilience to recurrent droughts?

Implications for forest regeneration. *Ecosphere*, *9*(6), e02282. https://doi.org/10.1002/ecs2.2282

Anjos, L. J. S., & de Toledo, P. M. (2018). Measuring resilience and assessing vulnerability of terrestrial ecosystems to climate change in South America. *Plos One*, *13*(3), e0194654. https://doi.org/10.1371/journal.pone.0194654

Arianoutsou, M., Koukoulas, S., & Kazanis, D. (2011). Evaluating post-fire forest resilience using GIS and multi-criteria analysis: An example from Cape Sounion National Park, Greece. *Environmental Management*, *47*(3), 384–397. https://doi.org/10.1007/s00267-011-9614-7

Arnan, X., Rodrigo, A., & Retana, J. (2006). Post-fire recovery of Mediterranean ground ant communities follows vegetation and dryness gradients. *Journal of Biogeography*, *33*(7), 1246–1258. https://doi.org/10.1111/j.1365-2699.2006.01506.x

Arthur, C. M., & Dech, J. P. (2016). Species composition determines resistance to drought in dry forests of the Great Lakes – St. Lawrence forest region of central Ontario. *Journal of Vegetation Science*, *27*(5), 914–925. https://doi.org/10.1111/jvs.12416

Ayala-Orozco, B., Gavito, M. E., Mora, F., Siddique, I., Balvanera, P., Jaramillo, V. J., et al. (2017). Resilience of Soil Properties to Land-Use Change in a Tropical Dry Forest Ecosystem. *Land Degradation & Development*, *325*(March 2017), 315–325. https://doi.org/10.1002/ldr.2686

Bahamondez, C., & Thompson, I. D. (2016). Determining forest degradation, ecosystem state and resilience using a standard stand stocking measurement diagram: Theory into practice. *Forestry*, *89*(3), 290–300. https://doi.org/10.1093/forestry/cpv052

Baker, W. L. (2018). Transitioning western U.S. dry forests to limited committed warming with bet-hedging and natural disturbances. *Ecosphere*, *9*(6), e02288. https://doi.org/10.1002/ecs2.2288

Ballard, H. L., & Belsky, J. M. (2010). Participatory action research and environmental learning: Implications for resilient forests and communities. *Environmental Education Research*, *16*(5–6), 611–627. https://doi.org/10.1080/13504622.2010.505440

Bates, J. D., & Davies, K. W. (2016). Seasonal burning of juniper woodlands and spatial recovery of herbaceous vegetation. *Forest Ecology and Management*, *361*, 117–130. https://doi.org/10.1016/j.foreco.2015.10.045

Beeton, T. A., & Galvin, K. A. (2017). Wood-based bioenergy in western Montana: The importance of understanding path dependence and local context for resilience. *Ecology and Society*, *22*(2). https://doi.org/10.5751/ES-09157-220209

Belote, R. T., Jones, R. H., & Wieboldt, T. F. (2012). Compositional stability and diversity of vascular plant communities following logging disturbance in Appalachian forests. *Ecological Applications*, *22*(2), 502–516. https://doi.org/10.1890/11-0925.1

Bernetti, I., Ciampi, C., Fagarazzi, C., & Sacchelli, S. (2011). The evaluation of forest crop damages due to climate change. An application of Dempster-Shafer method. *Journal of Forest Economics*, *17*(3), 285–297. https://doi.org/10.1016/j.jfe.2011.04.005

Bernhardt-Römermann, M., Gray, A., Vanbergen, A. J., Bergès, L., Bohner, A., Brooker, R. W., et al. (2011). Functional traits and local environment predict vegetation responses to disturbance: A pan-European multi-site experiment. *Journal of Ecology*, *99*(3), 777–787. https://doi.org/10.1111/j.1365-2745.2011.01794.x

Bhaskar, R., Arreola, F., Mora, F., Martinez-Yrizar, A., Martinez-Ramos, M., & Balvanera, P. (2018). Response diversity and resilience to extreme events in tropical dry secondary forests. *Forest Ecology and Management*, *426*(September 2017), 61–71. https://doi.org/10.1016/j.foreco.2017.09.028

Bialecki, M. B., Fahey, R. T., & Scharenbroch, B. (2018). Variation in urban forest productivity and response to extreme drought across a large metropolitan region. *Urban Ecosystems*, *21*(1), 157–169. https://doi.org/10.1007/s11252-017-0692-z

Bihn, J. H., Verhaagh, M., Brändle, M., & Brandl, R. (2008). Do secondary forests act as refuges for old growth forest animals? Recovery of ant diversity in the Atlantic forest of Brazil. *Biological Conservation*, *141*(3), 733–743. https://doi.org/10.1016/j.biocon.2007.12.028

Borkenhagen, A., & Cooper, D. J. (2018). Tolerance of fen mosses to submergence, and the influence on moss community composition and ecosystem resilience. *Journal of Vegetation Science*, *29*(2), 127–135. https://doi.org/10.1111/jvs.12610

Bottero, A., D’Amato, A. W., Palik, B. J., Bradford, J. B., Fraver, S., Battaglia, M. A., & Asherin, L. A. (2017). Density-dependent vulnerability of forest ecosystems to drought. *Journal of Applied Ecology*, *54*(6), 1605–1614. https://doi.org/10.1111/1365-2664.12847

Bottero, A., D’Amato, A. W., Palik, B. J., Kern, C. C., Bradford, J. B., & Scherer, S. S. (2017). Influence of Repeated Prescribed Fire on Tree Growth and Mortality in Pinus resinosa Forests, Northern Minnesota. *Forest Science*, *63*(1), 94–100. https://doi.org/10.5849/forsci.16-035

Bowditch, E. A. D., McMorran, R., Bryce, R., & Smith, M. (2019). Perception and partnership: Developing forest resilience on private estates. *Forest Policy and Economics*, *99*(March 2017), 110–122. https://doi.org/10.1016/j.forpol.2017.12.004

Broncano, M. J., Retana, J., & Rodrigo, A. (2005). Predicting the recovery of Pinus halepensis and Quercus ilex forests after a large wildfire in northeastern Spain. *Plant Ecology*, *180*(1), 47–56. https://doi.org/10.1007/s11258-005-0974-z

Brown, H. C. P., & Sonwa, D. J. (2018). Diversity within village institutions and its implication for resilience in the context of climate change in Cameroon. *Climate and Development*, *10*(5), 448–457. https://doi.org/10.1080/17565529.2017.1291409

Bruelheide, H., & Luginbühl, U. (2009). Peeking at Ecosystem : 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 : making to resist. *Ecology*, *90*(5), 1314–1325.

Buma, B., & Wessman, C. A. (2011). Disturbance interactions can impact resilience mechanisms of forests. *Ecosphere*, *2*(5), 1–13. https://doi.org/10.1890/ES11-00038.1

Buma, B., & Wessman, C. A. (2013). Forest resilience, climate change, and opportunities for adaptation: A specific case of a general problem. *Forest Ecology and Management*, *306*, 216–225. https://doi.org/10.1016/j.foreco.2013.06.044

Burkhard, B., Fath, B. D., & Müller, F. (2011). Adapting the adaptive cycle: Hypotheses on the development of ecosystem properties and services. *Ecological Modelling*, *222*(16), 2878–2890. https://doi.org/10.1016/j.ecolmodel.2011.05.016

Calderon-Aguilera, L. E., Rivera-Monroy, V. H., Porter-Bolland, L., Martínez-Yrízar, A., Ladah, L. B., Martínez-Ramos, M., et al. (2012). An assessment of natural and human disturbance effects on Mexican ecosystems: Current trends and research gaps. *Biodiversity and Conservation*, *21*(3), 589–617. https://doi.org/10.1007/s10531-011-0218-6

Camarero, J. J., Gazol, A., Sangüesa-Barreda, G., Cantero, A., Sánchez-Salguero, R., Sánchez-Miranda, A., et al. (2018). Forest Growth Responses to Drought at Short- and Long-Term Scales in Spain: Squeezing the Stress Memory from Tree Rings. *Frontiers in Ecology and Evolution*, *6*(February), 1–11. https://doi.org/10.3389/fevo.2018.00009

Candan, F., & Broquen, P. (2009). Aggregate stability and related properties in NW Patagonian Andisols. *Geoderma*, *154*(1–2), 42–47. https://doi.org/10.1016/j.geoderma.2009.09.010

Cantarello, E., Newton, A. C., Martin, P. A., Evans, P. M., Gosal, A., & Lucash, M. S. (2017). Quantifying resilience of multiple ecosystem services and biodiversity in a temperate forest landscape. *Ecology and Evolution*, *7*(22), 9661–9675. https://doi.org/10.1002/ece3.3491

Carnwath, G., & Nelson, C. (2017). Effects of biotic and abiotic factors on resistance versus resilience of Douglas fir to drought. *PLoS ONE*, *12*(10), 1–19. https://doi.org/10.1371/journal.pone.0185604

Carrillo-Saucedo, S. M., Gavito, M. E., & Siddique, I. (2018). Arbuscular mycorrhizal fungal spore communities of a tropical dry forest ecosystem show resilience to land-use change. *Fungal Ecology*, *32*, 29–39. https://doi.org/10.1016/j.funeco.2017.11.006

Chaer, G., Fernandes, M., Myrold, D., & Bottomley, P. (2009). Comparative resistance and resilience of soil microbial communities and enzyme activities in adjacent native forest and agricultural soils. *Microbial Ecology*, *58*(2), 414–424. https://doi.org/10.1007/s00248-009-9508-x

Chambers, J. C., Beck, J. L., Campbell, S., Carlson, J., Christiansen, T. J., Clause, K. J., et al. (2016). 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. *General Technical Report.*, *RMRS-GTR-3*(December), 143. https://www.fs.usda.gov/treesearch/pubs/53201

Chapin, F. S., Lovecraft, A. L., Zavaleta, E. S., Nelson, J., Robards, M. D., Kofinas, G. P., et al. (2006). Policy strategies to address sustainability of Alaskan boreal forests in response to a directionally changing climate. *Proceedings of the National Academy of Sciences*, *103*(45), 16637–16643. https://doi.org/10.1073/pnas.0606955103

Chapin, F. S., McGuire, A. D., Ruess, R. W., Hollingsworth, T. N., Mack, M. C., Johnstone, J. F., et al. (2010). Resilience of Alaska's boreal forest to climatic change. *Canadian Journal of Forest Research*, *40*(7), 1360–1370. https://doi.org/10.1139/X10-074

Chapin, F. S., Peterson, G., Berkes, F., Callaghan, T. V., Angelstam, P., Apps, M., et al. (2004). Resilience and Vulnerability of Northern Regions to Social and Environmental Change. *AMBIO: A Journal of the Human Environment*, *33*(6). https://doi.org/10.1639/0044-7447(2004)033

Chergui, B., Fahd, S., & Santos, X. (2018). Quercus suber forest and Pinus plantations show different post-fire resilience in Mediterranean north-western Africa. *Annals of Forest Science*, *75*(2). https://doi.org/10.1007/s13595-018-0742-6

Chompuchan, C., & Lin, C. Y. (2017). Assessment of forest recovery at Wu-Ling fire scars in Taiwan using multi-temporal Landsat imagery. *Ecological Indicators*, *79*(April), 196–206. https://doi.org/10.1016/j.ecolind.2017.04.038

Churchill, D. J., Larson, A. J., Dahlgreen, M. C., Franklin, J. F., Hessburg, P. F., & Lutz, J. A. (2013). Restoring forest resilience: From reference spatial patterns to silvicultural prescriptions and monitoring. *Forest Ecology and Management*, *291*, 442–457. https://doi.org/10.1016/j.foreco.2012.11.007

Clason, A. J., Macdonald, S. E., & Haeussler, S. (2014). Forest response to cumulative disturbance and stress: Two decades of change in whitebark pine ecosystems of west-central British Columbia. *Écoscience*, *21*(2), 174–185. https://doi.org/10.2980/21-2-3686

Cole, L. E. S., Bhagwat, S. A., & Willis, K. J. (2015). Long-term disturbance dynamics and resilience of tropical peat swamp forests. *Journal of Ecology*, *103*(1), 16–30.

https://doi.org/10.1111/1365-2745.12329

Craven, D., Filotas, E., Angers, V. A., & Messier, C. (2016). Evaluating resilience of tree communities in fragmented landscapes: linking functional response diversity with landscape connectivity. *Diversity and Distributions*, *22*(5), 505–518. https://doi.org/10.1111/ddi.12423

Creed, I. F., Spargo, A. T., Jones, J. A., Buttle, J. M., Adams, M. B., Beall, F. D., et al. (2014). Changing forest water yields in response to climate warming: Results from long-term experimental watershed sites across North America. *Global Change Biology*, *20*(10), 3191–3208. https://doi.org/10.1111/gcb.12615

Curran, T. J., Gersbach, L. N., Edwards, W., & Krockenberger, A. K. (2008). Wood density predicts plant damage and vegetative recovery rates caused by cyclone disturbance in tropical rainforest tree species of North Queensland, Australia. *Austral Ecology*, *33*(4), 442–450. https://doi.org/10.1111/j.1442-9993.2008.01899.x

Curzon, M. T., D'Amato, A. W., & Palik, B. J. (2016). Bioenergy harvest impacts to biodiversity and resilience vary across aspen-dominated forest ecosystems in the Lake States region, USA. *Applied Vegetation Science*, *19*(4), 667–678. https://doi.org/10.1111/avsc.12256

D'Amato, A. W., Bradford, J. B., Fraver, S., & Palik, B. J. (2013). Effects of thinning on drought vulnerability and climate response in north temperate forest ecosystems. *Ecological Applications*, *23*(8), 1735–1742.

Dănescu, A., Kohnle, U., Bauhus, J., Sohn, J., & Albrecht, A. T. (2018). Stability of tree increment in relation to episodic drought in uneven-structured, mixed stands in southwestern Germany. *Forest Ecology and Management*, *415–416*(December 2017), 148–159. https://doi.org/10.1016/j.foreco.2018.02.030

Daniels, J. M. (2004). *Assessing socioeconomic resiliency in Washington counties*. *General Technical Report - Pacific Northwest Research Station, USDA Forest Service*. Portland, Oregon.

Danielson, T. M., Rivera-Monroy, V. H., Castañeda-Moya, E., Briceño, H., Travieso, R., Marx, B. D., et al. (2017). Assessment of Everglades mangrove forest resilience: Implications for above-ground net primary productivity and carbon dynamics. *Forest Ecology and Management*, *404*(July), 115–125. https://doi.org/10.1016/j.foreco.2017.08.009

Das, P., Behera, M. D., & Roy, P. S. (2018). Modeling precipitation dependent forest resilience in India. *International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences - ISPRS Archives*, *42*(3), 263–266. https://doi.org/10.5194/isprs-archives-XLII-3-263-2018

DasGupta, R., & Shaw, R. (2015). An indicator based approach to assess coastal communities’ resilience against climate related disasters in Indian Sundarbans. *Journal of Child and Family Studies*, *24*(3), 85–101. https://doi.org/10.1007/s11852-014-0369-1

DeClerck, F., Barbour, M., & Sawyer, J. (2006). Species richness and stand stabilty in conifer forests of the Sierra Nevada. *Ecology*, *87*(11), 2787–2799. https://doi.org/doi:10.1890/0012-9658(2006)87[2787:SRASSI]2.0.CO;2

DeRose, R. J., & Long, J. N. (2014). Resistance and Resilience: A Conceptual Framework for Silviculture. *Forest Science*, *60*(6), 1205–1212. https://doi.org/10.5849/forsci.13-507

Derroire, G., Balvanera, P., Castellanos-Castro, C., Decocq, G., Kennard, D. K., Lebrija-Trejos, E., et al. (2016). Resilience of tropical dry forests – a meta-analysis of changes in species diversity and composition during secondary succession. *Oikos*, *125*(10), 1386–1397. https://doi.org/10.1111/oik.03229

Dessalegn, M. (2016). Threatened common property resource system and factors for resilience: Lessons drawn from serege-commons in Muhur, Ethiopia. *Ecology and Society*, *21*(4). https://doi.org/10.5751/ES-08768-210422

Di Mauro, B., Fava, F., Busetto, L., Crosta, G. F., & Colombo, R. (2014). Post-fire resilience in the Alpine region estimated from MODIS satellite multispectral data. *International Journal of Applied Earth Observation and Geoinformation*, *32*, 163–172. https://doi.org/10.1016/j.jag.2014.04.010

Diaconu, D., Kahle, H. P., & Spiecker, H. (2017). Thinning increases drought tolerance of European beech: a case study on two forested slopes on opposite sides of a valley. *European Journal of Forest Research*, *136*(2), 319–328. https://doi.org/10.1007/s10342-017-1033-8

Díaz-Delgado, R., Lloret, F., Pons, X., & Terradas, J. (2002). Satellite Evidence of Decreasing Resilience in Mediterranean Plant Communities After Recurrent Wildfires. *Ecology*, *83*(8), 2293–2303. https://doi.org/10.1890/0012-9658(2002)083[2293:SEODRI]2.0.CO;2

Ding, H., Pretzsch, H., Schütze, G., & Rötzer, T. (2017). Size-dependence of tree growth response to drought for Norway spruce and European beech individuals in monospecific and mixed-species stands. *Plant Biology*, *19*(5), 709–719. https://doi.org/10.1111/plb.12596

Dodd, M., Barker, G., Burns, B., Didham, R., Innes, J., King, C., et al. (2011). Resilience of New Zealand indigenous forest fragments to impacts of livestock and pest mammals. *New Zealand Journal of Ecology*, *35*(1), 83–95.

Dörner, J., Dec, D., Zúñiga, F., Sandoval, P., & Horn, R. (2011). Effect of land use change on Andosol’s pore functions and their functional resilience after mechanical and hydraulic stresses. *Soil and Tillage Research*, *115–116*, 71–79.

https://doi.org/10.1016/j.still.2011.07.002

Doughty, C. A. (2016). Building climate change resilience through local cooperation: a Peruvian Andes case study. *Regional Environmental Change*, *16*(8), 2187–2197. https://doi.org/10.1007/s10113-015-0882-2

Drever, C. R., Peterson, G., Messier, C., Bergeron, Y., & Flannigan, M. (2006). Can forest management based on natural disturbances maintain ecological resilience? *Canadian Journal of Forest Research*, *36*(9), 2285–2299. https://doi.org/10.1139/x06-132

Duveneck, M. J., & Scheller, R. M. (2016). Measuring and managing resistance and resilience under climate change in northern Great Lake forests (USA). *Landscape Ecology*, *31*(3), 669–686. https://doi.org/10.1007/s10980-015-0273-6

Dymond, C. C., Tedder, S., Spittlehouse, D. L., Raymer, B., Hopkins, K., McCallion, K., & Sandland, J. (2014). Diversifying managed forests to increase resilience. *Canadian Journal of Forest Research*, *44*(10), 1196–1205. https://doi.org/10.1139/cjfr-2014-0146

Dynesius, M., Hylander, K., & Nilsson, C. (2009). High resilience of bryophyte assemblages in streamside compared to upland forests. *Ecology*, *90*(4), 1042–1054. https://doi.org/10.1890/07-1822.1

Estevo, C. A., Nagy-Reis, M. B., & Silva, W. R. (2017). Urban parks can maintain minimal resilience for Neotropical bird communities. *Urban Forestry and Urban Greening*, *27*(October 2016), 84–89. https://doi.org/10.1016/j.ufug.2017.06.013

Fahey, R. T., Bialecki, M. B., & Carter, D. R. (2013). Tree growth and resilience to extreme drought across an urban land-use gradient. *Arboriculture and Urban Forestry*, *39*(6), 279–285.

Fahey, R. T., Fotis, A. T., & Woods, K. D. (2015). Quantifying canopy complexity and effects on productivity and resilience in late- successional hemlock — hardwood forests. *Ecological Applications*, *25*(3), 834–847.

Fernandez-Manso, A., Quintano, C., & Roberts, D. A. (2016). Burn severity influence on post-fire vegetation cover resilience from Landsat MESMA fraction images time series in Mediterranean forest ecosystems. *Remote Sensing of Environment*, *184*, 112–123. https://doi.org/10.1016/j.rse.2016.06.015

Fuller, L., & Quine, C. P. (2016). Resilience and tree health: A basis for implementation in sustainable forest management. *Forestry*, *89*(1), 7–19. https://doi.org/10.1093/forestry/cpv046

García-López, J. M., & Allué, C. (2012). A phytoclimatic-based indicator for assessing the inherent responsitivity of the European forests to climate change. *Ecological*

Indicators, *18*, 73–81. https://doi.org/10.1016/j.ecolind.2011.10.004

García-Romero, A., Oropeza-Orozco, O., & Galicia-Sarmiento, L. (2004). Land-use systems and resilience of tropical rain forests in the Tehuantepec Isthmus, Mexico. *Environmental Management*, *34*(6), 768–785. https://doi.org/10.1007/s00267-004-0178-z

Gazol, A., & Camarero, J. J. (2016). Functional diversity enhances silver fir growth resilience to an extreme drought. *Journal of Ecology*, *104*(4), 1063–1075. https://doi.org/10.1111/1365-2745.12575

Gazol, A., Camarero, J. J., Anderegg, W. R. L., & Vicente-Serrano, S. M. (2017). Impacts of droughts on the growth resilience of Northern Hemisphere forests. *Global Ecology and Biogeography*, *26*(2), 166–176. https://doi.org/10.1111/geb.12526

Gazol, A., Camarero, J. J., Vicente-Serrano, S. M., Sánchez-Salguero, R., Gutiérrez, E., de Luis, M., et al. (2018). Forest resilience to drought varies across biomes. *Global Change Biology*, *24*(5), 2143–2158. https://doi.org/10.1111/gcb.14082

Gazol, A., Ribas, M., Gutiérrez, E., & Camarero, J. J. (2017). Aleppo pine forests from across Spain show drought-induced growth decline and partial recovery. *Agricultural and Forest Meteorology*, *232*, 186–194. https://doi.org/10.1016/j.agrformet.2016.08.014

George, J. P., Grabner, M., Karanitsch-Ackerl, S., Mayer, K., Weißenbacher, L., & Schueler, S. (2017). Genetic variation, phenotypic stability, and repeatability of drought response in European larch throughout 50 years in a common garden experiment. *Tree Physiology*, *37*(1), 33–46. https://doi.org/10.1093/treephys/tpw085

Girard, F., Payette, S., & Gagnon, R. (2008). Rapid expansion of lichen woodlands within the closed-crown boreal forest zone over the last 50 years caused by stand disturbances in eastern Canada. *Journal of Biogeography*, *35*(3), 529–537. https://doi.org/10.1111/j.1365-2699.2007.01816.x

González-De Vega, S., De las Heras, J., & Moya, D. (2016). Resilience of Mediterranean terrestrial ecosystems and fire severity in semiarid areas: Responses of Aleppo pine forests in the short, mid and long term. *Science of the Total Environment*, *573*, 1171–1177. https://doi.org/10.1016/j.scitotenv.2016.03.115

Granda, E., Gazol, A., & Camarero, J. J. (2018). Functional diversity differently shapes growth resilience to drought for co-existing pine species. *Journal of Vegetation Science*, *29*(2), 265–275. https://doi.org/10.1111/jvs.12617

Guimarães, H., Braga, R., Mascarenhas, A., & Ramos, T. B. (2017). Indicators of ecosystem services in a military Atlantic Forest area, Pernambuco—Brazil. *Ecological Indicators*, *80*(May), 247–257. https://doi.org/10.1016/j.ecolind.2017.05.030

Hale, J. D., Pugh, T. A. M., Sadler, J. P., Boyko, C. T., Brown, J., Caputo, S., et al.

(2015). Delivering a multi-functional and resilient urban forest. *Sustainability (Switzerland)*, *7*(4), 4600–4624. https://doi.org/10.3390/su7044600

Halofsky, J. S., Halofsky, J. E., Burcsu, T., & Hemstrom, M. A. (2014). Dry forest resilience varies under simulated climate-management scenarios in a central Oregon, USA landscape. *Ecological Applications*, *24*(8), 1908–1925. https://doi.org/10.1890/13-1653.1

Halpin, C. R., & Lorimer, C. G. (2016). Trajectories and resilience of stand structure in response to variable disturbance severities in northern hardwoods. *Forest Ecology and Management*, *365*, 69–82. https://doi.org/10.1016/j.foreco.2016.01.016

Hancock, M. H., & Legg, C. J. (2012). Diversity and stability of ericaceous shrub cover during two disturbance experiments: one on heathland and one in forest. *Plant Ecology and Diversity*, *5*(3), 275–287. https://doi.org/10.1080/17550874.2012.723764

Harris, C. C., McLaughlin, W., Brown, G., & Becker, D. R. (2000). *Rural communities in the inland Northwest: an assessment of small rural communities in the interior and upper Columbia River basins.* Portland, Oregon. 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

Heer, K., Behringer, D., Piermattei, A., Bässler, C., Brandl, R., Fady, B., et al. (2018). Linking dendroecology and association genetics in natural populations: Stress responses archived in tree rings associate with SNP genotypes in silver fir (Abies alba Mill.). *Molecular Ecology*, *27*(6), 1428–1438. https://doi.org/10.1111/mec.14538

Heinimann, H. R. (2010). A concept in adaptive ecosystem management-An engineering perspective. *Forest Ecology and Management*, *259*(4), 848–856. https://doi.org/10.1016/j.foreco.2009.09.032

Helman, D., Lensky, I. M., Yakir, D., & Osem, Y. (2017). Forests growing under dry conditions have higher hydrological resilience to drought than do more humid forests. *Global Change Biology*, *23*(7), 2801–2817. https://doi.org/10.1111/gcb.13551

Hernandez-Montilla, M. C., Martinez-Morales, M. A., Vanegas, G. P., & De Jong, B. H. J. (2016). Assessment of hammocks (Petenes) resilience to sea level rise due to climate change in Mexico. *PLoS ONE*, *11*(9). https://doi.org/10.1371/journal.pone.0162637

Herrero, A., & Zamora, R. (2014). Plant responses to extreme climatic events: A field test of resilience capacity at the southern range edge. *PLoS ONE*, *9*(1), 1–12. https://doi.org/10.1371/journal.pone.0087842

Hirota, M., Holmgren, M., Van Nes, E. H., & Scheffer, M. (2011). Global Resilience of Tropical Forest and Savanna to Critical Transitions. *Science*, *334*(6053), 232 LP – 235.

http://science.sciencemag.org/content/334/6053/232.abstract

Hoffmann, N., Schall, P., Ammer, C., Leder, B., & Vor, T. (2018). Drought sensitivity and stem growth variation of nine alien and native tree species on a productive forest site in Germany. *Agricultural and Forest Meteorology*, *256–257*(April), 431–444. https://doi.org/10.1016/j.agrformet.2018.03.008

Hood, S. M., Baker, S., & Sala, A. (2016). Fortifying the forest: thinning and burning increase resistance to a bark beetle outbreak and promote forest resilience. *Ecological Applications*, *26*(7), 1984–2000. https://doi.org/10.1002/eap.1363

Huang, W., Fonti, P., Larsen, J. B., Ræbild, A., Callesen, I., Pedersen, N. B., & Hansen, J. K. (2017). Projecting tree-growth responses into future climate: A study case from a Danish-wide common garden. *Agricultural and Forest Meteorology*, *247*(July), 240–251. https://doi.org/10.1016/j.agrformet.2017.07.016

Ibarra, J. T., Martin, M., Cockle, K. L., & Martin, K. (2017). Maintaining ecosystem resilience: Functional responses of tree cavity nesters to logging in temperate forests of the Americas. *Scientific Reports*, *7*(1), 1–9. https://doi.org/10.1038/s41598-017-04733-2

Jacobs, B. F. (2015). Restoration of degraded transitional (piñon-juniper) woodland sites improves ecohydrologic condition and primes understory resilience to subsequent disturbance. *Ecohydrology*, *8*(8), 1417–1428. https://doi.org/10.1002/eco.1591

Jacquet, K., & Prodon, R. (2009). Measuring the postfire resilience of a bird-vegetation system: A 28-year study in a Mediterranean oak woodland. *Oecologia*, *161*(4), 801–811. https://doi.org/10.1007/s00442-009-1422-x

Jaramillo, V. J., Martínez-Yrízar, A., Maass, M., Nava-Mendoza, M., Castañeda-Gómez, L., Ahedo-Hernández, R., et al. (2018). Hurricane impact on biogeochemical processes in a tropical dry forest in western Mexico. *Forest Ecology and Management*, *426*(October 2017), 72–80. https://doi.org/10.1016/j.foreco.2017.12.031

Jarzebski, M. P., Tumilba, V., & Yamamoto, H. (2016). Application of a tri-capital community resilience framework for assessing the social–ecological system sustainability of community-based forest management in the Philippines. *Sustainability Science*, *11*(2), 307–320. https://doi.org/10.1007/s11625-015-0323-7

Johnson, A. B., & Winker, K. (2010). Short-term hurricane impacts on a neotropical community of marked birds and implications for early- stage community resilience. *PLoS ONE*, *5*(11). https://doi.org/10.1371/journal.pone.0015109

Johnstone, J.F., Allen, C. D., Franklin, J. F., Frelich, L. E., Harvey, B. J., Higuera, P. E., et al. (2016). Changing disturbance regimes, ecological memory, and forest resilience. *Frontiers in Ecology and the Environment*, *14*(7), 369–378. https://doi.org/10.1002/fee.1311

Johnstone, J.F., Chapin, F. S., Hollingsworth, T. N., Mack, M. C., Romanovsky, V., & Turetsky, M. (2010). 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. *Canadian Journal of Forest Research*, *40*(7), 1302–1312. https://doi.org/10.1139/X10-061

Johnstone, Jill F., McIntire, E. J. B., Pedersen, E. J., King, G., & Pisaric, M. J. F. (2010). A sensitive slope: Estimating landscape patterns of forest resilience in a changing climate. *Ecosphere*, *1*(6). https://doi.org/10.1890/ES10-00102.1

Kaarlejärvi, E., Hoset, K. S., & Olofsson, J. (2015). Mammalian herbivores confer resilience of Arctic shrub-dominated ecosystems to changing climate. *Global Change Biology*, *21*(9), 3379–3388. https://doi.org/10.1111/gcb.12970

Karavani, A., Boer, M. M., Baudena, M., Colinas, C., Díaz-Sierra, R., Pemán, J., et al. (2018). Fire-induced deforestation in drought-prone Mediterranean forests: drivers and unknowns from leaves to communities. *Ecological Monographs*, *88*(2), 141–169. https://doi.org/10.1002/ecm.1285

Kelly, C., Ferrara, A., Wilson, G. A., Ripullone, F., Nolè, A., Harmer, N., & Salvati, L. (2015). Community resilience and land degradation in forest and shrubland socio-ecological systems: Evidence from Gorgoglione, Basilicata, Italy. *Land Use Policy*, *46*, 11–20. https://doi.org/10.1016/j.landusepol.2015.01.026

Kerkhoff, A. J., & Enquist, B. J. (2007). The Implications of Scaling Approaches for Understanding Resilience and Reorganization in Ecosystems. *BioScience*, *57*(6), 489–499. https://doi.org/10.1641/B570606

Keyser, T. L., & Brown, P. M. (2016). Drought response of upland oak (Quercus L.) species in Appalachian hardwood forests of the southeastern USA. *Annals of Forest Science*, *73*(4), 971–986. https://doi.org/10.1007/s13595-016-0575-0

Kim, M., You, S., Chon, J., & Lee, J. (2017). Sustainable land-use planning to improve the coastal resilience of the social-ecological landscape. *Sustainability (Switzerland)*, *9*(7), 1–21. https://doi.org/10.3390/su9071086

Kipfer, T., Moser, B., Egli, S., Wohlgemuth, T., & Ghazoul, J. (2011). Ectomycorrhiza succession patterns in Pinus sylvestris forests after stand-replacing fire in the Central Alps. *Oecologia*, *167*(1), 219–228. https://doi.org/10.1007/s00442-011-1981-5

Knoot, T. G., Schulte, L. a, Tyndall, J. C., & Palik, B. J. (2010). The State of the System and Steps Toward Resilience of Disturbance- dependent Oak Forests. *Ecology and Society*, *15*(4), 5. https://doi.org/5

Knudby, A., Jupiter, S., Roelfsema, C., Lyons, M., & Phinn, S. (2013). Mapping coral reef resilience indicators using field and remotely sensed data. *Remote Sensing*, *5*(3), 1311–1334. https://doi.org/10.3390/rs5031311

Kunz, J., Löffler, G., & Bauhus, J. (2018). Minor European broadleaved tree species are more drought-tolerant than Fagus sylvatica but not more tolerant than Quercus petraea. *Forest Ecology and Management*, *414*(July 2017), 15–27. https://doi.org/10.1016/j.foreco.2018.02.016

Larson, A. J., Lutz, J. A., Gersonde, R. F., Franklin, J. F., & Hietpas, F. F. (2008). Potential site productivity influences the rate of forest structural development. *Ecological Applications*, *18*(4), 899–910. https://doi.org/10.1890/07-1191.1

Lawrence, D., Radel, C., Tully, K., Schmook, B., & Schneider, L. (2010). Untangling a decline in tropical forest resilience: Constraints on the sustainability of shifting cultivation across the globe. *Biotropica*, *42*(1), 21–30. https://doi.org/10.1111/j.1744-7429.2009.00599.x

Leão, T. C. C., Lobo, D., & Scotson, L. (2017). Economic and Biological Conditions Influence the Sustainability of Harvest of Wild Animals and Plants in Developing Countries. *Ecological Economics*, *140*, 14–21. https://doi.org/10.1016/j.ecolecon.2017.04.030

Lebrija-trejos, A. E., Bongers, F., Pérez-garcía, E. A., Meave, J. A., Lebrija-trejos, E., Ciencias, F. De, et al. (2008). 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*, *40*(4), 422–431. https://doi.org/10.1111/j.1744-7429.2008.00398.x

Leite, M. de S., Tambosi, L. R., Romitelli, I., & Metzger, J. P. (2013). Landscape Ecology Perspective in Restoration Projects for Biodiversity Conservation: a Review. *Natureza & Conservação*, *11*(2), 108–118. https://doi.org/10.4322/natcon.2013.019

Leuteritz, T. E. J., & Ekbia, H. R. (2008). Not All Roads Lead to : a Complex Systems Approach to the Comparative Analysis of Tortoises in Arid Ecosystems. *Ecology and Society*, *13*(1), www.ecologyandsociety.org/vol13/iss1/art1/. https://doi.org/1

Lin, T. C., Hamburg, S. P., Lin, K. C., Wang, L. J., Chang, C. Te, Hsia, Y. J., et al. (2011). Typhoon Disturbance and Forest Dynamics: Lessons from a Northwest Pacific Subtropical Forest. *Ecosystems*, *14*(1), 127–143. https://doi.org/10.1007/s10021-010-9399-1

Lloret, F., Estevan, H., Vayreda, J., & Terradas, J. (2005). Fire regenerative syndromes of forest woody species across fire and climatic gradients. *Oecologia*, *146*(3), 461–468. https://doi.org/10.1007/s00442-005-0206-1

Lloret, F., Keeling, E. G., & Sala, A. (2011). Components of tree resilience: Effects of successive low-growth episodes in old ponderosa pine forests. *Oikos*, *120*(12), 1909–1920. https://doi.org/10.1111/j.1600-0706.2011.19372.x

Lloret, F., Siscart, D., & Dalmases, C. (2004). Canopy recovery after drought dieback in holm-oak Mediterranean forests of Catalonia (NE Spain). *Global Change Biology*, *10*(12), 2092–2099. https://doi.org/10.1111/j.1365-2486.2004.00870.x

Long, J. N., Windmuller-Campione, M., & De Rose, R. J. (2018). Building resistance and resilience: Regeneration should not be left to chance. *Forests*, *9*(5), 1–12. https://doi.org/10.3390/f9050270

Lopez-Toledo, L., Anten, N. P. R., Endress, B. A., Ackerly, D. D., & Martínez-Ramos, M. (2012). Resilience to chronic defoliation in a dioecious understorey tropical rain forest palm. *Journal of Ecology*, *100*(5), 1245–1256. https://doi.org/10.1111/j.1365-2745.2012.01992.x

Lucash, M. S., Scheller, R. M., J. Gustafson, E., & R. Sturtevant, B. (2017). Spatial resilience of forested landscapes under climate change and management. *Landscape Ecology*, *32*(5), 953–969. https://doi.org/10.1007/s10980-017-0501-3

Luce, C., Morgan, P., Dwire, K., Isaak, D., Holden, Z., & Rieman, B. (2012). *Climate change, forests, fire, water, and fish: Building resilient landscapes, streams, and managers*. *General Technical Report RMRS-GTR-290*. Fort Collins, CO.

Ludwig, J. A., Coughenour, M. B., Liedloff, A. C., & Dyer, R. (2001). Modelling the resilience of Australian savanna systems to grazing impacts. *Environment International*, *27*(2–3), 167–172. https://doi.org/10.1016/S0160-4120(01)00078-2

Lyon, C. (2014). Place Systems and Social Resilience: A Framework for Understanding Place in Social Adaptation, Resilience, and Transformation. *Society and Natural Resources*, *27*(10), 1009–1023. https://doi.org/10.1080/08941920.2014.918228

Madrigal-González, J., Herrero, A., Ruiz-Benito, P., & Zavala, M. A. (2017). Resilience to drought in a dry forest: Insights from demographic rates. *Forest Ecology and Management*, *389*, 167–175. https://doi.org/10.1016/j.foreco.2016.12.012

Magis, K. (2010). Community resilience: An indicator of social sustainability. *Society and Natural Resources*, *23*(5), 401–416. https://doi.org/10.1080/08941920903305674

Magnuszewski, P., Ostasiewicz, K., Chazdon, R., Salk, C., Pajak, M., Sendzimir, J., & Andersson, K. (2015). Resilience and alternative stable states of tropical forest landscapes under shifting cultivation regimes. *PLoS ONE*, *10*(9), 1–20. https://doi.org/10.1371/journal.pone.0137497

Magruder, M., Chhin, S., Palik, B., & Bradford, J. B. (2013). Thinning increases climatic resilience of red pine. *Canadian Journal of Forest Research*, *43*(9), 878–889. https://doi.org/10.1139/cjfr-2013-0088

Malika, V. S., Lindsey, G., & Katherine, J. W. (2009). How does spatial heterogeneity influence resilience to climatic changes? Ecological dynamics in southeast Madagascar. *Ecological Monographs*, *79*(4), 557–574. https://doi.org/10.1890/08-1210.1

Malinga, G. M., Valtonen, A., Nyeko, P., & Roininen, H. (2014). High resilience of galling insect communities to selective and clear-cut logging in a tropical rainforest. *International Journal of Tropical Insect Science*, *34*(4), 277–286. https://doi.org/10.1017/S1742758414000460

Mallik, A. U., Kreutzweiser, D. P., Spalvieri, C. M., & Mackereth, R. W. (2013). Understory plant community resilience to partial harvesting in riparian buffers of central Canadian boreal forests. *Forest Ecology and Management*, *289*, 209–218. https://doi.org/10.1016/j.foreco.2012.09.039

Marqués, L., Camarero, J. J., Gazol, A., & Zavala, M. A. (2016). 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. *Forest Ecology and Management*, *381*, 157–167. https://doi.org/10.1016/j.foreco.2016.09.021

Martínez-Vilalta, J., López, B. C., Loepfe, L., & Lloret, F. (2012). Stand- and tree-level determinants of the drought response of Scots pine radial growth. *Oecologia*, *168*(3), 877–888. https://doi.org/10.1007/s00442-011-2132-8

Martínez-Yrízar, A., Jaramillo, V. J., Maass, M., Búrquez, A., Parker, G., Álvarez-Yépiz, J. C., et al. (2018). Resilience of tropical dry forest productivity to two hurricanes of different intensity in western Mexico. *Forest Ecology and Management*, *426*(October 2017), 53–60. https://doi.org/10.1016/j.foreco.2018.02.024

Matusick, G., Ruthrof, K. X., Fontaine, J. B., & Hardy, G. E. S. J. (2016). Eucalyptus forest shows low structural resistance and resilience to climate change-type drought. *Journal of Vegetation Science*, *27*(3), 493–503. https://doi.org/10.1111/jvs.12378

McLaren, K. P., & McDonald, M. A. (2003). Coppice regrowth in a disturbed tropical dry limestone forest in Jamaica. *Forest Ecology and Management*, *180*(1–3), 99–111. https://doi.org/10.1016/S0378-1127(02)00606-0

Merlin, M., Perot, T., Perret, S., Korboulewsky, N., & Vallet, P. (2015). Effects of stand composition and tree size on resistance and resilience to drought in sessile oak and Scots pine. *Forest Ecology and Management*, *339*, 22–33. https://doi.org/10.1016/j.foreco.2014.11.032

Messier, C., Puettmann, K. J., & Coates, K. D. (2013). *Managing Forests as Complex Adaptive Systems - Building Resilience to the Challenge of Global Change*. (C. Messier, K. J. Puettmann, & K. D. Coates, Eds.) (1st ed.). London: Routledge.

Mitchell, P. J., O'Grady, A. P., Pinkard, E. A., Brodribb, T. J., Arndt, S. K., Blackman, C. J., et al. (2016). An ecoclimatic framework for evaluating the resilience of vegetation to water deficit. *Global Change Biology*, *22*(5), 1677–1689. https://doi.org/10.1111/gcb.13177

Moen, J., & Keskitalo, E. C. H. (2010). Interlocking panarchies in multi-use boreal forests in Sweden. *Ecology and Society*, *15*(3). https://doi.org/10.5751/ES-03444-150317

Montúfar, R., Anthelme, F., Pintaud, J. C., & Balslev, H. (2011). Disturbance and Resilience in Tropical American Palm Populations and Communities. *Botanical Review*, *77*(4), 426–461. https://doi.org/10.1007/s12229-011-9085-9

Moretti, M., Duelli, P., & Obrist, M. K. (2006). Biodiversity and resilience of arthropod communities after fire disturbance in temperate forests. *Oecologia*, *149*(2), 312–327. https://doi.org/10.1007/s00442-006-0450-z

Moretti, M., & Legg, C. (2009). Combining plant and animal traits to assess community functional responses to disturbance. *Ecography*, *32*(2), 299–309. https://doi.org/10.1111/j.1600-0587.2008.05524.x

Moris, J. V., Vacchiano, G., Ravetto Enri, S., Lonati, M., Motta, R., & Ascoli, D. (2017). Resilience of European larch (Larix decidua Mill.) forests to wildfires in the western Alps. *New Forests*, *48*(5), 663–683. https://doi.org/10.1007/s11056-017-9591-7

Na-U-Dom, T., Garcia, M., & Mo, X. (2017). Ecosystem Resilience to Drought and Temperature Anomalies in the Mekong River Basin. *IOP Conference Series: Earth and Environmental Science*, *68*, 12012–12017.

Navarro-Cerrillo, R. M., Rodriguez-Vallejo, C., Silveiro, E., Hortal, A., Palacios-Rodríguez, G., Duque-Lazo, J., & Camarero, J. J. (2018). Cumulative drought stress leads to a loss of growth resilience and explains higher mortality in planted than in naturally regenerated Pinus pinaster stands. *Forests*, *9*(6), 1–18. https://doi.org/10.3390/f9060358

Newton, A. C., & Cantarello, E. (2015). Restoration of forest resilience: An achievable goal? *New Forests*, *46*(5–6), 645–668. https://doi.org/10.1007/s11056-015-9489-1

Nightingale, A., & Sharma, J. R. (2014). Conflict resilience among community forestry user groups: Experiences in Nepal. *Disasters*, *38*(3), 517–539. https://doi.org/10.1111/disa.12056

Nitschke, C. R., & Innes, J. L. (2008). A tree and climate assessment tool for modelling ecosystem response to climate change. *Ecological Modelling*, *210*(3), 263–277. https://doi.org/10.1016/j.ecolmodel.2007.07.026

O'Brien, M. J., Ong, R., & Reynolds, G. (2017). Intra-annual plasticity of growth mediates drought resilience over multiple years in tropical seedling communities. *Global Change Biology*, *23*(10), 4235–4244. https://doi.org/10.1111/gcb.13658

O'Hara, K. L. (2006). Multiaged forest stands for protection forests: concepts and applications. *Forest Snow and Landscape Research*, *80*(1), 45–55. https://doi.org/citeulike-article-id:13908937

O'Hara, K. L., & Ramage, B. S. (2013). Silviculture in an uncertain world: Utilizing multi-aged management systems to integrate disturbance. *Forestry*, *86*(4), 401–410. https://doi.org/10.1093/forestry/cpt012

Pardini, R., de Bueno, A. A., Gardner, T. A., Prado, P. I., & Metzger, J. P. (2010). Beyond the fragmentation threshold hypothesis: Regime shifts in biodiversity across fragmented landscapes. *PLoS ONE*, *5*(10). https://doi.org/10.1371/journal.pone.0013666

Pérez-Ramos, I. M., Zavala, M. A., Marañón, T., Díaz-Villa, M. D., & Valladares, F. (2008). Dynamics of understorey herbaceous plant diversity following shrub clearing of cork oak forests: A five-year study. *Forest Ecology and Management*, *255*(8–9), 3242–3253. https://doi.org/10.1016/j.foreco.2008.01.069

Pilaš, I., Medved, I., Medak, J., & Medak, D. (2014). Response strategies of the main forest types to climatic anomalies across Croatian biogeographic regions inferred from FAPAR remote sensing data. *Forest Ecology and Management*, *326*, 58–78. https://doi.org/10.1016/j.foreco.2014.04.012

Pinkerton, E. W., & Benner, J. (2013). Small sawmills persevere while the majors close: Evaluating resilience and desirable timber allocation in British Columbia, Canada. *Ecology and Society*, *18*(2). https://doi.org/10.5751/ES-05515-180234

Ponce Campos, G. E., Moran, M. S., Huete, A., Zhang, Y., Bresloff, C., Huxman, T. E., et al. (2013). Ecosystem resilience despite large-scale altered hydroclimatic conditions. *Nature*, *494*(7437), 349–352. https://doi.org/10.1038/nature11836

Poorter, L., Bongers, F., Aide, T. M., Almeyda Zambrano, A. M., Balvanera, P., Becknell, J. M., et al. (2016). Biomass resilience of Neotropical secondary forests. *Nature*, *530*(7589), 211–214. https://doi.org/10.1038/nature16512

Pretzsch, H., Schütze, G., & Uhl, E. (2013). Resistance of European tree species to drought stress in mixed versus pure forests: Evidence of stress release by inter-specific facilitation. *Plant Biology*, *15*(3), 483–495. https://doi.org/10.1111/j.1438-8677.2012.00670.x

Príncipe, A., van der Maaten, E., van der Maaten-Theunissen, M., Struwe, T., Wilmking, M., & Kreyling, J. (2017). 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 - Structure and Function*, *31*(2), 743–751. https://doi.org/10.1007/s00468-016-1505-3

Proença, V., Pereira, H. M., & Vicente, L. (2010). Resistance to wildfire and early regeneration in natural broadleaved forest and pine plantation. *Acta Oecologica*, *36*(6), 626–633. https://doi.org/10.1016/j.actao.2010.09.008

Rais, A., van de Kuilen, J. W. G., & Pretzsch, H. (2014). Growth reaction patterns of tree height, diameter, and volume of Douglas-fir (Pseudotsuga menziesii [Mirb.] Franco) under acute drought stress in Southern Germany. *European Journal of Forest Research*, *133*(6), 1043–1056. https://doi.org/10.1007/s10342-014-0821-7

Reiners, W. A., Driese, K. L., Fahey, T. J., & Gerow, K. G. (2012). Effects of Three Years of Regrowth Inhibition on the Resilience of a Clear-cut Northern Hardwood Forest. *Ecosystems*, *15*(8), 1351–1362. https://doi.org/10.1007/s10021-012-9589-0

Reyes, G., & Kneeshaw, D. (2014). Ecological Resilience: Is It Ready for operationalisation in forest management? In J. A. Daniels (Ed.), *Advances in Environmental Research* (pp. 195–212). New York, USA: Nova Science Publishers, Inc.

Riva, M. J., Liniger, H., Valdecantos, A., & Schwilch, G. (2016). Impacts of land management on the resilience of mediterranean dry forests to fire. *Sustainability (Switzerland)*, *8*(10). https://doi.org/10.3390/su8100981

Rivest, D., Paquette, A., Shipley, B., Reich, P. B., & Messier, C. (2015). Tree communities rapidly alter soil microbial resistance and resilience to drought. *Functional Ecology*, *29*(4), 570–578. https://doi.org/10.1111/1365-2435.12364

Roccaforte, J. P., Sánchez Meador, A., Waltz, A. E. M., Gaylord, M. L., Stoddard, M. T., & Huffman, D. W. (2018). Delayed tree mortality, bark beetle activity, and regeneration dynamics five years following the Wallow Fire, Arizona, USA: Assessing trajectories towards resiliency. *Forest Ecology and Management*, *428*, 20–26. https://doi.org/10.1016/j.foreco.2018.06.012

Roovers, P., Verheyen, K., Hermy, M., & Gulinck, H. (2004). Experimental trampling and vegetation recovery in some forest and heathland communities. *Applied Vegetation Science*, *7*(1), 111–118. https://doi.org/10.1111/j.1654-109X.2004.tb00601.x

Royer-Tardif, S., Bradley, R. L., & Parsons, W. F. J. (2010). Evidence that plant diversity and site productivity confer stability to forest floor microbial biomass. *Soil Biology and Biochemistry*, *42*(5), 813–821. https://doi.org/10.1016/j.soilbio.2010.01.018

Rubio-Cuadrado, Á., Camarero, J. J., del Río, M., Sánchez-González, M., Ruiz-Peinado, R., Bravo-Oviedo, A., et al. (2018). Long-term impacts of drought on growth and forest dynamics in a temperate beech-oak-birch forest. *Agricultural and Forest Meteorology*, *259*(April), 48–59. https://doi.org/10.1016/j.agrformet.2018.04.015

Rubio-Cuadrado, Álvaro, Bravo-Oviedo, A., Mutke, S., & Del Río, M. (2018). Climate effects on growth differ according to height and diameter along the stem in Pinus pinaster ait. *IForest*, *11*(2), 237–242. https://doi.org/10.3832/ifor2318-011

Rydgren, K., Økland, R. H., & Hestmark, G. (2004). Disturbance Severity and Community Resilience in a Boreal Forest. *Ecology*, *85*(7), 1906–1915.

https://doi.org/10.1890/03-0276

Sakschewski, B., Von Bloh, W., Boit, A., Poorter, L., Peña-Claros, M., Heinke, J., et al. (2016). Resilience of Amazon forests emerges from plant trait diversity. *Nature Climate Change*, *6*(11), 1032–1036. https://doi.org/10.1038/nclimate3109

Salamon-Albert, É., Abaligeti, G., & Ortmann-Ajkai, A. (2017). Functional response trait analysis improves climate sensitivity estimation in beech forests at a trailing edge. *Forests*, *8*(9). https://doi.org/10.3390/f8090324

Salvati, L., De Angelis, A., Bajocco, S., Ferrara, A., & Barone, P. M. (2013). Desertification Risk, Long-Term Land-Use Changes and Environmental Resilience: A Case Study in Basilicata, Italy. *Scottish Geographical Journal*, *129*(2), 85–99. https://doi.org/10.1080/14702541.2013.781209

Sánchez-Pinillos, M., Coll, L., De Cáceres, M., & Ameztegui, A. (2016). Assessing the persistence capacity of communities facing natural disturbances on the basis of species response traits. *Ecological Indicators*, *66*, 76–85. https://doi.org/10.1016/j.ecolind.2016.01.024

Sánchez-Salguero, R., Camarero, J. J., Rozas, V., Génova, M., Olano, J. M., Arzac, A., et al. (2018). Resist, recover or both? Growth plasticity in response to drought is geographically structured and linked to intraspecific variability in Pinus pinaster. *Journal of Biogeography*, *45*(5), 1126–1139. https://doi.org/10.1111/jbi.13202

Sarkki, S., Ficko, A., Wielgolaski, F. E., Abraham, E. M., Bratanova-Doncheva, S., Grunewald, K., et al. (2017). Assessing the resilient provision of ecosystem services by social-ecological systems: introduction and theory. *Climate Research*, *AdvanceVie*(February), 1–9. https://doi.org/10.3354/cr01437

Sarkki, Simo, & Heikkinen, H. (2012). The resilience of communities and nature-based livelihoods in northern Finland. In M. Nuttall, K. Tervo-Kankare, & T. Karjalainen (Eds.), *NGP Yearbook 2012: Negotiating resources, engaging people: Human-environment relations in the North* (Vol. 41:5, pp. 95–107). Oulu.

Savage, M., & Mast, J. N. (2005). How resilient are southwestern ponderosa pine forests after crown fires? *Canadian Journal of Forest Research*, *35*(4), 967–977. https://doi.org/10.1139/x05-028

Saxena, A., Guneralp, B., Bailis, R., Yohe, G., & Oliver, C. (2016). Evaluating the resilience of forest dependent communities in Central India by combining the sustainable livelihoods framework and the cross scale resilience analysis. *Current Science*, *110*(7), 1195–1207.

Schäfer, C., Grams, T. E. E., Rötzer, T., Feldermann, A., & Pretzsch, H. (2017). 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, *8*(6). https://doi.org/10.3390/f8060177

Schaffhauser, A., Curt, T., & Tatoni, T. (2008). The resilience ability of vegetation after different fire recurrences in Provence. *WIT Transactions on Ecology and the Environment*, *119*, 297–310. https://doi.org/10.2495/FIVA080301

Scheffer, M., Carpenter, S. R., Foley, J. A., Folke, C., & Walker, B. H. (2001). Catastrophic shifts in ecosystems. *Nature*, *413*(6856), 591–596. https://doi.org/10.1038/35098000

Schirpke, U., Kohler, M., Leitinger, G., Fontana, V., Tasser, E., & Tappeiner, U. (2017). Future impacts of changing land-use and climate on ecosystem services of mountain grassland and their resilience. *Ecosystem Services*, *26*, 79–94. https://doi.org/10.1016/j.ecoser.2017.06.008

Schoennagel, T., Balch, J. K., Brenkert-Smith, H., Dennison, P. E., Harvey, B. J., Krawchuk, M. A., et al. (2017). Adapt to more wildfire in western North American forests as climate changes. *Proceedings of the National Academy of Sciences*, *114*(18), 4582–4590. https://doi.org/10.1073/pnas.1617464114

Seidl, R., Rammer, W., & Spies, T. A. (2014). Disturbance legacies increase the resilience of forest ecosystem structure, composition, and functioning. *Ecological Applications*, *24*(8), 2063–2077. https://doi.org/10.1890/14-0255.1

Seidl, R., Spies, T. A., Peterson, D. L., Stephens, S. L., & Hicke, J. A. (2016). Searching for resilience: addressing the impacts of changing disturbance regimes on forest ecosystem services. *Journal of Applied Ecology*, *53*(1), 120–129. https://doi.org/10.1111/1365-2664.12511

Seidl, R., Vigl, F., Rössler, G., Neumann, M., & Rammer, W. (2017). Assessing the resilience of Norway spruce forests through a model-based reanalysis of thinning trials. *Forest Ecology and Management*, *388*, 3–12. https://doi.org/10.1016/j.foreco.2016.11.030

Selwood, K. E., Clarke, R. H., Cunningham, S. C., Lada, H., Mcgeoch, M. A., & Mac Nally, R. (2015). A bust but no boom: Responses of floodplain bird assemblages during and after prolonged drought. *Journal of Animal Ecology*, *84*(6), 1700–1710. https://doi.org/10.1111/1365-2656.12424

Serra-Maluquer, X., Mencuccini, M., & Martínez-Vilalta, J. (2018). Changes in tree resistance, recovery and resilience across three successive extreme droughts in the northeast Iberian Peninsula. *Oecologia*, *187*(1), 343–354. https://doi.org/10.1007/s00442-018-4118-2

Sharma, A., & Goyal, M. K. (2018). Assessment of ecosystem resilience to hydroclimatic disturbances in India. *Global Change Biology*, *24*(2), e432–e441. https://doi.org/10.1111/gcb.13874

Shinoda, M., Nandintsetseg, B., Nachinshonhor, U. G., & Komiyama, H. (2014). Hotspots of recent drought in Asian steppes. *Regional Environmental Change*, *14*(1), 103–117. https://doi.org/10.1007/s10113-013-0464-0

Silva Pedro, M., Rammer, W., & Seidl, R. (2015). Tree species diversity mitigates disturbance impacts on the forest carbon cycle. *Oecologia*, *177*(3), 619–630. https://doi.org/10.1007/s00442-014-3150-0

Singer, J., Hoang, H., & Ochiai, C. (2015). Post-displacement community resilience: Considering the contribution of indigenous skills and cultural capital among ethnic minority Vietnamese. *Asia Pacific Viewpoint*, *56*(2), 208–222. https://doi.org/10.1111/apv.12057

Smith, J. W., Moore, R. L., Anderson, D. H., & Siderelis, C. (2012). Community Resilience in Southern Appalachia: A Theoretical Framework and Three Case Studies. *Human Ecology*, *40*(3), 341–353. https://doi.org/10.1007/s10745-012-9470-y

Sohn, J. A., Saha, S., & Bauhus, J. (2016). Potential of forest thinning to mitigate drought stress: A meta-analysis. *Forest Ecology and Management*, *380*, 261–273. https://doi.org/10.1016/j.foreco.2016.07.046

Spasojevic, M. J., Bahlai, C. A., Bradley, B. A., Butterfield, B. J., Tuanmu, M. N., Sistla, S., et al. (2016). Scaling up the diversity-resilience relationship with trait databases and remote sensing data: The recovery of productivity after wildfire. *Global Change Biology*, *22*(4), 1421–1432. https://doi.org/10.1111/gcb.13174

Stampoulis, D., Andreadis, K. M., Granger, S. L., Fisher, J. B., Turk, F. J., Behrangi, A., et al. (2016). Assessing hydro-ecological vulnerability using microwave radiometric measurements from WindSat. *Remote Sensing of Environment*, *184*, 58–72. https://doi.org/10.1016/j.rse.2016.06.007

Stevens-Rumann, C. S., Kemp, K. B., Higuera, P. E., Harvey, B. J., Rother, M. T., Donato, D. C., et al. (2018). Evidence for declining forest resilience to wildfires under climate change. *Ecology Letters*, *21*(2), 243–252. https://doi.org/10.1111/ele.12889

Stuart-Haëntjens, E., De Boeck, H. J., Lemoine, N. P., Mänd, P., Kröel-Dulay, G., Schmidt, I. K., et al. (2018). Mean annual precipitation predicts primary production resistance and resilience to extreme drought. *Science of the Total Environment*, *636*(April), 360–366. https://doi.org/10.1016/j.scitotenv.2018.04.290

Summerville, K. S. (2013). Forest lepidopteran communities are more resilient to shelterwood harvests compared to more intensive logging regimes. *Ecological Applications*, *23*(5), 1101–1112. https://doi.org/10.1890/12-0639.1

Taeger, S., Zang, C., Liesebach, M., Schneck, V., & Menzel, A. (2013). Impact of climate and drought events on the growth of Scots pine (Pinus sylvestris L.) provenances. *Forest Ecology and Management*, *307*, 30–42.

https://doi.org/10.1016/j.foreco.2013.06.053

Tambosi, L. R., Martensen, A. C., Ribeiro, M. C., & Metzger, J. P. (2014). A framework to optimize biodiversity restoration efforts based on habitat amount and landscape connectivity. *Restoration Ecology*, *22*(2), 169–177. https://doi.org/10.1111/rec.12049

Temperli, C., Hart, S. J., Veblen, T. T., Kulakowski, D., Hicks, J. J., & Andrus, R. (2014). Are density reduction treatments effective at managing for resistance or resilience to spruce beetle disturbance in the southern Rocky Mountains? *Forest Ecology and Management*, *334*, 53–63. https://doi.org/10.1016/j.foreco.2014.08.028

Thompson, I. D., Okabe, K., Parrotta, J. A., Brockerhoff, E., Jactel, H., Forrester, D. I., & Taki, H. (2014). Biodiversity and ecosystem services: Lessons from nature to improve management of planted forests for REDD-plus. *Biodiversity and Conservation*, *23*(10), 2613–2635. https://doi.org/10.1007/s10531-014-0736-0

Ticktin, T., Quazi, S., Dacks, R., Tora, M., Mcguigan, A., Hastings, Z., & Naikatini, A. (2018). Linkages between measures of biodiversity and community resilience in Pacific Island agroforests. *Conservation Biology*, *0*(0), 1–11. https://doi.org/10.1111/cobi.13152

Toledo, V. M., Ortiz-Espejel, B., Cortés, L., Moguel, P., & Ordoñez, M. de J. (2003). The multiple use of tropical forests by indigenous peoples in Mexico: A case of adaptive management. *Conservation Ecology*, *7*(3), 9. https://doi.org/10.5751/ES-00524-070309

Torrico, J. C., & Janssens, M. J. J. (2010). Rapid assessment methods of resilience for natural and agricultural systems. *Anais da Academia Brasileira de Ciencias*, *82*(4), 1095–1105. https://doi.org/10.1590/S0001-37652010000400027

Townsend, P. A., & Masters, K. L. (2015). Lattice-work corridors for climate change: A conceptual framework for biodiversity conservation and social-ecological resilience in a tropical elevational gradient. *Ecology and Society*, *20*(2). https://doi.org/10.5751/ES-07324-200201

Trouvé, R., Bontemps, J. D., Collet, C., Seynave, I., & Lebourgeois, F. (2017). Radial growth resilience of sessile oak after drought is affected by site water status, stand density, and social status. *Trees - Structure and Function*, *31*(2), 517–529. https://doi.org/10.1007/s00468-016-1479-1

Van De Leemput, I. A., Van Nes, E. H., & Scheffer, M. (2015). Resilience of alternative states in spatially extended ecosystems. *PLoS ONE*, *10*(2), 1–17. https://doi.org/10.1371/journal.pone.0116859

Van Vierssen, N., & Wiersma, Y. F. (2015). A Comparison of All-Terrain Vehicle (ATV) Trail Impacts on Boreal Habitats Across Scales. *Natural Areas Journal*, *35*(2), 266–278. https://doi.org/http://dx.doi.org/10.3375/043.035.0207

Vanha-Majamaa, I., Shorohova, E., Kushnevskaya, H., & Jalonen, J. (2017). Resilience of understory vegetation after variable retention felling in boreal Norway spruce forests – A ten-year perspective. *Forest Ecology and Management*, *393*, 12–28. https://doi.org/10.1016/j.foreco.2017.02.040

Verbesselt, J., Umlauf, N., Hirota, M., Holmgren, M., Van Nes, E. H., Herold, M., et al. (2016). Remotely sensed resilience of tropical forests. *Nature Climate Change*, *6*(11), 1028–1031. https://doi.org/10.1038/nclimate3108

Viglizzo, E. F., Nosetto, M. D., Jobbágy, E. G., Ricard, M. F., & Frank, F. C. (2015). The ecohydrology of ecosystem transitions: A meta-analysis. *Ecohydrology*, *8*(5), 911–921. https://doi.org/10.1002/eco.1540

Vitali, V., Büntgen, U., & Bauhus, J. (2017). Silver fir and Douglas fir are more tolerant to extreme droughts than Norway spruce in south-western Germany. *Global Change Biology*, *23*(12), 5108–5119. https://doi.org/10.1111/gcb.13774

Wakelin, S. A., Macdonald, L. M., O'Callaghan, M., Forrester, S. T., & Condron, L. M. (2014). Soil functional resistance and stability are linked to different ecosystem properties. *Austral Ecology*, *39*(5), 522–531. https://doi.org/10.1111/aec.12112

Walker, X. J., Mack, M. C., & Johnstone, J. F. (2017). Predicting Ecosystem Resilience to Fire from Tree Ring Analysis in Black Spruce Forests. *Ecosystems*, *20*(6), 1137–1150. https://doi.org/10.1007/s10021-016-0097-5

Wallem, P. K., Anderson, C. B., Martínez-Pastur, G., & Lencinas, M. V. (2010). Using assembly rules to measure the resilience of riparian plant communities to beaver invasion in subantarctic forests. *Biological Invasions*, *12*(2), 325–335. https://doi.org/10.1007/s10530-009-9625-y

Waltz, A. E. M., Stoddard, M. T., Kalies, E. L., Springer, J. D., Huffman, D. W., & Meador, A. S. (2014). Effectiveness of fuel reduction treatments: Assessing metrics of forest resiliency and wildfire severity after the Wallow Fire, AZ. *Forest Ecology and Management*, *334*, 43–52. https://doi.org/10.1016/j.foreco.2014.08.026

Wardle, D. A., & Jonsson, M. (2014). Long-term resilience of above- and belowground ecosystem components among contrasting ecosystems. *Ecology*, *95*(7), 1836–1849. https://doi.org/10.1890/13-1666.1

Willig, M. R., Presley, S. J., & Bloch, C. P. (2011). Long-term dynamics of tropical walking sticks in response to multiple large-scale and intense disturbances. *Oecologia*, *165*(2), 357–368. https://doi.org/10.1007/s00442-010-1737-7

Wilson, D. J., Ruscoe, W. a, Burrows, L. E., Mcelrea, L. M., & Choquenot, D. (2006). 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. *New Zealand Journal Of Ecology*, *30*(2), 191–207.

Windmuller-Campione, M. A., & Long, J. N. (2015). 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*, *6*(4), 1157–1178. https://doi.org/10.3390/f6041157

Winter, M. B., Baier, R., & Ammer, C. (2015). Regeneration dynamics and resilience of unmanaged mountain forests in the Northern Limestone Alps following bark beetle-induced spruce dieback. *European Journal of Forest Research*, *134*(6), 949–968. https://doi.org/10.1007/s10342-015-0901-3

Wittkuhn, R. S., McCaw, L., Wills, A. J., Robinson, R., Andersen, A. N., Van Heurck, P., et al. (2011). Variation in fire interval sequences has minimal effects on species richness and composition in fire-prone landscapes of south-west Western Australia. *Forest Ecology and Management*, *261*(6), 965–978. https://doi.org/10.1016/j.foreco.2010.10.037

Wu, C. H., Lo, Y. H., Blanco, J. A., & Chang, S. C. (2015). Resilience assessment of lowland plantations using an ecosystem modeling approach. *Sustainability (Switzerland)*, *7*(4), 3801–3822. https://doi.org/10.3390/su7043801

Wu, T., & Kim, Y. S. (2013). Pricing ecosystem resilience in frequent-fire ponderosa pine forests. *Forest Policy and Economics*, *27*, 8–12. https://doi.org/10.1016/j.forpol.2012.11.002

Xu, C., Liu, H., Anenkhonov, O. A., Korolyuk, A. Y., Sandanov, D. V., Balsanova, L. D., et al. (2017). Long-term forest resilience to climate change indicated by mortality, regeneration, and growth in semiarid southern Siberia. *Global Change Biology*, *23*(6), 2370–2382. https://doi.org/10.1111/gcb.13582

Xu, Y., Shen, Z. H., Ying, L. X., Ciais, P., Liu, H. Y., Piao, S. L., et al. (2016). The exposure, sensitivity and vulnerability of natural vegetation in China to climate thermal variability (1901-2013): An indicator-based approach. *Ecological Indicators*, *63*, 258–272. https://doi.org/10.1016/j.ecolind.2015.12.023

Yan, H., Zhan, J., & Zhang, T. (2011). Resilience of forest ecosystems and its influencing factors. *Procedia Environmental Sciences*, *10*(PART C), 2201–2206. https://doi.org/10.1016/j.proenv.2011.09.345

Zang, C., Hartl-Meier, C., Dittmar, C., Rothe, A., & Menzel, A. (2014). Patterns of drought tolerance in major European temperate forest trees: Climatic drivers and levels of variability. *Global Change Biology*, *20*(12), 3767–3779. https://doi.org/10.1111/gcb.12637

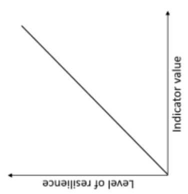
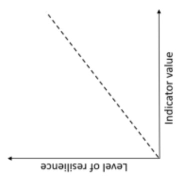
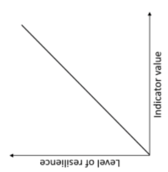
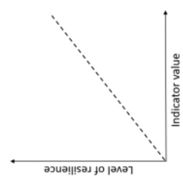
Zemp, D. C., Schleussner, C. F., Barbosa, H. M. J., & Rammig, A. (2017).

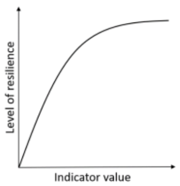
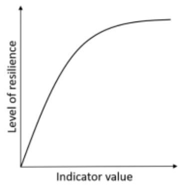
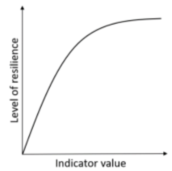
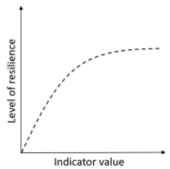
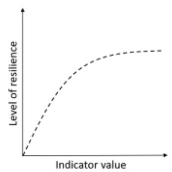
Deforestation effects on Amazon forest resilience. *Geophysical Research Letters*, *44*(12), 6182–6190. https://doi.org/10.1002/2017GL072955

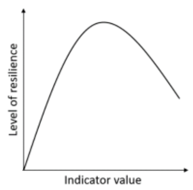
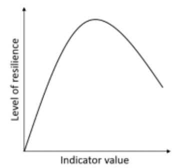
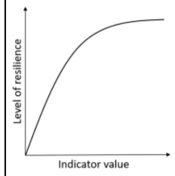
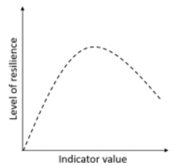
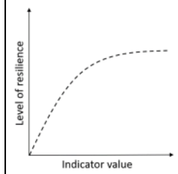
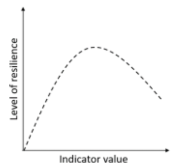
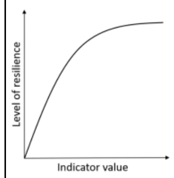
Zenner, E. K., Dickinson, Y. L., & Peck, J. E. (2013). Recovery of forest structure and composition to harvesting in different strata of mixed even-aged central Appalachian hardwoods. *Annals of Forest Science*, *70*(2), 151–159. https://doi.org/10.1007/s13595-012-0242-z

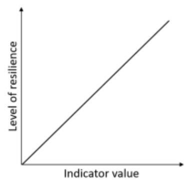
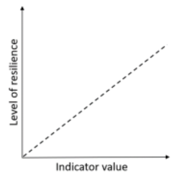
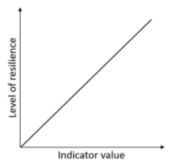
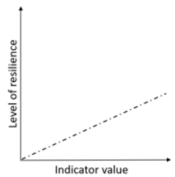
Appendix B

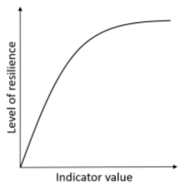
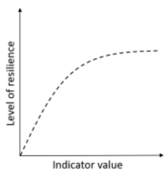
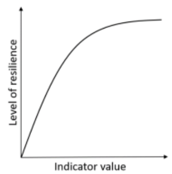
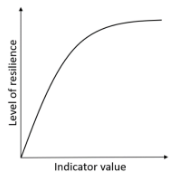
Table 8.1. A list of possible indicators, their response curves and weights for the three management goals in a Norway spruce forest dominated landscape. The curves are context dependend and may be different in another context.

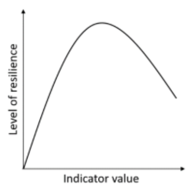
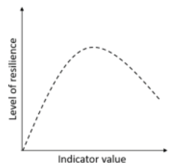
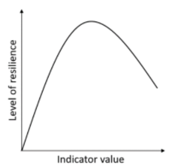
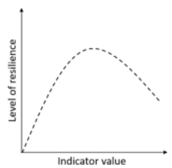
3.3.1. Number of technical options for forest management	Technology provides multiple opportunities to increase resilience through disturbance risk prevention and enhancing adaptive capacity.		 Importance: Medium While technological solutions can be more efficient than traditional forest management, they may threaten the subtle beneficial effects of management on recreational use.	 Importance: High Using advanced technical solutions in forest management supports management efficiency and may lead to improved outputs (e.g., through improved forest reproductive materials).	 Importance: Medium Technology is less influential on natural ecosystems and biodiversity, but integrative forest management can benefit from improved technological solutions.

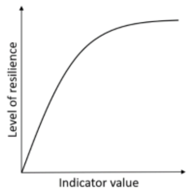
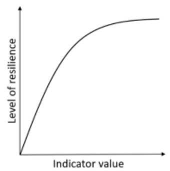
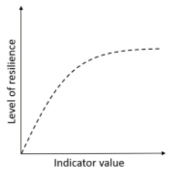
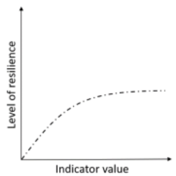
3.1.1. Evenness in representation of life stages of species and successional stages of communities, including old-growth features and natural regeneration	3.2.1. Option value of the stand (the difference in stand value between making a management decision and waiting to make that decision)	
Having multiple successional stages increases structural diversity, ensures forest regeneration and may also mitigate some disturbance risks.	Option value describes the possibility to wait until decision needs to be taken maintaining the economic flexibility.	
		
Importance: High Big trees are often perceived as beautiful whereas young forest has lower recreational value. In addition, structural diversity with some open spots is appreciated. Therefore, management might focus on maintaining more big trees and older stands at the expense of smaller ones.		Importance: High A forest diverse enough to allow for different development depending on demand changes over time has a larger value when we do not know what the future society demands. This can also include joint production, e.g. recreation and timber simultaneously
Importance: Medium Having a mixed portfolio of young and old stands creates more distributed income, which distributes also risks. However, old growth stages are less productive and decrease the economic feasibility of the forest enterprise.		Importance: Medium A forest structure flexible enough to allow for harvest of specific products when there is an increased demand, or damage of certain assortments, will increase the value, all other things equal. But it requires that changes in the forest are exercised; i.e. management should not have strict requirement of maintaining a certain forest structure over time
Importance: High Having all successional stages in the forest indicates that the ecosystem is healthy and capable of renewing itself. Especially old growth stages are crucial for biodiversity of birds, beetles and fungi.		Importance: Medium Here the value of waiting largely refers to conserving biodiversity if we may value it higher in the future, or if there is a risk of species dying out due to an unknown size of climate change, and the possibility of conserving more land than otherwise

2.3.1. The degree of involvement of all landscape actors in management decision making		
Considering diverse stakeholder demands facilitates high socio-ecological resilience, but if there are too many people involved decision making may become complicated and slow, reducing the resilience.		
		
	Importance: High Diverse stakeholder preferences are particularly important in multiple use forests.	
	Importance: Medium Involving stakeholders in decision-making may enhance societal acceptance for wood harvesting, but forest owners often place a high importance on their decision-making autonomy.	
	Importance: Medium Strong involvement of diverse interest groups is critical for achieving biodiversity protection objectives and enhance the social acceptance; however, forest owners often place a high importance on their decision-making autonomy.	

2.2.1. The degree of forest association membership of forest owners	
Association membership increases management capacity and know-how on good practices to enhance resilience. Forest associations provide and disseminate new knowledge and information. Furthermore, they represent the interests of private forest owners in policy discussions.	
	
	Importance: Medium Coordinated management helps managing diverse service demands in multiple use forests.
	Importance: High Management efficiency and increased know-how are important for wood production.
	Importance: Low Benefits of association membership are less affecting biodiversity.

2.1.1. The percentage of forest edge area relative to total forest area	
In Norway spruce dominated forest, forest edges are vulnerable to different forest disturbances (e.g. wind, pests). The damage by a disturbance may be lowered by increasing the percentage of core area relative to the total forest land area. The risk mitigation benefit stabilizes at a point where increasing the core area does not significantly reduce losses anymore.	
	
	Importance: Medium Reduced disturbance risk is desirable also in multipurpose forests, but recreational use appreciates stand edges and diverse pattern of forest stands.
	Importance: High To reduce risk of wind disturbance, reducing the amount of forest edge to highest possible degree is important.
	Importance: High Many species require large undisturbed areas of similar habitat to thrive. To protect these species, edge effects and fragmentation need to be avoided.

<table>
<tr><td colspan="2">1.3.1. Number of small-scale forest owners with different management strategies in a landscape</td></tr>
<tr><td colspan="2">Different forest owners in a landscape introduce diverse management objectives and this may enhance the provision of multiple ecosystem services. However, with smaller average property size, management gets inefficient, and this can hinder preventive measures to respond to disturbance risks (e.g. bark beetle outbreaks).</td></tr>
<tr><td colspan="2">
</td></tr>
<tr><td>
</td><td>Importance: Medium
Diverse forest ownership structure in the landscape may lead to more diverse landscape and facilitate the multiple ecosystem service provisioning in forests. However, increased number of (small-scale) forest owners imply need for more coordination of management objectives and interventions.</td></tr>
<tr><td>
</td><td>Importance: High
The economic outcome of the management will largely depend on the effectiveness and coordination among owners. A small number of forest owners might lead to uniformly managed landscape that might be less resilient overall. However, increased number of (small-scale) forest owners imply need for more coordination with risk of ineffectiveness of the management and conflicts between owners.</td></tr>
<tr><td>
</td><td>Importance: Medium
A larger number of owners increases the likelihood that some of them would favour biodiversity over other management objectives. Different forest owners and consequent more diverse landscape may ensure more connected habitats, but also entails the risk of uncoordinated action and ineffectiveness in conservation.</td></tr>
</table>

1.2.1. Number of marketed timber products	
A more diverse product portfolio reduces the risk of economic losses caused by forest disturbances or market fluctuations in Norway spruce forest. However, the additional benefit of more products decreases with increasing number of products.	
	
	Importance: High Diverse products create multiple income opportunities (e.g. bioenergy, pulp and saw wood) from the forest and may therefore support to cover the cost of maintaining recreational infrastructure and forest management to increase the recreational value of the forest.
	Importance: Medium Having several potential flows of income from diverse wood assortments is an important insurance for the forest enterprise but may lead to multiple and complex transactions.
	Importance: Low Management for biodiversity seeks for no economic gain from the forest and therefore the interest in forest products is low.

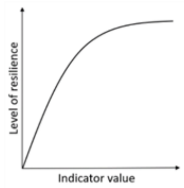
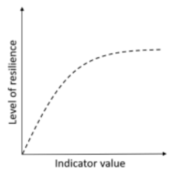
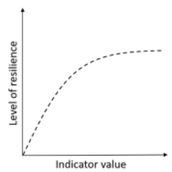
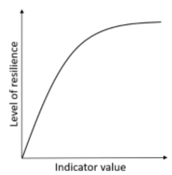
Indicator name		1.1.1. Stand Structural Complexity Index (SSC-index)	
Description		Diverse stand structures improve ecological resilience of Norway spruce forest. The additional benefits of having multiple layers and a perfect uneven-aged structure are limited.	
Response curve			
Management goal	**Management targeting multiple ecosystem services**		Importance: Medium Stand structure is an important feature for ecosystem service provisioning and recreation. However, diverse stand structure complicates management that is predicated upon a simple structure.
	Management targeting wood production		Importance: Medium Increasing structural diversity in stands provides higher operational certainty that contributes positively to resilience but leads also to higher management costs and more management complexity.
	Management targeting biodiversity conservation		Importance: High Diverse stand structure highly influences habitat and species diversity and contributes to forest stability.

Table 8.2. A list of possible balancing indicators, their response curves, and weights for the three management goals in a Norway spruce forest dominated landscape. The examples show which concrete resilience indicators could be balanced. These examples

are context dependent, and others can be used depending on the forest management context.

Examples on balancing resilience indicators	**Why these indicators need to be balanced**	**Management targeting multiple ecosystem services**	**Management targeting timber production**	**Management targeting biodiversity conservation**
4.1.1. Example for adaptive capacity: Balance between “Genetic diversity from natural regeneration” and “Planting of more adapted non-local species or provenances”.	Natural regeneration may provide genetic material best adapted to local conditions. However, where species are close to their physiological limits, artificial regeneration with more adapted non-local species or provenances might be a more resilient option.	“Genetic diversity from natural regeneration receives “High” importance, while “Planting of more adapted non-local species or provenances” receives “Medium” importance. Improved spruce seedling material might be planted in areas that need quick regeneration, however majority of the forests are naturally regenerated. See Fig. 8.1.	“Genetic diversity from natural regeneration” receives “Medium” importance, while “Planting of more adapted non-local species or provenances” receives “High” importance. Non-local provenances may perform better than natural regeneration if maintaining spruce forest is desired. See Fig. 8.2.	“Genetic diversity from natural regeneration receives “High” importance, while “Planting of more adapted non-local species or provenances” receives “Low” importance. Enabling natural regeneration of the species naturally present in the landscape may be more beneficial for biodiversity than planting improved seedling material. See Fig. 8.3.

4.2.1. Example for balancing diversity and adaptive capacity: "Species richness" and "Share of non-native tree species".	Assisted migration might improve the economic benefits associated with forest goods and ecosystem services compared to using only native species, as non-native tree species may be better suited for future climate and outperform native tree species. However, assisted migration risks to have potential maladaptation (i.e. failure of the planted tree species to establish) and the potential for introductions to become invasive, or introduce pests and/or diseases. The added benefit of native species richness and assisted migration decreases with additional number of species.	"Species richness" receives "High" importance and "Share of non-native species" receives "Medium" importance. Forests with native species tend to have higher acceptance by public than introduced species. However, having some areas with non-native species make forests more adapted to a range of current and future climatic conditions. See Fig. 8.4.	"Species richness" receives "Medium" importance and "Share of non-native species" receives "High" importance. Some of the native species may have good performance now and in the future, and therefore maintaining native species richness is desirable. However, when the stand consists of a formerly highly productive but currently vulnerable species, assisted migration with a more adapted species with high productivity could be more desirable. See Fig. 8.5.	"Species richness" receives "High" importance and "Share of non-native species" receives "Low" importance. Native species are crucial for biodiversity as they have co-evolved in the local environment. The risk of introduction of pests or invasive species with assisted migration makes it undesirable for biodiversity conservation. See Fig. 8.6.

5.1.1. Example for balancing between indicators “Stand Structural Complexity Index” and “Number of marketed timber products”	In structurally diverse forest spruce forest, the harvesting targets few big trees, which may provide fewer marketed timber products over the whole rotation period than structurally uniform forest were regular thinnings and final harvesting produce multiple wood products. However, with uneven aged management the provision of income is temporally more stable than in even-aged management.	“Stand structural complexity index” receives “Medium” importance and “Number of marketed timber products” receives “High” importance. Stand structure that enables the production of a high number of marketed timber products to provide steady income to fund forest management for recreation is preferred. See Fig. 8.7.	Both “Stand structural complexity index” and “Number of marketed timber products” receive “High” importance. Stand structure that enables the production of a high number of marketed timber products to provide stable income is preferred. See Fig. 8.8.	“Stand structural complexity index” receives “High” importance and “Number of marketed timber products” receives “Low” importance. Management for biodiversity conservation does not seek economic gain and therefore the number of timber products is not as important as diverse stand structure. See Fig. 8.9.
5.2.1. Example for balancing between indicators “Percentage of forest edge area relative to total forest area” and “Degree of forest association membership of forest owners”.	Being a member of forest association can facilitate coordination of forest management in the landscape and leave e.g. high habitat areas that cross property borders better protected. Similar coordination may be	Both “Percentage of forest edge area relative to total forest area” and “Degree of forest association membership of forest owners” receive “Medium” importance. Information sharing and planning and timing of the forest	Both “Percentage of forest edge area relative to total forest area” and “Degree of forest association membership of forest owners” receive “High” importance. Coordination of the forest management operations to avoid large edge areas between	“Percentage of forest edge area relative to total forest area” receives “High” importance and “Degree of forest association membership of forest owners” receives “Low” importance. Undisturbed forest core area is important to many species whereas benefits

	performed to maintain larger undisturbed core areas than without coordination.	management operations to avoid large edges reduces disturbance risks but might be more time demanding. See Fig. 8.10.	forest association members might have facilitation that coordination between non-member is lacking. See Fig. 8.11.	of association membership may not affect much biodiversity. See Fig. 8.12.
5.3.1. Example for balancing between indicators “Number of tree species in a stand” and “Option value of the stand”	Having multiple tree species present in a stand increases the option value of the stand as it allows to post-pone decision making. As time goes on, more information on species fitness has been gathered and better decisions on management can be made.	Both “Representation of species in all successional stages” and “Option value of the stand” receive “Medium” importance. Having multiple different successional stages varies landscape structure which increases recreational value, and it simultaneously increases option value. However, not all successional stages are as desired by the public that often prefers mature forest over younger one. See Fig. 8.13.	“Representation of species in all successional stages” receives “Low” importance and “Option value of the stand” receives “High” importance. High option value means that the forest owner has flexibility to adapt their decision making to the existing market conditions. The presence of multiple different successional stages has no high importance in itself but it might increase option value. See Fig. 8.14.	“Representation of species in all successional stages” receives “High” importance and “Option value of the stand” receives “Low” importance. Having multiple species in all successional stages indicates that the forest is viable in the future too. Having the economic flexibility from a high option value is not important. See Fig. 8.15.
6.1.1. Example for balancing between	Intense forest management geared towards high timber	“Timber production (in m3/ha/year)” receives	“Timber production (in m3/ha/year)” receives “High”	Both “Timber production (in m3/ha/year)” and

provisioning indicator "Timber production (in m3/ha/year)" and cultural service indicator "Recreational value (number of visitors per day) of the forest"	production decreases recreational values of the forest by making it less attractive to visitors.	"Medium" importance and "Recreational value (number of visitors per day)" receives "High" importance. In multifunctional forest optimization of trade-offs between different ecosystem services is core business	importance and "Recreational value (number of visitors per day)" receives "Low" importance. In forests dedicated for timber production, recreational values may be of secondary interest and financial losses due to recreation activities are preferred to be kept minimal.	"Recreational value (number of visitors per day)" receive "Low" importance. Timber production and recreation are considered potential threats to biodiversity conservation, and should be managed with focus on biodiversity protection requirements
6.2.1. Example for balancing between provisioning indicator "Timber production (in m3/ha/year)" and regulating indicator "Avalanche protection (percentage of forest area managed for avalanche protection)"	Intense forest management can lead to a decrease in forests' protective values against avalanches and landslides.	"Timber production (in m3/ha/year)" receives "Medium" importance and "Avalanche protection (percentage of forest area managed for avalanche protection)" receives "High" importance. In multifunctional forest optimization of trade-offs between different ecosystem services is core business.	Both "Timber production (in m3/ha/year)" and "Avalanche protection (percentage of forest area managed for avalanche protection)" receive "High" importance. The focus in forest management is on production, but damages caused by avalanches, e.g., soil loss, can lead to long-term production losses, so regulating services are of certain interest.	"Timber production (in m3/ha/year)" receives "Low" importance and "Avalanche protection (percentage of forest area managed for avalanche protection)" has "High" importance. Regulating services are of importance to biodiversity.
6.3.1. Example for	Some species are very	"Biodiversity conservation	Both "Biodiversity	"Biodiversity conservation

balancing between regulating indicator "Biodiversity conservation (percentage of strictly protected areas)" and cultural service indicator "Recreation activities (number of visitors per day)"	vulnerable or easily disturbed by humans and therefore require strictly protected areas where human influence is kept at minimum. However, these areas also attract visitors and management should be focused on balancing the demands with e.g. limiting access and zoning areas.	(percentage of strictly protected areas)" receives "Medium" importance and "Recreation value (number of visitors per day)" receives "High" importance. In multifunctional forest optimization of trade-offs between different ecosystem services is core business.	conservation (percentage of strictly protected areas)" and "Recreation value (number of visitors per day)" receive "Low" importance. Forest management priority is on production and therefore this balancing is not important.	(percentage of strictly protected areas)" receives "High" importance and "Recreation value (number of visitors per day)" receives "Low" importance. Forests are essentially managed for biodiversity conservation and the impact of recreational activities is wanted to be kept at minimum.
7.1.1. Example for balancing between indicators "Short-term resilience to wind disturbance" and "Long-term resilience to wind disturbance"	In Norway spruce forest, long-term resilience to wind disturbance requires regular management to make the trees grow in form that is more resilient to wind damages. However, the management may reduce the short-term resilience of forest to wind	Both "Short-term resilience to wind disturbance" and "Long-term resilience to wind disturbance" receive "High" importance. Management focuses on enhancing long-term resilience without decreasing short-term resilience significantly.	"Short-term resilience to wind disturbance" receive "Medium" importance and "Long-term resilience to wind disturbance" receive "High" importance. Short-term risks will be tolerated because the economic trade-off increases with age and value of trees.	Both "Short-term resilience to wind disturbance" and "Long-term resilience to wind disturbance" receive "Low" importance. Wind disturbances create different structures and deadwood, which is good for biodiversity.
7.2.1. Example for balancing indicator "Stand Structural	Similarly structurally diverse stands may create structurally homogeneous	Both "Structural diversity in stand level" and "Structural diversity in forest	"Structural diversity in stand level" receives "Low" importance and "Structural	Both "Structural diversity in stand level" and "Structural diversity in forest

Complexity Index" between stand and forest management unit level	landscape. In structurally diverse landscape, some sites can be homogeneous in structure to create diversity in the landscape.	management unit level" receive "High" importance. An attractive forest for biodiversity, recreation and high-quality timber will have both variation at stand and landscape level.	diversity in forest management unit level" receive "Medium" importance. For efficiency reasons, timber plantations keep stand structural variation low, but increase structural diversity between stands at forest level	management unit level" receive "High" importance. For biodiversity, both variation at stand and landscape level is important
7.3.1. Example for balancing between indicators "The degree of forest association membership of forest owners" and "Presence of forest owners associations in the national decision-making"	Forest management is regulated by legislation and policies that are implemented on local level. Having policies and legislation made without input from forest owners' representatives can cause inconsistencies and contradictions that negatively affect resilience. Large forest associations are likely more efficient in influencing policies than smaller ones.	"The degree of forest association membership of forest owners" receives "High" and "Presence of forest owners associations in the national decision-making" receives "Medium" importance. Coordinated management helps managing diverse service demands in urban forests. Having representation of forest owners in national decision-making is important for creating coherent policies for provisioning of multiple	"The degree of forest association membership of forest owners" receives "Medium" importance and "Presence of forest owners associations in the national decision-making" receives "High" importance. Having a strong presentation of forest owners that understand the conditions on local level on a national decision-making is important in order to avoid conflicting legislation and policies.	"The degree of forest association membership of forest owners" receives "Low" importance and "Presence of forest owners associations in the national decision-making" receives "Medium" importance. While benefits of association membership are not much affecting biodiversity, effective conservation cannot be done without involving forest owners. Therefore, forest owners should be involved in

		ecosystem services.		higher level decision-making.

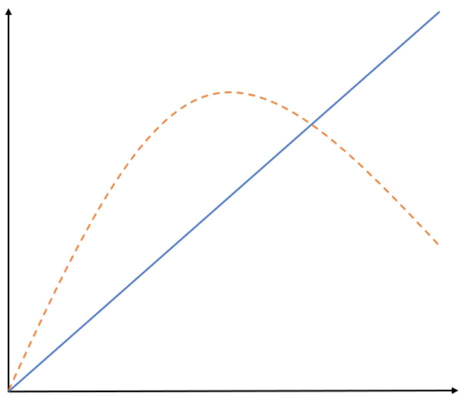


Figure 8.1. Example for adaptive capacity: Balance between "Genetic diversity from natural regeneration" (blue) and "Planting of more adapted non-local species or provenances" (orange) for management targeting multiple ecosystem services.

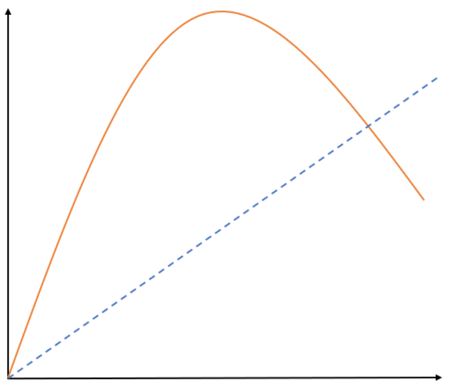


Figure 8.2. Example for adaptive capacity: Balance between "Genetic diversity from natural regeneration" (blue) and "Planting of more adapted non-local species or provenances" (orange) for management targeting timber production.

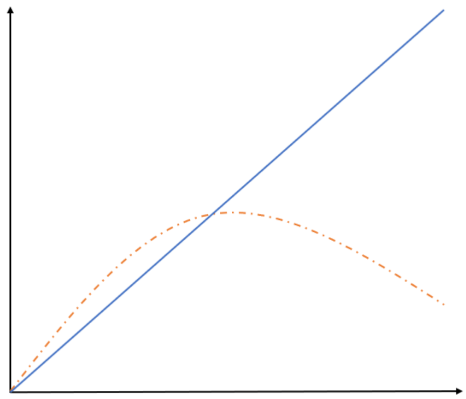


Figure 8.3. Example for adaptive capacity: Balance between “Genetic diversity from natural regeneration” (blue) and “Planting of more adapted non-local species or provenances” (orange) for management targeting biodiversity conservation.

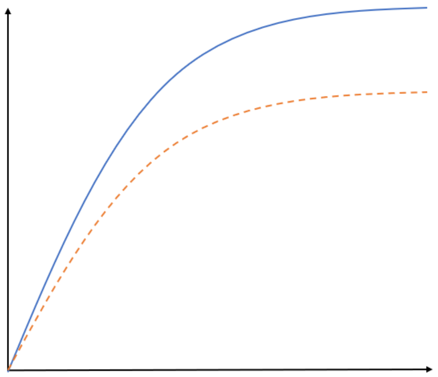


Figure 8.4. Example for balancing diversity and adaptive capacity: “Species richness” (blue) and “Share of non-native tree species” (orange) for management targeting multiple ecosystem services.

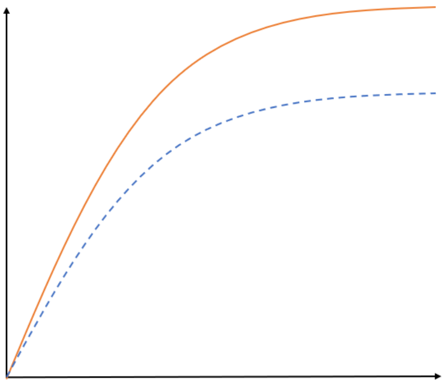


Figure 8.5. Example for balancing diversity and adaptive capacity: “Species richness” (blue) and “Share of non-native tree species” (orange) for management targeting timber production.

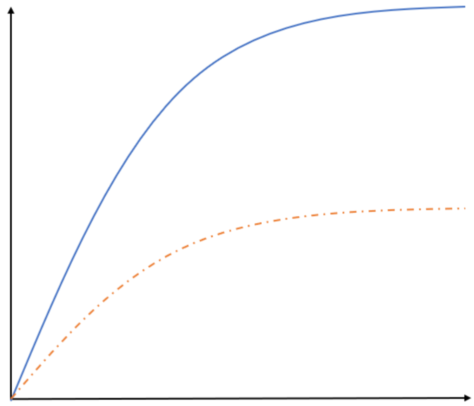


Figure 8.6. Example for balancing diversity and adaptive capacity: “Species richness” (blue) and “Share of non-native tree species” (orange) for management targeting biodiversity conservation.

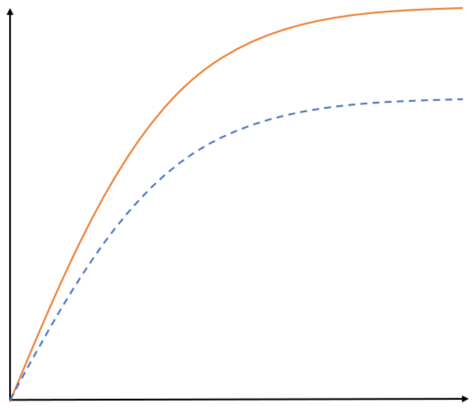


Figure 8.7. Example for balancing between indicators “Stand Structural Complexity Index” (blue) and “Number of marketed timber products” (orange) for management targeting multiple ecosystem services.

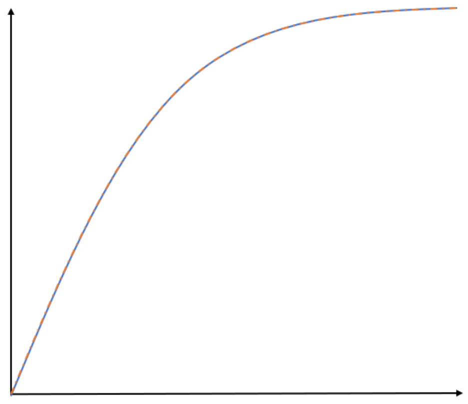


Figure 8.8. Example for balancing between indicators “Stand Structural Complexity Index” (blue) and “Number of marketed timber products” (orange) for management targeting timber production.

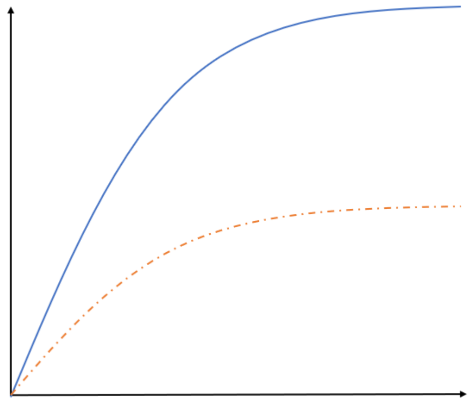


Figure 8.9. Example for balancing between indicators “Stand Structural Complexity Index” (blue) and “Number of marketed timber products” (orange) for management targeting biodiversity conservation.

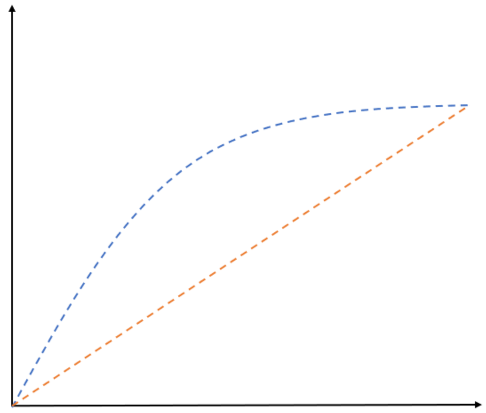


Figure 8.10. Example for balancing between indicators “Percentage of forest edge area relative to total forest area” (blue) and “Degree of forest association membership of forest owners” (orange) for management targeting multiple ecosystem services.

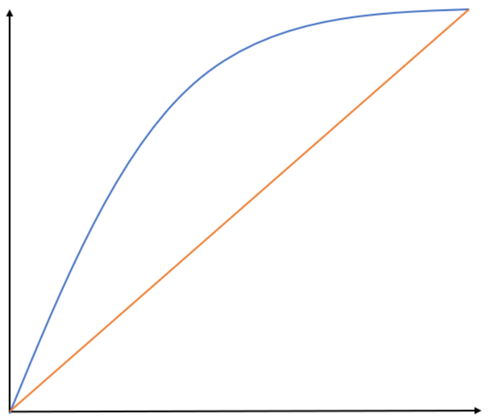


Figure 8.11. Example for balancing between indicators “Percentage of forest edge area relative to total forest area” (blue) and “Degree of forest association membership of forest owners” (orange) for management targeting timber production.

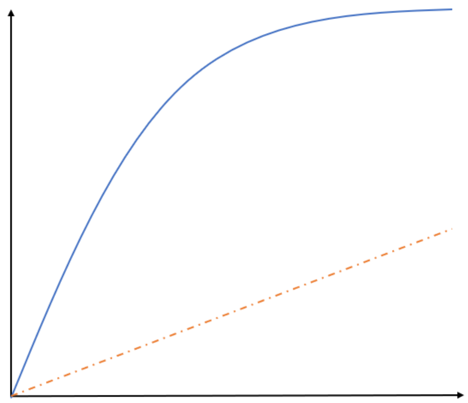


Figure 8.12. Example for balancing between indicators “Percentage of forest edge area relative to total forest area” (blue) and “Degree of forest association membership of forest owners” (orange) for management targeting biodiversity conservation.

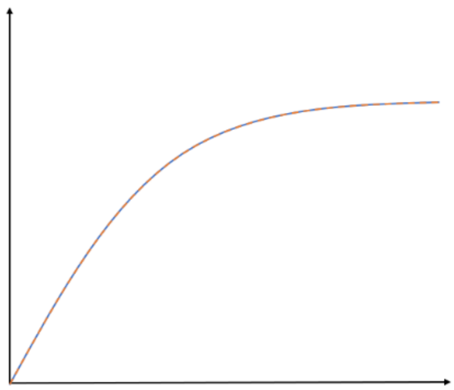


Figure 8.13. Example for balancing between indicators “Number of tree species in a stand” (blue) and “Option value of the stand” (orange) for management targeting multiple ecosystem services.

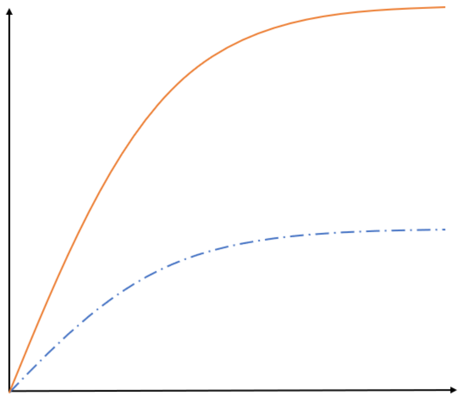


Figure 8.14. Example for balancing between indicators “Number of tree species in a stand” (blue) and “Option value of the stand” (orange) for management targeting timber production.

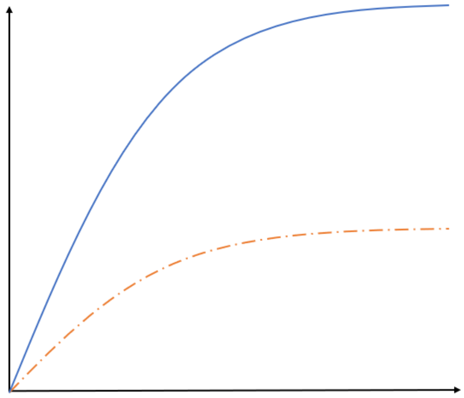


Figure 8.15. Example for balancing between indicators “Number of tree species in a stand” (blue) and “Option value of the stand” (orange) for management targeting biodiversity conservation.

Appendix C

Table 8.3. Metadata on sites and the measured trees.

Site	#trees	Species	Lat	Lon	Altitude	Measurement start date	Measurement end date
Bär.Mayr_Absamer.Vorberg_1559145547	9	Fagus sylvatica, Picea abies, Pinus sylvestris	47.3149	11.5112	875	01/04/2016	22/03/2019
Cada_CZ_J01_1559055028	4	Picea abies	50.0754	17.2507	1209,92	13/11/2013	25/04/2019
Cada_CZ_J08_1559055689	4	Picea abies	50.064	18.2577	185	14/11/2013	25/04/2019
Cada_CZ_SB3_1559056260	4	Picea abies	48.9923	13.8213	1266,88	16/11/2013	14/05/2019
Cada_CZ_SJ8_1559056710	4	Picea abies	49.1674	13.1888	1250,4	18/11/2013	14/05/2019
Carraro_IT.SC_1558624837	5	Picea abies, Pinus sylvestris, Larix decidua	46.4501	12.2168	1000	01/01/2018	31/12/2018
Cremonese_IT.Trf_1558973752	3	Larix decidua	45.82306	7.56083	2160	25/05/2017	25/11/2018
Delpierre.Berveiller.Dufrêne_FRFon_1559141157	12	Carpinus betulus, Quercus petraea	48.47	2.780	92	08/08/2012	01/01/2019

			634	055			
Delpierre.Cecchini_CHS01_1560497720	10	Quercus petraea	46.1708	5.238	260	31/01/2017	13/03/2019
Delpierre.Cecchini_CHS58_1560497349	10	Quercus petraea	46.9696	3.66	270	28/02/2017	06/02/2019
Delpierre.Cecchini_CHS72_1560437766	9	Quercus petraea	47.7955	0.3796	170	13/03/2017	13/02/2019
Delpierre.Cecchini_CHS81_1560498069	5	Quercus petraea	44.04	1.75	300	26/02/2016	17/04/2019
Delpierre.Delzon_Cheze_1560498976	10	Quercus petraea	42.9167	-0.0333	803	25/01/2016	21/02/2019
Delpierre.Delzon_Laveyron_1560498477	9	Quercus petraea	43.77611	-0.2167	131	27/01/2016	12/03/2019
Delpierre.Delzon_Peguere_1560500146	9	Quercus petraea	42.8667	-0.1167	1630	26/01/2016	04/06/2019
Delpierre.Lebourgeois_Charmes_1560436823	10	Quercus petraea	48.3725	6.293333	280	09/02/2017	07/03/2019
Edvardsson_Mycklemossen_1560341042	4	Pinus sylvestris	58.3662	12.1686	80	18/04/2018	31/05/2019
Ehekircher_Schmellenhof_1559046878	5	Picea abies	49.826	11.5713	510	12/05/2017	28/09/2018

Ehekircher_Schmellenhof_1559048617	7	Pinus nigra	49.8262	11.5686	508	12/05/2017	06/11/2018
Ehekircher_Schmellenhof_1559049762	5	Quercus robur	49.8241	11.5758	512	12/05/2017	06/11/2018
Ehekircher_Weinheim_1559050429	3	Corylus colurna	49.541	8.6842	155	14/04/2017	12/02/2019
Ehekircher_Weinheim_1559051061	6	Juglans nigra	49.541	8.677	170	14/04/2017	24/01/2019
Ehekircher_Weinheim_1559051567	5	Metasequoia glyptostroboides	49.5406	8.677	190	14/04/2017	18/01/2019
Fonti_LTAL_N08_1558171652	10	Picea abies, Larix decidua	46.3026	7.7411	804	30/10/2007	01/01/2019
Fonti_LTAL_N13_1558174487	10	Picea abies, Larix decidua	46.3918	7.7613	1361	23/10/2006	01/01/2019
Fonti_LTAL_N13W_1558202227	6	Picea abies, Larix decidua	46.3934	7.7639	1321	23/10/2006	01/01/2019
Fonti_LTAL_N16_1558180015	8	Picea abies, Larix decidua	46.3871	7.7643	1634	23/10/2006	01/01/2019
Fonti_LTAL_N19_1558180434	8	Picea abies, Larix decidua	46.3869	7.7738	1961	23/10/2006	01/01/2019
Fonti_LTAL_N22_1558180811	3	Larix decidua	46.3812	7.7728	2182	23/10/2006	01/01/2019

Fonti_LTAL_S16_1558176718	10	Picea abies, Larix decidua	46.3972	7.7554	1670	23/10/2006	01/01/2019
Fonti_LTAL_S19_1558177687	11	Picea abies, Larix decidua	46.3967	7.7459	1928	23/10/2006	01/01/2019
Fonti_LTAL_S22_1558202465	5	Larix decidua	46.3996	7.7426	2104	23/10/2006	01/01/2019
Forner.Valladares_Huertahernando.Plot.H_1561985218	4	Juniperus thurifera	40.8276	-2.2749	1134	06/10/2017	31/12/2018
Forner.Valladares_Huertahernando.Plot.I_1561986402	4	Juniperus thurifera	40.8257	-2.2769	1140	03/10/2017	31/12/2018
Forner.Valladares_Huertahernando.Plot.J_1561988479	3	Juniperus thurifera	40.8266	-2.2786	1147	03/10/2017	31/12/2018
Forner.Valladares_Maranchon.Plot.C_1561976943	4	Juniperus thurifera	41.0581	-2.1931	1343	04/10/2017	31/12/2018
Forner.Valladares_Maranchon.plot_A_1561943218	2	Juniperus thurifera	41.0657	-2.1963	1334	04/10/2017	31/12/2018
Forner.Valladares_Ribarredonda.Plot.N_1561991369	3	Juniperus thurifera	40.8717	-2.303	1034	03/10/2017	31/12/2018
Forner.Valladares_Ribarredonda.Plot.O_1561989248	4	Juniperus thurifera	40.8705	-2.3	1049	03/10/2017	31/12/2018

				01 2			
Forner.Valladares_Ribarredonda.Plot.Q_1561989812	4	Juniperus thurifera	40.8709	-2.2995	1036	03/10/2017	31/12/2018
Ganthaler.Mayr_Patscherkofel_1560238648	6	Picea abies	47.22161	11.46767	1626,48	01/05/2017	30/04/2019
Ganthaler.Mayr_Praxmar_1559147741	3	Picea abies	47.1525	11.1266	1895,76	01/05/2017	30/04/2019
Hentschel.Hentschel_GER_BB_1203_1559563452	4	Pinus sylvestris	52.9736	13.6439	70	05/04/2008	31/12/2018
Hentschel_GER_BB_1202_1558711520	4	Pinus sylvestris	53.1347	12.965	79	01/04/2018	30/09/2018
Hentschel_GER_BB_1202_1559563185	4	Pinus sylvestris	53.1347	12.965	79	04/04/2008	31/12/2018
Hentschel_GER_BB_1205_1559563672	3	Pinus sylvestris	51.7983	13.5639	133	31/12/2009	31/12/2018
Hentschel_GER_BB_1207_1559563846	4	Fagus sylvatica	53.1533	12.9883	90	31/12/2016	31/12/2018
Hentschel_GER_BB_1208_1559564073	4	Quercus petraea	52.165	14.4975	118	13/03/2009	31/12/2018
Hentschel_GER_BB_1209_1559564327	4	Quercus petraea	52.98	13.65	70	31/12/2014	31/12/2018

Janda_SK_JAK_053_1559058930	4	Picea abies	49.0086	19.198	1303,99	22/03/2014	08/08/2018
Janda_SK_JAK_071_1559059423	4	Picea abies	49.0098	19.1991	1263,71	22/03/2014	08/08/2018
Jezik.Blazenec.Ditmarova.Strelcova_Predna.Polana_1560257582	3	Picea abies	48.6296	19.4621	1350	01/05/2006	15/11/2006
Jezik.Blazenec.Jakus_Ocova_1560763196	10	Picea abies	48.6296	19.3049	535	11/04/2017	28/11/2018
Jezik.Ditmarova.Blazenec.Jakus.Strelcova_Predna.Polana_1560326951	5	Picea abies	48.6296	19.4621	1350	15/03/2017	15/11/2018
Knüsel.Conedera_Avegno.01_1558705965	7	Ailanthus altissima, Castanea sativa	46.212219	8.745667	320	12/03/2013	24/05/2019
Knüsel.Conedera_Avegno.02_1558704843	2	Ailanthus altissima, Castanea sativa	46.21417	8.739722	340	08/04/2014	21/05/2019
Krejza.Svetlík.Bellan_ES1000_1558962361	3	Picea abies	50.11777	17.24704	995	09/03/2016	12/12/2018
Krejza.Svetlík.Bellan_Habruvka_1558947620	3	Picea abies	49.3111	16.71253	489	09/03/2016	13/12/2018

Krejza.Svetlík.Bellan_Rajec_old_1558960237	4	Picea abies	49.4437	16.69649	625	10/03/2017	31/12/2018
Krejza.Svetlík.Bellan_Rajec_young_1558959567	3	Picea abies	49.44571	16.69711	622	17/03/2017	28/02/2019
Krejza.Svetlík.Bellan_Rovna_1559119345	3	Picea abies	49.48483	16.61466	381	13/03/2016	13/12/2018
Krejza.Svetlík.Bellan_Vidly_1558949728	3	Picea abies	50.10638	17.26714	798	09/03/2016	12/12/2018
Krejza_Bily.Kriz_1558365087	9	Picea abies	49.50206	18.53682	875	19/03/2016	20/12/2018
Krejza_Stitna.nad.Vlari_1558515130	7	Fagus sylvatica	49.03594	17.96986	550	01/11/2017	04/01/2019
Limousin.Ourcival_FR.Pue_1560782777	11	Quercus ilex	43.7415	3.5963	270	06/06/2003	01/01/2019
Matula_Plot.24_1559517984	7	Quercus faginea, Pinus nigra, Pinus sylvestris, Quercus ilex	40.67883	-1.94953	1369	20/10/2017	30/11/2018
Matula_SPA.1_1560266640	6	Pinus sylvestris, Quercus faginea	40.65919	-2.27042	1294	27/10/2017	31/12/2018

Matula_SPA.36_1560250439	6	Pinus nigra, Quercus ilex	40.81411	-2.21761	1211	27/10/2017	31/12/2018
Mikolás_SK_SRA_008_1_1559061737	4	Abies alba, Picea abies, Fagus sylvatica	49.1899	19.1095	978, 58	18/03/2015	12/04/2019
Mikolás_SK_SRA_010_2_1559062328	6	Abies alba, Picea abies, Fagus sylvatica	49.1864	19.1083	954, 87	18/03/2015	12/04/2019
Nabuurs.Lerink_De.Heul_1559309341	5	Pseudotsuga menziesii	52.04887	5.44303	6	21/02/2008	31/12/2018
Nabuurs.Lerink_Leesten_1559641683	5	Pseudotsuga menziesii	52.15662	5.90815	70	21/02/2008	31/12/2018
Nabuurs.Lerink_Loobos_1559289159	4	Pinus sylvestris	52.16678	5.74385	22	01/03/2008	31/12/2018
Nabuurs.Lerink_Motketel_1559315009	2	Fagus sylvatica	52.28551	5.9161	23	21/02/2008	31/12/2018
Nabuurs.Lerink_Nieuw.Milligen_1559640587	4	Pinus sylvestris	52.21813	5.80761	44	21/02/2008	31/12/2018
Nabuurs.Lerink_Quin_1559574338	4	Pinus sylvestris	51.38974	6.01242	11	12/05/2015	31/12/2018

Nabuurs.Lerink_Schoonloerveld_1561129080	3	Pseudotsuga menziesii	52.888864	6.68476	22	01/03/2008	31/12/2018
Nabuurs.Lerink_Vijlnerbos_1559633858	5	Fagus sylvatica	50.460004	5.58802	213	21/02/2008	01/06/2019
Nabuurs.Lerink_Zeesserveld_1559641099	2	Pinus sylvestris	52.506637	6.45437	5	21/02/2008	31/05/2019
Oberhuber_Tschirgant.xeric_1559054911	4	Pinus sylvestris	47.2311	10.8444	740	11/03/2015	08/11/2018
Oberhuber_Tschirgant_1558970324	16	Picea abies, Pinus sylvestris, Larix decidua	47.2314	10.8475	750	03/09/2010	08/11/2018
Obojes_Matsch_SF1_1559397841	6	Larix decidua, Pinus nigra	46.6777	10.5781	1160	22/03/2012	12/04/2019
Obojes_Matsch_SF2_1559385166	4	Larix decidua	46.6944	10.6129	1715	22/03/2012	12/04/2019
Obojes_Matsch_SF3_1559395615	4	Larix decidua	46.6977	10.6072	1990	23/05/2012	12/04/2019
Obojes_Matsch_SF4_1559396501	6	Larix decidua, Pinus cembra	46.66987	10.6422	2030	23/05/2012	12/04/2019
Obojes_Matsch_SF5_1559398670	8	Larix decidua, Pinus cembra	46.7389	10.6884	2100	23/05/2012	12/04/2019

Obojes_Matsch_WgN_1559400256	2	Pinus cembra	46.6961	10.6476	2320	01/07/2015	12/04/2019
Obojes_Matsch_WgS_1559399655	4	Larix decidua	46.7389	10.6884	2230	26/06/2015	12/04/2019
RATGEBER.BULTEAU.PEYRIE_Champenoux_1559248194	5	Quercus petraea	48.7208	6.34	240	01/01/2017	01/01/2019
RATHGEBER.BULTEAU.PEYRIE_Ban.D.Harol_1559249461	5	Fagus sylvatica	48.104	6.2098	420	01/01/2017	01/01/2019
Stangler.Kahle.Spiecker_Guenterstal_1559320776	13	Fagus sylvatica, Picea abies	47.95724	7.868327	750	01/01/2014	31/12/2018
Stangler.Kahle.Spiecker_Heibrain_1559320063	13	Fagus sylvatica, Picea abies	47.92656	7.87262	750	01/01/2014	31/12/2018
Stangler.Kahle.Spiecker_Schauinsland_1559319167	9	Fagus sylvatica, Picea abies	47.91342	7.903969	1250	01/01/2014	31/12/2018
Steppe.Luis.Salomon.Moreno.von.der.Crone_Experimental.forest.Aelmoeseneie	3	Fagus sylvatica	50.975	3.8043	43,1	23/04/2014	30/12/2018
Stojanovic.Krejza_Lanzhot_1558681315	7	Fraxinus excelsior, Quercus robur	48.6817	16.9464	155	24/03/2016	28/11/2018
Svoboda_RO_BEL_002_2_1559085017	3	Abies alba, Fagus sylvatica	45.6369	24.9659	1241,37	23/09/2014	19/10/2018

Svoboda_RO_BEL_004_1_1559057265	3	Abies alba, Fagus sylvatica	45.6414	24.965	1243,76	20/09/2014	19/10/2018
Svoboda_RO_FA9_457_1559057830	4	Picea abies	45.5715	24.6046	1600,14	10/09/2013	19/10/2018
Svoboda_RO_FA9_492_1559058338	2	Picea abies	45.5715	24.6067	1480,56	28/12/2013	19/10/2018
Tobin.Osborne.Saunders.Zou_Dooary.Forest	4	Picea sitchensis	52.9486	-7.2644	249	01/01/2015	05/04/2019
Trotsiuk_SK_JAV_016_1559059893	2	Picea abies	49.2132	20.1613	1476,11	23/03/2014	02/06/2018
Trotsiuk_SK_JAV_062_1559061076	1	Picea abies	49.2166	20.1645	1417,13	19/10/2013	02/06/2018
Uradnicek.Plichta_Pohansko_01_1558968267	15	Quercus robur	48.7216	16.90594	154	19/04/2018	16/01/2019
Urban_Bilovice_1557292040	5	Quercus petraea	49.2485	16.6867	320,61	06/07/2016	05/04/2019
Urban_Utechov_1557287734	3	Fagus sylvatica	49.2798	16.6487	386,81	16/02/2017	05/04/2019

Vejpustková_Benesovice_1559141173	6	Pinus sylvestris	49.7419	12.8614	385	01/01/2010	31/12/2018
Vejpustková_Lazy_1559142795	6	Picea abies	50.0433	12.625	875	01/01/2010	31/12/2018
Vejpustková_Vsetec_1559201018	6	Fagus sylvatica, Pinus sylvestris	49.23	14.3	615	01/01/2010	31/12/2018
Vejpustková_Zelivka_1559202253	6	Picea abies	49.6753	15.2297	440	01/01/2010	31/12/2018
Walthert_Alvaneu_1559299797	3	Pinus sylvestris	46.683	9.6411	1381	21/05/2014	31/12/2018
Walthert_Neunkirch_1559300768	3	Fagus sylvatica	47.6837	8.5339	586,3	04/04/2014	27/12/2018
Walthert_Saillon.Buche_1559303291	4	Fagus sylvatica	46.1713	7.1655	888,8	22/05/2015	31/12/2018
Walthert_Saillon.Eiche_1559302615	3	Quercus pubescens	46.1701	7.1664	793,2	13/03/2014	31/12/2018
Zin.Kuberski.Sterenczak_BF_03_1560196768	6	Pinus sylvestris	52.676669	23.75127	177,89	23/04/2015	31/12/2018
Zin.Kuberski.Sterenczak_BF_05_1560198208	3	Alnus glutinosa	52.672223	23.68712	165,86	24/04/2015	31/12/2018
Zin.Kuberski.Sterenczak_BF_09_1560198723	6	Betula L., Tilia cordata	52.767775	23.73877	178,75	30/04/2015	31/12/2018

Zin.Kuberski.Sterenczak_BF_10_1560199317	6	Fraxinus excelsior, Acer platanoides	52.77067	23.73653	171,8	15/05/2015	31/12/2018
Zin.Kuberski.Sterenczak_BF_12_1560370506	1	Tilia cordata	52.78151	23.78134	165	01/05/2015	31/12/2018
Zin.Kuberski.Sterenczak_BF_15_1560370880	3	Quercus robur	52.7554	23.84902	164,27	03/06/2015	31/12/2018
Zin.Kuberski.Sterenczak_BF_17_1560371380	6	Betula L., Pinus sylvestris	52.80281	23.84674	161,89	17/05/2015	31/12/2018
Zin.Kuberski.Sterenczak_BF_19_1560371753	3	Fraxinus excelsior	52.79235	23.89443	166,88	24/05/2015	31/12/2018
Zin.Kuberski.Sterenczak_BF_20_1560372273	4	Alnus glutinosa	52.77028	23.89939	160,02	20/05/2015	31/12/2018
Zin.Kuberski.Sterenczak_BF_21_1560372607	4	Acer platanoides	52.72732	23.86585	175,44	21/05/2015	31/12/2018
Zin.Kuberski.Sterenczak_BF_24_1560372991	3	Ulmus L.	52.73445	23.83206	170	28/05/2015	31/12/2018
Zin.Kuberski.Sterenczak_BF_27_1560373938	3	Pinus sylvestris	52.61	23.75	159,22	08/05/2015	31/12/2018

			566	227			
Zin.Kuberski.Sterenczak_BF_33_1560374435	5	Picea abies	52.632229	23.772212	164,67	30/04/2015	31/12/2018
Zweifel_Davos.Seehornwald_1562742428	9	Picea abies	46.815522	9.85558	1650	01/01/2013	31/12/2018

Table 8.4. The tree species properties based on literature.

Species	**Ring porosity**	**Deciduousness**	**Broad/needle leaf**	**Pioneer status**	**References**
	(diffuse/ring/coniferous)	(deciduous/evergreen)	(broad/needle leaf)	(3 classes; 1 is most pioneer)	
Abies alba	Coniferous	Evergreen	Needleleaf	3	Paluch and Jastrzebski 2013
Acer platanoides	Diffuse	Deciduous	Broadleaf	2	Petrokas, Baliuckas, and Manton 2020
Acer psuedoplatanus	Diffuse	Deciduous	Broadleaf	2	Petritan, Von Lüpke, and Petritan 2007
Ailanthus altissima	Ring	Deciduous	Broadleaf	1	Knüsel et al. 2017

Alnus glutinosa	Diffuse	Deciduous	Broadleaf	1	Petrokas, Baliuckas, and Manton 2020
Betula	Diffuse	Deciduous	Broadleaf	1	Petrokas, Baliuckas, and Manton 2020
Carpinus betulus	Diffuse	Deciduous	Broadleaf	3	Petrokas, Baliuckas, and Manton 2020
Castanea sativa	Ring	Deciduous	Broadleaf	2	
Corylus colurna	Diffuse	Deciduous	Broadleaf	2	
Fagus sylvatica	Diffuse	Deciduous	Broadleaf	3	Paluch and Jastrzebski 2013
Fraxinus excelsior	Ring	Deciduous	Broadleaf	2	Petrokas, Baliuckas, and Manton 2020
Juglans nigra	Diffuse	Deciduous	Broadleaf	1	Peters, McFadden, and Montgomery 2010
Juniperus thurifera	Coniferous	Evergreen	Needleleaf	1	
Larix decidua	Coniferous	Deciduous	Needleleaf	1	Schulze et al. 2007
Metasequoia glyptostroboides	Coniferous	Evergreen	Needleleaf	1	
Picea abies	Coniferous	Evergreen	Needleleaf	2	Paluch and Jastrzebski 2013
Picea sitchensis	Coniferous	Evergreen	Needleleaf	3	Chapin et al. 1994
Pinus cembra	Coniferous	Evergreen	Needleleaf	2	Bianchi, Bugmann, and Bigler 2021

Pinus nigra	Coniferous	Evergreen	Needleleaf	1	Vayreda et al. 2013
Pinus sylvestris	Coniferous	Evergreen	Needleleaf	1	Paluch and Jastrzebski 2013
Pseudotsuga menziesii	Coniferous	Evergreen	Needleleaf	2	Ishii and Ford 2002
Quercus faginea	Ring	Deciduous	Broadleaf	2	Kouba et al. 2015
Quercus ilex	Ring	Evergreen	Broadleaf	2	Kouba et al. 2015
Quercus petraea	Ring	Deciduous	Broadleaf	2	Petrokas, Baliuckas, and Manton 2020
Quercus pubescens	Ring	Deciduous	Broadleaf	2	Kunstler, Curt, and Lepart 2004; Toïgo et al. 2018
Quercus robur	Ring	Deciduous	Broadleaf	2	Petrokas, Baliuckas, and Manton 2020
Tilia cordata	Diffuse	Deciduous	Broadleaf	3	Petrokas, Baliuckas, and Manton 2020
Ulmus	Ring	Deciduous	Broadleaf	2	Petrokas, Baliuckas, and Manton 2020

Table 8.5. Comparison of the models with different distributions and their AIC values.

Model distribution	**Model function**	**AIC values**
Poisson	pr_length ~ min_twd_stan_max + temp_max * spei_min + wood_anatomy + period_number + (1|site/series) + (1|year)	71756.61

Poisson with random ID effect	pr_length ~ min_twd_stan_max + temp_max * spei_min + wood_anatomy + period_number + (1|site/series) + (1|year) + (1|index)	61024.24
Zero-inflated Poisson with random ID effect	pr_length ~ min_twd_stan_max + temp_max * spei_min + wood_anatomy+ period_number + (1|site/series) + (1|year) + (1|index), zi~ spei_min + temp_max + min_twd_stan_min + wood_anatomy + period_number)	61038.24
Negative binomial	pr_length ~ min_twd_stan_max + temp_max * spei_min + wood_anatomy+ period_number + (1|site/series) + (1|year)	61114.61

Appendix D

Table 8.6. Summary of the measures to increase resilience to disturbances mentioned in the literature and the first set of interviews.

Proposed management practices	**Specific measures**	**n of studies (N=165)**	**n of interview respondents (N=42)**	**% of studies**	**% of interview respondents**
Convert to and increase mixed-species management	Mixed species management	17	31	10	74
	Avoid monocultures	1	2	1	5
	Maintain genetic variation	2	0	1	0
Favour natural regeneration	Natural regeneration	3	5	2	12
	Enhance advanced regeneration beneath canopy	0	1	0	2
Remove biomass to fire-resilient forest	Creating fuel breaks	6	0	4	0
	Prescribed burning	23	2	14	5
	Mechanical fuel alteration	14	1	8	2
	Grazing	4	0	2	0
	Fire suppression	1	0	1	0
	Establish open forest	0	1	0	2
	Have fire prevention system	0	1	0	2
Favour native tree species	Have strict rules on what can be planted	0	1	0	2

	Use indigenous species	0	10	0	24
Favour best adapted tree species (both native and exotic) with active management	Artificial planting and choosing proper genotype	10	0	6	0
	Introducing new species/assisted migration	2	2	1	5
	Selection of planting site	1	0	1	0
	Using suitable/adapted tree species	0	5	0	12
Create heterogeneous forest structure and manage competing vegetation	Selection cutting	4	0	2	0
	Gap cutting	4	0	2	0
	Continuous cover forestry	2	0	1	0
	Heterogeneous landscape	2	0	1	0
	Variable retention	1	0	1	0
	Restoration cutting	1	0	1	0
	Increased structural diversity	0	9	0	21
	Seedling culture	1	0	1	0
	Girdling	1	0	1	0
	Steaming	1	0	1	0
	Cover cropping	1	0	1	0
Favour long rotation age and deadwood	Leaving deadwood to the forest	2	3	1	7
	Long rotation age	1	1	1	2
	Setting forest aside	0	1	0	2

Intensify forest management with denser stands and shorter rotation age	Short rotation period	7	1	4	2
	Dense stands	2	1	1	2
	Clear cutting	3	0	2	0
	Diverse clone plantation	1	0	1	0
Change to suitable thinning and harvesting regime to avoid disturbances	Plowing	0	1	0	2
	Different thinning regimes	32	3	19	7
	Pruning	1	0	1	0
	Coppicce	1	0	1	0
	Suitable planting lines	0	1	0	2
	More gradual forest edges	0	1	0	2
	Broadleaved shelterbelts	0	1	0	2
	Pro sylva	0	1	0	2
Manage game and damage by small mammals	Remove logging residuals	2	0	1	0
	Increased game management	5	3	3	7
	Chemical repellents	6	0	4	0
	Tree guards	2	0	1	0
	Adding diversionary food	2	0	1	0
	Fencing	1	0	1	0
	Considering fauna in forest planning	0	1	0	2
Manage insect and	Biological control	14	1	8	2
	Insecticides	6	1	4	2

pathogen outbreaks	Enhancing presence of natural predators	6	0	4	0
	Insect trapping	7	0	4	0
	Monitoring	5	2	3	5
	Treating ground vegetation	3	0	2	0
	Planting non-host species around the stands	3	0	2	0
	Mechanical control	1	0	1	0
	Stump logging	1	0	1	0
	Maintain diverse underground vegetation	1	0	1	0
	Storing salvage logged wood nearby forest	1	0	1	0
	Keep mixed stands next to plantations	1	0	1	0
	Integrated pest management	1	1	1	2
	Reduce host tree density	1	0	1	0
	Research on pests and diseases	0	1	0	2
Maintain forest health	Salvage logging	8	0	5	0
	Sanitary cutting	8	2	5	5
Work with a forest	Planning of forest retention and cutting areas	15	1	9	2

management plan	Adding risk factor to forest management plans	3	1	2	2
	Having sustainable management concept	0	1	0	2
	Optimizing harvesting and salvage cutting areas	2	0	1	0
	Opening forest tracks	1	0	1	0
Consider soil and site preparation accordingly	Draining	1	1	1	2
	Using fixed forest roads	0	2	0	5
	Liming soils	0	2	0	5
	Retaining water in the forests	0	2	0	5
	Conserve and restore soil quality	0	3	0	7
	Preserving understory vegetation	0	1	0	2
Increase the knowledge of the experts and general public	Forest functions	0	1	0	2
	Suitable provenances	0	1	0	2
	Risks to forests and humans	0	1	0	2

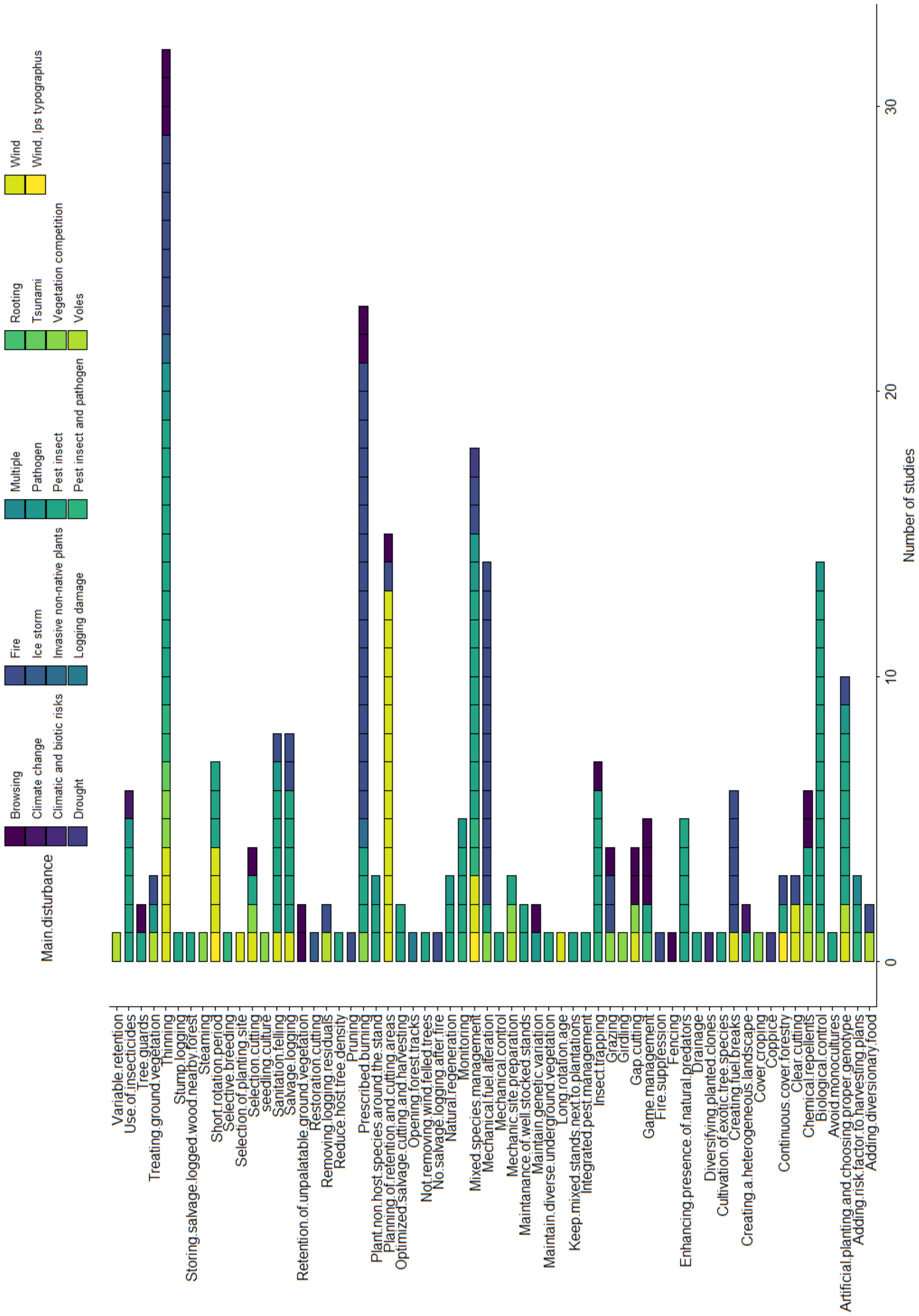


Figure 8.16. The identified measures to increase resilience to disturbance from the literature review.