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Review article

Ecological assessment of forest management approaches to develop resilient forests in the face of global change in Central Europe

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A R T I C L E I N F O

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A B S T R A C T

The effects of global change pose major challenges for both practical forest management and forest ecological research if European forests are to be managed in such a way that they can continue to provide their many services to people in the future. The number of studies on impacts of global change on forest ecosystems has increased enormously over the last decade, but the evidence on how to improve the resilience and resistance of forests is of varying quality and in some cases contradictory. For that reason a group of experts from the Ecological Society of Germany, Austria and Switzerland (GfOe), Section Forest Ecology decided to review the relevant scientific information and to assess its degree of confidence to provide guidance for future forest adaption options. Our review of research on the impact of global change on European forests and associated forest management strategies to adapt forests identified 35 scientific statements that were grouped into the following thematic priorities: (1) selection of tree species and promoting diversity, (2) genetics, (3) forest structures, (4) forest functions, ecosystem services and nature's contribution to the lives of people, (5) silvicultural systems, (6) natural regeneration, successional processes and wildlife management, and (7) future research and monitoring methods. Our analyses showed that most of the statements reflect validated research findings. However, many of them were incomplete and would not yet allow transfer to broad application in the form of silvicultural adaptation strategies. Future studies should focus on the identification of climate-resilient tree species and provenances, their regeneration processes and their resistance to pathogens and pests under drought conditions. Species- and site-specific scientific findings must be translated into silvicultural techniques/ measures such as the determination of tree species mixtures, thinning and harvesting intensities and tree regeneration methods. We identified significant gaps in the application of forest monitoring practices needed to obtain reliable information on the provision of ecosystem goods and services. This review provides a comprehensive basis to develop a roadmap for future forest adaptation research to improve our level of confidence for science-based management recommendations.

Introduction

Forest ecosystems are crucial for regional water and carbon cycles (Bonan, 2008), and they provide numerous "ecosystem goods and services" (Glatthorn et al., 2021). In Central Europe forests are the most diverse and species-rich habitats in the cultural landscape (Uhler et al., 2021). This highlights the importance of developing and applying forest management concepts that aim to sustain these ecosystems in order to maintain biodiversity and functionality, and to mitigate the effects of global change.

A special feature of forest management has always been dealing with uncertainty due to long life cycles of trees and related organisms. Global change dramatically increases this uncertainty about how forests, their tree species, species compositions and structures will develop (Lindner et al., 2014; Wagner et al., 2014). Drought and heat events have been documented to an increasing extent (Forzieri et al., 2021; Robinson et al., 2021; Rousi et al., 2022; Hermann et al., 2023; Felsche et al., 2024) and are expected to rise dramatically in frequency and intensity in the coming decades (Fischer et al., 2021; Hermann et al., 2023). They pose a major threat to European forests (Bastos et al., 2021), with serious consequences for all related natural and human systems (Zeder & Fischer, 2020; Kautz et al., 2022; Niggli et al., 2022; Rohde, 2023). In the last decade, Central Europe has experienced the most extreme global change-type drought events ever directly recorded (Schuldt et al., 2020), events unprecedented in the previous 2000 years (Büntgen et al., 2021). Mean growing season (April to October) air temperatures of 3.3 °C above the long-term average were documented across Austria, Germany and Switzerland in 2018 (Schuldt et al., 2020). Furthermore, Central Europe is heating up faster than other parts of the world and mean annual air temperature has already increased by 1.5 °C in Germany from 1881 to 2018 Umweltbundesamt (German Environment Agency) 2023.

The physiological stress arising for trees is caused by low soil water availability accompanied by a high vapour pressure deficit (Duursma et al., 2019; Grossiord et al., 2020; Schuldt et al., 2020; Kahmen et al., 2022). Changes in the above- and below-ground resource distribution in trees will ultimately lead to the drought-induced death of the trees when the internal water and carbon stores are exhausted (e.g., Bloom et al., 1985; Meier & Leuschner, 2008; Nikolova et al., 2011, 2020; Cochard et al., 2021; Walthert et al., 2021). The death of trees of certain species due to extremely high temperatures in combination with drought (Breshears et al., 2009), with mortality ultimately brought about by the interaction of many abiotic and biotic factors (Eamus et al., 2013), is being detected more and more frequently worldwide (Hammond et al., 2022). Massively elevated tree mortality rates have been documented for all major tree species following the 2018–2020 and 2022 droughts in Central Europe (Schuldt et al., 2020; Obladen et al., 2021; Senf & Seidl, 2021a; Gazol & Camarero, 2022), even in species previously considered drought tolerant such as Scots pine (*Pinus sylvestris* L.) (cf., Leuschner & Meier, 2018; Bose et al., 2024).

These developments have caused unprecedented levels of forest disturbance that pose a large challenge for forest management (Gardiner et al., 2013; Gregow et al., 2017; Oeser et al., 2017; Senf & Seidl, 2021a; WBW, 2021; Hermann et al., 2023). Most public forest management agencies and their research institutions in Central Europe have already started to develop concrete management strategies to respond to these climate changes and increasing uncertainty (e. g. Rebetez et al., 2006; Vacek et al., 2023). While these agree on certain actions, such as the conversion of pure, high-risk stands to mixed forests, other suggested adaptation options differ more strongly, depending on how much emphasis is placed on economic, ecological and social values of forests. For example, there is an intense debate taking place amongst scientists and foresters regarding the amounts of dead wood to be retained in disturbed forest areas (Bütler & Schlaepfer, 2004; Müller & Bütler, 2010; Leverkus et al., 2021), the selection of tree species (Krumm & Vítková, 2016; Hauck, 2023), and whether non-management might be an option (Jandl et al., 2019; Thorn et al., 2020). One difficulty in making recommendations is that past events are only partially representative of what can be expected in the future (Bugmann, 2020). Moreover, owing to the longevity of trees, silvicultural decisions made today should place forests on suitable development trajectories for the next hundred years or more, which is a major challenge given the uncertainty of the future. This highlights the need for a robust scientific assessment of the management strategies recommended to increase the resistance, resilience and adaptive capacity of future forest ecosystems and to identify the most significant knowledge gaps that need to be addressed (Himes et al., 2023). Forests managed for adaptive capacity are characterized by a high degree of resistance (low impact to their condition and function in the face of disturbance) and resilience (Hörl et al., 2020), i.e. they recover to their previous state or even benefit from this disturbance (Thorogood et al., 2023). In times when the extent and frequency of extreme events caused by climate change are increasing and disturbances are inevitable, ecosystem resilience of managed forests becomes increasingly important (Messier et al., 2019).

To evaluate silvicultural and other adaptation approaches, it is important to consider the nature of the ecosystem services to be provided (MA, 2005). The consideration of future ecosystem services provision with socio-cultural relevance recognizes the significance of the impact at all spatial levels (local, regional, global) and on all areas of human life (Intergovernmental Platform on Biodiversity & Ecosystem Services, IPBES 2016). This is also of increasing importance in the densely populated areas of Central Europe, where forests are subject to particularly high utilisation pressure and multiple social demands (Ellis et al., 2019). For example, certain stands may achieve high levels of timber production at the expense of carbon storage and biodiversity (Schwenk et al., 2012; Assmuth et al., 2021; Messier et al., 2022). In view of climate change, however, the problem is not only that not all ecosystem services are provided equally well, but also the question of the extent to which forests will still be able to provide ecosystem services to the usual extent in the future (Díaz et al., 2018; Manning et al., 2018; Kadykalo et al., 2019). In this context, the "nature's contribution to people" (NCP) approach is used to establish a realistic relationship between global change and the resulting consequences and the perception of changes to the availability of ecosystem services for humans (Díaz et al., 2018; Hill et al., 2021; Simonienko et al., 2023; Isaac et al., 2024; Queirolo et al., 2024). According to Hill et al. (2021, p. 910), the NCP approach offers, "space for the recognition of diverse and evolving culturally mediated ideas about what people derive from, and co-produce with, nature." NCP focuses on the interplay between humans as part of nature and as the main influencing factor of global change, but also as a directly regulating factor, for example, in forest management (Christie et al., 2019; Martín-Forés et al., 2020).

Building on this theoretical background, we focus here on the establishment of climate-resilient multifunctional forests from an ecological perspective, without explicitly taking economic considerations into account. Irrespective of their original political context, the evaluation categories of the NCP (see methodological description) are used in this article to assess the level of knowledge and confidence associated with suggested forest adaptation options, hereafter called statements. These categories are already established and have proven useful for such purpose. The individual steps taken in this article have the following objectives:

- incorporate the expertise of the scientists involved to thematically structure existing statements on strategies to manage forests in the face of global change;
- determine and evaluate the validity of these statements based on scientific knowledge and publications;
- identify knowledge gaps, contradictory results and necessary research;
- discuss the inclusion of uncertainties in practical forest management for topics identified as being particularly relevant, such as tree species selection, drought stress mitigation and multifunctionality.

Methodological approach

This paper is the result of a workshop organised by the Forest Ecology Division of the Ecological Society of Germany, Austria and Switzerland (GfOe). Over two days, 53 experts from the fields of forest ecology and conservation, silviculture, landscape ecology, ecophysiology, botany and zoology met online to develop and discuss four thematic priorities related to climate change and forest ecosystems in Central Europe. The workshop was motivated by publications in German-speaking countries aimed at informing forest managers about goals and measures to promote resistance, resilience and adaptive capacity of future forest ecosystems in the face of global change. The first step was to identify and group the topics in these management recommendations. The result is a systematic classification of the many individual recommendations into the seven main groups (Table 1). The statements compiled here are obviously given high priority in the practice-oriented literature and in the recommendations for silvicultural measures. This also means that the authors of these publications expect that successful measures for adapting forests to global change can be implemented in this way. On this basis, we carried out our in-depth analysis, to assess how well these statements are supported by scientific evidence. We identified and categorized the core topics from these practice-relevant publications and checked, against the background of our own scientific expertise, whether these statements are actually supported by scientific studies or empirical evidence and are not merely based on expert knowledge.

The following thematically overarching blocks were identified during the workshop: 1) selection of tree species and diversity, 2) genetics, 3) forest structures, 4) forest functions, ecosystem services and nature's contribution to people, 5) silvicultural management systems, 6) natural regeneration, successional processes and wildlife management, and 7) future scientific research and monitoring methods. The 35 general statements and their allocation to the seven core blocks formulated by our consortium of scientific peers were then reviewed by smaller groups for scientific evidence. The smaller groups were assigned according to the scientific expertise of the co-authors. As there are always thematic overlaps, the co-authors were also able to work on different statements in different compositions of the expert teams. The composition of interdisciplinary teams of experts was intended to enrich the development of the statements, but was also a major challenge. Before work began in the statement-related groups, a decision was made on the selection of suitable evaluation categories. To assess the degree of confidence in each statement, a four-level categorisation was used, based on the quantity, quality, and agreement of evidence for each statement ('four-box model', adopted from the Intergovernmental Science-Policy

Table 1

Summarising statements addressing the most important goals and measures required to increase the resilience of future forest ecosystems to global change through management strategies in Germany, Switzerland and Austria. (The following references were used: 1 – BfN (Bundesamt für Naturschutz/ Federal Agency for Nature Conservation), 2020; 2 – NABU (Nature & Biodiversity Conservation Union), 2019; 3 – DVFFA (Deutscher Verband Forstlicher Forschungsanstalten) 2019; 4 - WBW (Scientific Advisory Board on Forest Policy), 2021; 5 - Federal States: Bolte et al., 2009a; Ministry of the Environment, Climate Protection and the Energy Sector Baden-Württemberg, & LUBW (State Institute for the Environment Baden-Württemberg), 2021; StMUV (Climate-Report Bavaria), 2021; Schröder et al., 2014; MLUK (Ministerium f..r Landwirtschaft, Umwelt und Klimaschutz des Landes Brandenburg) 2020; HessenForst, 2017; LU (Ministry of Agriculture, Environment and Consumer Protection), Mecklenburg-Western Pomerania, 2010; NW FVA (Nordwestdeutsche Forstliche Versuchsanstalt, and Niedersächsische Landesforsten), 2019; Ministry of Climate Protection, Environment, Agriculture, Nature & Consumer Protection of North Rhine-Westphalia, 2014; MKUEM (Ministerium für Klimaschutz, Ministerium für Klimaschutz, Umwelt, Energie und Mobilität), 2020; SMUL (Saxony State Ministry for Environment and Agriculture), 2015; Ministerium für Umwelt, Landwirtschaft und Energie des Landes Sachsen Anhalt, and Nordwestdeutsche Forstliche Versuchsanstalt, 2020; Profft & Frischbier 2008a,I. b; Frischbier et al. 2010, Thuringia; 6 - Brang et al., 2016, Switzerland; 7 – BFW (Bundesforschungs- und Ausbildungszentrum für Wald, Naturgefahren und Landschaft), 2012, Austria; 8 – Zischg et al., 2021, Switzerland; 9 – Glatthorn et al., 2024, Austria, Switzerland, Germany).

I. Selection of tree species and promoting diversity
Natural forest conditions should be used as reference systems. Habitat connectivity of different floristic and faunal groups must be ensured.[1]
Future forest community constellations differ from current potential natural vegetation.[5,8]
Near-natural forests dominated by deciduous tree species and high overall species diversity with various species constellations should be favoured. Species diversity reduces risk of abiotic and biotic damage. [2,3,4,6,7]
Pioneer species are likely to be better adapted to climate change than climax tree species and are therefore increasingly important for forest management.[3,5]
A high degree of ecological continuity and continuity of habitats at different spatial scales is needed.[4]
Alternative and non-native tree species have the potential for integration under future climate conditions.[3,4,5,9]
Tree species distribution should be related to bioclimatic envelopes and not oriented along their current site and climate limit.[9] The differentiation between tree species-specific local and regional climate conditions is important and should be used as a dynamic element, because of increasing uncertainty.
The adaptation of tree species to future climate conditions should be based on empirical information.[5]
More detailed relations of tree species to temperature, water and nutrient availability during the vegetation period must be considered. A positive climate adaptation potential is predicted for Scots pine.[5]
The importance of rare tree species increases. Shifts in tree species competition are presumed.[5]
Trees with long crowns show a higher tendency towards drought resistance.[6]
Regional tree species compositions are adapted to the temperature, the amount and temporal distribution of precipitation and topographical parameters. Increasing risk is assumed for productive Norway spruce stands. The decrease of the proportion of Norway spruce should be pursued, but in the alpine region an increase of growth is expected.[5,7]
II. Genetics
Natural selection processes should be promoted through forest management.[1]
The use of provenances adapted to present and future climate conditions is recommended.[2,3,4,5]
High intraspecific genetic diversity ensures the potential of trees for future adaptation. Genetic differences within the distribution range of tree species should be carefully monitored. High numbers of pollinators and seed producing trees should be ensured. Populations should include a high number of individuals. The results of previous provenance studies are of limited use.[5]
Tree species with high local and regional genetic diversity have a higher potential for future adaptation to climate extremes such as drought or frost periods.[5,6,7]
Drought adapted provenances are preferred.[6]
Provenances with higher frost resistance or snow stability are preferred.[7]
III. Forest structures
Natural forest structures should be used as a reference.[1,4]
The overall proportions of mixed forests should be enhanced, e.g., by forest restoration and transformation.[1,2,3,4,5,6]
Regular and staggered thinning is recommended to increase the stability of trees and forest stands to windthrow and drought stress.[3]
Forest management should aim for adapted, highly productive and richly structured mixed forests (structural diversity). Future forest structures should combine various tree age and size classes in space and time. Structural heterogeneity should be promoted through multiple canopy layers and small-scale tree species mixtures ranging from single trees up to larger groups of trees.[2,4,5,6,7]
At the larger spatial scale mosaics of different stand types should be combined. Artificial regeneration should be used to increase the spatial heterogeneity. Forest structures should form future habitats in a reasonable scope.[5]
Higher forest densities have positive effects for rockfall protection in mountain regions.[7]
IV. Forest functions, ecosystem services and nature's contribution to people
The proportions of dead wood must be increased and integrated into management concepts to create diverse habitat conditions, nutrient and water reserves.[1,2,5] Dead wood of various tree species, different dimensions and degrees of decomposition helps to create diverse habitat conditions.[4] Accumulations of dead wood can increase the risk of fire during drought periods.[5]
Forest micro-climate conditions and the related water balance and soil functions should be promoted through management.[1,3]
Forests provide a variety of forest functions and ecosystem services that are used by a large number of forest owners [1,2,5,6] and compensated by public funds.[4]
The use of long-lived wood products should be supported to extend carbon storage.[4]
The importance of ecosystem services differs between local and regional scales. Important ecosystem services linked to forest ecosystem management are carbon storage, soil protection, closed nutrient cycles and water retention. The management of carbon storage should be supported by the reduction of large disturbed forest areas. Forest management should create habitats at different spatial scales.[5]
Important ecosystem services linked to the management of forest ecosystems are carbon storage and filter effects to increase water quality. Forest management should increase biological diversity.[6]
The forest protection function must be ensured in mountain regions.[7]
V. Silvicultural systems
New silvicultural methods must be developed to mitigate the negative effects on the forest's inner- climate. Thinning should be intensified to improve water availability for individual trees.[1]
Near-natural forests with a cool and humid forest climate should be established by reducing thinning frequency and intensity.[2]
The increase of uncertainty caused by higher abiotic and biotic risks is expected, followed by increasing forest protection problems.[4,6,7]
Thinning intensity should be increased and production cycles reduced/adapted in exposed forest stands to increase individual tree and stand stability, to reduce competition for site resources among trees, to achieve higher silvicultural flexibility and lower risk of large-scale disturbances, especially in Norway spruce. Thinning deficits should be avoided to support individual tree stability.[3,4,5,6,7]
Forest management should limit total stand volumes. Disturbed areas of different sizes should be given special consideration in forest management planning and related silvicultural actions. Adaptive management with flexible planning periods must be developed.[4]
Silvicultural methods target the spread of risk and the development of climate-adapted methods. Silvicultural measures should reduce risk of abiotic and biotic damage. These measures must include site and growth specific considerations and consider the economic cost. Risk thresholds must be defined according to site conditions and increased uncertainty must be integrated in forest planning. Thinning and regeneration measures (forest restoration) should support deciduous tree species and increase the proportions of mixed stands. Shelterwood systems can be used to reduce climate extremes like late frosts.[5]

(*continued on next page*)

Table 1 (*continued*)

I. Selection of tree species and promoting diversity
Forest management concepts should be developed that include both active and passive adaptation. Individual tree stability should be increased by thinning. Various sizes and types of cuttings and gaps should be initiated. An early regulation of competition and tree species combinations is necessary.[6]
The regulation of competition by thinning is necessary.[7]
VI. Natural regeneration, successional processes and wildlife management
The establishment of site-adapted tree species through natural regeneration is preferred.[1,2,4] Artificial regeneration methods like advance planting[3] or direct seeding can actively support the change of tree species composition to more adapted forest communities.[4,5]
A proportion of about 10 % of forest areas should be left unmanaged for free successional development.[2]
Priority areas should be defined to establish regeneration actively.[3]
Light-demanding, early successional and pioneer tree species should be integrated in existing silvicultural systems.[4,6] Drought adapted and fast-growing pioneer tree species (e.g., silver birch, European aspen) should be integrated into existing silvicultural systems. On disturbed areas, the succession of pioneer tree species can provide a nurse crop to protect future late-successional tree species. Additional planting is necessary to increase the proportion of mixed forests and to decrease the time needed for conversion. The frequency and capacity for fructification, seed production and masting are criteria of the species-specific potential of climate adaptability. Long regeneration periods should involve different masting years and a high number of seed producing trees. Early spacing and non-commercial thinning are needed to control competition and maintain tree species diversity.[5]
Continuous layers of naturally regenerated mixed tree species established by group shelterwood cutting are preferred. Long regeneration periods should be used to include different seed years and a sufficient number of seed producing trees. Additional retention trees should be left, particularly on large disturbed areas.[6]
The intensity of game browsing often determines the success of the regeneration of particular tree species.[1,2,3,4,5,6,7] Therefore, the densities of browsing ungulates should be kept to a level that facilitates regeneration of all tree species.[5,6,7]
VII. Future scientific research and monitoring methods
Current monitoring systems need to be expanded and complemented[1] to measure the changes in site conditions and the main factors causing abiotic and biotic disturbance and damage.[4,5] Interdisciplinary research networks operating at different spatial scales, growth trials and long-term study areas should be established to evaluate forest protection systems.[1,3,5]
An intensification of basic and applied forest research is needed.[2, 4]
New research approaches should include ecosystem services and risk analyses.[3]
High-resolution climate data can be used as a basis for the selection of future tree species. Studies on the establishment, development and growth of non-native tree species and the related abiotic and biotic risks should be initiated.[4] Further tests are needed for non-native species to determine their physiological and genetic adaptability to climate change.[5]
Genetic resources and provenances must be continuously tested with regard to their stress tolerance by means of in-situ and ex-situ experiments. The effects of climate extremes can be tested experimentally.[5]
The revision of extended site information maps is necessary, taking into consideration the local and regional climatic water balance and identifying critical sites. The development of site related and physiological indicators relevant for tree species is needed. Future forest development types must be defined and scenarios under changing climate conditions developed. Forest planning models are needed. Integrative forest protection measures should be developed. [5]
Silvicultural experiments must be established to test adaptive management strategies.[6]
More detailed information about future site conditions is required, while the continuous improvement of climate forecasts and the integration of uncertainty are also needed. More detailed information about the factors influencing insect pests is needed.[7] Remote sensing methods can be used to control pest insects and diseases.[5]

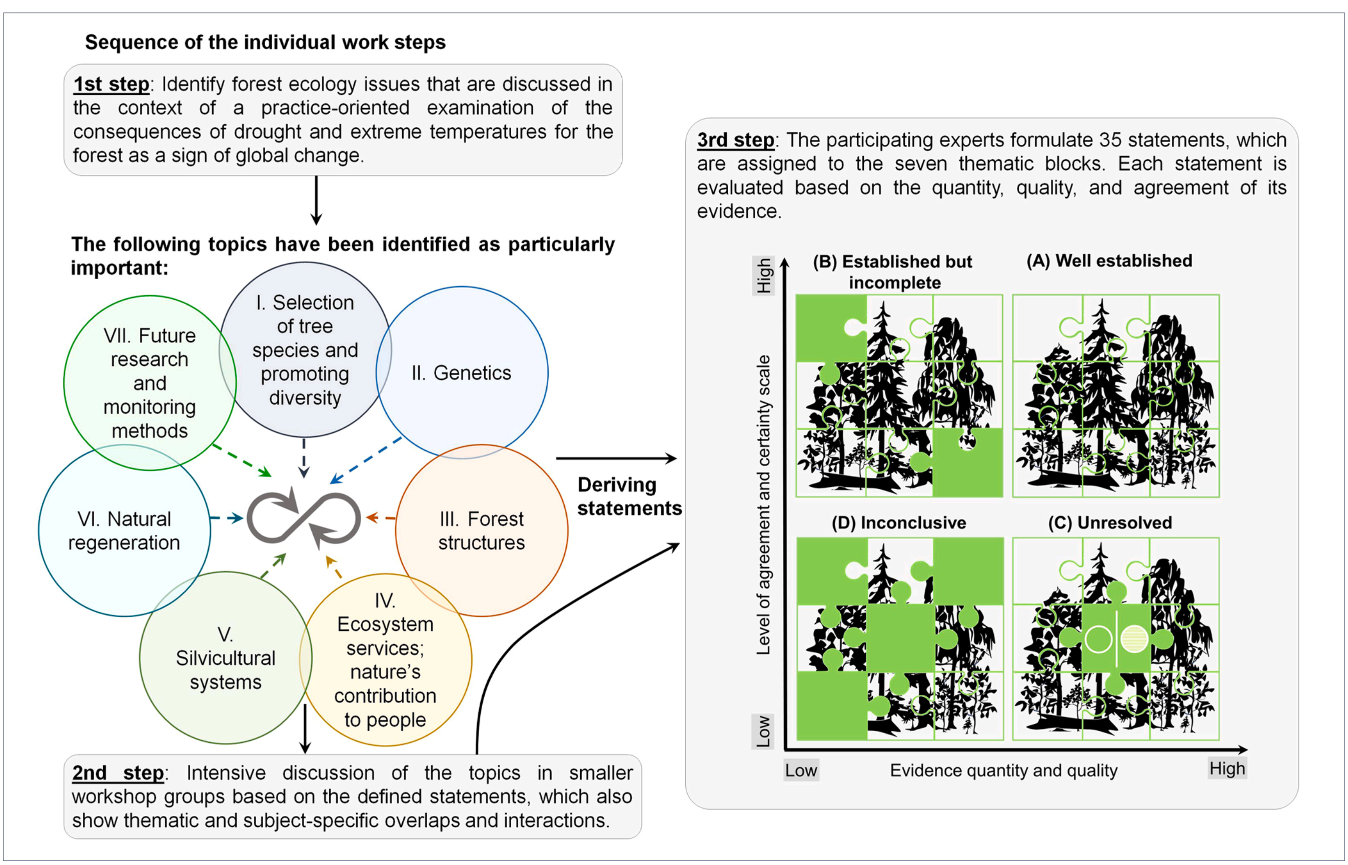

Fig. 1. Schematic overview of the three-step process to (1) identify 35 general statements, (2) formulate seven specific core topics, and (3) evaluate each statement's evidence according to the adapted "four-box model" (IPBES 2016).

Platform on Biodiversity & Ecosystem Services, IPBES 2016, Fig. 1):

- Well established: supported by comprehensive meta-analyses or other syntheses or multiple independent studies that agree.
- Established but incomplete: general agreement although only a limited number of studies exist; no comprehensive synthesis and/or the studies that exist address the question imprecisely.
- Unresolved: multiple independent studies exist but conclusions are not in agreement.
- Inconclusive: limited evidence, recognizing major knowledge gaps.

Although IPBES is primarily a policy-oriented platform, we decided to use this methodological approach to evaluate the evidence for the statements, because the four levels allow a good gradation of the ratings. The final classification of the statements was based on the assessment of the respective expert group and after reviewing the available scientific publications.

Results of the evaluation process

The preliminary work undertaken by the workshop groups was subsequently used as the basis for a more intensive analysis of the thematic blocks and led to the formulation of 35 statements that briefly summarise the current state of research for each thematic area. A validation by existing studies and publications facilitated the final evaluation using the IPBES categories approach. Most of the statements (22/35) fell into the category 'established but incomplete' (B), highlighting that general agreement exists for several statements but further studies are needed for a comprehensive synthesis. The distribution of all 35 statements across the four levels of confidence is depicted in Fig. 2.

The detailed information on the individual statements including the classification and evaluation can be found in Table 2.

Selection of tree species and promoting diversity

For most of the recommended actions summarised in Table 2, the selection of tree species or provenance under consideration of local site factors and regional climatic aspects is of high importance in terms of ensuring the continuity of ecosystem services (Albert et al., 2017; WBW 2021). Climate change will lead to a shift in bioclimatic zones at the local and regional level (Zischg et al., 2021) and it is highly likely that climates will arise that have not yet existed in central Europe (Buras & Menzel, 2019; Illés & Móricz, 2022). Given their longevity, tree species currently selected under forest management will most likely have to cope with remarkable changes to the climate until the end of the 21st century. This highlights the need for a mechanistically sound classification of the drought- and heat-tolerance of temperate tree species and provenances in order to model future species distributions at high spatial resolution.

1st Statement: site requirements of native and non-native tree species are known. (established but incomplete)

Ellenberg's indicator values described the niche and habitat parameters of central European tree species that determine the establishment success and growth (Ellenberg, 1974; Tichý et al., 2023). The developed ecograms are one basis for more recent approaches describing edaphic and climatic habitat requirements for common native and some non-native tree species (Ellenberg & Klötzli, 1972; Ellenberg, 1988; Roloff & Grundmann, 2008; Bartsch et al., 2020; De Avila et al., 2021). Soil physical properties related to water availability seem to be more important than soil chemical properties, as most temperate tree species native to central Europe occur on different sites with different base saturation and outside their optimal growth conditions (Seltmann et al., 2021; Brichta et al., 2024). The optimal distribution range of central European tree species is, therefore, primarily determined by physical conditions of the soil and climate (Gauer, 2014). There have been few systematic studies of the hydraulic properties of forest soils, however, which are subject to uncertainty (Puhlmann & von Wilpert, 2012), or on the effective rooting depth of tree species as a function of physical soil properties and the type of stand establishment (i.e., planting, direct seeding).

2nd Statement: the classification of the drought and heat resistance of common native tree species is based on sound physiological data. (inconclusive)

To date, no robust scientific assessment of the resistance to weather extremes is available for central European tree species. Available indices describing drought resistance originate from Ellenberg's indicator values and are based on habitat preferences only, complemented by personal observations (Niinemets & Valladares, 2006; Roloff & Grundmann, 2008; Leuschner & Meier, 2018). Consequently, Ellenberg's indicators should be interpreted with caution as they do not consider climatic extremes and the need for robust empirical plant physiological data should be reiterated at this point. Initial progress has been made in this area in the recent past (Kahmen et al., 2022; Leuschner, 2024; Leuschner & Meinzer, 2024; Hauck et al., 2025).

3rd Statement: climatically analogous regions are one way of identifying climate-resistant tree species for future site conditions. (inconclusive)

Climate analogues, such as those developed for agriculture (Ramírez-Villegas et al., 2011) and for cities (Rohat et al., 2018; Esperon-Rodriguez et al., 2022), have recently been proposed to convey projections of forest sites with statistically similar climates across space and time (Hallingbäck et al., 2021; Mette et al., 2021). These analogues are accessible to forest owners and managers. The Swiss 'Tree App' (Brang et al., 2020) is based on the definition of analogous site types through a projected shifting of elevation belts (Frehner et al., 2018). The latter approach was further developed and complemented with transformation pathways for three climate projections, also including forest site type information (Zischg et al., 2021). The resulting maps enable forest managers to take climate change into account when selecting

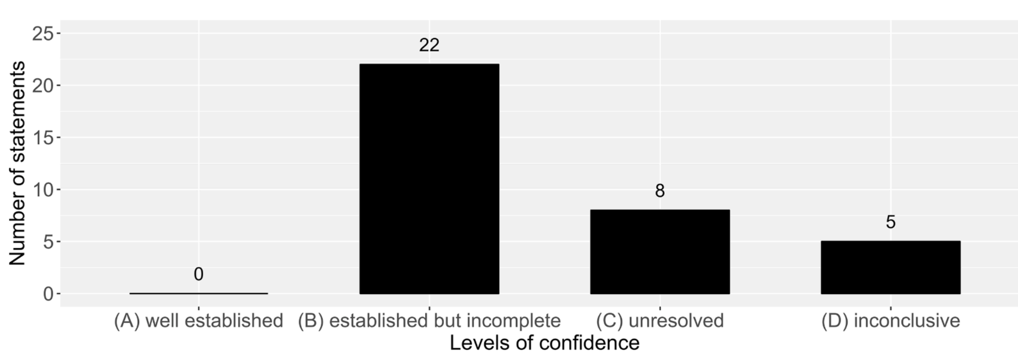

Fig. 2. Number of statements per level of confidence adopte d from IPBES (2016). For details, refer to Table 2.

Table 2
Statements developed during the workshop. (**A – Well established**: comprehensive meta-analysis or other synthesis or multiple independent studies that agree. **B – Established but incomplete**: general agreement although only a limited number of studies exist; no comprehensive synthesis and/or the studies that exist address the question imprecisely. **C – Unresolved**: multiple independent studies exist but conclusions do not agree. **D – Inconclusive**: limited evidence, major knowledge gaps.) NCP- "nature's contribution to people".

Thematic groups of statements	Assessment of evidence
I. Selection of tree species and promoting diversity	
Site requirements of native and non-native tree species are known.	(B)
The classification of the drought and heat resistance of common native tree species is based on sound physiological data.	(D)
Climatically analogous regions are one way of identifying climate-resistant tree species for future site conditions.	(D)
Plant traits necessary to evaluate a species' drought resistance are known.	(B)
Tree diversity can mitigate impacts of drought on forest ecosystems.	(C)
Global change increases the risk of outbreak of pest insects and pathogens in temperate forests.	(B)
Non-native tree species are host to native insects and native pathogens but might affect their communities.	(B)
Greater tree diversity reduces the risk of damage by herbivorous insects.	(B)
Greater tree diversity reduces the risk of damage from pathogens.	(C)
Non-native tree species have a high potential for drought resistance.	(C)
II. Genetics	
Global change influences the composition and spatial distribution of tree species.	(B)
Inter-population genetic variability enables the identification and selection of drought-adapted provenances.	(B)
The use of seeds or seedlings from locally adapted origins promotes the resilience of forests to future climate conditions.	(C)
Natural selection acting on seedlings in forests and after disturbance will result in the survival of more resilient genotypes.	(C)
III. Forest structures	
The diversity of the temporal and spatial arrangement of key structures in forests improves the resilience of forests to climate extremes.	(B)
IV. Forest functions and ecosystem services	
NCP are determined by the initial stand situation, the management type and the intensity.	(B)
Silvicultural systems have different effects on the categories of regulating service that are particularly important for mitigating climate fluctuations.	(C)
V. Silvicultural management systems	
Land-use history, and the degree of ecological continuity, strongly impact forest functioning and resilience.	(B)
Combining different silvicultural systems at larger spatial scales increases structural diversity, supports resilience and mitigates climate change effects.	(B)
Increasing inter-annual fluctuations and extreme weather conditions lead to adaptation problems in silvicultural management strategies.	(B)
Forest management and landscape-scale conservation planning require consideration of mixed ownership to cope with global change.	(B)
Continuous canopy cover and forest conversion with site-appropriate tree species maintain micro-climatically balanced conditions and relatively closed energy and nutrient cycles even in the face of global change.	(B)
VI. Natural regeneration, successional processes and wildlife management	
Extreme climate events affect all stages of regeneration such as flowers, seeds, seedlings and young plant development and associated processes within the regeneration cycle.	(B)
Frequent drought events increase overstorey tree mortality and impact upon tree species regeneration.	(B)
Positive and negative interactions between regenerated tree species will change depending on the developmental stage and the above- and belowground adaptation of the young trees to climate change.	(C)
Forest disturbances influence ecological processes, spatial patterns of ground vegetation, the regeneration of tree species, associated taxa and associated services.	(B)
Plant-associated microbiomes adapt to drought, helping trees and forest ecosystems respond to drought events.	(D)
Infestation with pests and pathogens affects the establishment of young host trees and changes the future species composition.	(D)
Species-specific browsing in interaction with the effects of climate change leads to structural changes in forest regeneration and the future species composition of forests.	(B)
VII. Future scientific research and monitoring methods	
Existing monitoring networks provide sufficient information on changes to forest condition.	(B)
Existing monitoring systems evaluate the ecosystem services provided.	(C)
Relevant soil properties are recorded with the degree of spatial accuracy adapted to the respective forest structure and management concept.	(B)
Physical and chemical soil properties can be regionalised in detail.	(B)
The monitoring of strictly protected forests provides information for the management and development of current and future forests.	(B)
Forest monitoring programmes contain information on low-value timber and non-native tree species.	(D)

'future suitable' tree species (Temperli et al., 2023). Both methods have already been integrated in regional silvicultural guidance, but further empirical testing and a broader scientific discussion is needed. Furthermore, climatic extremes are not covered by this approach. Beyond the illustrative value for tree species selection, climate analogues are expected to provide insights into projected ecosystem properties and visual examples of various silvicultural options (Mette et al., 2021). The latest approach projects the site potential based on the potential natural vegetation using process-based models at continental level (Hickler et al., 2012; Hengl et al., 2018) or finely resolved maximum likelihood projections of vegetation types (Fischer et al., 2019a). A critical point to be noted for this approach is that the future climate is unlikely to be the same as today's climate and a balance between vegetation characteristics and climate cannot be expected (Hobbs et al., 2018). This no-analogue problem must be more strongly incorporated into future considerations to be able to integrate the dynamics of physiological processes, structural and vegetation-related shifts, and changes in the natural disturbance regimes into management strategies (Pfeiffer et al., 2020; Gougherty et al., 2024). Thus, the transferability and dynamic projection of biotic interactions (competition, trophic chains, mutualism) and emergent ecosystem properties therefore requires future research and validation.

4th Statement: plant traits necessary to evaluate a species' drought resistance are known. (established but incomplete)

Tremendous efforts have been made to build up large databases (e.g., Kattge et al., 2020) and to use trait-based modelling approaches to estimate the impact of climate change on forested ecosystems and future species ranges (Zakharova et al., 2019; Xu & Trugman, 2021). Predicting mortality risk, however, remains challenging as commonly used tree traits such as height, wood density or specific leaf area are not mechanistically linked with drought resistance, which might explain controversial results (O'Brien et al., 2017). Plant hydraulic traits have successfully been linked to cross-species patterns of drought-induced tree mortality in multiple independent studies and comprehensive meta-analyses (Anderegg et al., 2016; Adams et al., 2017; Brodribb et al., 2019; Laginha Pinto Correia et al., 2019; Li et al., 2020; Nolan et al., 2021). Several complementary processes are involved (Trugman et al., 2021; Hajek et al., 2022). The strategy for regulating water potential is still largely undescribed and highly debated for most temperate tree species (but see Leuschner et al., 2019; Kahmen et al., 2022; Schumann et al. 2024; Waite et al., 2024), and species-specific adaptation strategies to drought need to be investigated (Hartmann et al., 2021). Combinations of tree traits or variables also highlight the specific trait syndromes needed to characterize a species' drought adaptation strategy, rather than focusing on individual traits alone (e.g., Choat et al., 2018; Blackman et al., 2019; Cochard et al., 2021). Trait syndromes of interest are known and have successfully been used to predict lethal desiccation time (Blackman et al., 2019; Petek-Petrik et al., 2023, 2023) as well as integrated in plant hydraulic models to predict future tree mortality events (e.g., Brodribb et al., 2019; De Kauwe et al., 2022). However, they are not yet available for most temperate tree species.

5th Statement: tree diversity can mitigate impacts of drought on forest ecosystems. (unresolved)

The importance of mixed-species forests in modulating the drought response (resistance and resilience) of individual trees and stands remains controversial for central Europe (Ammer 2019; Grossiord, 2020). Positive diversity effects have been documented (see Grossiord, 2020), although they seem to largely depend on species identity or local site and stand conditions rather than tree diversity *per se* (Hackmann et al. 2024). Importantly, a substantial body of research observed mixed, neutral or negative effects of diversity on drought responses (Metz et al. 2016; Jourdan et al., 2019; Vanhellemont al., 2019; de Streel et al., 2020; Espelta et al., 2020; Grossiord, 2020; Jourdan et al., 2020; Vannoppen et al., 2020; Gillerot et al., 2021; Jacobs et al., 2021; Martin-Blangy et al., 2021; Pardos et al., 2021). The controversial results could be due to species-specific neighbourhood effects (Hajek et al., 2022; Hackmann et al., 2024). In addition, different results are explained by the target variables considered, such as growth losses, individual tree mortality or the resilience of regeneration after drought. The underlying mechanisms, for example, resource partitioning, hydraulic lift, microclimate amelioration, biotic interactions, selection and statistical averaging effects but also potential mitigation effects, are far from resolved. The available information about the role of different metrics of diversity (compositional, functional, structural) on drought resistance and resilience also remains inconclusive.

6th Statement: global change increases the risk of outbreak of pest insects and pathogens in temperate forests. (established but incomplete)

Global change significantly increases the risk and intensity of pathogen and insect infestations. It affects the survival, reproduction, development, dispersal and distribution of pathogens and herbivores (Dale et al., 2001; Pureswaran et al., 2018; Simler-Williamson et al., 2019; Canelles et al., 2021). The relationship between tree species and the pathogens and pest insects adapted to them follows a natural dynamic, which is due to the high mobility of insects and their rapid reproductive cycles (Ramsfield et al., 2016). This interaction will change with the loss of the forest structure or changes in the tree species composition. Higher temperatures often enable the production of more generations of pest inescts (including, e. g. the bark beetle *Ips typographus*) per year (Wermelinger 2004; Haynes et al., 2014; Pureswaran et al., 2018; Bentz et al., 2019, Jacoby et al. 2019), and/or lower winter mortality (Pureswaran et al., 2018; Simler-Williamson et al., 2019). However, the effects of temperature on pest insects and pathogens seem to be species-specific (Haynes et al., 2014; Pureswaran et al., 2018), and may affect pest species directly when temperatures become too hot or through changes in abundances of antagonists (Jactel et al., 2019). Higher temperatures lead to physiological changes in tree defence mechanisms, altering the susceptibility of host trees (Wermelinger, 2004; Anderegg et al., 2015). Pest species may also be indirectly affected by changes in abundance of their natural mutualists, competitors and antagonists (Ayres & Lombardero, 2000; Jactel et al., 2019; Canelles et al., 2021). Warmer and wetter conditions favour pathogen pests, while warmer and drier conditions favour herbivore calamities (Seidl et al., 2017). Furthermore, the uncontrolled introduction of pests and diseases poses a particularly high risk, which is especially linked to anthropogenic factors such as trade and mobility (Roques et al., 2006; Pureswaran et al., 2018). Our ability to accurately predict the effects of interactions between trees, pests, pathogens and global change is rather limited at present.

7th Statement: non-native tree species are host to native insects and native pathogens but might affect their communities. (established but incomplete)

In a comprehensive review on the effects of the seven non-native tree species studied most with respect to their general effects on native biodiversity (and soil properties) in European forests (i. e. *Acacia dealbata, Ailanthus altissima, Eucalyptus globus, Prunus serotina, Pseudotsuga menziesii, Quercus rubra*, and *Robinia pseudoacacia*), Wohlgemuth et al. (2022) show that effects are species specific. Effects on insect diversity were often neutral for all these tree species, but several studies also showed negative effects, with a high proportion of negative effects being found on the Douglas fir (*Pseudotsuga menziesii*) and the Black Locust (*Robinia pseudoacacia*). Recruitment of native pest insect species was shown to be positively correlated with time since introduction and the geographic extent of tree plantations (Branco et al., 2015; Castagneyrol et al., 2016). The presence of congeneric native species facilitates the recruitment of specialist herbivores, including bark beetles (Bertheau et al., 2009; Branco et al., 2015). Although there are no related species in Europe, Douglas fir (*Pseudotsuga menziesii* (Mirbel) Franco) can be used by native herbivorous insects and pathogens due to its relatively similar chemical composition to spruce (Schmid et al., 2014). The risk of pest insect or pathogen outbreaks for non-native tree species is likely to increase in the future through expansion of the host ranges of native pest species and the introduction of invasive pest species due to global (plant) trade (Felton et al., 2013; Gossner, 2016). Non-native tree species can affect forest ecosystems by altering nutritional resources or creating structural differences resulting in altered niche availability and changes to the microclimate within forest stands (Gossner, 2016). These changes may have repercussions for the herbivore communities, higher trophic levels and interspecific interactions (Schmid et al., 2014; Gossner, 2016). For example, the diversity and abundance of spiders as generalist predators on Douglas fir has been reduced, which may have an impact on pest control (Schuldt & Scherer-Lorenzen, 2014). However, it was found that sapling herbivory and tree sucking damage on beech was lower in Douglas fir mixtures than in pure beech stands (Matevski et al., 2023). Furthermore, Matevski and Schuldt (2023) found that Douglas fir can promote small-scale spider diversity, abundance and biomass. Finally, recent work has also shown that the negative effects of non-native Douglas fir on canopy beetle abundance and diversity compared to beech were generally mitigated in mixtures with beech (Wildermuth et al., 2024). While knowledge of the consequences of the cultivation of non-native tree species for forest biodiversity is increasing, we still have only limited knowledge on the ensuing interspecific interactions, e. g. among organisms of higher trophic levels.

8th Statement: greater tree diversity reduces the risk of damage by herbivorous insects. (established but incomplete)

According to the insurance hypothesis, high tree species diversity might make forests less susceptible to pest damage (Pautasso et al., 2005). Higher tree diversity on the stand scale reduces the insect herbivore damage caused by many feeding guilds (Guyot et al., 2016; Jactel et al., 2021) and reduces the damage caused by specialised insect herbivores especially, while it can promote generalists (Bauhus et al., 2017; Jactel et al., 2021). Pure stands can be more recognisable to specialists and these occur in higher densities. By contrast, higher tree diversity on the stand level may result in higher levels of herbivory by generalist herbivores as this may enable diet mixing. Due to limits in herbivore diet breadth, lower levels of herbivore damage also become more likely for generalist herbivores with increasing phylogenetic distance or functional trait dissimilarity between neighbouring tree species (Jactel et al., 2021). In the context of managing ecosystem resilience this suggests the selection of phylogenetically more distant tree species with different functional traits may be more important than increasing the number of species in the stand *per se* (Bauhus et al., 2017; Jactel et al., 2017, 2021). Non-native tree species can contribute to this higher resilience in mixed forest stands (Pötzelsberger et al., 2020; Topanotti et al., 2024), likely also due to their differences in functional traits.

9th Statement: greater tree diversity reduces the risk of damage from pathogens. (unresolved)

Foliar fungal and soil-borne pathogen richness and infestation were shown to depend on tree species and local biodiversity (Jactel et al., 2017; Liu & He, 2019). Local tree diversity was shown to reduce the level of fungal pathogen infestation (Pautasso, 2022), not only through simple host dilution effects, i.e., by reducing the host proportion (Janzen-Connell effects), but also through more complex interactions between local neighboring trees such as reduced chances of propagule dispersal between hosts (Hantsch et al., 2014). Tree diversity only had a minor effect on foliar disease incidence in a Pan-European study and the direction of the effect depended more on tree type, with disease incidence decreasing in conifers but not broadleaved species with increasing tree diversity (Nguyen et al., 2016).

Management practices that resulted in higher stand densities, drastic reductions in genetic diversity and cultivation of trees outside their native range increased problems with native pathogens (Ennos, 2015). Impacts of a wide range of forest management options such as reduced forest connectivity, reduced tree density, removal of diseased trees or increased tree species diversity were shown to increase resilience to forest pathogens (Roberts et al., 2020). Tree morbidity can only be induced when pathogens and host trees interact. However, there is only limited knowledge of how disease agents themselves react to climate change and their host trees – and even less on how this affects forest pest and pathogen damage (Simler-Williamson et al., 2019; Pautasso, 2022).

10th Statement: non-native tree species have a high potential for drought resistance. (unresolved)

Non-native tree species with limited invasive potential (Vor et al., 2015) have in the recent past often been suggested as a solution to mitigate the impacts of drought and to establish climate-resilient forests. For several of the well-established species, however, such as red oak (*Quercus rubra* L.) and Douglas fir, there is a climatic similarity between the area of origin and the area of cultivation in Germany (Mette et al., 2013; Sanders et al., 2014; Lange et al., 2022; Thomas et al., 2022). Therefore, the extent to which non-native tree species more generally exhibit higher drought resistance than native species remains questionable with only few studies on a low number of tree species currently available (Eilmann & Rigling, 2012; Lévesque et al., 2013; Leuschner, 2024; Leuschner & Meinzer, 2024; Cavelier et al., 2025; Hauck et al., 2025). More promising are tree species that have evolved in regions with frequent heat, drought and frost exposure (Schmiedinger et al., 2009; Alizoti et al., 2022). However, long-term data from growth trials are largely lacking (e.g., Frischbier et al., 2019; Glatthorn et al., 2024), and the physiological properties associated with drought resistance have not been described. As the growing conditions prevailing on open areas may initially hamper the growth of shade-tolerant species (Frischbier et al., 2019), and the edaphic conditions may also influence the initial performance (Glatthorn et al., 2024), such site-specific factors must be considered when assessing the suitability of introduced (non-native) tree species. Although the cultivation of climate-resistant, non-native species could bring benefits, there is little information on the susceptibility of these species to European pests and pathogens (Vor et al., 2015; Pötzelsberger et al., 2020; Nicolescu et al., 2023). It is not known whether they could introduce new pathogens to central Europe. Furthermore, the risk that certain non-native tree species might pose to native biodiversity is difficult to evaluate due to inconsistencies in risk assessment tools (Bindewald et al., 2020). While certain non-native species (e.g., Douglas fir, silver lime, Oriental beech) seem promising for the establishment of climate-resilient mixed forests, the scientific basis necessary to evaluate their suitability from various perspectives is not yet established (Kohler et al., 2024).

Genetics

In addition to structural diversity, the preservation and promotion of genetic diversity are important elements with regard to the adaptation of forest ecosystems to, and their resilience in the face of, global change (Fady et al., 2016). In the research field of forest genetics, with its growing scientific and technical possibilities, there is intense debate about how, and to what extent, it should and can influence the selection, characteristics, adaptation and survival of species and populations to strengthen the resilience of forests to global change (Koskela et al., 2007; Fady et al., 2016). Genetic research is closely linked to the developmental stages of forest trees (Ratnam et al., 2014; Konnert et al., 2015), but is also directly influenced by silvicultural measures, as the following statements show.

11th Statement: global change influences the composition and spatial distribution of tree species. (established but incomplete)

Immobile and long-lived species such as trees spread relatively slowly, but palaeoecological data suggest that tree populations are either able to adapt to changing environmental conditions or migrate quite rapidly when the climate becomes favourable (e.g., McLachlan et al., 2005; Tinner et al., 2018). Tree species must colonise new habitats or adapt to changing environmental conditions in an existing habitat (Rellstab et al., 2016). Natural migration distances of 100 to 1000 m per year have been assumed to be necessary to compensate for the environmental changes predicted for the 21st century (Aitken et al., 2008). For millennia humans have – whether on purpose or by chance – supported the migration of tree species (Tinner et al., 2018; Krebs et al., 2022). The idea that humans can assist natural processes by deliberately moving species to suitable habitats to fill the gap between their migration capability and the expected rate of climate change is increasingly being discussed as an adaptive management option (Ste-Marie et al., 2011; Krutovsky et al., 2012), variously referred to as 'assisted migration' (Vitt et al., 2010), 'assisted colonisation' (Hunter, 2007), 'managed relocation' (Minteer & Collins, 2010) or 'translocation' (Shirey & Lamberti, 2010). In this regard, modeling approaches indicate that the absence of effective countermeasures to climate change will have severe ecological and economic consequences (Hanewinkel et al., 2013; Chakraborty et al., 2024), including changes in tree species abundance and diversity (Buras & Menzel, 2019).

12th Statement: inter-population genetic variability enables the identification and selection of drought-adapted provenances. (established but incomplete)

The potential to decrease drought vulnerability by introducing more drought-adapted provenances is likely to be limited by species-specific drought resistance (George et al., 2015; Gazol et al., 2018). Still, molecular studies, although typically focusing on single traits rather than on trait syndromes of drought tolerance, and provenance trials in common gardens, which are mostly conducted with juvenile or young trees, agree on genetically determined differences in drought resistance between provenances in many major European forest tree species (Thiel et al., 2014; George et al., 2015; Harter et al., 2015; Montwé et al., 2015; Buhk et al., 2016; George et al., 2017; Bachofen et al., 2018; Trujillo-Moya et al., 2018; George et al., 2020; Zas et al., 2020). Both dynamic and static forest species distribution models (Huber et al. 2021) predict less extreme drought-induced tree range contractions where the assisted migration of drought-adapted provenances is considered (Benito Garzón et al., 2011; Oney et al., 2013; Valladares et al., 2014; Chakraborty et al., 2024). As both directional local adaptation and stochastic genetic drift may cause genetically determined drought tolerance, provenances from dryer regions are not necessarily more resilient (Richter et al., 2012; Taeger et al., 2013a; Taeger et al., 2013b; Buhk et al., 2016; George et al., 2017). The performance of a given provenance also depends on the broader local site conditions (Glatthorn et al., 2024) and weather factors throughout the year (Taeger et al., 2013a; Taeger et al. 2013b; Thiel et al., 2014; Buhk et al., 2016; Gazol et al., 2018; George et al., 2020). Therefore, favouring drought-adapted provenances alone will not guarantee successful climate change adaptation in forestry. Genotype-phenotyp association studies on adult trees indicate that individuals, rather than provenances, are potential candidates for breeding and transplantation programmes, given the high diversity of genetically and epigenetically determined drought responses within populations (Jump et al., 2006; Hajek et al., 2016; Heer et al., 2018; Trujillo-Moya et al., 2018; Pfenninger et al., 2021). The choice of origin should therefore be considered in connection with the species-specific and population-internal vulnerability to drought (Frei et al., 2018; Šeho & Janßen, 2019).

13th Statement: the use of seeds or seedlings from locally adapted origins promotes the resilience of forests to future climate conditions. (unresolved)

As the prevailing climate is expected to shift, locally adapted populations might in the near future be subject to less than optimum conditions. Evidence for Swiss stone pine (*Pinus cembra* L.) indicates that the current rate of allele frequency shift is too slow to keep track with a fast pace of climate change (Dauphin et al., 2021), which will result in a maladaptation of the respective population to the new environmental conditions (genomic offset; see Rellstab et al., 2021). Assisted migration of pre-adapted genotypes may be a measure to counteract the impact of climate change. Yet the translocation of genotypes also entails risk, due to hidden maladaptations (Frank et al., 2017; Stauffer, 1992) or uncertainties over future climate conditions. A telling example is the failed translocation of Iberian *Pinus pinaster* (Ait.) in southwest France, where a severe frost caused high mortality of the introduced genotype, 35 years after its large-scale introduction (Benito-Garzón et al., 2013).

14th Statement: natural selection acting on seedlings in forests and after disturbance will result in the survival of more resilient genotypes. (unresolved)

Tree species might be able to acclimate to changing environmental conditions at the recruitment stage. It is likely that the combination of heat and drought will result in significantly reduced rates of seedling establishment (Richter et al., 2012) and increased seedling mortality rates. Some studies have shown that high plasticity might not help to compensate for increasing temperatures and drought frequency (Gárate-Escamilla et al., 2019; Muffler et al., 2021). Local adaptation was found for traits such as growth rates, root:shoot ratio and mortality, for example, for European beech seedlings (Rose et al., 2009; Thiel et al., 2014; Bolte et al., 2016). However, Tíscar et al. (2018) also suggested that seedling survival in the first year is more dependent on micro-habitat conditions, in particular for less stressful environments (Vizcaíno-Palomar et al., 2014). Moser et al. (2017) reported a strong effect of spring weather but no significant effect of seed origin on seedling emergence and mortality for *Pinus sylvestris* and *Picea abies*. Empirical data on the establishment of seedlings of the target tree species under the influence of drought and heat are still largely lacking.

Forest structures

Influencing the diversity of forest structures in space and time is a key tool of forest management. So far, the main focus has been on the compatibility of site suitability for possible tree species constellations and the objectives of the timber industry (marketable assortments and qualities). Positive effects of structural diversity can be superposed by climate extremes (fire, drought, storm) and site-specific characteristics (waterlogging, steep slopes) (Magh et al., 2019; Scherrer et al., 2023a). The increasing instability of single-layered forests is associated with high losses of forest area, which, due to global change, have reached an extent that can no longer be compensated for without structural measures. The admixture of deciduous, resprouting tree species in coniferous forests can help to mitigate fires after periods of drought (Xanthopoulos et al., 2012) and increase the species diversity of flora and fauna by top-down and bottom-up biotic interactions (Brockerhoff et al., 2017). The spatial distribution of differently sized trees and canopy gaps in natural forest systems are usable as an orientation to devise close-to-nature silviculture (Drössler et al., 2016; Meyer et al., 2017; Meyer, 2019; Hammond et al., 2020). Natural forest systems show a high diversity in vertical and horizontal structure making them interesting study objects in terms of structural development and response to climate change (Feldmann et al., 2018a; Stiers et al., 2018). Statement 15 shows which silvicultural measures have been used to date to increase the structural diversity of future forests.

15th Statement: the diversity of the temporal and spatial arrangement of key structures in forests improves the resilience of forests to climate extremes. (established but incomplete)

There is a close relationship between forest structure and climatic conditions. They can directly or indirectly be modified by silvicultural measures. Key structures are stem density, tree height and dimension, root:shoot ratios, vertical and horizontal tree species composition, canopy gaps, and the type and volume of dead wood (Franklin et al., 2002; Pretzsch et al., 2014; Nikolova et al., 2019; Wieczynski et al., 2019; Ehbrecht et al., 2021). Forest structures and the response traits of tree species are the drivers forming environmental niches and the resultant diversity of flora and fauna. For example, selective crown thinning (also referred to as ‘thinning from above’ or ‘high thinning’) and group selection cutting have been shown to support tree vitality (Albrecht et al., 2012) and stability (Rottmann, 1989; Nykänen et al., 1995; Sharma et al., 2019), and enhance resistance against drought, storms and snow loads (Bréda et al., 1995; Bachofen & Zingg, 2001; Ammer, 2017; Petriţan et al., 2021). The spatial distribution of differently sized trees and canopy gaps in natural forest systems can be used as an orientation to devise close-to-nature silviculture (Nagel and Svoboda, 2008; Drössler et al., 2016; Meyer et al., 2017; Feldmann et al., 2018b; Meyer, 2019, 2020; Hammond et al., 2020). In this context, knowledge of adapted tree species mixture forms (single-trees or groups) and densities should be taken into account in the management of deciduous tree species for the production of quality wood at the early stages of development (Petriţan et al., 2009; Pretzsch & Zenner, 2017; Weidig & Wagner, 2021). In addition to regular maintenance and regeneration measures, the existing management repertoire for the structural design of forests must be extended to the area of forest restoration.

Forest functions, ecosystem services and nature’s contribution to people (NCP)

Based on the analysis by De Groot et al. (2002), forest functions describe the capacity of forests to provide specific goods and services for the benefit of humans via natural processes and structural elements (regulation, habitat, production, information). The four basic categories (provisioning, regulating, cultural, supporting) are included in the consideration of ecosystem services (MA, 2005) and are further expanded by the NCP approach, which includes both positive and negative nature-based effects on the quality of human life (Kadykalo et al., 2019; Simonienko et al., 2023). This inclusion of negative influences is particularly important in light of global change and the resulting disturbances in forests and loss of forest areas. The associated statements take up this approach and emphasize the expansion of future research to include context-specific perspectives and relation values when considering and comparing impacts on the socio-cultural quality of life influenced by specific forest ecosystems (Queirolo et al., 2024).

16th Statement: NCP are determined by the initial stand situation, the management type and the intensity. (established but incomplete)

NCP, superseding the system of ecosystem services (MA, 2005), are benefits humans obtain from ecosystems (Díaz et al., 2018). Positive and negative effects can be expected for the different NCP categories (Brauman et al., 2020). By setting forests without active management as a baseline, we expect this renunciation to have positive effects on habitat creation and maintenance (NCP 1), pollination and dispersal of seeds (NCP 2) and future resilience to disturbances (NCP 9). The effects on climate (NCP 3) and on air, water and soil resources (NCP 4, 6–8) are negligible, albeit with exceptions on a small, local scale (see also next section). Negative effects are identified for the NCP 13 'materials, companionship and labour' in the national forestry and wood-processing sector. Most non-material NCPs (16–18) will be affected inconsistently (Díaz et al., 2018; NPC 16 'physical and psychological experiences', NCP 17 'supporting identities', NCP 18 'maintenance of options'). In any case, disturbed forests also offer a chance to enhance learning (NCP 15). A recent review undertaken for temperate and boreal forests (Thom & Seidl, 2016) indicated that most regulating NCPs are negatively influenced by disturbances while effects on biodiversity are positive.

17th Statement: silvicultural systems have different effects on the categories of regulating service that are particularly important for mitigating climate fluctuations. (unresolved)

The quality of different ecosystem services depends on the specific above- and belowground development of forest structures and dynamics induced by silvicultural measures. Mitigating the effects of climate fluctuations through silvicultural measures includes, for example, the intensity of felling measures, the rotation length and the mixing regime (Felton et al., 2024). Microclimate, temperature buffering, water retention potential and water quality are determined by parameters like tree species, crown cover, tree age, gap size, tree species mixtures and regeneration methods (Rothe & Binkley, 2001; Schenk et al., 2020; Zellweger et al., 2020; De Frenne et al., 2021; Vilhar, 2021; del Campo et al., 2022; Kemppinen et al., 2024). Strip cuttings and clearcuts create larger areas with a degree of canopy openness that may lead to climate extremes and changes to the water retention potential (Keenan & Kimmins, 1993), higher nitrate concentrations (Rothe & Mellert, 2004) and greater risk of erosion in mountain forests (Borrelli et al., 2017). In this respect, however, the regeneration potential of pioneer tree species can be increased if natural succession processes are integrated into the silvicultural treatment strategy (Taki et al., 2013; Brockerhoff et al., 2017). A long known theoretical example of silviculture is the use of so-called 'pre-forests' or 'nurse-crops' (in German 'Vorwald'; Fiedler, 1962), but the system has not yet been the subject of sufficient empirical study and has been little integrated in practice (Heger, 1952; Zerbe & Meiwes, 2000; Stark et al., 2013). Coppice systems connect growth stages across different spatial scales and have a positive impact on the diversity of floral and faunal species underrepresented in closed forests (Buckley, 2020).

Silvicultural systems

The choice of silvicultural system has always been closely linked to the objectives of forest owners, and the social framework conditions, and is optimised for these specific objectives under scientific supervision and practical application (Mason, 2004; Nyland, 2016; Wagner et al., 2020; Toraño Caicoya et al., 2023; Szmyt & Dering, 2024). Despite detailed knowledge and a high level of development of silvicultural technologies, the achievement of these goals is increasingly fraught with uncertainty due to global change (Brang et al., 2014; Stiers et al., 2020; Achim et al., 2022; Szmyt, 2024). Extreme weather events often lead to large-scale disruption and the temporary loss of large areas of forest and the associated ecosystem services. This requires an ecological and economic reassessment of the silvicultural options with regard to future objectives and the further treatment of the areas in question. The complete abandonment of silvicultural measures can be accompanied by longer, economically unfavourable development periods or jeopardise the achievement of objectives or NCPs (e.g., preservation of a certain tree species composition, wood quality; see statement 16). On the other hand, it is obvious that the continuation of silvicultural measures and systems that focus exclusively on one tree species or objective is risky (Friedrich et al., 2021). The following statements show that the search for adapted silvicultural systems for the development of forests with diverse functions and objectives represents a particular challenge. Well-structured and comprehensible recommendations for action must be drawn up so as to implement scientifically sound findings in practice under a wide range of site conditions.

18th Statement: land-use history, and the degree of ecological continuity, strongly impact forest functioning and resilience. (established but incomplete)

The history of the use of European forests is diverse and bears witness to intensive human influence, which is characterized by changes in the type of use, tree species and structure of the forests (Verheyen et al., 2004; Wulf 2023). The few European forest areas with long ecological continuity have experienced many weather extremes and climate fluctuations in the past, so that they are probably better adapted to the effects of observed climate change (von Oheimb et al., 2014; Mausolf et al., 2018a; Thom et al., 2018; Stritih et al., 2021). These forests show a high structural habitat diversity and particularly high richness of forest specialist species of different organism groups, which leads to a higher resilience of these forest ecosystems to abiotic and biotic disturbances (Fritz et al., 2008; Nordén et al., 2014; Bradshaw et al., 2015; Bergès & Dupouey, 2021). However, observations of greater resilience may be context dependent if old-growth forests harbor keystone species that are less adapted to climate change, when such changes exceed the range of physiological amplitude of the species. In this context, disturbance events create opportunities for the migration of species that are better adapted to new conditions (Scherrer et al., 2022). In terms of research on ecosystem resilience, old-growth forests can serve as valuable reference systems. Ecological continuity and old-growth conditions of ancient woodlands can be fostered through the following: (i) maintenance of ecological continuity at the landscape level adopting the concept of managing 'sustainability units' of ecological continuity (Mölder et al., 2019); (ii) conservation and development of structural attributes related to 'old-growthness' (Keeton, 2006; Fritz et al., 2008; Bauhus et al., 2009) and creating suitable habitats for diverse groups of organisms (Nordén et al., 2014); (iii) careful consideration of site effects influenced by forest management practices within these valuable forest stands (von Oheimb et al., 2014); and (iv) use of an adaptive approach focusing on ecosystem structure to maintain ecological function, adaptation potential and integrity of forests in times of climate change (Safford et al., 2012).

19th Statement: combining different silvicultural systems at larger spatial scales increases structural diversity, supports resilience and mitigates climate change effects. (established but incomplete)

The effects of silvicultural management depend on tree species composition, management history, site and local climate conditions. Silvicultural systems vary widely in their management intensity and the degree of naturalness (Szmyt & Dering, 2024). Active and passive management types can be applied to adapt forests to climate change (Millar et al., 2007; Bolte et al., 2009b; Nyland, 2016; Mauser, 2021; Szmyt, 2024). Low intensity small scale silvicultural systems work well in forests which are close to the respective natural forest type (Jandl et al., 2019; Krumm et al., 2020). The application of different silvicultural systems at landscape level has a positive ecological impact and also spreads the risk in economic terms compared to a single dogmatic system that is implemented everywhere (Schall et al., 2018). Tree species mixtures can be enhanced by tending measures and selective crown thinning during stand development (Bréda et al., 1995; Quine et al., 1995; DeRose & Long, 2014). The regulation of stand density may play an important role in climate resilience. The preservation of retention trees promotes biodiversity and the resilience of forests by acting as 'lifeboats' and 'ecological memory' (Gustafsson et al., 2020). Both the extension and the shortening of rotation lengths can increase the resilience of forests to climate change, and maintain the continuity of forest ecosystems and the related services (Lindner et al., 2008). The effects of silvicultural systems on carbon mitigation are still the subject of much debate (Kun et al., 2020; Schulze et al., 2020a; Schulze et al., 2020b; Nagel et al., 2023; Keith et al., 2024).

20th Statement: increasing inter-annual fluctuations and extreme weather conditions lead to adaptation problems in silvicultural management strategies. (established but incomplete)

In the boreal and temperate latitudes, a synchronisation of natural processes takes place due to the seasonality (Martinez del Castillo et al., 2022). The development and growth of tree species are strongly determined by the weather conditions of the previous year (Harvey et al., 2020; Aldea et al., 2021). Strong inter-annual fluctuations in weather conditions therefore have an impact on growth and reproduction processes that are difficult for individual trees or tree species to compensate for. According to Matula et al. (2023), the resulting changes in the dynamics of the growth rate, the growth rate maxima, and the timing of the growth period, as well as the resulting changes in biomass production, have so far been little studied. The authors show that the earlier start of growth and the earlier realization of maximum radial growth also leads to a later end of the vegetation period, so that the tree species cannot convert these into further growth despite longer-lasting favorable climatic growth conditions. Under the influence of extreme temperatures and heat, the growing season ends even earlier. These effects show clear tree species specifics (Giesecke et al., 2010; Mund et al., 2010; Brichta et al., 2024), and plant physiological studies prove the increased occurrence of mortality when extreme dry periods and heat coincide (Allen et al., 2010; Kijowska-Oberc et al., 2020; Bose et al., 2024). This raises the question of whether and to what extent silvicultural measures can mitigate these effects.

The age or size of trees or stands, and especially the age distribution in forests, can have an impact on climate change resistance and resilience if stability parameters are also linked to age (Mathes et al., 2024). Maintaining a sufficient number of individuals can be crucial for the survival of the overall population, especially in the case of particularly rare tree species. For various reasons, dissimilarity in age can help spread risk and, in the case of disturbance events, contribute to the continuity of forest properties at the particular location, which is in turn important for habitat continuity (Nordén et al., 2014). Habitat continuity is greater in uneven-aged forests than in even-aged, even in the absence of climate change-induced disturbances (Joelsson et al., 2017; Kuuluvainen et al., 2021).

21st Statement: forest management and landscape-scale conservation planning require consideration of mixed ownership to cope with global change. (established but incomplete)

In many regions, small private forests are the dominant ownership type. This form of ownership is largely characterised by small property sizes (often < 5 ha) and pronounced habitat fragmentation. The forest owners' heterogeneous objectives (Urquhart & Courtney, 2011; Tiebel et al., 2021) and management approaches (Haugen, 2016) pose a challenge for forest management and conservation planning in forest landscapes. There is a need for well-balanced climate adaptation measures that incorporate both socio-economic and forest conservation aspects in mixed-ownership cultural landscapes. A cross-ownership approach to forest planning is required (Ohmann et al., 2007; Fischer et al., 2019b; Loeb & D'Amato, 2020; Szmyt & Dering, 2024).

22nd Statement: continuous canopy cover and forest conversion with site-appropriate tree species maintain micro-climatically balanced conditions and relatively closed energy and nutrient cycles even in the face of global change. (established but incomplete)

Many forests in Central Europe are characterized by the uniform cultivation of coniferous tree species such as Norway spruce or Scots pine, which were also cultivated on unsuitable sites (Fritz, 2006; Hansen & Spiecker, 2016). The long-term preservation of a protective canopy shelter of overstorey trees is of great importance for the development of late successional species. Forest conversion, i.e. the establishment of site-adapted tree species under a homogenous shelter of coniferous tree species is one option to improve the biological activity and chemical status of the organic layer (Ammer et al., 2006; Berger, 2007; Skłodowski et al., 2018), which may in turn lead to better nutrition of the shelter trees (Rothe & Binkley, 2001). The long-term preservation of a protective canopy shelter of old wood is of great importance in this context, particularly with regard to late successional species. However, broad empirical evidence on the latter is missing. The second layer of trees increases the total canopy cover, reducing ground vegetation cover and the maximum surface temperatures, while the relative humidity increases (Kovács et al., 2017; Davis et al., 2019). This can decrease the probability of bark beetle infestations and strengthen antagonists (Lüdge, 1971; Jäkel & Roth, 2004; Wehnert et al., 2021). The adaptation potential and the ecological and economic effects of less commonly used tree species (e.g., lime, sycamore, northern red oak) for forest conversion have rarely been studied. Fast above- and belowground development of early successional tree species is advantageous for carbon storage, mitigation of nutrient exports and erosion control, especially under changing conditions with higher temperatures, drought and extreme precipitation events (Stark et al., 2015). Forest management practices that retain a substantial amount of living trees after harvest, such as continuous cover, retention or selective cutting, not only reduce carbon losses related to tree harvest, but also sustain carbon fluxes from trees to the soil, thus supporting the soil food web and replenishing soil organic matter and carbon stocks (Mayer et al., 2020; Prescott & Grayston, 2023). However, it is likely that in the course of climate change, the physical structure of future forest ecosystems will change in parallel with the changes in tree species composition, which in turn will have an impact on the protective effect, e.g. as a temperature buffer (Zellweger et al., 2020).

Natural regeneration, successional processes and wildlife management

The various linked tree species-specific regeneration processes within regeneration cycles are directly controlled by autecological interactions. Individual species-specific regeneration stages and the associated processes are very sensitive to climatic extremes such as drought and frost due to their physiological and morphological nature (Leck et al., 2008; Beloiu et al., 2020; Charrier et al., 2021). Silviculturists have developed a wide range of regeneration systems over time to offset the negative effects of environmental factors such as extreme temperatures and rainfall deficits (Pommerening & Grabarnik, 2019). It can be assumed that global change not only contributes to the intensification of climate extremes, but also leads to disturbances of the entire forest ecosystem (Senf & Seidl, 2021b). These disturbances lead to climatic extreme effects not experienced previously in early tree developmental stages (Charrier et al., 2021). The functionality of regeneration processes for pioneer and late successional forest species must be reclassified to accommodate global change. It is necessary to consider which regeneration systems can be used or adapted to future environmental conditions as the effects of climate extremes (e.g., drought, late frost) and the damage caused by wild ungulates accelerate (Didion et al., 2011; Bebi et al., 2023).

23rd Statement: extreme climate events affect all stages of regeneration such as flowers, seeds, seedlings and young plant development and associated processes within the regeneration cycle. (established but incomplete)

Linkages between climate parameters and seed production are difficult to predict and inconsistent (Kelly et al., 2013; Crone & Rapp, 2014; Bogdziewicz et al., 2017). Temperatures in the previous summer can affect seed production in the following year (Drobyshev et al., 2014; Vacchiano et al., 2017; Hacket-Pain et al., 2018). Flowering and fruiting are hampered by frost events and by hot and dry summers (Nussbaumer et al., 2020). Drought mainly leads to decreased sapling growth and survival (Herrero et al., 2013; Vander Mijnsbrugge et al., 2019). Analyses of the effects of drought on seedlings showed decreasing or insufficient biomass production and hampered shoot and/or root development (van Hees, 1997; Lendzion & Leuschner, 2008; Rose et al., 2009; Herrero et al., 2013; Vander Mijnsbrugge et al., 2019). However, acclimatisation of young plants of certain species of deciduous trees to drought is possible (Löf & Welander, 2000; Beloiu et al., 2020).

24th Statement: frequent drought events increase overstorey tree mortality and impact upon tree species regeneration. (established but incomplete)

Drought events and bark beetle infestations reduce the vitality and foliage density of canopy trees (Stadelmann et al., 2014; Walthert et al., 2021) and thus reduce their resilience to extremes. Storm events can create gaps or lead to a complete destruction of the overstory tree layer, changing the shelter effects provided for late successional tree species and making it more difficult to control small scale regeneration patterns and species-specific competition (Thom et al., 2023). The increase in light-demanding ground vegetation leads to reduced abundance and growth rates of seedlings and saplings (Kalt et al., 2021; Ambs et al., 2024), and to higher mortality (De Lombaerde et al., 2021). The plant propagation technologies, planting time and planting techniques used (e.g., container plants) can temporarily help to mitigate drought effects (Zadworny et al., 2014; Grossnickle & El-Kassaby, 2016). The future success of direct seeding is driven by the climate-induced seed production, micro- and safe-site conditions, the time of seeding, the process of germination determined by seed reserves and weather conditions, as well as the presence of seed predators (Grossnickle & Ivetić, 2017; Bogdziewicz et al., 2020). Root competition for water by overstory mature trees was also found to play an important role (Ammer et al., 2002).

25th Statement: positive and negative interactions between regenerated tree species will change depending on the developmental stage and the above- and belowground adaptation of the young trees to climate change. (unresolved)

The interactions between young plants are influenced by changes in the abiotic and biotic environmental factors, which manifest themselves in the various stages of tree development in the form of competition or facilitation (Carón et al., 2015; Dănescu et al., 2018). The potential for intra- and interspecific competition depends on the availability of growth-inducing environmental factors and the quantity of reserves during early development stages. Regionally predicted decreases of precipitation and the displacement of water into deeper soil layers will strengthen the competition pressure between juvenile trees, whereas facilitation effects of overstorey trees are also at risk due to extreme drought and storm events. A higher risk of climate-induced disturbances in the aboveground tree layers reduces their competitive pressure on young trees (Ammer, 2002) but increases the competitive potential of the warmth- and light-demanding plants of the understorey. The establishment of early successional tree species and tree provenances originating from dry sites can probably benefit from climate change, because the development stages and the connecting processes are already adapted to site and climate extremes (Taeger et al., 2013b; Seidel et al., 2019). To further validate these initial results, further studies are needed that consider regeneration-specific and environmental factors that influence the regeneration stages of tree species, as well as their interactions (Hemery et al., 2010; Kijowska-Oberc et al., 2020; Solé-Medina & Ramírez-Valiente, 2023). The potential for aboveground competition is also influenced by local biotic factors such as browsing by ungulates (Kupferschmid et al., 2018) or the development of insect pests and rodents (Sobek et al., 2009), but there have been hardly any systematic experimental studies to clarify these relationships (Ammer & Vor, 2013; Clasen et al., 2015; Ramirez et al., 2019; Nopp-Mayr et al., 2020; Reimoser & Stock, 2020). The preferred tree species are more susceptible to damage and require additional energy for their further growth or for the development of new shoots (Kupferschmid et al., 2017). Seedlings and saplings of tree species with extensive fine root systems or taproots can reach deeper soil layers and use the soil water more efficiently. Relevant information about the effects of high seedling densities or mixtures and interactions influenced by water are lacking (Carón et al., 2015).

26th Statement: forest disturbances influence ecological processes, spatial patterns of ground vegetation, the regeneration of tree species, associated taxa and associated services. (established but incomplete)

The spatial variability of disturbance intensity on large disturbed areas often leads to a heterogeneous pattern of surviving organisms within the vegetation, the regeneration of tree species and the associated services. When the disturbed areas are small, it may be that no management is required to (1) maintain the ecosystem services demanded by society, or (2) increase the speed at which they are provided again. Small-scale disturbances arising due to the mortality of individual trees or tree groups, or the mostly small gaps created by management, are quickly filled by surrounding adult trees and existing regeneration (e.g., Scherrer et al., 2021; Ambs et al., 2024). On areas of large-scale disturbance, created by events such as storm or forest fire, the forest structure is initially characterised more by environmental factors and local site conditions than by the forest type prior to the disturbance (Wohlgemuth & Moser, 2018; Scherrer et al., 2023b). For some originally predominant tree species, cultivation outside their natural range leads to a loss of regeneration capacity (Scherrer et al., 2022), while for other tree species (e.g., Norway spruce) it leads to increased regeneration and the occupation of niches (Rozman et al., 2015; Tsvetanov et al., 2018). Nurse plant effects and rapid post-disturbance establishment of ground vegetation can reduce erosion and soil carbon loss, particularly on steep mountain sites (Gómez-Aparicio et al., 2008; Mayer et al., 2017). In the Swiss forests, typical pioneer species such as rowan, birch, willow and poplar can be found in small areas and in heterogeneous distribution 10 to 20 years after windthrow, mixed with climax tree species (Wohlgemuth & Kramer, 2015). In the case of large-scale forest disturbances, the direct sowing or planting of target tree species may be necessary as a method of artificial regeneration and subsequent mixture regulation (Coates, 2000; Asselin et al., 2001). In some cases it is also necessary to regulate the highly competitive accompanying vegetation (Wolf et al., 2004; Royo & Carson, 2006; Vodde et al., 2015; Wohlgemuth & Kramer, 2015; Kalt et al., 2021).

27th Statement: plant-associated microbiomes adapt to drought, helping trees and forest ecosystems respond to drought events. (inconclusive)

Awareness of the functionality of trees and their associated microbiome, the holobiont, has increased significantly in recent years (Vandenkoornhuyse et al., 2015; Anthony et al., 2022). In the context of climate change and particularly drought, tree fungal associations forming mycorrhizae have attracted interest as they may play a significant role in the water and nutrient supply of trees (Bergmann et al., 2020). Nevertheless, their effects on water flow are still not well understood (Allen, 2007). Specific combinations of plant genotype and mutualistic ectomycorrhizal fungi communities improve the survival and growth of trees (Gehring et al., 2017). With the help of new sequencing techniques, first network-oriented studies reveal a close interplay among mycorrhizae and additional microorganisms of the rhizosphere, highlighting the potential of these techniques to elucidate the role of the microbiome in tree acclimation to drought events

(Creamer et al., 2015).

28th Statement: infestation with pests and pathogens affects the establishment of young host trees and changes the future species composition. (inconclusive)

Drought renders some tree species more vulnerable to infestation, while warming may either promote or hamper the outbreak of pests and pathogens. Such species-specific interactions of climate change and pest or pathogen effects on tree regeneration may alter future species composition (Sobek et al., 2009). However, whether pests or pathogens avoid certain tree species in the regeneration stage is unclear, as there were for instance no differences in insect leaf herbivory levels between saplings and adults of eight oak species (Galmán et al., 2019). Naturally regenerating stands may be less affected by pests or pathogens than plantations (Enderle et al., 2017). Drought stress can make seedlings more susceptible to pests (Stanosz et al., 2001), and warming can promote the outbreak of insect pests by accelerating their regeneration cycle (McKone et al., 1998; Williams et al., 2003; Karolewski et al., 2007). However, a warmer climate may also mitigate disease outbreak if warmer temperatures are unfavourable for pests or pathogens, as with ash dieback (Davydenko et al., 2013; Hauptman et al., 2013; Grosdidier et al., 2018).

29th Statement: species-specific browsing in interaction with the effects of climate change leads to structural changes in forest regeneration and the future species composition of forests. (established but incomplete)

Browsing by herbivores significantly affects the growth of seedlings and saplings and regeneration overall and strongly hampers silvicultural flexibility. Despite various countermeasures (e.g., adaptation of the hunting regime, fencing, use of anti-browsing agents), the browsing situation on forest land remains tense in large parts of Europe due to high densities of wild ungulates (Apollonio et al., 2010; Nopp-Mayr et al., 2023). Current recording methods document the consequences of browsing (e.g., preferred tree species) and other damage caused by herbivores very accurately and comprehensively (Kupferschmid et al., 2019). This also applies to wildlife ecology research, which deals with behavior and all aspects of population development (Martín-Fernández et al., 2023; Nopp-Mayr et al., 2023). Despite this extensive information, it is difficult to predict the very complex interactions between herbivores and vegetation development under changing climate conditions, as many regional influencing factors must also be taken into account in the analysis (Cailleret et al., 2014; D'Aprile et al., 2020).

In areas with regular snow cover, the climate-induced decline in snow cover combined with increasing ungulate populations leads to a significant change in the species composition of regeneration (Brodie et al., 2012) and to increased browsing intensity on seedlings in natural forests (Akashi et al., 2022).

Generalizing interaction effects of browsing and climate change on tree regeneration is therefore difficult and requires constructive political and socio-economic cooperation in addition to scientific assessment (see Bebi et al., 2023 for Switzerland). Observational and simulation studies show that browsing can counteract warming-induced growth of tree species, as well as amplify drought-induced growth reduction (Didion et al., 2011; Fisichelli et al., 2012; Herrero et al., 2012). Further studies that explicitly deal with the connection between tree species regeneration, ground vegetation development and the behavior of herbivores are necessary to be able to formulate more generally valid statements.

Future scientific research and monitoring methods

Forest monitoring systems have the potential to provide a detailed assessment of the impacts of global change on forests at high spatial and temporal resolution (Hartmann et al., 2018; Zweifel et al., 2023; Ferretti et al., 2024). The objectives and methods of established monitoring systems are not yet sufficiently geared to monitoring the effects of global change on the growth, vitality and development of forests. The following remarks show that a particular challenge for established monitoring systems is to adapt them to the increasingly uncertain evolution of environmental factors in order to map the responses of forests to global changes and to take advantage of the increasing possibilities offered by real-time sensor networks (Vorobevskii et al., 2024), remote sensing methods and digital tools (e.g., Hristova et al., 2022; Kükenbrink et al., 2022).

30th Statement: existing monitoring networks provide sufficient information on changes to forest condition. (established but incomplete)

Most ground-based assessment and inventory programmes are often either disjointed, too narrow in scope and/or do not operate at a sufficiently fine temporal resolution, which can hinder scientific understanding, the timely provision of information and rapid decision making. This in turn leads to suboptimal use of technical resources (Ferretti et al., 2024). There is an urgent need for advanced forest inventory and monitoring (AIM) programmes such as SwissAIM launched in 2022 (Ferretti et al., 2024). Another example is the annual forest condition survey (BMEL 2024, Germany), a large-scale and long-term monitoring system implemented to assess crown thinning compared to a fully leafy or leafy crown. The results collated overt the last 39 years show that currently only 20 % of the trees across all tree species possess vital crowns without defoliation. Compared to the first investigations in 1984, deciduous tree species are currently particularly prone to reduced crown vitality. At the same time, it can be shown that in some species trees with low crown vitality exhibit a strong increase in fruit production, but this is not consistent for all tree species (Hacket-Pain & Bogdziewicz, 2021; BMEL 2024). Further connection with other parameters pertaining to climate, soil and soil water balance, age, growth and mortality of tree species is particularly important to derive statements on causal relationships, future tree species composition and forest management strategies (Lebourgeois et al., 2018; Dervishi et al., 2022). Connection with dendrochronological and paleobotanical studies (e.g., pollen analyses), which reach further back into the past, will allow for conclusions to be drawn about the extent of changes to the vitality and growth of tree species in response to the environment (Küchler et al., 2015; van der Maaten et al., 2024). With the use of new recording techniques such as remote sensing and satellite-based monitoring approaches like the Forest Condition Monitor, it will be possible to create simple drought-related indices for entire regions (Buras et al., 2021). So far, however, their resolution is not sufficient to record individual trees, and there is still no direct physiological connection between the green of the tree crowns and the water status of the trees and thus their vitality (D'Odorico, 2023). Furthermore, there is no common and openly accessible database for the different inventories, which hampers systematic analyses. Other ground-based monitoring measures have specific objectives with a particular focus (e.g., on conservation) and therefore do not provide the breadth of information or spatio-temporal resolution required to draw general conclusions about changes to forest condition. A combination of remote-sensing and ground-based real-time monitoring networks such as the TreeNet infrastructure (Zweifel et al., 2021), which covers 61 sites across Switzerland, or the Czech dendronet network (http://www.emsbrno.cz/p.axd/en/DendroNETWORK.DendroNET.html), hold promise as a means to assess forest health continuously (cf., Hartmann et al., 2018).

31st Statement: existing monitoring systems evaluate the ecosystem services provided. (unresolved)

The different categories of ecosystem services are affected by global change in different ways (Locatelli, 2016). Due to the classification of ecosystem services into areas with a natural science focus (see section IV) and areas with a socio-cultural focus, the monitoring systems and methods are particularly diverse (MA, 2005). The various disciplines have developed professional and successfully applied monitoring methods for their core topics and the associated ecosystem services, for example, provision of plant and animal products, raw materials (Suz et al., 2015; Holzwarth et al., 2020; Siwulski et al., 2020), climatological (Malik et al., 2023), hydrological (Brauman, 2015), pedological (Nerger et al., 2016) and biological services (Gardner, 2010; Storch et al., 2023). The technical implementation and the spatial recording levels differ between the service categories examined (Dick et al., 2014; Raudsepp-Hearne & Peterson, 2016). They range from individual-based or small-scale monitoring methods to remote sensing (Osberger et al., 2014; Larrieu et al., 2018; Hui et al., 2019; Augusto & Boča, 2022; Kacic & Kuenzer, 2022; Massey et al., 2023) recording methods used to map global relationships (Marín et al., 2021; Estoque et al., 2022). The challenge for future forest research lies in quantifying the relationships between different service categories (Cord et al., 2017; Mansourian & Stephenson, 2023) and in developing methods for the spatial and temporal upscaling and downscaling of different services of forest ecosystems (Dick et al., 2014; Rau et al., 2018; Bierkens et al., 2000; Wiersma & Schneider, 2022). Monitoring based on the natural sciences involves the regular, systematic and targeted recording of certain forest parameters (Cord et al., 2017), while the socio-cultural performance of forests is often measured by means of surveys or interviews (Scholte et al., 2015; Márquez et al., 2023). To successfully combine socio-cultural services with other service categories, forest structures are increasingly being included in surveys and in the evaluation of visual preferences, as examples from Switzerland show (Frick et al., 2018; Hegetschweiler et al., 2020). Further approaches are being pursued with the help of indicators (Storch et al., 2018), the development of complex models (Gutsch et al., 2018; Blanco et al., 2020) and the design of digital twins of the forest (Buonocore et al., 2022). Many approaches are currently being tested for the first time and will require extensive research in the future if the changes to ecosystem services as a result of global change are to be well understood.

32nd Statement: relevant soil properties are recorded with the degree of spatial accuracy adapted to the respective forest structure and management concept. (established but incomplete)

Precise information on the physical and chemical conditions of the soil is required to create climate-resistant forests with a high diversity of tree species. To facilitate the selection of suitable tree species and tree species mixtures (Rabbel et al., 2018) it will be necessary to adapt the systems for the inventory and monitoring of soil properties. It is known that the abiotic soil conditions influence root development (Brunner et al., 2015; Nikolova et al., 2020), water consumption, and the growth and health of trees at all stages of development (Thomas et al., 2002, 2018; Putzenlechner et al., 2023). The German National Forest Soil Inventory (NFSI), a periodic grid-based (8 × 8 km) assessment, was established late in the 1980s to investigate the major soil properties and their changes over time (Wellbrock et al., 2019). The aim of the NFSI is to provide a powerful calibration dataset with profile-based, harmonised and parameterised soil information, but so far there is no guarantee that the results can be extrapolated or interpolated at the level of individual forest stands (Wellbrock et al., 2019). There is a need for improved integration of soil profiles, maps and predictive mapping as projection and prediction depend on the availability and quality of regional and local forest soil maps with sufficient information and spatial resolution, as exemplified by the forest site inventory of the eastern and north-eastern part of Germany (Petzold & Benning, 2017). Soil property maps for the entire forest area have also been created in Switzerland, based on data from 2071 soil profiles and six different modelling approaches for digital soil mapping (Baltensweiler et al., 2021). The prediction performance showed large differences for the individual soil properties, however, and future mapping campaigns are needed to reduce the uncertainty. Remote sensing data, such as data derived from Sentinal-2 time series, will become increasingly valuable to describe disturbance regimes and to link these data with fine-scale soil maps (Putzenlechner et al., 2023).

Relevant properties of ecosystem processes such as tree regeneration may vary at small spatial scales. Recent inventory protocols either exclude sources of soil variability (e.g., as induced by specific microsite characteristics and spatial tree distribution) or average them out by composite soil sampling and mixing. Therefore, soil heterogeneity is commonly excluded from studies on ecosystem functioning (Baeten et al., 2013; Ratcliffe et al., 2017).

33rd Statement: physical and chemical soil properties can be regionalised in detail. (established but incomplete)

Environmental variables that constitute a limiting resource for growth (e.g., water availability) or factors that have direct effects (e.g., water storage capacity or nutrient stocks) are preferable to those that exert indirect influences (e.g., soil texture) when working with tree species distribution models (Austin & Smith, 1989). As predictors for resources are usually not available at a broader scale, the focus has recently shifted to direct soil functions such as the plant-available water capacity (AWC) of soils (Rehschuh et al., 2017; Reich et al., 2018; Fuchs et al., 2021; Meusburger et al., 2022; Putzenlechner et al., 2023). AWC is crucial for temperate tree species distribution, especially at the lower end of water availability (Piedallu et al., 2013; Mellert et al., 2018). Although soil chemical properties are less important for predicting species distribution than soil physical properties (Gauer, 2014), the base saturation (BS) is a valuable site factor as it describes the availability of certain macronutrients (K, Ca, Mg) (Blume et al., 2016). Interactions between BS and AWC can explain small-scale variation in the growth of Norway spruce (Brandl et al., 2014). In recent years, considerable effort has been invested into moving from qualitative or semi-quantitative to quantitative site characteristics (Schmidt-Walter et al., 2019). Comprehensive site information systems are available in some German federal states (Taeger et al., 2016). These include legacy soil data as well as data from recent surveys at an appropriate spatial resolution (Petzold et al., 2016; Putzenlechner et al., 2023). However, this is not the case for all regions of Germany. In combination with the data from the German Weather Service and the Level II monitoring programme, this data can potentially be used to regionalise the climate data relevant to the water balance of forests (Rukh et al., 2022). At the continental level, however, high resolution maps for projections that combine climate and soil characteristics and functions crucial for site-adapted and sustainable management decisions are still generally lacking (Gauer et al., 2011; Puhlmann & von Wilpert, 2012; Kolb et al., 2019).

34th Statement: the monitoring of strictly protected forests provides information for the management and development of current and future forests. (established but incomplete)

The monitoring of strictly protected forests has the potential to provide a better understanding of long-term dynamics in forest ecosystems (Schultze et al., 2014; Meyer, 2019; Mathys et al., 2021). Such changes can be detected by, for example, comparing proportions of tree species observed in recent years with those reported in earlier surveys. European beech (*Fagus sylvatica* L.) is one species already exhibiting declining proportions on warmer sites with a higher probability of drought (Schuldt et al., 2020; Umweltbundesamt, 2023). Observations in strictly protected forests offer unique opportunities to study specific effects of forest structures, as well as dispersal, colonisation and establishment processes of species in general, but also of species that are considered a threat in managed forests, such as bark beetles (Hlásny et al., 2019; Storch et al., 2019). These areas can be used as reference sites to evaluate the effects of different forest management concepts. Numerous studies have been carried out to characterise the occurrence of dead wood in protected forests, and the associated effects (Puletti et al., 2019; Vandekerkhove et al., 2009; Thorn et al., 2020), so that the dead wood targets could also be integrated into forest management plans (Vítková et al., 2018). Carbon sequestration has been studied by a space-for-time approach (Nagel et al. 2023) but time series data is needed to get more detailed insights, especially in regard of rare forest types (i.e. others than beech forests). To better apply strictly protected forests as model systems, further study is required, addressing the regeneration ecology of tree species, carbon sequestration and water retention with regard to the influence of global change. Since most strictly protected forests have been managed until some decades ago and have an altered structure, it is important to integrate true virgin/-primary forests where this is possible (Ammer et al., 2018; Meyer et al., 2021). As yet there are few studies looking at the impact of patch sizes and transition areas between strictly protected forest areas and their connectivity with surrounding landscape elements (e.g., managed forests), which might help assess the impact of global change at the landscape level (Parviainen & Frank, 2003; Sabatini et al., 2020).

35th Statement: forest monitoring programmes contain information on low-value timber and non-native tree species. (inconclusive)

Several systematic policy-driven forest monitoring systems exist in Germany, Austria and Switzerland. However, currently only the plots of the 'Intensive long-term monitoring of forest ecosystems' programme (Level II plots as part of the 'International Co-operative Program on Assessment and Monitoring of Air Pollution Effects on Forests', ICP Forests) represent continuous monitoring capable of determining the cause and effect of environmental factors and forest response (Gessler et al., 2022; Michel et al., 2023). The 68 Level II areas in Germany cover the most important tree species and growing conditions, and potential future forest tree species (e.g. Douglas fir and larch) are each part of a Level II area. However, other non-native tree species such as red oaks and secondary forest tree species are not included in Level II monitoring at all (Etzold et al., 2019; Michel et al., 2023). In Switzerland, the network of 19 Level II plots contains five forest sites on former coppice (i.e., low-value timber) forests. In Austria, 16 Level II areas are being monitored that are representative of the development of climax tree species (Michel et al., 2023). To obtain detailed information about the development and management of early successional or non-native tree species, whose increasing importance for future forest development has already been explained in detail (e.g., statements 17, 26), this range of tree species and the associated forest types should be more closely integrated into the existing monitoring systems.

Discussion

As the classification and evaluation of the core statements according to the IPBES categories have shown (Fig. 2), many issues are underpinned by extensive studies, but their informative value repeatedly reveals gaps arising from ongoing climate changes and recurrent extreme events. In addition, the arrangement according to the seven thematic categories made it possible to determine where particularly pressing issues for future forest management under global change are emerging. The identification of the corresponding research priorities shows that intensive studies are required in the future, particularly in the areas of tree species and provenance selection, as well as measures to promote regeneration and structural complexity. According to the experts involved, there is also an immediate need to adapt the existing monitoring systems. The use of innovative technical systems such as terrestrial laserscanning is of great importance in this regard and will open up completely new possibilities to document climate influences. Finally, the focus of research and practice will in future shift from the primacy of raw material production to ensuring diverse ecosystem services. The various approaches to possible measures that were compiled in the statements on the adaptation of forest ecosystems to climate change are summarized once again in Fig. 3. Based on the different initial condition of the forests and the different disturbance intensities and causes, there are process- and structure-related options for further forest management, which are assigned to the seven thematic groups of statements (Fig. 3).

The uncertainty of tree species selection and management

According to our literature survey, a mechanistic understanding of the drought and heat tolerance of tree species is becoming increasingly important (see section I.; Dyderski et al., 2018). Despite extensive studies, new methodological approaches and silvicultural experience of site-specific tree species selection (statements 2–3), there remains a great deal of uncertainty in predicting tree species responses to global change (Trugman et al., 2021). As long as there is no mechanistically sound classification of the drought and heat tolerance of candidate tree species, there is a risk that even tree species that are considered classically drought-tolerant will not necessarily survive future droughts. Aubin et al. (2016) provides a systematic overview of the functional traits of plants regarding adaptation to changing environmental conditions in order to examine the basis for the application of models. This can be attributed, among other things, to the fact that the traits needed for modelling approaches are not yet available for most species (statement 4).

The current argumentation put forward by many ecological and economic forest stakeholders, therefore, is primarily based on strategic risk diversification in forest management (von Detten & Hanewinkel, 2017). For the development of climate-adapted forests, it is recommended that single-layered pure stands be transformed to mixed forests rich in structure and species so as to reduce the risk of a complete forest destruction in the event of an extreme climate event (De Boeck et al., 2018; Messier et al., 2019; Pardos et al., 2021) and to reduce insect pest and pathogen outbreaks (Jactel & Brockerhoff, 2007; Bauhus et al., 2017; statement 8–9). Although the information on different tree species regarding their site preferences and the prognoses on their adaptability under changing climatic conditions is extensive (Gessler et al., 2024), many questions arise regarding advantageous stand structures and mixture constellations (statement 5). It is assumed that a larger number of tree species at a particular site may reduce the risk of losing all co-occurring species during or after an extreme climate event, but there is a lack of robust data for many tree species and stand constellations needed to prove that tree species diversity also guarantees increased resilience and resistance to climate change (Pretzsch et al., 2013; Ovenden et al., 2022). Under extreme drought beneficial species interactions may shift and more negative effects such as competition for water resources may occur (Haberstroh & Werner, 2022). It is necessary, therefore, to investigate which specific tree species mixtures facilitate beneficial above- and belowground neighbourhood interactions (Pardos et al., 2021; Hajek et al., 2022), while at the same time providing a variety of ecosystem functions that meet future demands on forest ecosystems (Paul et al., 2019). So far, studies on interactions between tree species have mainly focused on competitive relationships seeking to optimise their growth potential at different stages of development (Pretzsch & Zenner, 2017). The forecasts show that the extent and frequency of future drought events cannot be compared with past events (cf., Leuschner & Meier, 2018; Büntgen et al., 2021).

A differentiated consideration of tree species composition and site conditions is necessary (Nguyen et al., 2016). In large parts of central Europe, forest soil science and site ecology have a long tradition and provide detailed information for forest management planning down to the stand level (Busse et al., 2019; Wellbrock et al., 2019). Adapting appropriate tree species mixtures to small-scale site conditions and accounting for variation in soil chemical and physical properties requires intensification of site inventories and the incorporation of legacy soil and site data (Petzold et al., 2016; Stritih et al., 2021). Both past and existing tree species constellations exert an influence on site potential, as do past measures such as melioration or liming (Achilles et al., 2021; van Straaten et al., 2023).

Species mixtures can improve the nutritional status of individual trees compared to pure stands on fertile sites (de Streel et al., 2021), but comprehensive knowledge is lacking for both established and potential new species constellations (statement 1). The effects of structural resistance due to specific tree species combinations and mixture constellations have not yet been conclusively clarified (statement 5). A question that arises for silvicultural practice is which vertical

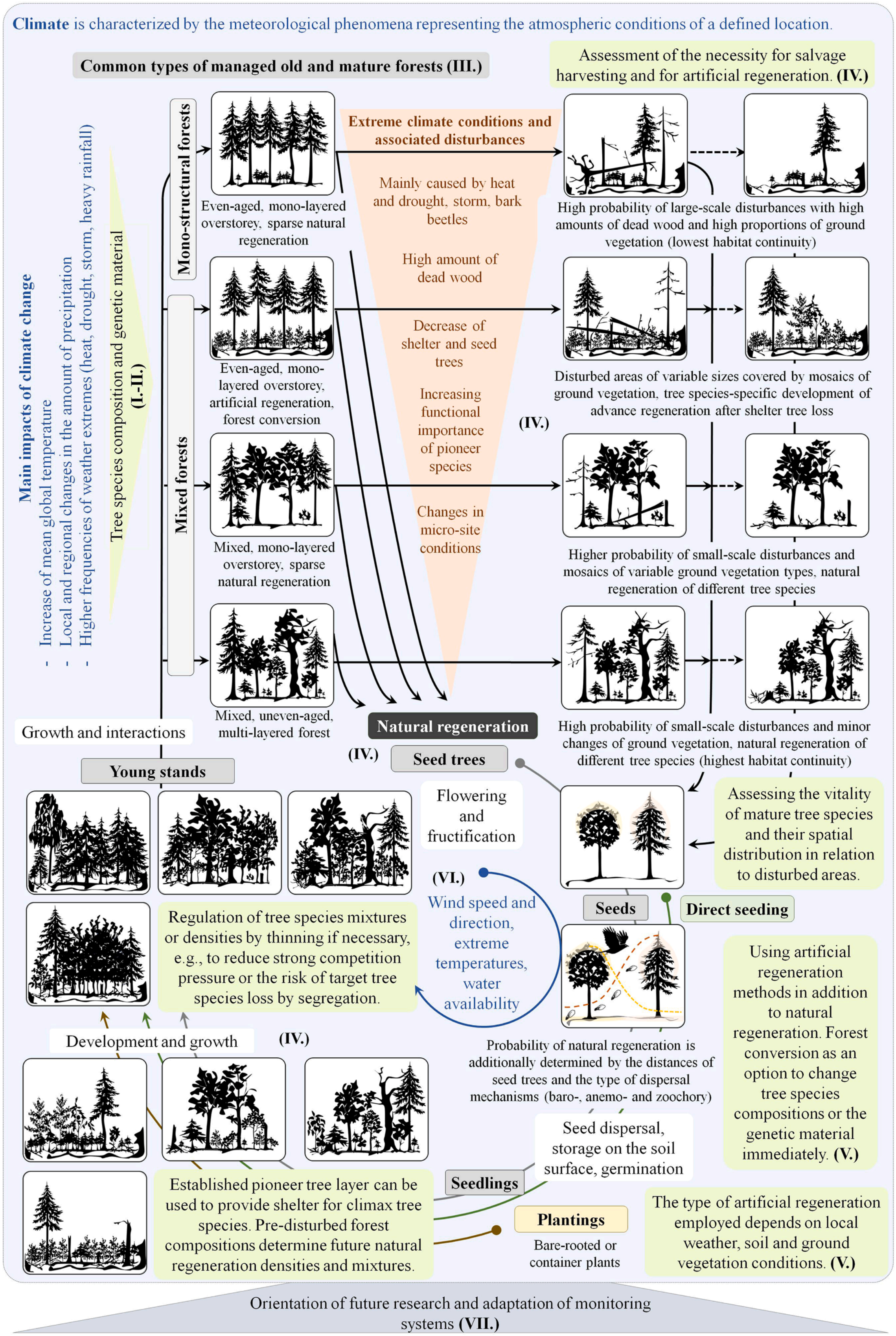

Fig. 3. Chronology of climate-induced disturbances and related forest development options considering different initial stand conditions and the level of resistance (stand) and resilience (regeneration). (I.-VII. denote the seven main topics).

stratification ensures optimal adaptation to drought and whether smaller or larger groups of tree species mixtures are advantageous at stand level.

The introduction of non-native tree species with limited invasive potential is often mentioned as an option to cope with the global changes occurring in the 21st century (statement 10). For most temperate tree species of North America and East Asia there is a climatic similarity between their area of origin and their area of cultivation in central Europe (Pötzelsberger et al., 2020; Gauli et al., 2022; Ovenden et al., 2022). There are also well-confirmed statements on higher drought tolerance, e.g. for specific provenances of *Pseudotsuga menziesii* (Eilmann & Rigling, 2012; Lévesque et al., 2013; Wohlgemuth et al., 2021), *Pinus nigra* J.F. Arnold (Bachofen et al., 2019) or *Cedrus atlantica* (Endl.) Manetti ex Carrière (Frei et al., 2018) compared to the tree species native to central Europe. It should not be forgotten that site-specific factors appear to be important for initial performance (Frischbier et al., 2019; Glatthorn et al., 2024), but the risk from new pests and diseases associated with the introduction of non-native tree species in the long-term needs to be considered (statement 10). In this context, the need for information on the development of non-native tree species in mixtures with native tree species must be emphasized once again.

Climate-induced bottlenecks within the regeneration cycle of tree species

The selection and provision of site-specific tree species is of primary importance for all stages and processes within the regeneration cycle (Boucher et al., 2020; Axer et al., 2021; Muffler et al., 2021). However, due to the climate-induced species- and stage-specific interactions, it is not possible to come to a general conclusion (statements 24–25). Tree species and provenances should be tested and studied, “at the limit of their ecological range [...] to understand the physiological basis for responses” (Spittlehouse & Stewart, 2003, p. 8; see also Frei et al. 2018). This applies especially to trees in the early developmental stages as they are more sensitive than site-adapted adult trees (statement 13). The success and continuity of regeneration of tree species depends on the extent of local and regional climate extremes and the available niches (statement 14). Endemic tree species are probably at risk of being displaced and becoming extinct (McLaughlin et al., 2002; Thomas et al., 2004; Hannah et al., 2005; Peterson et al., 2006). The survival of the species depends on migration, adaptation or ex situ conservation strategies (statement 12). The measure of assisted migration is derived as an anthropogenic regeneration and reforestation option to accelerate migration (Williams & Dumroese, 2013) or extend the use of seeds or seedlings from outside the natural range as ‘assisted colonisation’ (Peterson St-Laurent et al., 2018).

The timing of climate drivers is different for flowering, fruiting and seedling development (Fig. 3; e.g., Övergaard et al., 2007; Wohlgemuth et al., 2016; Nussbaumer et al., 2018). Seed dispersal, seed storage and germination are essential stages in the successful development of tree species (statement 23). Wind-dispersed seeds may profit directly from warmer temperatures, lower amounts of precipitation, and stronger and more frequent winds at the right time (Teller et al., 2016). The estimation of future developments in climate-induced zoochorous dispersal processes is very difficult (Johnson et al., 2019), because of the strong species-specific interconnectedness of seed traits and seed dispersing animals (e.g., Pesendorfer et al., 2016). Evidence for behavioural responses of these zoochore vectors is lacking (Johnson et al., 2019), but many European tree species (e.g., oak, beech, rowan) are dependent on these dispersal vectors (Vargas et al., 2023).

In slightly disturbed forest ecosystems a closed canopy provides for low fluctuations in temperature and consistently humid conditions on the soil surface, which is an existential basis for the germination of tree seeds (Walck et al., 2011; von Arx et al., 2013). With increasing frequencies of drought, and higher intensity summer droughts in central Europe, only those tree seedlings that can achieve prompt above- and belowground reactions will survive (statements 22, 24, 25). Especially important in this regard are a well-developed fine root network or deep tap roots (Urbieta et al., 2008; Vizcaíno-Palomar et al., 2014; Tíscar et al., 2018; Varsamis et al., 2020). It has been suggested to adjust the time of germination locally to avoid frost and summer drought during the emergence of seedlings (Urbieta et al., 2008; Varsamis et al., 2020). Less vigorous seedlings may also be more susceptible to attack by pathogens (Roberts et al., 2020).

Projected future climate conditions suggest that intra- and interspecific interactions (competition vs facilitation) of juvenile plants will shift along the stress gradients of different forest ecosystems, particularly with regard to their functional traits (Schwinning & Kelly, 2013; Carón et al., 2015). Climate-induced disturbances in overstorey tree layers will reduce the competition pressure that mature trees exert on juvenile trees (Ammer, 2002). However, the removal of overstorey trees also means that the facilitative effects for the regeneration layer are lost (Ettinger & HilleRisLambers, 2017). At the same time, the competitive potential of species that are tolerant of high temperatures and that of light-demanding species of ground vegetation increases (Balandier et al., 2006), which can prevent or delay the development of trees (statement 26).

The extreme temperature conditions caused by large-scale disturbances (Bogenrieder et al., 1998) have a direct influence on the development of soil seed banks, germination and on the development of young trees (Dietze & Clark, 2008; Tiebel et al., 2018). The lack of vital seed trees in areas of large disturbance can also prevent successful regeneration (statement 20), but this is a consequence of previous forest management strategies that should not be repeated in the future (Kneeshaw & Bergeron, 1996; Rother et al., 2015; Thom et al., 2020; statement 22).

Silvicultural options for forest restoration and drought stress mitigation in times of global change

The silvicultural restoration options should be adapted to the respective forest condition (deviation from near-natural systems) or to the degree and extent of climate-induced disturbances (Senf & Seidl, 2021a; statement 26). Yet they are also determined by the economic and technical effort involved (Schall & Ammer, 2013; Fuchs et al., 2022). Large-scale climate-related disturbances were the exception rather than the rule given the formerly high continuity of European forests following the last postglacial recolonisation. The ‘historically old forests’ are characterised by the presence of various buffer functions such as well-developed (statement 18), typical forest soils, root properties and their associated community of soil organisms (Fichtner et al., 2014; Leuschner et al., 2014; Buczko et al., 2017). The autochthony of plants associated with continuous population development implies a genetic adaptation to existing global conditions, but as has already been mentioned, this does not necessarily imply an adaptability to changing climatic conditions (statements 12, 14). Knowledge about the effects of silvicultural measures under past and present climate conditions is necessary to analyse their transferability to changing climate conditions. In accordance with Leibundgut (1909–1993), we should also consider the following questions in every silvicultural decision with a view to adapting forests to climate change ‘Where do you come from, who are you, where will you go?’. The silvicultural restoration options range from supportive measures that blend harmoniously into the natural processes to abrupt measures aimed, for example, at immediate enrichment with mixed tree species. The uncertainty of accurately estimating the time until the onset of disturbance, because future conditions are unknown (statement 20), poses great challenges to forestry (e.g., continuous cover forestry, retention tree systems and networks of historical land-use forms) and concrete operations (e.g., selective cuttings, thinnings from above). An abrupt reduction in stand density can, at least in old stands that have been kept dense over decades, entail the risk of damage, disease and increased tree mortality, especially in older, formerly closed spruce and beech stands (Schuldt et al., 2020).

Therefore, further adaptations of a forest stand to climate change can be controlled particularly well if the intervention intervals (for thinning, maintenance measures) are relatively short and the intensity is low (Keenan & Kimmins, 1993; Rothe & Mellert, 2004). The technique of using shelterwood continuity and single tree selection as minor disturbances to increase structural habitat quality and diversity are proven silvicultural methods adopted to create a climate-resilient, site-adapted generation of trees (Dreger & Schulz, 2003; Jaloviar et al., 2018; Skłodowski et al., 2018; Heine et al., 2019).

Others advocate more intensive forest management, as the low intensity of intervention increases the risk of catastrophic failures in the long-term. Preventing such failures is often essential, especially in forests with a protective function (Scherrer et al., 2023c). Adaptive forest management with high intervention intensity has been proposed to promote tree species diversity of climatically adapted species. However, the long-term management effects on forest structures are site- and stand-specific (e.g., Nikolova et al., 2019) and therefore difficult to generalise (statement 19). The degree of structural richness is a matter of debate and even less is known about tree species- and site-specific effects and interactions of root systems in relation to drought and climate resilience (Meier & Leuschner, 2008; Magh et al., 2019; Nikolova et al., 2020). So far, little is known about the impact of highly structured stands, but it seems as if structural more divers stands are more resilient under drought (Jones et al., 2019; Mathes et al., 2024). It also remains to be seen to what extent, and for how long, a reduction in the number of stems will affect the water supply of the remaining trees across all species. Initial long-term studies by Giuggiola et al. (2013) for *Pinus sylvestris* show that a reduction in basal area can also reduce competition for water and mitigate the effects of drought.

Natural regeneration methods, and direct seeding as a near-natural silvicultural regeneration technique, have grown in importance over the last two decades (Ammer & Mosandl, 2007). As water is crucial for seed germination and very early seedling performance (Ammer et al., 2008), more frequent and longer drought periods will increase the risk of failed direct seedings (Huth et al., 2017). In addition, it is becoming more difficult to control and modify microsite conditions to create suitable safe sites. Supporting regeneration techniques such as soil scarification may also lead to nutrient leaching and decrease water availability during periods of drought (Rappe George et al., 2017).

A more abrupt conversion of the tree species in the canopy of an old stand is achieved by advance planting in combination with interventions in the upper stand (e.g., by creating gaps or shelter cuts). It is not yet clear whether negative microclimatic conditions can be offset by the timing or interval of interventions. It is particularly important to understand the species-specific physiological and morphological responses upon canopy release (statement 24). The abrupt loss of shelter trees as a result of global change-induced disturbances increases the risk to the achievement of the two goals of restoration, namely a 'sustainable' and a 'functional' ecosystem (Wagner, 2007), especially for shade-tolerant tree species (Lemoine et al., 2002; Diaconu et al., 2017; Hlásny et al., 2017; Mausolf et al., 2018b; Weidig & Wagner, 2021). Light-demanding tree species such as pines and oaks can benefit from a reduction in the number of stems (Aldea et al., 2017; Schmitt et al., 2020; Steckel et al., 2020; Huth et al., 2022). It has been demonstrated for advance plantings of European beech that silvicultural management needs to combine overstorey shelter effects and high densities of young trees to produce future stems of high slenderness and quality (Blaschkewitz, 2018; Weidig & Wagner, 2021). A high-density planting design may buffer against increased mortality and incidence of disease (Roberts et al., 2020). When species mixtures are planted, they should be (phylogenetically) diverse as mixing tree species susceptible to a pathogen with non-susceptible species improves resilience to pathogens (Roberts et al., 2020). Knowledge of the effects of the spatial scale of mixed plantings on rates of pathogen infection is scarce, but mixing may be important on the scale of the forest stand due to neighbourhood effects.

The importance of broadleaved pioneer tree species (statement 17) relates to the positive effects on topsoil chemistry, biological activity and the general state of the ecosystem (Zerbe & Meiwes, 2000; Huber, 2005; Stark et al., 2015; Hilmers et al., 2018; Dubois et al., 2020). From a silvicultural point of view, natural succession or the direct seeding of pioneer tree species (nurse trees) should be used more frequently, especially on large, disturbed areas with suitable ground vegetation (Rammig et al., 2006; Anderson-Teixeira et al., 2013; Willoughby et al., 2019). The planting of bare-root seedlings is limited by site-specific water availability and the drought resistance of species and provenances, but these effects can be compensated using container plants and additional supportive measures such as hydrogels and the inoculation of plants with mycorrhiza (Grossnickle & El-Kassaby, 2016; Khan et al., 2016; Nickel et al., 2018).

Innovative monitoring methods and compensation for ecosystem goods and services

The theoretical socio-ecological concepts of ecosystem services as nature's contributions to people are of increasing importance in terms of implementing climate-adapted forest management (statements 16). This is hindered by the fact that traditional silvicultural systems have been developed with a focus on tree growth and the demand for high quantities and high quality wood (Nyland, 2016; Bartsch et al., 2020). Drought-induced increases in tree mortality reduce the growing stock (Schelhaas et al., 2003; Bose et al., 2024) and result in high direct and indirect economic losses for forest enterprises and the timber processing sector (Möhring et al., 2021). Many other ecosystem services, for example, soil and habitat protection, carbon storage and recreation can also be provided by forest management and silvicultural systems, but so far combinations of the different service categories are not achieved in an optimal way (e.g., European Environment Agency, 2015). In addition to the use and expansion of monitoring systems (statement 31), practical implementation can only succeed if incentive systems are created for forest owners that provide ecosystem services in a targeted manner and promote these services through adapted treatment concepts (Vacek et al., 2023). Changes to forest ecosystems driven by climate impacts need to be documented and integrated into silvicultural practices, and modifications of these practices are required (e.g., statements 19, 20, 24). In this respect a representative and intensely monitored network of control sites, i.e. strict forest reserves, is a prerequisite. Cross-scale information about the spatial arrangement of forest management systems is of crucial importance in terms of coordinating multiple forest management goals (statement 34), and controlling their achievement by forest managers (Pohjanmies et al., 2019; Wagner et al., 2020). Only the continuity of monitoring systems and the development of complex databases guarantee the consolidation of extensive information while also enabling evaluation approaches across different spatial scales and the combination of diverse ecosystem services and nature's contributions. Many of the current forecasts concerning the negative and positive regulatory effects of forests are mostly based on assumptions or merely represent case studies (statement 17). Areas of forest characterised by low value timber and/or non-native tree species will be essential parts of the forests of the future and so functional knowledge of such forest systems and species, and monitoring tools, will become increasingly important (statement 35).

Most effects depend heavily on silvicultural treatments following disturbances (Thorn et al., 2018; Hagge et al., 2019). For example, carbon storage potential is reduced where management is not adapted (Seidl et al., 2014). The effects are, however, expected to vary with disturbance type (Senf et al., 2019). Forest disturbances are not a general obstacle to non-material NCPs, as tourism in disturbed forest landscapes shows (Sacher et al., 2022; statement 31). Disturbed areas, e.g. after windthrow, increase arthropod diversity, especially species groups such as pollinators or saproxylic species are even increasing in the first three years after the event (Kortmann et al., 2021; Wermelinger et al., 2025). In many regions, the perceived restorativeness is of great importance for touristic use (Simonienko et al., 2023; Queirolo et al., 2024). Although the perceived recreational value, explained by the personal cognitive abilities of forest visitors, decreases with increasing disturbances in forests, disturbed areas are still perceived by forest visitors as valuable recreational space (Kortmann et al., 2021). However, the duration of this effect is largely unclear, as are the possibilities for influencing this effect through silvicultural measures.

Conclusions

Europe's forests are increasingly exposed to the pressures of global change, which cause species-specific effects on vitality, intra- and interspecific interactions, and changes in site-specific distribution at all stages of forest development. Innovative monitoring techniques and procedures will significantly improve the possibilities with respect to differentiated data collection, processing and the forecasting of climate-induced forest development. However, the long-term establishment of complex monitoring systems requires an enormous financial budget and design coordination when implementing new modules. Nevertheless, the complexity of forest ecosystems and their connectedness with the diversity of anthropogenic influences and demands make it difficult to derive general statements about tree species selection and silvicultural practices. The analysis of the various statements on the development of European forests under global change illustrates that the current knowledge is characterized by the limited validity of spatial and temporal dynamics and the related effects of silvicultural measures. These relationships require the development of diverse silvicultural treatment strategies, some of which are regionally specific, and the continuous review of their impacts on forest ecosystems with the associated sustainability of nature's contributions to people. Different silvicultural systems with different management intensities, applied at different spatial and temporal scales, should be combined in future to ensure the diversity of nature's contributions to people and to minimize risk.

Author contributions

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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