Wissenschaftlicher Beirat
für Waldpolitik
beim Bundesministerium für
Ernährung und Landwirtschaft

Adaptation of forests and forestry

to climate change

- Executive Summary -

Report of the Scientific Advisory Board

on Forest Policy

November 2022

Members of the Scientific Advisory Board on Forest Policy

Prof. Dr. Jürgen Bauhus (Chairman);
University of Freiburg, Faculty of Environment and Natural Resources, Institute of Forest Sciences

Prof. Dr. Ute Seeling (vice chair);
University of Applied Sciences Bern – School of Agricultural, Forest and Food Sciences HAFL

Prof. Dr. Matthias Dieter;
Thünen Institute for International Forestry and Forest Economics, Hamburg

Prof. Dr. Nina Farwig;
University of Marburg, Department of Biology

Prof. Dr. Ing. Annette Hafner;
University of Bochum, Faculty of Civil and Environmental Engineering

Prof. Dr. Ralf Kätzel;
Eberswalde Forestry State Center of Excellence, Department of Forest Ecology and Monitoring

Prof. Dr. Birgit Kleinschmit;
Technical University of Berlin, Institute for Landscape Architecture and Environmental Planning

Prof. Dr. Friederike Lang;
University of Freiburg, Faculty of Environment and Natural Resources, Institute of Forest Sciences

Dr. Marcus Lindner;
EFI European Forest Institute, Bonn, and Univ. of Eastern Finland, Faculty of Nat. Sciences and Forestry

Prof. Dr. Bernhard Möhring;
University of Göttingen, Faculty of Forest Sciences and Forest Ecology, Institute of Forest Economics

Prof. Dr. Jörg Müller;
University of Würzburg, Biocenter, Chair of Animal Ecology and Tropical Biology

Prof. Dr. Manfred Niekisch;
University of Frankfurt, Institute for Ecology, Evolution, and Diversity

Prof. Dr. Klaus Richter;
Technical University of Munich, Chair of Wood Science

Prof. Dr. Ulrich Schraml;
FVA Forest Research Institute Baden-Württemberg, Freiburg

Executive board
BMEL, Department 513, 513@bmel.bund.de

Scientific support
Dr. Regina Rhodius; Dr. Rüdiger Unseld
Univ. Freiburg, Faculty of Environment and Natural Resources, Institute of Forest Sciences

The members of the WBW take full responsibility for this report.

Imprint

Publisher

Scientific Advisory Board on Forest Policy (WBW) at the
Federal Ministry of Food and Agriculture Germany (BMEL)

Secretariat:
Federal Ministry of Food and Agriculture Germany (BMEL)
Division 513

Postal address: 11055 Berlin
Telephone: 030 / 18 529 – 3741
E-Mail: 513@bmel.bund.de

Text

Scientific Advisory Board on Forest Policy WBW Wissenschaftlicher Beirat für Waldpolitik
Citation for this publication: Scientific Advisory Board on Forest Policy (2022): Adaptation of forests and forestry to climate change. Berlin, 53 S.

Authors: J. Bauhus, M. Dieter, N. Farwig, A. Hafner, R. Kätzel, B. Kleinschmit, F. Lang, M. Lindner, B. Möhring, J. Müller, M. Niekisch, K. Richter, U. Schraml, U. Seeling

Image sources

Jürgen Bauhus, Waldbau, Univ. Freiburg, Birgit Kleinschmit, ILU, TU Berlin, Rüdiger Unseld, Waldbau, Univ. Freiburg, Friederike Lang, Bodenkunde, Univ. Freiburg, Annette Hafner, Ruhr-Universität Bochum, Ulrich Schraml, FVA Baden-Württemberg, Julian Frey, FELIS, Univ. Freiburg, Daten- und Kartendienst der LUBW, Ulrich Schraml, FVA Baden-Württemberg, Tobias Modrow, Waldbau, Univ. Freiburg, Kyle Kovach, Geobotanik, Univ. Freiburg

Table of Contents

Summary

Climate change is altering our forests in numerous ways. The impacts on forests, their ecosystem services, and forestry will likely be predominantly negative. In addition to rising temperatures and changes in precipitation distribution, it is above all the increase in extreme events and their interactions that will cause significant disturbances to forests. The massive, widespread forest damage resulting from the dry, hot years of 2018-2019 is already an indication of the speed at which these changes may advance in Germany, too. There is, therefore, an urgent need to develop comprehensive concepts for forest adaptation and management aiming as far as possible to buffer negative consequences. This will enable forests to continue to offer their diverse ecosystem services to our society in the future as well. As with climate change mitigation, policy makers will also be called on in the case of adaptation to climate change to put in place the framework conditions that will offer future generations the same options for the use of forests as the current generation in a spirit of intergenerational justice. Like climate change mitigation, forest adaptation presents an urgent and massive challenge to all stakeholders that will necessitate shifts in paradigms at numerous levels. It was against this backdrop that the Scientific Advisory Board on Forest Policy (*Wissenschaftlicher Beirat für Waldpolitik*, WBW) drew up this report.

The report drew on validated scientific findings and its recommendations for action focus on the main opportunities for influencing the maintenance and improvement of the provision of ecosystem services by forests in a changing climate. The report begins by outlining the known current impacts of climate change on forests and their ecosystem services and identifies opportunities for adaptation in different areas of forest management and use. They include forestry, wood processing, bioeconomy, nature conservation, soil protection, water protection, health care, recreation, and tourism. The conclusions drawn from this resulted in concrete recommendations for adaptation measures in a total of 13 areas of action. The recommendations aim is to create conditions that ensure the continued provision of the ecosystem services of forests in the future in line with societal needs.

To this end, forests should evolve, where necessary with silvicultural support, towards diverse, resilient, and adaptive woodlands. This includes the active and passive promotion of the diversity of site-adapted tree species and their functional and genetic diversity as well as the protection of forest soil and its functions, which must be maintained and improved by means of suitable measures. To this end, concrete measures for the adaptation of forest stands are recommended, especially in the phases of regeneration and forest stand tending. They must be backed by improved regional and supra-regional data on the suitability of locations and tree species.

Forest biodiversity is an important basis for the adaptability and diversity of all processes that make ecosystem functions and services possible in the first place. Comprehensive consideration must, therefore, be given to this aspect from the genetic through to the ecosystem level when adapting forests to climate change. This raises more particularly the question as to which species, populations, and habitats are most at risk, and whether and to what extent these will or may shift as a consequence of climate change. The protection of biodiversity should, therefore, be taken into account across the board, i.e. outside protected areas, too. Consequently, special attention should be paid to the future structure and composition of tree species in forests. Natural biotopes, habitats, and ecosystems are to be preserved and promoted as far as possible as part of adaptation at the landscape level. The promotion of biotope networks should ensure the mobility options of species. In the case of less mobile species, the option of targeted introduction in future distribution ranges should be used. Representative biodiversity monitoring and consideration of climate change when developing conservation targets should enable the most efficient nature conservation possible in forests.

The conservation of forests and their diverse ecosystem services very much depends on their protection from biotic and abiotic risks, which will increase in the future. There is, therefore, a need for significantly improved risk management in close connection with monitoring boasting a high degree of temporal and spatial resolution, something which is deemed to play a key role in the forest adaptation process. To prevent large-scale damage to forests, operational forest protection will have to be supplemented by national forest protection management, improved control of harmful organisms and forest diseases, objective damage assessment and risk prevention, and the acceleration of restorative measures for forest conversion, too.

Increasing extreme weather events, reductions in forest productivity, and changes in the spectrum of tree species, coupled with rising costs for adaptation, risk management, monitoring, and ecosystem services, will reduce the earnings from traditional forestry with its emphasis on raw timber production in the long term. These developments will merely serve to exacerbate the existing structural

problems, especially in the small-parcel private and corporate forests. Against this backdrop, the effective implementation of adaptation measures is dependent on the creation of stable institutional structures. They include the appropriate management of non-state forests and more efficient structuring of forestry support. This should be accompanied by the development of information platforms, the creation of incentives for proactive forest management, and the formation of larger management units.

Given the expected drop in forest productivity and shift in the composition of tree species towards more hardwood, the supply of the raw material wood will become a major challenge in the long term, especially from domestic forests. This will also necessitate an adjustment of the downstream wood-based industry and timber use. To this end, value chains must be established which optimize the economic and climate-impacting use of unprocessed wood from domestic forest management and support the transformation to a bioeconomy as the basis for new environmentally friendly products. Incentive systems and technical processes should be developed that lead to an increase in material use and a reduction in direct energy use, especially in the case of timber categories that have been difficult to market up to now (calamity timber, large-dimensioned coniferous wood, hardwood). Timber construction plays a key role here as it is an available bridge technology[1] that can be used right now in climate change mitigation and for the preservation of non-renewable resources. To be able to partially replace the declining domestic supply of coniferous wood categories, the preconditions for the production of new mechanical pulp sources from recovered and waste wood must be met. To ensure an adequate supply of coniferous wood in the long term, the low-risk cultivation of climate-adapted coniferous species in mixed stands should be put in place. Temporary market distortions in the aftermath of large-scale disturbances should be countered with responsive markets, appropriate logistics, and storage structures.

Forests are an important foundation for what is known as cultural ecosystem services. The attractiveness of forests for recreational and leisure use in the wake of expected climatic changes is likely to increase. At the same time, there will be changes to familiar forest and landscape images and altered conditions for a wide variety of recreational activities in forests. Providing recreational services and reducing potential conflicts between recreational use and timber harvesting will increase management expenses, particularly in urban areas. In addition to communication and conflict mitigation measures, the remuneration of ecosystem services for recreation, sports, and tourism will, therefore, be an important component in the future design of climate-resilient recreational forests.

The actions needed to maintain and enhance the provision of forest ecosystem services are very extensive and costly. According to estimates by the Scientific Advisory Board for Forest Policy, the costs of the rapid and effective adaptation of forests to climate change exceed a level that non-governmental forest owners can be expected to bear within the framework of their public service obligation. At present, the revenues of forest enterprises are based almost exclusively on proceeds from timber sales, whereas the provision of socially important ecosystem services for climate change mitigation, water protection, nature conservation, recreation, etc., which have not been remunerated up to now, are perceived as burdens. Therefore, a key recommendation of this report is that public authorities put in place remuneration systems for forest ecosystem services that provide forest enterprises with reliable, long-term revenues from the provision of ecosystem services. We believe that a fundamental and efficient way of doing this involves not remunerating individual ecosystem services but rather viewing the foundation for the future provision of ecosystem services – the ability[2] of forests to adapt to climate change – as a service. Consequently, payment based on the condition of the forests is recommended; this is seen as a necessary complement to the measure-based funding currently in place.

Rapidly advancing climate change is accelerating the erosion of the relevance of previous empirical knowledge and leading to increased uncertainty. To effectively and efficiently adapt forests, forest management, the wood-based industry, and other relevant sectors to climate change, the recommendation is to step up research in the forest sciences and timber products. In particular, this involves a strategic orientation and the development of

[1] 1 What is meant by bridge technology in this context is that timber construction is currently the only ready-to-use technology *(negative emission technology)* that makes it possible to store carbon on a significant scale outside ecosystems. "Bridge" in this context means that this technology should be deployed immediately to implement this carbon storage until other technologies, such as *carbon capture and storage* or *carbon capture and usage,* reach readiness (TRL 9) in the future. This does not mean that thereafter timber construction will cease to be important. The term underscores the urgency of implementing this carbon storage option immediately.

[2] Adaptive capacity refers to the ability of systems, institutions, people and other living beings to adapt to potential harm, to seize the advantages or to react to the effects (IPCC (2013/14).

new research approaches along the lines of sustainability research that are geared to urgency, solutions, and implementation. This will necessitate corresponding long-term research infrastructures and capacities as well as improved networking and cooperation between existing research institutes. To promote the transformation process, the WBW also makes recommendations on changes in education and training, communication strategies, and the removal of barriers and conflicts surrounding adaptation in the various sectors.

Preamble

Adaptation of forests and their management to climate change to safeguard their ecosystem services

Climate change will alter our forests in many ways. The negative impacts on the functions and ecosystem services of forests and their management will very likely prevail. Therefore, to protect our life-sustaining systems, top priority should be given to minimizing as far as possible the effects on forests and ecosystem services and preparing for unavoidable changes. Consequently, climate change mitigation efforts must be stepped up in most areas to avoid massive damage. This goal also underpins the international agreements on climate change mitigation. However, even if we succeed in achieving these goals, both nationally and internationally, there is general agreement that changes to our ecosystems will occur (IPCC 2019, IPBES 2019). We are already seeing significant shifts in the composition of tree species and increases or changes in biotic and abiotic disturbances in the form of the mass propagation of bark beetles, new forest diseases, droughts, forest fires, and storms. Forest ecosystems and their plant and animal communities will experience novel climatic conditions over large areas during this century. They will also be exposed to new diseases and pests which they have been unable to adapt to throughout their long evolutionary history up to now (Fei et al. 2019, Hoffmann et al. 2019). Consequently, some species will disappear and new ones will appear in our forests. The changes in species communities and climatic conditions will also lead, in many cases, to changes in ecosystem functions. The question, therefore, is not whether but how dramatically and rapidly our forests and, by extension, the provision of ecosystem services, will change.

Forests are strongholds of biodiversity and German society depends on the diverse ecosystem services provided by forests in many ways. Our forests serve as areas for recreation, leisure, and inspiration, as suppliers of raw materials, water reservoirs, carbon stores, sinks, climate regulators and so much more. Many of these ecosystem services could not be provided of the desired quantity and composition without active forest management.

Climate change brings about modifications not only to environmental conditions and forests but also to the societal expectations of forests. These changes may also be occurring so rapidly that the institutional adaptive capacity of forest enterprises and administrations is unable to keep pace. In addition, societal expectations of forests continue to grow and there are very different ideas about how forests should adapt to climate change.

This report looks at the key ecosystem services and analyses how climate change will affect their provision and use. At the same time, this report elaborates proposals on how, despite these changes, biodiversity can be protected in the future too, how the ecosystem services of forests can be provided at a high level, and how the sectors that depend on them, such as forestry and the wood-based industry, water management or tourism, can perform their important functions for society.

Ecosystem services in the context of climate adaptation

Multifunctionality is a model for large parts of the forestry industry in Germany and many forest enterprises do uphold this principle. The emphasis in this model is on fulfilling all the important functions of forests for society. In the forest sciences, a concept of forest functions was developed in the 1950s. It consists of a systematic compilation of all forest services that meet human needs (Dieterich 1953). In addition to the raw material function, site-specific functions were also identified (impact on climate, effect on the water balance, protection against erosion, etc.), which form the basis of the so-called beneficial effects of forests (Dieterich 1953). Internationally, a similar concept was developed around the turn of the millennium – ecosystem services (ESs). In the classification of the Millennium Ecosystem Assessment (2005), a distinction is made between supporting, provisioning, regulating, and cultural ecosystem services.

Both concepts – multifunctionality and ecosystem services – are based on a comprehensive view of forests that takes into account both what forests provide and what people need. Even if a stringent alignment of the concepts with each other and their differentiation from each other has still to be undertaken (Benz et al. 2020), they seem to be so similar that they can co-exist and recourse could be made to the one or the other concept. Multifunctionality, as understood in this report, therefore means the simultaneous provision of numerous ecosystem services. Here, simultaneity does not refer to the individual forest stand, but to larger spatial units such as enterprises or landscapes.

In this report, we build on the concept of ecosystem services as classified in the Millennium Ecosystem Assessment (2005). In this concept supporting ecosystem services include, for example, soil formation, maintenance of nutrient cycles, production of biomass, decomposition of organic matter, or the preservation of genetic diversity. These supporting ecosystem services that describe the functioning of ecosystems are often referred to as ecosystem functions (Garland et al. 2020). Supporting ecosystem services, in turn, depend on ecosystem structure and composition, i.e. to a major degree on biodiversity (Noss 1990). They provide the basis for the other three types of ecosystem services, also known as final ecosystem services. These are components of nature that are directly enjoyed, consumed, or used to foster human well-being (Boyd and Banzhaf 2007). Provisioning ecosystem services include, for example, raw materials such as wood, food in the form of huntable animals, or drinking water. Regulating ecosystem services encompass pollination, climate change mitigation, soil and erosion protection, protection from rock slides and avalanches, water retention, or population control of harmful organisms. Recreation, aesthetic enjoyment, spiritual experiences, and the like come under cultural ecosystem services. In turn, the use of these ecosystem services may have an impact on ecosystem structure and composition.

Many ecosystem services cannot be used directly but only indirectly by humans. Enterprises and institutions are often positioned between the ecosystems and the people who want to use their services. They afford people access to these services. They include, for example, enterprises in the forestry sector and the wood-based industry that provide wood products to end users, waterworks that transport drinking water from forests to households, and tourism companies. The ability to function and the profitability of these enterprises and institutions may also be significantly impacted by climate change (for instance Hall et al. 2011, Hanewinkel et al. 2013). Climate change and the associated introduction of new species partially associated with it, including diseases and harmful organisms, lead to direct modifications to the structure and composition of forests on the one hand, and a direct impact of changes in the abiotic environment on ecosystem processes on the other.

Climate change adaptation, as understood in this report, aims to meet the needs of all forest ecosystem services sustainably. The starting points for adaptation are, therefore, located on the following levels (Fig.1):

1. the ecosystem, where efforts are made to maintain ecosystem functions through changes to structure and composition. Depending on the ecosystem's adaptive capacity, this adaptation can either occur passively, i.e. based on the natural adaptive capacity of the ecosystem, or actively, for instance, by cultivating climate-tolerant tree species and increasing the diversity of tree species.
2. enterprises and institutions that provide ecosystem services. These facilities, and the value chains they are part of, are also potentially affected by climate change. They require resilient structures and processes which will enable them to adapt to long-term changes and still be capable of functioning even in the aftermath of extreme events such as drought or fire. This will enable them to continue achieving their goals.
3. the use of ecosystem services that have a loopback to ecosystems. This use can both reduce and enhance ecosystem resilience and adaptive capacity. For example, groundwater extraction in forests can significantly reduce their resilience to and ability to recover from climatic drought stress.

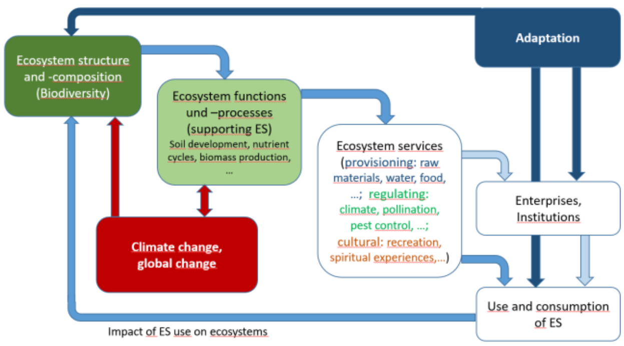

Fig.1: Concept of ESS on which the report is based, their interactions with climate change, and parameters for adaptation to ensure sustainable provision of ecosystem services. Base: Millennium Ecosystem Assessment (2005); the supporting ecosystem services are considered here as ecosystem functions. Parts of the figure were taken from Kienast et al. (2009).

The goals of adaptation are therefore to maintain or increase the resistance[3], resilience[4] , and adaptive capacity, firstly, of forest ecosystems and, secondly, of the societal systems including enterprises and institutions that are directly or indirectly dependent on these services. In both cases, the goal of adaptation is to reduce vulnerability[5] and risks[6]. To achieve this goal, both short- and long-term adaptation measures will be needed. Another goal of adaptation efforts is to reduce the potentially conflicting goals of different adaptation options or adaptation strategies in different sectors and to strengthen synergies.

Adaptation options dependent on forest management and vulnerability

Against the backdrop of future uncertainties and because "no single solution can address all the anticipated challenges" (Millar et al. 2007), most approaches to the adaptation of forest ecosystems to climate change advocate the development and implementation of option portfolios (Millar et al. 2007, Aplet and Mckinley 2017, Dudney et al. 2018). In this context, the different adaptation options are oriented not only toward the vulnerability of the ecosystems but also toward the overarching management objectives which may differ in intensity. Management intensity ranges from very low, such as forest reserves, especially zones for the protection of natural processes such as core zones of national parks and natural forest reserves, to intensive, for instance, even-aged pure stands of non-native species requiring frequent maintenance intervention and a short rotation (Kahl and Bauhus 2014). In the international context, these intensively managed forests would be referred to as plantations or other planted forests (FAO 2020). In Germany, productive forests with intensive tending, small target diameters, and therefore short production times (< approximately 60 years), for instance, spruce, Douglas fir, or valuable broadleaved tree stands, could come under this category. While protected areas and intensively managed areas in Germany account for only a small proportion of the total forest area, the majority of that area is managed as near-natural forests. A trio of these various management intensities is called a TRIAD and was put forward by forest ecologists as a system for the sustainable management of forest landscapes (Seymour and Hunter 1992, Côté et al. 2010). In landscapes managed according to this concept, protected areas and intensive forest use systems generally account for no more than 20 percent of the total landscape, with the remainder given over to near-natural managed areas. The latter serves as a matrix for protected areas to link up populations of forest species and as a buffer for intensively managed stands. Up to now, this concept has mainly been implemented in North America.

Structure and target group of the report

To develop robust proposals for the adaptation of our forests and the sectors that depend on them, Chapter 1 begins with the possible impacts of climate change on forest ecosystems. Chapter 2 provides an abridged version of the key facts that led to the central recommendations for the action set. In Chapter 3 we look at the overarching strategies, policies, and legal instruments for the adaptation of forests and forest enterprises. On that basis, we formulate key cross-sector policy recommendations in the fourth and last chapter.

This report is intended for political stakeholders at the federal-, state-, and local-levels. At the same time, this report also aims to provide key impetus at the European level, where important aspects of adaptation to climate change could be factored into a new forest strategy. Both the scientific foundations and the proposed adaptation options should likewise serve as guidance for decision-makers in forest enterprises as well as the other sectors, directly and indirectly, dependent on forests.

---

[3] Resistance means the ability of organisms and ecosystems to withstand stress and disturbances.

[4] According to IPPC (2013/14): Resilience is the capacity of social, economic and environmental systems to cope with a hazardous event or trend or disturbance, responding or reorganising in ways that maintain their essential function, identity and structure, while also maintaining the capacity for adaptation, learning and transformation.

[5] According to IPPC (2013/14): Vulnerability is the propensity or predisposition of a system to be adversely affected. Vulnerability encompasses a variety of concepts and elements, including sensitivity or susceptibility to damage and the inability to cope and adapt.

[6] Fellmann (2012): In the context of the specific probabilities of occurrence of biophysical or socioeconomic changes, vulnerabilities turn into climate risks.

1

Impact of climate change on forests and their ecosystem services

In the face of looming climate change, the type of services that ecosystems will be able to provide will very much depend on their ability to adapt to changing environmental conditions. By definition, ecosystems are complex interactive networks made up of the individual members of many species, their habitats, and their environmental conditions. In other words, they are open systems that are subject to various external influences. They are also dynamic systems that can respond to these influences.

1.1 Impact on forests

Impact on resistance and resilience

The ability of ecosystems to tolerate exogenous stresses and disturbances constitutes their ecological stability (Kalbe 1997, Grimm and Wissel 1997). Ecological stability consists of five characteristics (Van Meerbeck et al. 2021): (a) resistance – the ability to withstand change triggered by stress or a disturbance, (b) resilience – the speed at which a system returns to its original state after a change, (c) recovery – the ability to fully return to the original state, (d) latitude – the maximum degree by which a system variable can be changed and (e) tolerance – the ability of a system to tolerate disturbances. The term resilience has become a central element in the stability concept of the ecosystem theory. The term technical resilience is also referred to as a component of ecological equilibrium stability (Pimm 1984, Seidl et al. 2019). Holling (1973) distinguishes between the concept of resilience and that of ecological stability because dynamic systems can evolve in different directions and still retain their ability to function. As the diversity of different individual response norms increases within an ecosystem, so do the opportunities for adaptation. Thus, the more diverse nature's "response" is, the more likely it is to withstand (especially extreme) diverse environmental influences. As long as physiological and genetic processes facilitate adaptation to environmental conditions, the risk of "non-adaptation" is low (Kätzel 2008; Reed et al. 2010).

Impact on site suitability for tree species

Tree species in central Europe have differing climatic and site requirements (Thomas 2018) and present significant differences in terms of their drought tolerance (Zang et al. 2011, Klein 2015, Dyderski et al. 2018). The natural spread of tree species results from their physiological site requirements, competitive relationships with other species, the disturbance regime, and the opportunities for species to colonize the site (Huston and Smith 1987; Bartsch and Röhrig 2016). Climate change is altering site conditions. Rising temperatures and changes in precipitation levels and distribution coupled with more frequent or even longer lasting dry, hot periods influence tree growth, the natural disturbance regime, for example by encouraging harmful insects, pathogens, and fire, and the competitive relationship between tree species (Lindner et al. 2014). Drought- and heat-sensitive species that are also cold-tolerant are increasingly being forced northwards and into higher mountain zones and are being replaced in their original sites by other species. Along the warm-dry limit of distribution, elevated drought stress can increase tree mortality that can even culminate in area-wide forest dieback.

Changes in the disturbance regime and natural hazards

"A disturbance regime describes the temporal and spatial dynamics of all disturbances in a landscape and their interactions over time" (Jentsch et al. 2019). Ecological disturbances can range from minor disturbances caused by the death of a single tree to large stand-renewing and site-altering events such as storms, intense fires, and mass outbreaks of herbivorous insects. Disturbance regimes, to which certain forest ecosystems are exposed, are typically characterized by the type of disturbance such as fire, windthrow, flooding, mass insect propagation, their intensity, spatial spread, and the frequency and randomness of their recurrence (Pickett and White 1985, Attiwill 1994). Climate change and other effects of global change, such as species introduction, go hand in hand with changes in the disturbance regimes to which forests are exposed.

Therefore, there are concerns that forest ecosystems may experience either new types of disturbance or more intense or frequent disturbances than they have in the past (Dale et al. 2001). The frequency and intensity of abiotic disturbance factors such as drought and heat are changing. However, no reliable information could be provided up to now on possible trends of other climatic disturbance factors such as storms or heavy rain. Based on a set of climate change scenarios, Seidl et al. (2014) noted that the damage caused by wind, bark beetles, and forest fires in Europe will probably continue to increase up to 2030.

Impact on biodiversity

The spread and composition of biological communities are very much influenced by climate. Therefore, climate change can directly affect biodiversity and its functions. Moreover, species do not respond to climate change in isolation but in interaction with other species. Accordingly, climate change can also have indirect effects, through the lack of interaction partners, competition with invasive species, or changes in forest structure. Decades of biodiversity monitoring (for instance Peñuelas and Filella 2001, Thackeray et al. 2016) indicate that current climate change is already affecting phenological patterns, including shifts in the timeline of life cycle events of plants and animals (for a meta-analysis see Parmesan and Yohe (2003). The life cycle events of animals also present changes such as the earlier return of bird species from overwintering grounds than was the case a few decades ago (Mitrus et al. 2005) or their even spending the entire year in their breeding grounds. Long-term monitoring data already clearly show that global warming leads to shifts in the distribution ranges of, for instance, butterflies (Parmesan et al. 1999) or also of the common holly or the laurel cherry (Walther et al. 2001). Predicting future species communities is very complex because future interactions are very difficult to forecast. This is also because numerous species are unable to move to a new distribution range because of their specific habitat needs.

Changes in the nutrient and carbon balance

The nutrient balance of forest ecosystems is very much influenced by anthropogenic factors. Climate change and extreme weather events act in combination with persistent atmospheric deposition and acid inputs. At the latest since the discussion about forest dieback, the nutrient balance of forest ecosystems has been extensively and continuously investigated within the framework of European and national forest soil inventories and monitoring programs. Acid, sulfur, and nitrogen inputs lead to the leaching of cations such as magnesium or potassium. The studies show that this problem has become much less significant with the decline in acid inputs that has occurred in recent decades (Riek et al. 2016, Prietzel et al. 2020). However, nitrogen inputs into forest ecosystems are still very high (UBA 2015). The consequences of forest resilience to drought are the subject of current research (Millar and Stephenson 2015) which does, however, raise many unanswered questions. Oversupplying plants with nitrogen can increase the risk of hydraulic stress in plant tissue. This problem is further exacerbated by reduced root growth when there is high N availability. On the other hand, poor nutrient supply also reduces the water efficiency of plants during periods of drought (Gessler et al. (2017). Drought likewise changes the dynamics and reduces the capacity of the soil to store nitrogen. When precipitation resumes after dry-warm phases, there may be surges in mineralization, and leaching of rapidly released nutrients may occur (Brödlin et al. 2019). To date, however, there is no evidence of a nationwide, climate-driven trend in nutrient availability or nutrient leaching. In addition to the complex interplay between many opposing processes, this is also due to the change in the type and intensity of atmospheric deposition occurring in parallel to climate change. Numerous studies have demonstrated the major importance of forest soil for carbon storage (DeVos et al. 2015). Generally, in temperate climates, temperature increases will likely lead to the decomposition of organic soil matter (Hagedorn et al. 2010). However, whether this effect is offset by increased biomass production or by drought-induced inhibition of carbon decomposition has not yet been fully elucidated.

Changes in the water cycle

Climatic changes have various consequences for the water cycle in forests. Rising temperatures, coupled with an extended growing season, trigger overall higher potential evaporation with the consequence that less water can leach into and infiltrate groundwater (Spekat et al. 2007). Although precipitation levels increase in winter months, they more frequently encounter soils that are already waterlogged or frozen and leaching cannot take place. In the same way, rising temperatures and the increasing number of hot days in the summer months lead to soil dehydration and, by extension, to reduced infiltration capacity and increased surface runoff. Precipitation, which increasingly occurs as heavy rainfall, can then hardly be absorbed by the dry soils in summer and the waterlogged soils in winter, but runs off the above ground and increases erosion. Observations from the groundwater monitoring network of the federal states show that, compared to the multi-year mean, months with below-average low groundwater levels are becoming significantly more frequent. In particular, precipitation deficits occurring over several consecutive years lead to falling groundwater levels or reduced spring discharges. In addition to lower precipitation levels in summer, evaporation increases due to higher temperatures and extended growing seasons (Hartmann 2011). This also results in a deterioration of the water balance, something that has been very clearly documented by drought damage in recent years.

Changes in the biomass productivity of forests

The acceleration of forest growth in recent decades appears to be primarily due to temperature increases, the lengthening of growing seasons, and significant increases in atmospheric CO_2 concentrations and nitrogen inputs (Pretzsch et al. 2018). Model-based growth simulations showed that climatic changes alone, without any increase in CO_2 concentrations and nitrogen inputs, would have reduced growth from 1981 to 2010. The acceleration of growth was higher on sites rich in nutrients than on sites that were poor in nutrients. It is very unlikely that these positive growth trends will continue in the second half of the 20th century. Other regional inventory-based analyses already indicate declining growth trends.

1.2 Impact on forest ecosystem services

A specific feature of forestry is that a large number of "positive external effects" are generated during the production of raw timber. Today, they are usually referred to as "ecosystem services." In many cases, these societal services are often deemed to be more important than marketable services in the public perception (Lorenz and Elsasser 2018, Hampicke and Schaefer 2021), although this observation applies more to urban than rural populations. However, the provision of regulating and cultural ecosystem services, such as climate change mitigation, water protection, recreation, etc., regularly results in only negligible revenues for forest enterprises (Ermisch et al. 2015).

Provision of unprocessed wood

In Germany, unprocessed wood is mainly used in the sawmill and wood-based industries, the timber-based material industry, and the pulp industry, as well as for energy production. About two-thirds of the raw timber harvested in domestic forests is used for the production of materials and about one-third is used directly for energy (Jochem et al. 2015). The large sawmills specialize to 96 percent in coniferous wood and supply a good two-thirds of the national log volume. The primary woodworking and wood-processing industry in Germany have grown accustomed to the reliable long-term availability of coniferous wood up to now. About 85 percent of the wood used as material in Germany is coniferous wood (Jochem et al. 2015, Thünen Institute 2020a). The lion's share of value added in the forestry and timber cluster, amounting to EUR 57 billion a year (Becher 2016, Thünen Institute 2020b), is therefore dependent on the regular availability of coniferous wood. In the short term (up to 2030), coniferous wood volumes will likely remain high, but with a sizeable proportion coming from calamity timber uses. In the medium term (up to 2050), the unscheduled coniferous wood that became available prematurely during the droughts in 2018/2019 will be in short supply in the timber market. In the long term, coniferous wood will become very scarce in Germany. This has to do with the high vulnerability to risk particularly of the spruce tree species and with the forest conversion that has been ongoing now for about 30 years. In many instances, forests dominated by coniferous wood were and are still being converted into hardwood and mixed forests. The forestry industry will be forced to accept revenue losses in the short term due to low raw timber prices and in the medium and long term due to low volumes.

Supply of non-wood forest products

Forests also supply numerous non-timber forest products (NTFPs) (Sacande and Parfondry 2018). They include wild and semi-wild non-wood forest species and products, as well as products in the early stages of domestication, such as the crops of fruit trees or shrubs. There is growing evidence that non-wood forest products represent an important yet underappreciated segment of forest goods and services in temperate regions. Particularly in international policy debates, they are seen as an essential component of multifunctional forest management and sustainable forestry. Little research has been conducted on how the availability of non-wood forest products will evolve compared to demand as a consequence of climate change. It is plausible that the opening up of forest stands in the wake of disturbances will favor the development of some species (berries, game). However, available studies also present critical assessments of future potential uses (Calama et al. 2019, Herrero et al. 2019).

Climate change mitigation

Forests first of all play a balancing role concerning the local microclimate. In forests, air and soil temperatures are higher at night and lower during the day than in open areas (von Arx et al. 2012). Because of the greater heat exchange with open areas these differences are less pronounced in air temperature than in soil temperature (Mitscherlich 1981). In addition to influencing their microclimate, forests have a major impact on the climate in the surrounding neighborhood. This factor is exploited in both agroforestry systems and conventional agriculture (Zellweger et al. 2019). Trees and forests play an important role in improving the climate in cities, too. The ability of forest ecosystems to capture greenhouse gases in the atmosphere is of particular relevance. At the same time, they influence the earth's surface albedo and, by extension, the radiation budget. European forests in temperate zones make an important contribution to the terrestrial carbon sink and carbon store (Luyssaert et al. 2010). The downstream sector of timber use contributes to climate mitigation performance by maintaining and expanding carbon storage in wood products and by making efficient use of wood in long-lived products, especially in buildings (Hafner and Schäfer 2017). If wood products are used to replace the products made from other raw materials currently in use, whose production or use is usually associated with higher greenhouse gas emissions, then material substitution potentials will come into play. If wood from sustainable forest management is used that does not deplete the forest carbon store, then it will be possible to replace fossil fuels not only in materials but also in energy production.

Soil protection

The soil balance is negative worldwide (Montgomery 2007) because the speed of soil loss caused by erosion is much higher than the rates of new soil formation. The net formation of new soil in Germany takes place primarily under forests because forests provide year-round closed vegetation cover. This counteracts the erosion of mineral soil material. Low external energy input, a different quantity, and quality of biomass incorporated into the soil, and a special microclimate result in soil formation processes taking place under forests that differ from those in open areas, grassland sites, or arable soils. Major risks for forest soil arise from changing climatic conditions combined with increasing disturbances, calamity usage, and the associated reduction in canopy cover. This makes surfaces vulnerable to erosion which leads, in turn, to the loss of fine-textured soil, humus, and the nutrients they contain and reduces space for roots. The consequences are impeded reforestation and permanent site degradation. In this context, the composition of tree species has a major impact on soil characteristics (Dawud et al. 2016) and soil development (McCarthy 2001, Phillips und Marion 2004).

Supply of drinking water, water protection, and flood protection

Forests are an important factor in the overall water cycle. They slow down ground-level air currents and promote the ability of vegetation cover to absorb and store water and its evaporation. This is the basis for the ecosystem services provided by forests in terms of drinking water supply, water protection, and flood protection. Nonetheless, due to high transpiration performance and interception, the groundwater recharge under forests is lower than under arable land (Ahrends et al. 2018). Forests are also of key importance for the supply of high-quality drinking water. The more frequent occurrence of intense rainfall events (UBA 2019) increases surface runoff as the drought conditions that often precede it, reduce the soil's water retention capacity. Drought damage and the associated losses of leaf area reduce stand interception. Forest fires, in particular, which are expected to occur more frequently, threaten two of the forests' ecosystem services that involve feeding high-quality water into groundwater and surface waters and preventing flood peaks.

Recreation, sports, health, and tourism

As "social sites", forests are an important foundation for diverse cultural ecosystem services (MEA 2005). Forests provide an attractive "backdrop" for nature-based recreation, exercise, aesthetic experiences, and tranquillity, along with the social interaction sought by athletes, hunters, and other recreation seekers (Elsasser et al. 2009, Schraml 2009, Getzner and Meyerhoff 2020). Many of these activities are part of tourism offerings and are therefore of major relevance for the regional economy (Zandersen and Tol 2009, Bertram and Larondelle 2017, Tyrväinen and Väänänen 1998). In principle, it can be assumed that the attractiveness of forests for recreational and leisure use will continue to increase in the course of the expected climatic changes (Hahne et al. 2012). The expected changes in the forest ecosystem may also limit recreational and leisure use and its marketing to tourists. Many changes are expected, especially for winter tourism (Endler and Matzarakis 2011). Some important changes include the heightened potential for conflict with forest enterprises after disturbances, the lengthening of the growing and recovery seasons, increased health hazards from allergens and infections, or heightened risks for forest visitors.

2

Fields of action in forestry in the context of climate change

The following chapter provides an abridged version of the key facts that led to the central recommendations for action set out in Chapter 4. They cover, in line with the recommendations, the different areas of forest management.

2.1 Sustainable forest management and forest enterprises

Silvicultural risk management

Mixing tree species is a key element in most alternative silvicultural approaches and strategies. The goal is to enable forests to cope more effectively with the uncertainties arising from global changes (Puettmann et al. 2015 Bauhus et al. (2017b). Mixed stands are capable of increasing resistance, resilience, and adaptive capacity (Bauhus et al. (2017). The mixing of tree species can, in principle, be integrated into all forms of current forest management, from near-natural to intensively managed forests. Mixed stands can act as a buffer for forest management not only against environmental changes and disturbances but also against changes in societal demands. This impact of mixing at the stand or landscape level is due to two main effects: a) ecological insurance, as a high number of functionally diverse species increases the likelihood that some of them will be better equipped to deal with stress and disturbances (Yachi and Loreau 1999), and (b) species interactions which alter the way an individual species responds to stress and disturbance making it more or less resistant in mixed than in pure stands (Bauhus et al. (2017b). Effects similar to those generated by mixing species can be achieved by mixing trees of different dimensions in uneven-aged, structured stands (Dănescu et al. 2016, Pretzsch et al. 2018). Both the desired increase in the diversity of tree species in stands and the reduction of production times necessitate, in many cases, more elaborate regeneration procedures and frequent silvicultural interventions, especially during the development phases of young forests. In many cases, the specific tree species combinations can only be achieved with the assistance of artificial regeneration. On many sites tree, species/provenances have to be replaced that are no longer considered suitable for a future climate. Often, silvicultural interventions do not cover their costs in young and pole stands. The desired mixed stands are also very high maintenance and therefore generate substantial follow-up costs (for instance Puettmann et al. 2015, Bauhus et al. 2017c).

Significant changes in current distribution ranges are predicted for several major and minor tree species native to Germany. Climate-adapted tree species or provenances should possess high-stress tolerance to drought, heat, and late frosts (possibly storms) coupled with sufficient growth production and material use prospects (Bolte et al. 2009, Zang et al. 2014, Thurm et al. 2018). The most urgent use for alternative tree species is predominantly for sites and risk regions where there is a current or anticipated widespread loss of the main tree species and natural regeneration is not leading to the desired diversity of tree species. A distinction must, therefore, be made between replacement and supplementary tree species. The former aim to replace the previous tree species whereas the latter supplement the regeneration of the existing tree species (for instance in the form of natural regeneration) to develop stands that are generally better adapted and contain more species. The results of previous cultivation trials show that the generalizing evaluation of the cultivation suitability of species based on one (or fewer) provenances used can lead to errors of judgment. This applies in particular to adaptation to contributory meteorological factors. Provenance trials that take into account a wide range of ecotypes within the distribution range of a species or from regions with a similar climate in the future, for instance in south-eastern Europe, therefore continue to constitute an essential test for the provenances grown. The use of non-native species is often criticized from a nature conservation perspective because these tree species have only a low degree of relatedness to native tree species (Gossner 2016). Generally speaking, they provide a habitat for fewer native species and some are seen as invasive or potentially invasive (Felton et al. 2013, Dumas 2016). The assessments differ considerably in some cases, mostly because they adopt different methodological approaches (Bindewald et al. 2020).

In forest plant breeding under the conditions of climate change, one important objective is to provide reproductive material that is adaptable and powerful enough to cope with the expected environmental changes whilst performing all forest functions. This necessitates continuous processing and, due to the long generation cycles of forest tree species, long-term test approaches. Forest genetics and forest plant breeding have a proven catalog of methods at their disposal, with further options expected as a result of major advances in molecular biology. The intensity of breeding research to date varies depending on the tree species. So far, intensive breeding research has only been carried out on a few tree species in Germany. Depending on the management goals, the dominant breeding objective was to increase qualitative and quantitative growth performance, including carbon sequestration. However, this "domestication" of trees focused on production-oriented management and not on climate adaptation (Fladung 2008). The question now arises as to the extent to which the characteristics of relevance to climate adaptation, namely (1) increased drought stress tolerance, (2) increased heat stress tolerance, and (3) adapted (late) frost tolerance can be enhanced through forest plant breeding. One harbinger of hope is genome analysis which can be used to select those plus trees from provenances and populations that have been particularly successful at surviving extreme weather events (selection breeding). It is only since 2013 that provenance research and forest plant breeding have attracted more attention in the context of climate change. Since then, strategies and programs with major and minor tree species have been developed. Given the long-term nature of tree breeding projects, short-term breakthroughs are not to be expected, especially since provenance trials have not been conducted up to now in Germany for very many (native and non-native) alternative tree species.

Forest protection

Rising temperatures lead to improved reproductive conditions for several pest organisms (Wermelinger 2004, Biedermann et al. 2019). The increase in weather extremes and storm events exposes forest trees to physiological stress and reduces their ability to defend themselves. In this context, large-scale temporal synchronization can be observed for many disturbance events (Senf and Seidl 2018). This means that, despite high spatial variability, mass propagations of insects spread almost simultaneously over large areas with far-reaching consequences for forest management. Consequently, what is needed here are supra-regional strategies. The damage to stressed trees caused by existing forest diseases triggered by pathogenic fungi in diplodia shoot dieback or sooty bark disease is increasing significantly as a consequence of climate change. The introduction of organisms in the course of climate change is also relevant. Experts believe that the combination of climate change and globalized trade is particularly critical since it is impossible to predict which organisms will be introduced, and how they will behave in new combinations with other species and under different climatic conditions. In particular, the emergence of new species communities, especially the interactions between insects and fungi, are likely to play an important role in the future. However, little is known about them and they are difficult to predict. Climate change is also affecting vertebrate populations. For deer and wild boar in, particular, it is common knowledge that population densities will continue to rise across Europe as temperatures climb and snow depths decrease (Melis et al. 2006, Melis et al. 2009, Hothorn et al. 2015). This will further increase browsing pressure on young plants, depending on the tree species.

Operational risk management

In practice, it has proven useful to adopt an analytical approach to risk identification and assessment, i.e. the overall entrepreneurial risk is broken down into various risk factors and the expected levels of damage and probabilities of occurrence are estimated. The expected scale of damage and its probable occurrence together determine the economic significance of risk. The risk factor, climate change, leads to very different concepts of alternative operational planning with differing types of risk behavior due to varied perceptions of and attitudes towards risk (individual risk preference) and individual operational objectives. It is possible to minimize risk by prioritizing highly resilient tree species and stand types in the event of reduced productivity or by selecting productive stands that come with an increased risk. This includes the cultivation of exotic tree species, a combination of risky and resilient strategies, or withdrawal from operational silvicultural management. Given the uncertainty of climate projections and the associated potential impacts on the growth, productivity, and stability of different tree species, current knowledge suggests that promoting mixes of tree species and combining different types of stands at the forest enterprise level are key components in operational risk management. A high level of structural diversity in an enterprise generally increases resistance and resilience to disturbances and helps to buffer the negative effects of climate change, as long as they vary in intensity from tree species to tree species. The spatial operational structure with different types of stand and age classes can also reduce the risk of disturbance, for example, caused by storm damage.

Soil protection and water management

Rising temperatures and changing precipitation patterns have numerous negative effects on soil and water protection and the regulating effect of forests on the area-based water regime. Likewise, the type of management influences both forest soil and the forest moisture regime. Consequently, the protection of soil and water is crucial for the adaptation of forests and forest management to climate change. By regulating the climate in forests, forest vegetation can mitigate the negative impacts of climate change on essential processes in the soil. The key here is to maintain closed vegetation cover. Against the backdrop of the major anthropogenic impact on vegetation, soil, and site climate, it must be emphasized that humans are also becoming increasingly relevant as a site factor in forest planning. The goal must be to maintain or, if possible, increase the high level of carbon storage in forest soil while maintaining functioning nutrient and water cycles and preserving the habitat function of forest soil for plants and soil animals. Similarly, the formation and development of soil should not be impaired.

Forest enterprises, their economic results, and sources of income

In Germany, 48 percent of forests are privately owned, 29 percent belong to the federal states, 19 percent to corporations, and 4 percent to the federal republic. Forest management and the performance of other tasks associated with forest ownership are usually carried out by forest enterprises. In Germany, they are extremely diverse. In addition to the type of ownership and enterprise size, they differ in terms of the tree species present, the local situation, the regional location, stocking levels, management systems, and the range of operational services. They may also pursue very different goals. For example, a municipal forest enterprise in a densely populated area may prioritize the development of recreational woodland. A large public forestry administration in an area-based country may aim for multifunctionality and, by extension, the equally important provision of the forest's various ecosystem services. A smaller private forest may prioritize covering its own needs for firewood. The economic situation of forest enterprises can be described based on results from the BMEL Forest Enterprise Monitoring Network, whereby only forest enterprises with a minimum size of 200 hectares were included in the survey. In the main product area "production of timber and other products", all ownership types closed the year 2017, i.e. before the large-scale forest damage, with, on average, a positive operating result (state forest EUR 46/hectare, corporate forest EUR 98/hectare, private forest EUR 157/hectare). In contrast, the product areas "protection and rehabilitation" and "recreation and environmental education" chalked up negative results for all ownership types and had to be co-financed from raw timber production. In terms of the "economic performance" of the various tree species, it is clear that the spruce tree species has made by far the highest contribution to forest enterprise earnings due to its high productivity per unit area and its good average revenues. The loss of this tree species, as a result of the storm and bark beetle damage and climate change, is therefore extremely painful economically for forest enterprises. Currently, approximately two working hours can be remunerated from the mean revenue from one cubic meter of raw timber. At the beginning of the 1970s, it was eight hours (Möhring und Dög 2019). This number illustrates the rationalization pressure on forest business administration in recent decades. It also explains why there have been large-scale cutbacks in staff and a driving forward of mechanization in forests. Estimates from 2020 indicated a volume of timber from damaged areas from the 2018-2020 drought years of approximately 180 million cubic meters of harvested timber and a damaged area of around 290,000 hectares that needed reforesting. A conservative estimate of the economic damage to forest enterprises identified a volume of almost EUR 13 billion. The overall damage thus amounts to almost 10 times the annual net entrepreneurial income in the forestry sector. Many forest enterprises are facing "ruin" as a result of stand losses. Others have only been hit by the lack of marketability of timber coupled with the drastic nationwide decline in timber prices and have sustained merely minor inventory/incremental losses.

Timber harvesting and forest operations

To depict the manifold repercussions of climatic change for the people who work in forests, it makes sense to differentiate between working conditions that have been directly modified as a result of climate change and changing ecosystem conditions which then lead indirectly to changes in working conditions in forest operations. It is essentially periods of extreme heat, heavy precipitation, and storms that make working conditions more difficult and necessitate a high degree of flexibility to make ongoing organizational adjustments to work processes. During hot periods, forest activities have to be carried out in the early morning or late afternoon. The processing of windthrown timber, which is likely to become more frequent in the future, is dangerous and requires special expertise and a high degree of mechanization. Prolonged periods of winter frost, the preferred period for soil-conserving timber harvesting, are becoming less frequent. As a consequence of the climate-induced shift to mixed stands with a high proportion of hardwood, the technology and timber harvesting methods will also have to be adapted in the future. At the same time, there will be greater diversification in the felling yields from wood species and categories. As a result, stand maintenance and timber harvesting will become less efficient as a consequence of decreasing performance and rising costs. In addition, stand establishment in particular will have to be adapted. In the future, an increased volume of land will likely be used for planting although human resources and technology are often already in short supply.

Interactions and adaptation obstacles

The long-term nature of forest production leads to a decoupling between silvicultural measures, such as stand establishment, and current market requirements of, for example, timber categories. Production conversions which can be completed rapidly in other sectors of the economy, inevitably take decades in forest enterprises. The concepts and tools developed in the past to measure and manage forest sustainability usually consider old forest stands of different ages to be representative of development over time. They are based on the assumption that environmental conditions remain stationary. Current changes and uncertainties regarding forest productivity and stability fundamentally challenge "tried and tested" concepts of "sustainable forest management." However, these traditional concepts of forest protection and management are deeply entrenched. Consequently, the increasing erosion of the value of this practical knowledge is an obstacle to adaptation. Practical illustration based on forest images only functions to a limited degree in the context of rapidly changing climatic and site conditions. To make matters worse, many forest enterprises have experienced very high substance losses in some cases as a result of the extreme weather events of 2018-2020. This has dramatically weakened their economic basis for adaptation measures. Moreover, adaptation measures in forest stands are usually associated with increased silvicultural and operational costs generated by special plantings or increased forest protection. In many cases, there is still a lack of prospects for high-quality material timber use for the tree species favored today. Overall, adaptation measures usually require a higher input of financial resources. This is set against reduced profits in the future compared to the status quo, especially due to less productive forest stocking and higher risk costs. Sustainable forest management is considered to be a very near-to-nature form of land use and is now widespread. Nevertheless, there is an inbuilt tension between management based on market principles including the use of modern technology and nature conservation, since conservation and the exploitation of natural resources usually compete with each other.

But there are also basic synergies in this area. For example, promoting the stability and adaptability of forests to climate change is in the interest not only of forest enterprises but also of the public at large as it will ensure the preservation of forest ecosystems and the ongoing provision of ecosystem services that are important to society. The "climate mitigation" aspect is particularly important because the sink capacity of forests, the storage capacity of wood products, and material and energy substitution all benefit from vigorous, vital, and sustainably used forests with major CO_2 sequestration potential. Long-lived wood products in multi-stage utilization cascades are particularly effective. They also foster the creation of regional value-added, jobs and the implementation of a circular economy desired by society. Synergies can also be achieved in the area of modern forestry technologies such as highly mechanized harvesting methods, for example, by reducing forest management costs, increasing the effectiveness of forestry measures in the respective area, improving occupational safety, and counteracting the widespread shortage of labour. The synergies of sustainable forest management and wood use geared to climate adaptation become clear, particularly in a comprehensive sustainability assessment that takes into account the long-term material cycles in ecosystems and societal systems, and also factors in global displacement effects.

2.2 Wood-processing industry and bioeconomy

Import of wood and wood-based products

Germany is very actively engaged in the international trade in wood and wood-based products and is currently one of the world's largest exporters of these products. In the future, climate change may lead to dramatic changes in the supply volume of raw timber in terms of both outflow and inflow. The possible oversupply of timber from damaged areas suggests that exports of raw timber will help to ease the situation in the German raw timber market in the future, too. However, given the major dependency on transport costs, this contribution will be limited. Conversely, Germany’s secure footing in international trade and the market's flexible response to varying supply volumes means that, in principle, there will also be a sufficient supply volume of wood-based products in Germany even if raw timber, especially medium-dimensioned coniferous wood from domestic forests, were to become scarce at some point in the future. Nevertheless, the question arises as to the scale on which the medium and long-term shortage of coniferous wood can be offset by imports into Germany as drought and consequential damage are expected to drastically reduce coniferous wood resources in neighboring European countries, too. Given the enormous coniferous wood resources in the boreal zone of the northern hemisphere, it cannot be assumed globally that there will be a shortage of coniferous wood in the medium term. Rather, the question is at which processing stage will wood products arrive in Germany under these circumstances and what impact will this have on income and employment in the forestry and wood cluster.

Tapping into new sources of raw materials

The coniferous wood supply will decrease in the future and the importance of hardwood species in the raw timber supply from German forests will increase. Meanwhile (data from the 2012 National Forest Inventory), 80 percent of securely established regeneration consists of hardwood trees. However, there will be no dominant commercial tree species because the potential uses of hardwood species are more diverse and heterogeneous than those of coniferous wood. Many stand-forming, hardwood species grow more slowly and thus have longer production times than most coniferous species. At the same time, they have a significantly lower stem timber share of harvested biomass relative to volume. If this trend continues, it will lead to a medium-term decrease in the general round wood potential, as fewer wood resources will be made available to the market per time unit. The remedy might be to adjust the composition of tree species toward productive mixed forests with a higher proportion of coniferous species that are tolerant of mixing and climate and boast good wood characteristics. As a result, the composition and quality of the future categories for supplying the wood-based industry will become more heterogeneous. In addition, there are opportunities to increase volumes, particularly from primary production and waste wood management, the utilization of which necessitates targeted measures and incentives.

Wood – a raw material available on a decentralized basis for the bioeconomy and bioenergy

Already today, almost two times more hardwood is available than 20 years ago. Most of the additional volume is channeled into energy generation. Beech and oak are the dominant hardwood tree species in Germany. The potential volume of hardwood logs in the future will be about 60 percent higher than the volume of wood used in the period 2013 to 2017. If the economic and technical preconditions for competitive products are put in place, the incremental hardwood categories could generate more value-added than is the case today. However, they will not be able to fully replace coniferous wood in terms of comparable quantities, qualities, or the same beneficial climate and environmental effects. For the material use of hardwood, by far the largest quantitative potentials are to be found in the low-cost wood categories, especially in the wood-based materials and packaging sectors. Further potential for the use of higher-quality hardwood categories lies, for example, in the areas of furniture, windows and exterior doors, solid parquet flooring, and solid wood panels that go hand in hand with the fine-tuning of specific processing and finishing technologies. The aim here is to derive higher added value from the given diversity of hardwood species and characteristics. Lower-quality hardwood and coniferous wood could be increasingly used in other areas of the bioeconomy. The possibilities for developing new materials and chemical substances for material use are very diverse and have progressed to varying degrees. Increased cascade use is expected to impact the wood energy market in the medium term. It gives preference to the primary material use of timber and sees energy recovery as the last step in the wood value chain. The more biorefinery applications guarantee forest owners low-value material timber sales on economically lucrative terms, the more the medium-sized wood energy producers in particular will then turn to waste wood as their primary category.

Material use in the construction sector

The construction sector represents the main use for long-lived wood products. The construction of wooden buildings can replace alternative raw materials and materials in product systems with the same function. As a rule, this process involves higher energy input (material substitution). At the same time, it builds up an additional carbon store that remains in place until the material is combusted at the end of the utilization cascade. It contributes to climate adaptation primarily in the following ways: the construction of wooden buildings to be implemented now at short notice which will help to achieve climate neutrality by 2045 and the utilization of coniferous wood from native forests, thereby advancing forest conversion and increasing carbon storage in long-lived wood products. A long-term goal should be to immediately encourage municipalities and cities to engage in more area-wide timber construction and not just build a few showcase projects. In addition, buildings must be specifically designed and constructed to be highly energy efficient. The wood products used in this process should come from sustainable forest management. This can be done, for example, through the use of certified wood or proof of provenance from the region. The prerequisite for the material use of timber in the construction sector is the nationwide training of architects and engineers in timber construction to be able to guarantee the comprehensive availability of planning expertise in the field of timber construction. In addition, increased standardization is an important prerequisite to enabling the more cost-effective erection of multi-story wooden buildings and to giving timber construction planners and engineers with little experience in this field easier access to timber construction. Federal states building codes, general technical building regulations, and approvals of construction products should be further developed in such a way that an inbuilt disadvantage can be ruled out from timber construction up to the high-rise building limit. At the same time, the building authorities responsible for granting permits should be equipped to evaluate these more recent constructs in a technically sound manner. Municipalities and project developers must be in a position to plan the implementation of timber construction at the earliest stages of a project. To be able to tap into the existing potential of the wood volumes and qualities stored in the building infrastructure, wood products, and wood structures must be developed in a recycling-friendly manner through adapted product and connection design. Efficient processing, cleaning, and sorting procedures for recovered and waste wood must be used, and the legal basis (Ordinance on the Management of Waste Wood – *AltholzV*) must be adapted. In addition, cascade utilization must be further intensified through fiscal models.

Changing value chains

A sufficient supply of timber categories in terms of quality and quantity is a key prerequisite for value-added within these sectors. In addition, efficient and robust machine and process technology are needed to efficiently transform the high-volume raw timber categories and make them available logistically. Another characteristic of the sector is the high degree of material flow connectivity within and between the value chains. This leads to the almost complete exploitation of raw materials in the material and energy use of raw timber that has been predominant to date and is dependent on efficient supply chain management. It is to be expected that increasingly large quantities of calamity timber will have to be processed during timber harvesting. Forest service providers will have to respond to fluctuating demand at very short notice: from greatly increased processing demand to the cancellation of contracts at short notice should the timber markets collapse. Since large volumes of calamity timber cannot be removed and processed promptly, maintaining the value of this wood becomes more important. Debarking units fitted into harvesters are one way of avoiding further colonization of the wood by bark beetles. This will enable dry storage along forest roads. To prepare for future disturbances, the storage infrastructure can be improved in forests, transport hubs, and wood processing plants. This can be flanked by investments in digitalization, IT-based logistics, and Industry 4.0 developments. Timber transport logistics constitute another potential bottleneck when managing large volumes of calamity timber. For example, loading stations for rail transport are in short supply. While processing capacities are currently being exploited to a major degree almost everywhere, it is already foreseeable that there could be a shortage of raw materials in the future in regions where forest stands have been used prematurely across large areas as a result of a bark beetle outbreak. International cooperation within the industry could help in the future to cushion fluctuating demand and counteract the loss of value added within Europe. There is a need for development, for example, in the handling of heterogeneous and inferior wood qualities or the conversion and expansion of product ranges to process more calamity timber. The foreseeable shift in the spectrum of tree species towards more hardwood will increase the need for technological methods for the more flexible processing of different wood categories soon. The investment cycles in new technical processing technologies are long and must, therefore, go hand in hand with the forecast developments in the raw materials sector.

Interactions and adaptation obstacles

Securing the supply of raw materials, even under more uncertain climatic conditions in the future, is a central societal task of forest enterprises. The interactions with nature conservation are, in some cases, less synergistic. It is true to say that logging can also create important habitats for light-loving species in forests but removing wood from the stands always means a loss of habitat potential for a whole range of forest species, especially ones that are dependent on the structures in later forest succession stages. These conflicts can be mitigated through appropriate forest management systems such as retention forestry which aims to continuously provide forest structures to maintain viable populations of these species. Shortages in the supply of raw materials in a globalized world are usually buffered by imports. However, relocation effects abroad must not be ignored. It is safe to assume that relocating timber production abroad will not lead to net improvements, i.e. from a global perspective, in climate or biodiversity protection. The forecast changes in raw material supply have implications for the economic added value from raw timber marketing. The variety of wood species and qualities will influence category composition and size for timber buyers. Smaller categories and possibly mixed categories are to be expected. Raw timber is procured in larger supply radii, supported by a further expansion of electronic information exchange between the wood-based industry and forestry. In addition, the market partners will have to define new category parameters for the wood species and mixes that will be used more diversely in the future. Cascade and waste wood utilization are deemed to have the greatest short-term and medium-term potential for generating new sources of wood to compensate for forest-side supply changes. The quantity and quality of future waste wood flows can be promoted by encouraging recycling and deconstruction, particularly in timber construction and furniture applications. The interactions between forest management, raw timber supply, and timber market supply already show direct effects on value chains under normal planning conditions. Extreme weather events linked to climate change will significantly increase market supply disturbances and this will have direct repercussions for value chains. There is a need for adaptation both in the efficient and safe harvesting of timber and in the temporary storage of calamity timber in forests (logistics, storage technology, quality maintenance, environmental aspects, legal aspects, costs) and, if necessary, as sawn timber. The wood products plants to be set up as part of the biorefinery technologies will require a secure and season-independent supply of the specific raw material categories from the forestry sector. For a continuous supply, timber will have to be harvested on a year-round basis, with challenges from expected climate extremes (soil softening, labour organization, and supply chain management, including logistics) or correspondingly large capacities will have to be available for temporary timber storage. The wood-based industry, with its key use of wood for construction, relies extensively on coniferous wood, particularly for climate-efficient structural construction applications. In the future, the incremental hardwood categories could be used in biorefinery technologies with higher value-added than today. This will lead to synergies with the adaptation of forests to climate change and an improvement in naturalness. The short-term competitive pressures in supply versus energy timber categories will pose significant challenges to supply planning. In the medium to long term, the material-chemical use of small-dimensioned hardwood in biorefineries will probably prevail, partly because the biomass share in the energy sector will decrease due to ongoing improvements in building energy standards. The adaptation of biorefinery processes must be accompanied by process technology development and scaling for product manufacturing. In addition to evaluating techno-economic feasibility, the positive effects on resource conservation and climate change that can be achieved with the selected processes and the targeted products are of crucial importance. Assuming that the EU's climate policy goal of net climate neutrality by 2045 is achieved, the positive substitution effects of timber use will diminish from then on at the latest. However, carbon storage in long-lived products will continue and can contribute to negative emissions. There will also be another interaction between long-term carbon storage in long-lived products in timber construction, particularly to an increasing degree in multi-story construction and the adding of storeys to existing buildings, and the different federal states building codes and their treatment of fire safety concerns in timber construction.

2.3 Nature conservation management

Species and biotope protection

Strategies to protect species and biotopes in a changing climate adopt two key approaches. First, they seek to ensure that potential shifts in the spectrum of species and habitats are possible in landscapes and to identify and, where possible, protect the species and regions most at risk. Protected areas have always played a crucial role in the conservation of species and habitats. However, aside from a few exceptions, their planning has not taken into account climate change or the long-term, large-scale dynamics of ecosystems. Most of the expected shifts in the distribution ranges of species will not be possible inside the boundaries of protected areas. Second, many of the previously designated habitat types will not be able to keep pace in the future. There will be new combinations of species in communities that are scarcely predictable at all. However, distribution ranges and habitats can only be shifted to a limited degree. For instance, species that live in the highlands of low mountain ranges cannot simply move to higher locations as temperatures rise. Habitat fragmentations prevent or even render impossible shifts in areas, particularly of less mobile species. Facilitating the movement of species across the landscape should, therefore, be a nature conservation priority.

Design and management of protected areas/changes in protection goals

The fixing of protection goals is an essential foundation for the management of protected areas. It is foreseeable that climate change will affect some protection goals or render them obsolete. Although the problem has been known for some time, regional climate change scenarios have been virtually ignored or insufficiently considered when designating protected areas (Hoffmann et al. 2019). The problem is exacerbated by the fact that any expansion of existing protected areas is not usually possible due to differences in forest ownership relationships or fragmentation of the landscape. Furthermore, the very static approach often adopted in planning and managing protected areas makes adaptation difficult. This also concerns the prohibition of deterioration in Natura 2000 areas, where section 33 Federal Nature Conservation Act (*BNatSchG*) prohibits any actions by forest managers that lead to deterioration of Natura 2000 protected habitats, communities, and species. However, if climate-related or disturbance-related degradations from a reference condition described in the management plan are identified, they should not be blamed on forest managers. Temporary forest reserves could be a prudent concept for overcoming some of these problems if a) it is foreseeable that the protected habitat, community, or species will be of limited duration such as a deadwood-rich, early successional phase of stand development after a disturbance (WBW and WBBGR 2020) or b) the medium- to long-term fulfillment of the protection goal is too uncertain in the context of climate change-induced modifications, and therefore needs to be reviewed.

Assisted migration

Due to their long history of use, fragments are all that is left of many habitats in Germany. Should rapid climate changes cause local habitats to lose their suitability, then there is a risk of isolated incidences becoming extinct. In principle, efforts could be made to combat this with habitat improvements or connecting elements in landscapes. However, certain habitats, such as old trees, cannot be recreated in just a few decades. The active translocation of species is an option that is regularly used already today for tree, shrub, and herbaceous plant species. For insects or low-mobility vertebrates such as amphibians and reptiles, there is still uncertainty about the prospects for success and the need for translocation. Nevertheless, awareness is growing that these translocations will be necessary, particularly in conjunction with climate change, and that they only pose minor risks for other species (Thomas 2011) as long as they are indigenous and introduction takes place in the projected distribution range (Webber et al. (2011). A meta-analysis of insects showed that the most important success factor was the number of individuals introduced. Weather, climate, and habitat quality were also mentioned as factors (Bellis et al. 2019). In the case of plants, the conservation of species via seed banks and targeted introduction in former distribution ranges has been an established nature conservation measure for some time now. Active introduction through inoculation has already been used successfully in the case of fungal species (Abrego et al. (2016). Ultimately, all active introductions should adhere to the principles set out in the Guidelines for Reintroduction of the International Union for Conservation of Nature (IUCN), in the context of climate change, too (IUCN 2013).

Biological invasions

Biological invasions are seen as a major driver of biodiversity decline worldwide, in forests too. In nature conservation, non-native species are referred to as invasive if they have significant undesirable impacts on other species, communities, or biotopes (Nehring et al. 2013). One consequence of forest adaptation to climate change could be an increase in the spread of invasive species 1) as a result of climate change itself or 2) as a result of adaptation strategies, such as the introduction of tree species. It is difficult to predict interactions between invasive pests and climate change. Nevertheless, a picture is emerging of an exacerbation of the cumulative impacts on forest ecosystems (Ramsfield et al. 2016). Also, the loss of species is accompanied by massive declines in biodiversity, and the functionality of our forests is already relatively poor in tree species. While forestry production can switch in part to substitute tree species, this is only possible to a limited extent for native biodiversity.

Here, there is a need to rapidly launch research programs to identify resistances and breed resistant individuals and populations when species-threatening diseases occur (Sollars et al. 2017, Enderle et al. 2019). To adapt forests to climate change, recourse is also made to introduced tree species. The use of non-native species is viewed critically from a nature conservation perspective as these tree species, which are not closely related to native tree species (Gossner 2016), generally provide habitat for fewer native species, and some of them are deemed to be (potentially) invasive (Felton et al. 2013, Dumas 2016). Several assessments are available of the (potential) invasiveness of tree species already introduced in the past (Nehring et al. 2013, Vor et al. 2015). Some of these assessments diverge to a major degree (Bindewald et al. 2020).

Conflicts and synergies between the goals of forest management and nature conservation

This debate on introduced species, which is still conducted on an emotional level because of the lack of evidence (Gossner 2016), but also the shortening of production times to reduce vulnerability to disturbances, are major sources of conflict (Reif et al. 2010). Another conflict of aims arises from protecting temperature-sensitive species by maintaining a closed canopy (for instance de Frenne et al. 2021) and from promoting advance regeneration by thinning the crown cover to increase the system’s resilience to disturbances (Bauhus et al. 2013). These different goals can obviously only be achieved through spatial separation. Whereas the forestry side believes active forest conversion is necessary to adapt the composition of tree species to a future climate, the nature conservation side prefers passive adaptation via natural regeneration and succession processes (Reif et al. 2010). Synergies between forest management and nature conservation adaptation strategies include diversifying tree species, increasing mix proportions and structural diversity in near-natural forests, and giving greater consideration to previously rare tree species in forest conversion (Ampoorter et al. 2020).

2.4 Recreation, sports, health care, and tourism

The vast majority of Germans visit forests in Germany for leisure and recreational activities. Forests are traditionally used for recreational activities such as hiking, nature watching, or mushroom picking. In recent decades, forest-related recreational behavior has undergone significant diversification. Forests are also increasingly providing the backdrop for sports such as jogging, walking, mountain biking, or "geocaching". The marketing of nature-based leisure activities is seen as a growth sector. For some years now, the health-promoting effect of forests has not only been seen as a positive 'side effect' of trips to forests; spending time in the forest is also being used as a preventive and therapeutic instrument. Forests and their management are expected to become more important as a consequence of climatic changes as cities evolve into heat islands in the course of climate change. Forests close to cities play a particularly important role in recreation near where people live. Due to their filtering effect for pollen, forests help to reduce allergy and disease potential but also to temper expected heat waves. The expected changes in the forest ecosystem due to climate change may have both limiting and beneficial effects on forest-related recreation and leisure activities. The following changes should be stressed: 1) changes to forest microclimate due to disturbances such as large-scale gaps in canopy cover, 2) changes in the familiar forest and landscape appearance, for instance through the increased occurrence of deadwood after extreme events, 3) changes in the framework conditions for sporting activities such as shorter winter seasons, but also extended seasons for activities such as hiking and cycling, 4) risks after extreme events such as falling branches or falling trees, which impair the quality of paths and traffic safety for forest visitors and people who work in the forest, 5) increase in health hazards due to allergens and vector-based diseases, triggered by a changed spectrum of species, higher pollen production by grasses and trees, longer vegetation periods and a more extensive spread of the allergens and harmful organisms produced.

Conflicts between recreational use and forest management

For future forest management, both the expected climate change-related modifications and the increased demand for recreational and leisure uses outlined above will result in conflicts and a need for action. Maintaining path quality and respecting traffic safety obligations after extreme weather events result in a higher workload for responsible forest owners or forest enterprises. In addition to managing costs, forest owners also face liability issues. In the course of climate change, what is known as calamity uses will already lead to a temporal and spatial expansion of forest management operations (noise, path condition, closures) which are perceived as annoying by visitors. One reason for the less-than-perfect consideration of the needs of people in search of recreation is the lack of a database on the needs and activities of leisure seekers in forests. Germany still has a major deficit in this area compared to the long-term monitoring carried out in Finland, Denmark, and Sweden or the socio-cultural monitoring in Switzerland.

The lack of visibility about the ownership situation regarding forests, which are freely accessible at all times, means that the heterogeneity of forest owners and their performance are hardly taken into account at all in the public debate about the recreational contribution of forests. It is estimated that enterprises in private and corporate forests alone will incur costs of EUR 100 million per year for recreation services (WaSEG 2019). Especially in forests close to urban areas, forest enterprises bear additional expenses. So far, there are hardly any financing models up and running for this. For Germany, the Thünen Institute believes that people are willing to pay EUR 30 per person annually for forests in their residential area. When extrapolated to the entire German population, this results in a willingness to pay EUR 2.4 billion a year. For one hectare of forest in Germany, the benefit of forests as local recreation areas, therefore, amounts to EUR 211/hectare. In contrast, the costs of privately owned forests in the form of supplementary charges and reduced proceeds amount to EUR 13/hectare and year. Consequently, the provision of recreational services by forests is worthwhile in macroeconomic terms, as the benefits significantly outweigh the costs. However, whether the exclusion of forest owners from the overall economic benefits is fair must be judged at the political level.

Conflicts of recreational use with the protection of species, Nature and wildlife conservation

The increasing interest in spending time in nature has implications for the quality of wildlife habitats or their habitat use. In addition to altered use behavior, they include heightened flight behavior, loss of energy or fitness, reduced care for offspring, and generally lower reproduction. Overall, the disturbances caused by leisure seekers may have effects on wildlife and their populations similar to those described for predation. For individual species or species groups, disturbances have been documented on a scale that makes intensive recreational use also a problem for species conservation. In the highlands of low mountain ranges, for example, there are already many conflicts between forest use for tourism and recreation and nature conservation concerns. For certain species groups and ecosystems whose distribution ranges will shift upward with climate change, this may exacerbate these conflicts. From the point of view of people who engage in leisure pursuits, their interest groups, and tourism destination management, these problems sometimes result in high costs for the preparation of events or the approval of infrastructure. Conversely, for protected area management, enforcing rules is a challenge.

Knowledge about the preferences of forest visitors can also lead to synergies between forest management and recreational and leisure uses. Thus, silvicultural strategies aimed at climate-adapted and structurally rich forests create forest landscapes and forest structures in the medium and long term that are appreciated by large sections of the population. At the same time, studies indicate that species diversity and structurally rich forests have a positive impact on recreational potential and can lead to a decrease in harmful organisms. Synergies between different sectors can also be established concerning the protection of soil and cultural monuments. The inclusion of monuments in forest function mapping is an opportunity to also integrate them into the digitalization of forest roads and extraction lines proposed in the report. To protect both forest soil and monuments, working methods or forestry machines that handle soil carefully can be used during clearing work in the aftermath of extreme weather events. Reference is also made to the links between spending time in nature and overall environmentally friendly behavior.

2.5 Monitoring

Forest environmental monitoring is a statutory task of the federal governments in Germany. The Ordinance on Surveys for Environmental Forest Monitoring (*ForUmV*) and an implementation concept agreed on by the federal government and the federal states sets out the minimum criteria for the survey data and the procedures to be applied. The long time series in environmental forest monitoring, in some cases up to 30 years, enable unique analyses of the condition and development of forests in Germany, the evaluation of which is only just beginning. Against the backdrop of increasing weather anomalies, environmental forest monitoring must also be aligned with the new challenges. The lack of knowledge about future forest development and the effects of previously unknown extreme weather events on forests must be remedied by stepping up monitoring to enable timely corrections of adaptation measures. In this respect forest monitoring currently has several weak spots. One of them stems from the process-induced focus on main tree species. This leads to a lack of information on the vitality development of less common tree species, which may, however, become increasingly important as a result of climate change. In addition, important information on the vitality development of forest stands of all ownership types at year-round or event-related (storms, calamities) time points, in different ecosystem types, management systems and forest structures (pure and mixed stands) is not currently available to a sufficient degree. There are other deficits in meteorological data for determining the forest microclimate with automated measurements that also record soil temperature, and in the quantification of stand precipitation. Other weak spots in the context of climate change have to do with the lack of important links between the procedures and results of environmental forest monitoring and the fact that there are no coordinated procedures between the federal government and the federal states for accompanying monitoring surveys at the state level, such as browsing or forest protection monitoring. Given the current challenges facing the forestry sector that are posed by large-scale forest damage and climate change but also by general societal developments (demographic change, protection of biodiversity, promotion of the bioeconomy, remuneration of ecosystem services, etc.), there is an even more urgent need to find a solution to this problem.

3

Overarching strategies, policies, and legal instruments for the adaptation of forests and forest enterprises

3.1 Overarching strategies and policies

There are a variety of political regulations that, on the one hand, have implications for forest adaptation to climate change and, on the other hand, need to be considered in the context of developing new climate adaptation proposals if a coherent climate adaptation policy is to be achieved. The main political regulations are briefly presented below. The three central strategies and policies of the EU are listed first, followed by the strategies of the federal government.

EU Green Deal and related strategies

The Green Deal recognizes that forest ecosystems are under increasing pressure as a result of climate change. Forest areas in the EU should therefore be improved in terms of both quality and area to achieve EU goals for climate neutrality and environmental improvement.

EU Forest Strategy

The EU Forest Strategy (European Commission 2021) emphasizes the multifunctional use of forests and covers a broad spectrum in forest management with goals in the following areas of action: (i) supporting the socio-economic functions of forests to promote rural areas and the forest-based bioeconomy within the limits of sustainability, (ii) protecting, restoring and expanding EU forests to combat climate change, reversing biodiversity loss and maintaining resilient multifunctional forest ecosystems, (iii) strategic forest monitoring, reporting and data collection, (iv) a strong research and innovation agenda to improve knowledge on forests, (v) an inclusive and coherent EU forest policy framework and (vi) stepping up the implementation and enforcement of existing EU legal provisions relating to forests and forest management.

EU Biodiversity Strategy

In 2020, the EU Commission drew up the "EU Biodiversity Strategy for 2030 - More space for nature in our lives" as part of the European Green Deal (European Commission 2020). The EU Biodiversity Strategy also aims to improve the quantity, quality, and resilience of forests in the EU, especially concerning fires, droughts, harmful organisms, diseases, and other threats that are expected to increase as a result of climate change. The goals are to be achieved by designating legally protected areas that cover at least 30 percent of the land and sea area in the EU, strict protection of 10 percent of the EU land area, including all remaining primary and virgin forests, and effective implementation of existing EU legal provisions through clearly defined conservation goals and measures.

Consequently, this strategy aims not only to significantly step up species protection but also to counteract the disadvantages to biodiversity caused by climate change. To enable forests to fulfill their functions in terms of biodiversity and climate, all forests should be kept in a good condition. Resilient forests play an important role in providing raw materials, products, and services that are of key importance to the circular bioeconomy. They should support a more resilient economy.

German Strategy for Adaptation to Climate Change (DAS)

To meet the challenges of climate change on the national level, the federal government adopted the German Strategy for Adaptation to Climate Change (DAS) in 2008. In 2015 and 2020, the adaptation strategy was updated and the measures set out in the action plans of the adaptation strategy are to be evaluated and updated every four years (The Federal Government 2020). The German Adaptation Strategy has adopted a cross-sectoral approach, i.e. the coordination of all relevant ministries has already taken place and the called-for measures had already been approved by the time they were announced.

Climate Action Plan 2050

In the federal government's Climate Action Plan (BMU 2016), the focus in the area of action – land use and forestry – is on maintaining and improving the greenhouse gas sink capacity of forests. At the same time, in line with the Forest Strategy 2020, the climate mitigation performance of sustainable forest management and the associated timber use is to be promoted. The model in the Climate Action Plan is, therefore, oriented toward the findings of the Intergovernmental Panel on Climate Change (IPCC). It states that the protection and sustainable management of forests is an appropriate and cost-effective means of reducing greenhouse gas emissions. In this context, the Climate Action Plan also adopts the perspective of the Forest Strategy 2020 (see below) concerning the role of wood as a renewable raw material that can make a significant contribution to climate change mitigation by storing carbon in long-lived products and substituting materials with comparatively disadvantageous greenhouse gas and ecological balances as well as fossil fuels.

Forest Strategies 2020 and 2050

In the federal government's Forest Strategy 2020 (BMEL 2009), one of the decisive findings is to preserve and permanently secure the forest as a CO_2 sink. Whereas the National Biodiversity Strategy focuses solely on natural CO_2 storage options, the Forest Strategy 2020 also includes CO_2 storage in wood products and the substitution potential of wood products in the possible solutions, without, however, setting concrete targets for this (BMELV 2011). The Forest Strategy 2050 continues to emphasize the close link between forest and climate policy. Thus, the role of forests in climate change mitigation and climate adaptation of forests is the first area of action to be mentioned right at the beginning of the strategy.

National Biodiversity Strategy (NBS)

The National Biodiversity Strategy (NBS) adopted in 2007 (BMUB 2007) aims to implement the international Convention on Biological Diversity (CBD). The Convention adopted at the Conference on the Environment and Development in Rio de Janeiro advocates the "ecosystem approach". It presents ecological viability as the criterion for economic and societal decisions. To adapt forests to climate change, the NBS advocates the cultivation of diverse mixed forests and pursues the goal of increasing the responsiveness of sensitive species and biotic communities to climate-related changes (BMUB 2007).

Peatland Conservation Strategy

The Federal Ministry for the Environment (BMU), with the support of the Federal Agency for Nature Conservation (BfN), has developed a peatland conservation strategy as a discussion paper (Nitsch and Schramek 2020, BMU 2020). It is intended to set the course for the conservation of peatland areas as biodiversity hotspots and long-term carbon stores. According to the BMU (2020), approximately 300,000 hectares of peatland soil in Germany is currently used for forestry or is covered with woody plants. In the context of forest management, forests in use on drained peatlands play an important role. From the perspective of climate adaptation, the BMU (2020) attaches crucial importance to maintaining and improving the water retention capacity of forests, especially concerning drought events.

National Bioeconomy Strategy

In July 2013 the German Government adopted the first bioeconomy strategy, one of the most recent policy strategies of direct relevance for climate change mitigation. A revised version was published in the spring of 2020 (BMBF and BMEL 2020). It identifies goals, strategic approaches, and measures for a shift towards a biobased economy. A biobased economy should be able to make do with as few fossil resources as possible, provide sustainably manufactured products and services, and thus combine economic growth with ecological compatibility. The transformation to a resource-efficient economy based on renewable resources is to be advanced and the consumption of fossil fuels is to be significantly reduced.

3.2 Legal instruments

Forest law provisions

In Germany, forest policy is primarily the responsibility of the federal states. As a rule, the federal states forest laws set out these forest law obligations within the framework of the definition of so-called "sound forest management". The owner of a forest is duty bound to manage its forest soundly, in particular sustainably, and, at the same time, to take into account the protective and recreational function of the forest. Sound forest management uses, regenerates, tends, and protects the forest in line with the established findings of science and the tried-and-tested rules of practice. The federal government participates in the financial promotion of the forestry sector as stipulated in the Act concerning the Joint Task for the "Improvement of Agricultural Structures and Coastal Protection" (*GAK*). Forest law provisions that need to be considered when adapting forests to climate change include the Act on Forest Reproductive Material (*FoVG*).

Nature conservation law, soil protection, water law

Nature conservation laws (Federal and state governments) also contain provisions that directly and indirectly affect forests and the forestry sector. The provisions regarding the choice of tree species are particularly important for the adaptation of forests to climate change. Other sections of nature conservation law do not address the impact of climate change on the protected habitats, communities, and species regulated under nature conservation law either. According to section 33 (1) *BNatSchG*, "All changes and disturbances that can lead to a significant impairment of a Natura 2000 site in terms of its components relevant to the goals or purpose of conservation [...] are inadmissible". However, this will not stop modifications to Natura 2000 sites as a consequence of climate change. Concerning forest soil, national soil protection legislation must be complied with. National provisions result from numerous laws and ordinances. The Federal Soil Protection Act (*BbodSchG*) and the Federal Soil Protection Ordinance (*BbodSchV*) as well as other legal provisions at the federal state level are of particular importance. The purpose of the Federal Soil Protection Act is to "sustainably secure or restore the functions of the soil. To this end, harmful changes to the soil must be prevented, the soil and contaminated sites, as well as the water pollution caused by them, must be rehabilitated and precautions must be taken to prevent adverse effects on the soil" (section 1 *BBodSchG*). So far, the Federal Soil Protection Ordinance has not been very specific concerning precautionary soil protection. Nevertheless, there are strict rules and voluntary undertakings for example within the framework of forest certification and the use of machinery in forests. Another legal instrument is the European Water Framework Directive (WFD; Directive 2000/60/EC). It is intended to achieve good quality for water bodies in the European Union.

Commercial and antitrust law

Instead of direct support, small-structured corporate and private forests in Germany in particular have received indirect support from state forestry administrations for decades. In the course of EU audits, it was determined that the remuneration for state-based support services, which is far lower than the market rate, is also to be regarded as problematic under state aid law (WBW 2018). As a consequence, these developments led to a considerable restriction of the hitherto commonplace indirect support of non-state forestry and a significant increase in the cost of state support for private and corporate forests.

Fuel Emissions Trading Act

To achieve the climate change mitigation goals, the Act on National Certificate Trading for Fuel Emissions (*BEHG*) was promulgated on 19 December 2019 as part of the climate package. As a result, the heat and transport sectors are also included in emissions trading from 2021 and the combustion of coal, diesel, gasoline, etc. will be financially penalized. Solid biogenic fuels such as wood, pellets, etc. are excluded from this. Subsequently, a political agreement was reached to increase certificate prices. In 2021, the introductory price per tonne of CO_2 was EUR 25 and it will rise to EUR 55 by 2025 (BEHG section 10 (2)).

Forest Damage Compensation Act

The goals of the "Act to Compensate the Effects of Special Damage Events in Forestry" (Forest Damage Compensation Act) (*ForstSchAuslG*) in the version of 29 August 1969 were to prevent a non-cyclical drop in raw timber prices in the event of damage events without endangering the supply of the wood-based industry, as well as to make the economic consequences for forest enterprises "more bearable", for instance by forming a tax-free reserve/operational compensation fund or the flat-rate reduction of the income tax rate for calamity timber. Overall, it has to be said that the provisions of the Forest Damage Compensation Act are no longer up to date. The restriction on scheduled logging was not enforced until three years after the start of the series of calamities in January 2018 (also due to concerns under European law). In addition, the tax relief partly ran into the ground because hardly any positive income was generated by the sales of calamity timber.

Federal Climate Change Mitigation Act

The Act stipulates that by 2030 Germany must have reduced its greenhouse gas emissions by at least 65 percent of the 1990 level. CO_2 emissions are expected to fall by 88 percent by 2040. Germany is to be climate neutral by 2045, five years earlier than in the previous Climate Change Mitigation Act. Within the LULUCF sector (land use, land use change, and forestry), the climate mitigation performance of forest ecosystems is offset against that of other land use categories such as cropland, grassland, wetlands, or settlements. The increased carbon stocks in peatland areas and forests are envisaged in the Climate Mitigation Act as a means to improve the emission balance in the LULUCF sector.

3.3 Financial instruments and tax provisions

The state has various ways of encouraging certain behavior by its citizens. The spectrum ranges from relatively weak, non-binding instruments such as the mere provision of information to laws and regulations that prescribe certain behavior for its citizens. In contrast to this regulatory approach in which the state claims the right to a particular act or foregoing said act, the state transfers the power of disposal to its citizens when selecting a financial instrument. They are free to steer their behavior and factor the financial compensation opportunities for government-desired behavior into their decision-making processes. The previous chapter on legal instruments is now followed by a brief presentation of the existing financial instruments.

Financial support for forest management

According to the Basic Law, the federal states are primarily responsible for forest management. A legal basis is required for the federal government to participate in funding. Today, this legal basis is furnished solely by the Joint Task for the Improvement of Agricultural Structures and Coastal Protection (*GAK*). It also integrates EU funding contributions under the European Agricultural Fund for Rural Development (*EAFRD*). The goal of GAK funding is defined in law: It is intended to foster the efficiency and competitiveness of agriculture and forestry and to ensure the sustainable performance of rural areas (*GAKG*, sections 1, 2). Funding is generally limited to private and municipal forests. At present, this generally involves the pro rata funding of the respective costs. Concerning the steering impact of financial incentives, it should be noted that forest owners are free to take up the corresponding offers or not (Elsasser et al. 2020). The private forestry sector receives comparatively little support from the public sector. The Forest Enterprise Monitoring Network lists funding for 2017 in private forests of > 200 ha as approximately EUR 9/hectare. This is a very different situation compared to agriculture where direct payments and subsidies for agriculture enterprises amount to approximately EUR 410/hectare (BMEL 2019b). In addition, direct payments from the EU make up the bulk of this amount. They are made available to agriculture enterprises without any further services from their side. In contrast, funding in the forestry sector is usually tied to the implementation of specific measures for which forest enterprises also incur costs.

Tax regulations

The Forest Damage Compensation Act (*ForstSchAusglG*) introduces the option of risk prevention through the creation of a tax-free reserve for enterprises with a legal obligation to keep accounts. The funds that are deposited in a special bank account serve as "self-insurance" in the event of a calamity and can be used to cover measures to repair forest damage. Other tax relief options under the Forest Damage Compensation Act have to do with the flat rate for operating expenses, the valuation of timber stocks from calamity usage, and the reduced tax rate under section 34b (3) (1) of the German Income Tax Act (*EstG*) (quarter rate) for calamity usage in the financial year of a logging restriction. Section 34b of the German Income Tax Act is a key tax provision for calamity usage in private forests. To ensure that calamity incidents do not unjustifiably exacerbate tax progression in enterprises, tax incentives for such extraordinary timber uses have been in place since 1920 (Moser 2011). Currently, income from calamity usage is taxed at half the rate. If extraordinary uses exceed the sustainable felling budget, the ¼ tax rate is applied to this income. In each case, this refers to the tax rate that would be applicable if the income tax rate were to be applied to total taxable income. It should be pointed out here that this kind of tax relief only comes into play if significant forest income is generated from calamity uses. This presupposes that timber revenues are well above the cost of harvesting and storing the timber. Under the framework conditions in the years 2019/2020, this was no longer the case in most instances which meant that the corresponding tax relief provisions "came to nothing" on many occasions.

Remuneration of forest ecosystem services

The state has the option of purchasing certain services. This option is an integral part of the public procurement system. In the same way that consulting services are purchased as preliminary services for government work, ecosystem services can also be purchased by the state. Ecosystem services can also entail preliminary services such as purifying water under forests to provide drinking water for the population, as well as goods for end use, such as providing recreational space. However, unlike traditional public procurement, this option for paying for services for the public has not gained acceptance in the ecosystem services sector. Remuneration for forest-environmental and forest-climate services constitutes aid according to the EU policy framework (EU-COM 2014), which is permissible under certain conditions but must be notified through the EU. These EU legal provisions must be taken into account when developing remuneration instruments for forests. In the past, no instruments for paying or remunerating ecosystem services have emerged despite regularly recurring political demands. Nor can this be attributed to a lack of relevant proposals (for instance Franz 2017, Franz et al. 2017, Franz et al. 2018, Müller et al. 2020). However, the current federal government has made the introduction of instruments to remunerate forest ecosystem services a key objective in its forest policy

(Deutscher Bundestag 2021). From a federal perspective, two ecosystem services in particular are the focus of remuneration efforts: the remuneration of climate mitigation performance and the remuneration of nature conservation services.

3.4 Communication, consulting, training and research

Communication

In particular, the forestry administrations and forest enterprises of the federal states have a statutory duty to provide information and education. Many private funding bodies also perform this task. Traditionally, the emphasis is on communicating the principles of sustainable forest management and on the target group of young people. The particular communication challenges thrown up by the very rapidly changing forest landscapes as a consequence of climate change are only beginning to be recognized in the sector and the forest sciences. In the meantime, the interpretations of the causes of damage and the need for action presented by some stakeholders are attracting a great deal of attention in the media. People interested in forests have a wide range of plant activities at their disposal which allows them to become actively involved in reforestation. The opportunities for civil society, too, to submit suggestions, demands or criticisms regarding forest planning have not been developed to any major degree in Germany and are limited to individual enterprises or model projects. This is probably one of the reasons why critics of forest enterprises are increasingly searching for avenues to express themselves on social media as well as organizing citizens' action groups critical of forestry administrations.

Consulting

About half of the privately owned forests in Germany are less than 20 hectares in size. Providing advice to private and corporate forest owners is an important task of the state. The free offers available to forest owners consist of expert forestry consulting services. This always consists of information about forests and their management, funding opportunities, and technical education and training or instruction in forming forestry alliances. These consulting services are provided free of charge to forest owners because the services provided by private and corporate forests ultimately benefit the public at large.

Training

Forestry courses are available at five institutions of higher education and four universities in Germany. These accredited degree programs cover the full spectrum of education in forest management and forest sciences and all the required competencies. A large volume of new content has been added to the classical ecological, economic, wood science, technical, and social science disciplines in the field of forestry in the recent past. In addition to the courses at institutions of higher education and universities, forestry training centers also run courses for forestry practitioners in all area-based federal states. The practical part of the forester apprenticeship takes place in a forest enterprise. Two-thirds of the apprenticeships are offered in state forestry enterprises and about one-third in private ones. While motor-manual timber harvesting is a major topic in forestry courses, highly mechanized harvesting using harvesters and forwarders are usually only touched on briefly.

Research

Many different institutes in Germany are researching the subject of forests, forest management, and timber use. Forestry research in Germany has traditionally been carried out primarily by the forestry faculties at the universities of Dresden, Freiburg, Göttingen, and Munich, as well as by the forest experimental stations of the federal states and the federal government's departmental research body, the Thünen Institute. In addition to the above-mentioned universities, forest-related research is also underway in biological, geographic, and environmental science faculties, especially on forest ecology issues. Whereas universities focus on basic research in addition to applied research and teaching, departmental research institutes focus on long-term monitoring, applied research, and knowledge transfer. The universities and the Thünen Institute have a stronger national and international focus whereas the forest experimental stations of the federal states traditionally have a strong regional focus. In addition, the Julius Kühn Institute (JKI, specializing in forest protection issues), the German Centre for Forest Operations and Technology (*KWF*, specializing in the application-related issues of forestry process engineering), and the universities of applied sciences are important players at the national level. Furthermore, there are wood research facilities spread across Germany with different work foci. Research capacity is concentrated in six to eight regional clusters, depending on the definition, comprising nearly 80 percent of permanent positions in forest research and about 70 percent in wood research. Third-party research funding amounted to around EUR 150 million a year for the period 2015 to 2020, with about two-thirds of this going to forest research and one-third to wood research (Isermeyer et al. 2021).

4

Recommendations for action

4.0 Introduction and summary of the main recommendations

The recommendations cover fourteen different areas of action. They are aimed not only at policymakers at the state-, rural district, and local levels, but also at other stakeholders in the above-mentioned fields who can make a relevant contribution to the necessary transformations. Since the generational task of adapting our forests and their management to climate change to safeguard the ecosystem services provided by them affects many areas, the recommendations for action contain numerous recommendations, some of which are detailed. The most important recommendations are summarised first.

Our recommendations constitute a model for the forests of the future and for how they should be used sustainably for the benefit of society. The future development of forests in this century could take very different paths. These development paths will be influenced not only by climate change but also by shifts in the demands made on forests by forest owners and society, and by technological progress. The WBW has already identified the drivers of these developments in its expert opinion "Guiding Principles for a Forest Strategy 2050" (WBW 2020). Due to a large number of necessary assumptions, it is not possible to credibly present the concrete development trajectories resulting from the diverse combinations of the various influencing factors and the effects they will have on forests and society in detail. Even very advanced climate models are unable to adequately depict extreme weather events that have a decisive impact on forests and their ecosystem services. Technical and societal developments such as the implementation of climate neutrality planned by 2045 or the future demand for ecosystem services are also very difficult to predict. At the same time, our current needs and also our ideas of the future have an impact on what forests and our relationship with them will look like in the future.

The WBW recommendations aim to steer climate adaptation decisions and actions for our forests in a direction that will ensure that future generations have the same options for forest ecosystem services as today's generation. In the context of the sustainable governance of the forest ecosystem with the long lifetimes of trees and extended production periods, the sustainability principle of intergenerational equity plays a special role in sustainable transformation. Although changes in climate and society are very likely to alter the weightings between different ecosystem services, our forests should continue to be havens for biodiversity in the future. In this way, forests will mainly be home to the same species we find there today, albeit in altered ecological communities and possibly at different locations in the landscape. Forests should continue to provide sufficient quantities of clean drinking water, protect soils, store CO_2 in biomass, soils, and wood products, provide tomorrow's society with a space for recreation, health, and leisure activities, enable forest owners to generate a source of income and, by supplying the renewable resource wood, promote the path already taken towards climate neutrality in the economy. Not every forest will be able to provide all of these different ecosystem services in the same way, nor will they be in demand everywhere on the same scale. Therefore, as is already the case now, the various forest owners and different site conditions will result in the fixing of priorities. However, due to the small-scale mixture of different forest ownership types and also the diversity of the sites in Germany, the overarching goals can be balanced and reached at the landscape level.

The WBW recommendations aim to secure these diverse options for ecosystem services in the long term. They can be summarised as follows:

1. Maintain and develop diverse, resilient, and adaptive forests: Functioning and productive ecosystems are the basis for ecosystem services. Consequently, forests that are not deemed to be capable of adaptation today, must evolve in this direction (see 4.1). Since, in many cases, natural adaptation processes are unable to keep pace with the speed of climate change, this process must, at least in part, be actively steered and supported. Here, the prevailing focus is on the conservation and development of diverse forests. In addition to the diversity of site-adapted tree species and their functional and genetic diversity, this also involves structural and species richness in general. This is

because diverse forest ecosystems tend to have higher levels of resistance, resilience, and, as a rule, adaptability due to the spreading of risk and the multiple interactions. The protection of forest soils and their functions contributes significantly to the ecological stability of forests. The WBW recommendations aim to empower forest owners by giving them the resources they need to move ahead with this necessary forest adaptation on a sound scientific basis while protecting biodiversity (see 4.4) and soils (see 4.5). To ensure that forests continue to be well-suited places for recreational and leisure use even under changing climatic conditions, societal demands and changes must be addressed to the same degree as ecosystem changes (see 4.7).

2. Improve risk management: In many cases, forest conservation also necessitates actively protecting forests from biotic and abiotic hazards that are expected to increase in the future (see 4.2). Consequently, significant improvements will have to be made to risk management (see 4.3) in close connection with monitoring boasting high temporal and spatial resolution (see 4.9). Both risks and disturbances that have occurred must be identified and localized more promptly than in the past. Their economic, societal and ecological consequences must be assessed so that preventive, precautionary, and control measures can be launched promptly. New methods of forest protection monitoring play a major role in this context. Since disruptions will still occur, structures and capacities (for instance wet timber preservation yards) must also be kept in a permanently operational state to effectively manage future damage. To strengthen risk management in private and corporate forests, the preparation of in-house risk management plans should be promoted under the Joint Task for the Improvement of Agricultural Structures and Coastal Protection (*GAK*).

3. Establish inter-enterprise, high-resolution forest monitoring: (see 4.9) Forest monitoring occupies a key position in the forest adaptation process not just because of the important role it plays in risk management (for instance risk identification, and damage quantification). It can also be used to quantify forest trends, biodiversity, ecosystem services, and their take-up, and to verify the effectiveness of forestry measures. It supplements the inventories at the enterprise level and, thus, also generates the evidence base for adaptive management and societal discourses on forestry. Current forest monitoring mainly consists of the Forest Condition Survey, the National Forest Inventory, the National Forest Soil Inventory, and the Forest Enterprise Monitoring Network. Consequently, in many cases, it no longer meets the current and future requirements for spatial and temporal resolution. It is, therefore, to be extended to include modern methods of digitalization and remote sensing, species identification, and monitoring of societal and economic indicators in such a way that area-based statements are possible, the networking of several elements of forest monitoring is ensured, the provision of information is accelerated, and the species spectrum of target organisms is widened. Significant investment in research and capacity building will be needed.

4. Adapt institutional structures: (see 4.10) Increasing damage events, a drop in forest productivity, and changes in the tree species spectrum, coupled with rising costs for adaptation, risk management, monitoring, and ecosystem services, will reduce revenues from traditional forest management focused on raw timber production in the long term. These developments will aggravate the already existing structural problems in small-parcel private and corporate forests and will necessitate the creation of stable institutional structures that are financially secure in the long run. This is the only way that private and corporate small forest owners will be able to meet the diverse demands placed on forests in an enduring manner. To this end, we recommend the establishment of stable, efficient structures for the management of non-state forests and the development of information platforms, the creation of incentives for active forest management, the formation of larger management units, and more efficiently structured forest promotion.

5. Remunerate ecosystem services: (see 4.8) We believe the greatest current challenge for forest policy on the path to a rapid and effective adaptation of forests to climate change stems from the fact that the income of forest enterprises is currently based almost exclusively on the revenues from timber sales. Other services for climate change mitigation, water protection, nature conservation, recreation, etc. are generally perceived as burdens by forest enterprises since the provision of these services does not generate income but mostly revenue losses or additional costs. We, therefore, recommend that the public sector give its support to financing and business models that provide forest enterprises with plannable, long-term income from the provision of ecosystem services. We believe one basic way of doing this would be to remunerate the adaptation or adaptability of forests to climate change, the basis for the future provision of all ecosystem services. This type of remuneration should supplement the support provided under the Joint Task for the Improvement of Agricultural Structures and Coastal Protection (*GAK*). In contrast to the GAK, it is not the individual adaptation measures (for instance forest conversion) that would be remunerated but the results. Forest enterprises would receive ongoing remuneration for the part of their forests that can be deemed to be sufficiently resilient and adaptive. For a system of this kind, some degree of differentiation would be possible depending on the level of adaptedness and adaptability, for example, a traffic light system. A system of this kind should distinguish between forests that, based

on current knowledge, can be considered largely resilient and adaptive, forests that are moving in this direction thanks to forest conversion measures, and forests that should be classified as at-risk. The criteria for these classifications and the valid indicators to be recorded in a standardized manner would have to be developed on a scientifically sound footing by a broadly-based working group (for instance with representatives of science, forestry practice, and certification companies), and submitted to the BMEL as the representative of the federal government.

6. Promote sustainable timber use: (see 4.6) One ecosystem service provided by forests that is essential to society is the supply of timber. The adaptation measures proposed in this report change the volumes and composition of timber supply. For them to be realized at all and not to fail due to market resistances, the downstream wood-based industry and timber use would have to be adapted to the altered productivity and tree species composition of the forests, to other categories, and a higher proportion of incidental uses. For the preservation and expansion of this ecosystem service that involves the sustainable supply of timber, value chains would have to be put in place speedily, which optimize the economic and climate-effective use of domestic unprocessed wood and thus significantly support the transformation into a bioeconomy. Incentive systems should be designed more for material use than for direct energy use. Timber construction plays a central role. Its share in building construction should be significantly increased through the rapid implementation of the extensive, long-term use of timber in the construction sector. Furthermore, technical processes must be developed that are suitable for processing wood categories that have been difficult to market up to now (calamity timber, large-dimensioned coniferous wood, hardwood) with high added value. To be able to partially replace the declining domestic supply of coniferous wood categories in the future, the conditions must be created for the generation of new mechanical pulp sources from recovered and waste wood.

7. Strengthen, improve the connectivity of and realign research capabilities: (see 4.13) To research the adaptation of forests, the forestry sector, the wood-based industry, and other relevant sectors to climate change efficiently and effectively, a reorientation of research on forest science, forest ecology, and wood products is recommended. This does not primarily involve new research content (it results from the challenges), but rather a stronger strategic orientation and the development of new research approaches along the lines of sustainability research oriented towards urgency, finding solutions and implementation, the creation of corresponding long-term research infrastructures and capacities (for instance forest laboratories located in regional clusters and processed in collaborative research projects), improved networking and cooperation between existing research institutes as well as the improved provision and increased exchange of data and models, among other things, to promote joint syntheses.

To foster the transformation process, we also make recommendations on changes in education and training (4.12) and the communication of climate adaptation strategies (see 4.11). The recommendations are presented in detail in the following sub-chapters.

4.1 Maintain and develop resilient and adaptive forests

The promotion and expansion of resilient, adaptive forests can essentially be undertaken during the regeneration phase of forests, but also with interventions during the stand maintenance phase. The following recommendations are, therefore, divided between these two phases.

Appropriate regeneration measures can set the course for increasing the resistance, resilience, and adaptability of forest stands. With this in mind, the response to changing environmental factors should entail presenting the largest possible number of genetically different individuals for selection. This can be achieved by composing regeneration from different tree species, different origins of a tree species, the natural regeneration of a tree species that is rich in individuals, and different regeneration ages. The main prerequisites for this are: (1) the dynamization of forest development types and use of site-appropriate tree species with due consideration of climate change, (2) ongoing promotion of regeneration and advance regeneration of existing stands, (3) the preservation and expansion of tree species diversity, (4) the safeguarding and targeted improvement of high genetic diversity, (5) the use of disturbances to transform forests, (6) and amending existing regulations to extend reforestation periods after harvesting or disturbances. In addition, (7) habitat connectivity and expansion should be taken into account for the creation of new forests and reforestation. Recommendations for forest conservation and risk management to create and maintain resilient forests can be found in 4.2 and 4.3. To increase the resilience and adaptability of forests in the stand development phases that follow from securely established regeneration, we also recommend additional (8) maintenance measures to develop structured, ecologically stable mixed stands. Specifically, the following measures are recommended:

1. Develop dynamic target type planning for forest stands on a site-by-site basis: Forest development types (operational target types) are an important basis for silvicultural planning and consulting. They provide an opportunity to combine different proportions of tree species while maintaining a high probability of survival under current and future site conditions. The previous federal state specific forest development types should be urgently adjusted, if this has not been done already, based on tree species suitability models. In many cases, additional soil-related information is needed to assess the future soil moisture regime in different climate change scenarios (see 4.5).

In the future, it should be possible to compare the climate and tree species suitability models underlying forest development types at regional or national levels. This would increase the reliability of consulting services and simplify knowledge transfer. Regular revisions of forest development types should include a growing wealth of information on genetic variation within tree species and documented practical experience.

2. Continuously promote regeneration and advance regeneration: Forest resilience should be increased by establishing advance regeneration. This could help to avoid a variety of problems and the high costs associated with regeneration in the aftermath of disturbances. In particular, high-risk stands should systematically undergo advance regeneration as part of forest conversion measures with tree species of the respective forest development type. Shade-intolerant tree species for which advance regeneration is difficult or impossible under the canopy should be integrated into the stand matrix (for instance along outer and inner forest edges such as forest roads) in such a way that they can reach the areas to be regenerated via natural seed dispersal after a disturbance. The establishment of pioneer and rare tree species as future seed sources in the stand matrix should be encouraged as well as the conservation of old seed trees.

To promote structured, species-rich, and productive forests, the regeneration process should be undertaken with an extended timeline and spatial differentiation on sufficiently large forest areas, which may also include several stands. The additional costs incurred due to more frequent maintenance interventions should be compensated within the framework of the existing subsidies for young stand maintenance by subsidy rates adjusted to longer periods.

3. Maintain and expand tree species diversity: To spread risks and strengthen adaptive capacity, forest regeneration should be rich in tree species, genetically diverse, and adapted. Within the selected forest development type, future stands should be established with at least three site-appropriate tree species in stable spatial configurations of mixtures (where this is possible on the respective site). Mixing should be a precondition for the granting of funding for regeneration activities. Appropriate (stable) spatial configurations of mixtures should be recommended for these combinations of tree species. The different tree species in each forest development type should belong to different functional types in terms of their stress and disturbance tolerance to diversify response patterns to disturbances (for instance not three conifer species with a similar vulnerability to drought, heat, and bark beetles). Since the cultivation risk of some site-native tree species will increase significantly at many locations, tree species diversity should be maintained or increased by integrating additional tree species where necessary.

The question of tree species selection plays a central role in forest adaptation as many ecosystem services are closely linked to tree species. Many supporting and regulating ecosystem services are closely linked to the diverse interactions and biodiversity of the entire ecosystem. They are, therefore, supported particularly by native tree species. For some provisioning ecosystem services, it comes down to the specific characteristics of tree species, for instance, coniferous wood for supplying sawable logs for timber construction. Therefore, when selecting tree species for a specific site and when planning tree species proportions in forest landscapes, it is important to keep in mind the provision of ecosystem services in the forests as well as for value chains. Wherever native tree species are lost (for instance ash), alternative tree species should be in a position to provide a habitat for as many of the species as possible that depend on native tree species. To protect biodiversity, the genetic potential of native tree species, including previously rare species, and their provenances should be exploited first. Where adaptation goals cannot be met with these species, tree species should be used that are most likely to support a large proportion of dependent biodiversity due to their close relationship with native species (for instance Turkey oak, Turkish fir). Where tree species with important production functions are lost (for instance spruce), alternative tree species should be capable of taking over these functions (for instance fir, Douglas fir).

At sites where introduced tree species are grown, they should be embedded in a matrix of native tree species and the proportion of areas of stands and landscapes attributed to them should be limited to a level that does not threaten native biodiversity. Very little is known about these proportions at present and they should, therefore, be elucidated. At all events, there should be a weighing of interests between cultivability and the risks for the alternative tree species used. This should be based on long-term experience and risk assessments (for instance on invasiveness) in Germany, other cultivation areas, and in the natural distribution range. This weighing of interests should be taken into account in federal states guidelines on the eligibility of alternative tree species (positive or negative lists).

Alternative tree species include site-appropriate (rare) native tree species, tree species already introduced (for instance red oak or Douglas fir), species from neighboring regions of south (eastern) Europe, and other tree species for which it is as yet little or no cultivation experience in central Europe. Suitable provenances and, in the case of trees not subject to the Act on Forest Reproductive Material (FoVG), suitable areas of occurrence must be used. Against the backdrop of climate change, the legal provisions on forest reproductive material are of particular importance. In particular, the list of species of trees governed by the provisions of this Act should be widened while maintaining the current categories. In the future, this must apply systematically to all woody plant species intended for cultivation in forests. Furthermore, the areas of provenance have to be restructured to ensure that there is an equal number of uniform areas of provenance for each woody plant species. The 46 basic ecological units combined with altitudinal zoning are a suitable option for this. We do not recommend the reintroduction of the category "source-identified". Instead, for selected woody plant species, some of the minimum criteria for approval of source material in the "Selected" category could be relaxed in the Forest Reproductive Material Authorisation Ordinance (*FoVZV*).

The most promising alternative tree species, based on the current state of knowledge, for which little cultivation experience is available to date, need to be tested in coordinated collaborative trials in Germany and central Europe on as broad a range of sites as possible. The recommendations of the federal states working group "Forest Genetic Resources and Forest Seed Law" concerning the work assignments of the silviculture policy officers of the federal states are a good basis for this. They should be extended to include other tree species.

Practical cultivation trials with new tree species should only be funded if specific criteria regarding trial design (for instance minimum size of trial plots, browsing protection, canopy cover, reference tree species) and tree species are met and minimum duration, scientific monitoring, and documentation are ensured.

4. Safeguard and increase genetic diversity: In addition to tree species diversity, intra-species phenotypic plasticity is a critical foundation for adaptability at the population level. The function of the genetic system (for instance flowering, seed formation and dispersal, migration) and the maintenance of genetic diversity are, therefore, crucial for phenotypic traits that have an (epi-)genetic basis (heritability) (for instance diverse stress tolerances, phenological traits). The first step is to examine the adaptability of the sources of seed production ("selected stocks", seed orchards) and, if necessary, reassess or replace them. At the same time, their current site conditions should be included in crop authorization registers. This would be a precondition for the targeted use of site-adapted (and not only "source-identified") reproductive material in artificial regeneration.

Recommendations on provenance, including exchange provenances ("climate-adapted seed stocks") or the targeted mixing of propagation material from different provenances, need to be overhauled. Given the diversity of locations within regions of provenance, the suitability of existing boundaries of regions of provenance needs to be reviewed in the medium term.

To facilitate the introduction of alternative European tree species, including the production of reproductive material from adapted native stands, regions of provenance or a region of provenance should be designated for Germany. This applies to tree species that are regulated only in European forest seed law but not in German forest seed law (for instance Turkey oak, downy oak, and various pine species). In addition, the designation of suitable harvest stands under forest seed law must be made possible for tree species that were not subject to seed law regulations to date, for instance, wild service trees. What is needed is an initiative to procure seeds of suitable provenance/tree species abroad based on contractual agreements and minimum standards.

5. Use disturbances to transform forests: Large-scale disturbances, such as the drought damage in 2018-2020, present major challenges when it comes to managing damage and regenerating damaged areas, but they are also an opportunity to substantially advance planned forest adaptation. However, to take advantage of disturbances for adaptation through artificial regeneration, appropriate capacity is needed to rapidly grow a large number of

individuals of the desired tree species/provenances. Since natural regeneration has prevailed in most areas (85 percent) of German forests in recent decades, production capacities for propagating material have decreased accordingly. The availability of and the demand for seeds and seedlings are subject to major fluctuations and randomness that are not easy to synchronize. Consequently, adequate seed reserves for storable seeds need to be established, for instance, by state forest enterprises. In this context, building up seed reserves, for instance, in state nurseries to bridge calamity-based shortages in crop production, also take on greater importance. To permanently increase production capacity in private nurseries, state forest enterprises with a limited breeding capacity of their own could enter into long-term supply contracts with private nurseries that set out minimum purchase quantities. This would provide security for nurseries on the one hand and counteract the loss of valuable reproductive material on the other.

The scarcity of plants for reforesting disturbed areas can also be mitigated by extending reforestation periods or by first establishing nurse crops (see 6). In addition, the need for propagating material for reforestation can be reduced by lowering the number of plants per unit area. For this purpose, for example, grove plantings are suitable in combination with natural regeneration between the groves.

Climatic conditions in open areas that emerge after a disturbance are often extreme and can lead to major difficulties in regenerating a successional stand. Relict structures (dead standing and lying trees, high stumps, crown deadwood, etc.) could be used to promote regeneration processes by reducing incoming and outgoing solar radiation, wind movement, and also browsing. However, there is still a lack of reliable evidence on the effectiveness of these structures. This should be obtained through targeted research. Increased efforts as a result of retaining or shaping structural elements should be encouraged, as should the creation of nurse crops. Training in silvicultural management options in the course of reforestation after a disturbance should be increasingly offered in continuing education programs.

6. Extend reforestation deadlines: Forest owners are required by law to speedily reforest felled areas. Depending on the different federal state legislations in place, unstocked forest areas must generally be reforested or successfully regenerated within 2-3 (in a few cases 5-6) years. Any incomplete regeneration must be concluded within five years. Much longer periods are necessary and expedient when it comes to achieving structured, uneven-aged stands. We, therefore, recommend where this is possible with due consideration of soil protection, an amendment to forest legislation to allow for longer periods of reforestation of up to ten years. Extended regeneration periods would open up the possibility of allowing natural regeneration to progress towards the establishment and only then, where necessary, would this be supplemented with artificial regeneration. Longer regeneration periods, however, require intensive monitoring of regeneration progress and the development of understorey vegetation to ensure that the time slot for the unproblematic establishment of the seedlings (without costly control of competing vegetation) is not missed.

7. Consider connectivity and biotope networking when establishing new forests and in reforestation activities: To improve species migration and genetic exchange among populations, the connectivity or expansion of habitat patches should be considered when creating new forests or reforesting existing ones.

8. Promote tending to develop structured, ecologically stable mixed stands: Ongoing, initially intensive tending is needed to maintain structured, ecologically stable mixed stands. This will increase the vitality and stability of individual trees, will shorten production and hazardous periods, will prevent segregation, and will help to maintain climate-adapted tree species. Loss-making maintenance interventions to develop resistant, resilient, and adaptive forests should, therefore, be funded by federal programs in private and corporate forests.

4.2 Improve forest protection against biotic risks

Climate change repeatedly leads to an increased predisposition to infestation by pathogens and phytophagous insects in long-lived organisms such as trees. In addition, warming promotes the activity and population development of many relevant species including insects, mammals, and fungi. Mass propagation in stands with predisposed trees then also results in the infestation of vital individuals. In addition, the combination of globalization and climate change is also likely to lead to new species and species combinations.

Today, forests and forest landscapes rich in structure and tree species are deemed to be the most important preventive strategy (see Chapter 4.1). Monitoring populations and damaging effects on trees are also important (see Chapter 4.9). Highly differentiated strategies in terms of space, time, and technology are needed to cater to the very different life cycles and habitat preferences of individual species. In this context, the elimination of populations is only actively sought for introduced species (for instance quarantine pests such as the Asian long-horned beetle). In the case of indigenous pests, the objectives range from local reduction to protect a group of trees (for instance from oak processionary moths) and the protection of a stand (for instance from gypsy moths), to landscape-wide control to avert damage to vital trees (for instance by the eight-toothed bark spruce beetle).

To mitigate this worsening situation, the following specific proposals are put forward for forest protection management and the control and eradication of harmful organisms:

1. Establish forest protection management on a supra-regional level and provide scientific backing for strategies: Since harmful organisms do not stop at ownership boundaries, forest protection measures can only be organized on a cross-ownership basis. In the crisis during the period 2018-2020, it became apparent that the structures in place at the time, especially in private and corporate forests, were not suited to taking up the special challenges in the area of forest protection, including traffic safety. Against this backdrop, the recommendation is to establish area-wide forest damage monitoring and forest damage management across different types of ownership, including the securing of funding; see also the WBW opinion (2019) on the subject of "Risk prevention and the management of extreme events in the forestry sector".

Prevention should take priority over damage control and natural disaster management. Consequently, we recommend the establishment of model procedures with clear steps, thresholds, and permits but also exclusion zones for control measures long before mass propagation occurs. In this context, a distinction needs to be made concerning the degree of protection or the value of the stands on a supra-regional level for or against control (for instance for seed stands, occurrences of highly endangered species, forests of major importance for recreation and tourism).

Since the effectiveness and ecological and economic impacts of many practical strategies are often unclear, all major forest conservation strategies should be scientifically monitored at the supra-regional level by the competent federal forest experimental stations to establish an appropriate, publicly available evidence base.

Recommendations for the silvicultural use of recently introduced tree species should take into account findings on invasion biology from the very outset. In the case of many tree species, including previously rare native species, an increasing forest protection risk is to be expected with expanding acreages, which needs to be assessed.

2. Improve control of harmful organisms: Forest protection should follow the problem-solving approach adopted in integrated plant protection. It applies combinations of silvicultural, mechanical/technical, and biological or biotechnical methods. In the case of acute danger to local protected habitats, communities, and species, plant protection products (PPPs) are also used. The primary objective here is to keep populations of harmful organisms below a defined damage threshold and to minimize collateral damage (for instance to organisms other than the target species or groundwater). Procedures that did not have a sufficient evidence base to date should be accompanied by replicated, scientific studies with control areas.

Forestry is not an important economic sector for the manufacturers of plant protection products. Consequently, only relatively few plant protection products have been approved. Even in the case of tried-and-tested products, applications for the extension of approval are not submitted very often because of the costs involved. Efforts should be made to ensure that a sufficient number of suitable agents are available permanently for the main application areas of plant protection products in forestry. If necessary, government support for the development and approval of plant protection products should be provided, ideally at the EU level.

As a consequence of the introduction of pests in the course of globalization and their migration as a result of climate change, it is necessary to rethink the increasingly restrictive political and administrative framework for the use of plant protection products in forests. This is especially true when the entire forest stands and their natural regeneration capacity are threatened by pests. The rapid spread of pests into new areas by definition prevents forest trees from adapting to them as host plants there. In forest trees, reproduction times are so long that they are barely able to adapt to the pests that reproduce at a much faster rate. Against this backdrop, political preconditions must be put in place for the provision, new development, and further development, approval, and use of plant protection products for forest applications. They must be backed by the promotion of research and development projects. It is also important that aspects of environmental compatibility, economy and forest conservation be adequately taken into account when authorizing their approval and use.

3. Offer effective protection against browsing damage during regeneration: In many places, the steady increase in cloven-hoofed game populations in recent decades has been the main obstacle to the growth of species-rich natural regeneration. The societal and political debate on this issue has not yet brought about any substantial change in the situation. Consequently, the construction of fences to protect crops and natural regeneration areas in private and corporate forests should be encouraged whenever necessary. In addition, economic incentives should be created for the successful establishment of species-rich regeneration without fencing. General bans on fence construction in state forests should be lifted. In addition, hunting laws need to be amended to enable forest owners to adjust the game populations in their forests in such a manner that regeneration of all tree species is possible even without browsing protection measures.

4.3 Further develop risk management to deal with extreme events

In the course of modifications induced by climate change, high-amplitude extreme events occur more frequently. Systematic risk management is required to counter the resulting disturbances. The basis of any risk management is the definition of subjects of protection (people, ecosystem services, forest assets, and infrastructure). Risk management itself encompasses (1) the analysis (probability of occurrence and magnitude) and assessment of risks (economic, societal, and environmental consequences), (2) the development of prevention strategies (for instance increasing ecosystem resilience, and mitigation measures), (3) precautions and readiness (for instance early warning systems, response infrastructure, mobilization and coordination plans, competent personnel) (4), the initial response (control) and (5) management of the disturbance in the event of damage. Our recommendations aim both to bring about modifications in these various components of risk management and to improve operational risk management overall (6). For the monitoring aspects that are closely linked to risk management, we refer to the recommendations in Chapter 4.9. Specifically, the following measures are recommended:

1. Analyse and assess risks: To support prevention and preparedness, what is needed are robust analyses of forest vulnerability and models for the probability of occurrence as well as the potential spread of various disturbances such as fire, bark beetles, or storm as a function of climatic factors, soils, stocking and landscape context, including topography. These models could be (further) developed and regularly updated, particularly by the forest experimental stations by way of close coordination and cooperation. Their results, for instance, risk maps and simulations, could be made available to all forest owners.

A more precise definition of risk analysis and, depending on the situation, the necessary monitoring instruments should be undertaken on a stand-by-stand basis in forest management planning.

2. Expand and further develop preventive measures: Already now instruments are available to implement and promote preventive measures in forest enterprises (GAK) to reduce the risk of disturbances in forests. They encompass, for instance, establishing and maintaining vegetation-free firebreaks or hardwood strips for forest fire protection, hardwood underplanting and advance planting in coniferous stands, and the creation of mixed stands, etc. (see also the recommendations on resilient and adaptive forests in 4.1). However, there are many enterprises, especially smaller ones, which have neither the insight nor the capacity to implement such preventive measures.

To ward off large-scale disturbances, such as those caused by fire or bark beetles, there is also a need to develop and implement inter-enterprise preventive measures. This includes the planning of forest firebreaks and control lines at the landscape level, the clearance of munition remnants in polluted forests (which both increase the risk of forest fires and make control more difficult), and the maintenance of technical infrastructure. Prevention also means ensuring that forest roads built and maintained for forest management are designed to withstand extreme weather events.

3. Take precautions to deal with natural disasters: When damage occurs, it is necessary to locate and quantify the scale as quickly and accurately as possible using remote sensing (drones, aircraft, and satellite-based methods) and mobile apps to document the damage. This is the prerequisite for initiating operational countermeasures or administrative measures to help forest owners process and repair the damage and rebuild the forests (see recommendations on monitoring, Chapter 4.9, and forest protection, Chapter 4.2).

To respond adequately to large-scale disturbances, there is a need for sufficiently well-trained staff, the creation and maintenance of inter-enterprise infrastructure to combat damage (in the case of a forest fire for instance fire ponds, water taps, etc.), and to deal with damage (for instance wet timber preservation yards in the case of storm damage). Since risk prevention is generally very cost-intensive and can only be implemented within the framework of sustainable forest management, it is recommended that the corresponding measures in the predominantly small-structured private and corporate forests be afforded appropriate financial backing, similar to that currently envisaged in the GAK framework plan (2019-2022) (see also point 6). Inter-enterprise damage control infrastructure should be established and maintained by the competent federal states authorities as part of their statutory tasks. Precautionary measures also include developing and continuously updating operational plans and building communications networks, including full network coverage in forests. The local forest enterprises should be involved in drawing up regional contingency plans. Support for forest protection infrastructure should be provided permanently, and its suitability in an emergency should be verified through regular exercises.

The building up of adequate financial reserves is an important instrument of risk prevention in enterprises. Therefore, the legal basis should be amended in such a way that private forest enterprises can form a tax-free reserve as their provision. The taxable drawdown of this reserve should be left to forest enterprises in general. In public forests, the articles of association and establishment laws should be adjusted accordingly for risk prevention.

The transfer of rare hazards, which pose a threat to the enterprise’s existence, to insurance companies should also be promoted as a risk prevention instrument for enterprises. This would be particularly helpful when it comes to covering a high demand for liquidity after a damaging event, for example, for reforestation. Pro rata support for forest damage insurance could significantly increase the willingness of forest owners to take out a premium. Support for insurance solutions could be justified by the public interest in rapid reforestation and the associated maintenance or fastest possible restoration of forest services. The promotion of an insurance solution by the public authorities appears to be a much less complicated administrative option than the staging of policy negotiations and implementation on a case-by-case basis after each calamity.

4. Improve intervention and initiation of emergency measures: Certain types of disturbance can engender further disturbances. For example, windthrow in coniferous stands can lead to bark beetle outbreaks or an increased risk of forest fires. Therefore, particularly rapid responses are needed here.

The targeted deployment of emergency measures is dependent on the accurate and timely localization and quantification of disturbances and damage, and the efficient coordination of emergency responders. This can only be ensured by comprehensive, cross-ownership monitoring; see recommendations on "Early detection of disturbances and timely provision of information" in Chapter 4.9. For the development and maintenance of the necessary monitoring systems, the forest experimental stations of the federal states must be equipped with the appropriate staff and infrastructure. Their monitoring systems must be coordinated with each other to ensure that the information can be easily aggregated at the supra-regional and federal levels.

5. Optimize aftercare and restoration: Wherever infested or dead trees pose a threat to human life or neighboring forests, they should be removed immediately. In this case, the processing of the wood should be highly mechanized to protect the people working in the forests as far as possible. If the measures appear necessary but no break even can be achieved, funding should be provided (as was already the case after the damage in 2018-2020). Where there is no need to remove these trees and no restrictions on future management are to be expected, the damaged wood can be left on site in full or in part as standing and lying deadwood to avoid conditions similar to open spaces, to protect the soil and to encourage biodiversity and natural regeneration processes. The targeted conservation of these deadwood structures could be done as part of the concepts for forest nature conservation. In the case of private or corporate forests, they could be remunerated, for example, through contract-based nature conservation measures.

Disturbed areas, where necessary, also provide opportunities for accelerated forest conversion with climate-adapted, light-loving tree species that benefit from good growing conditions in open areas. Reforestation is already being funded through the Joint Task for the Improvement of Agricultural Structures and Coastal Protection (*GAK*). To be able to make use of these irregular situations that arise after disturbances, appropriate capacities for the cultivation of the desired tree species and provenances must be built up and kept available. This will ensure that adequate numbers of the required tree species with sufficient genetic diversity can be sourced from the envisaged areas of provenance at short notice; see recommendations for the development of resilient forests (Chapter 4.1).

6. Promote operational risk management: Careful, comprehensive planning, with due consideration of the components listed above, is a necessary yet costly foundation of risk management. The WBW, therefore, recommends supporting the preparation of operational risk management plans for private and corporate forests within the framework of the Joint Task for the Improvement of Agricultural Structures and Coastal Protection (*GAK*). As part of this support, minimum risk management standards should be drawn up, and consideration of inter-enterprise aspects should be a requirement.

4.4 Secure and increase biodiversity

When adapting forests to climate change, the goal must be the comprehensive conservation of biodiversity from the genetic through to the ecosystem level. To this end, (1) the diversity of biotopes, habitats, and ecosystems must be preserved and promoted over the entire area, outside protected areas as well. This includes (2) the restoration of structurally poor and less adaptive forests along the lines of "prestoration" (restoration aimed at ensuring the future functionality of ecosystems under climate change conditions through appropriate tree species (combinations) and structures. To allow for climate change-induced shifts in species and communities in landscapes, (3) ecosystem permeability and connectivity should be ensured. For species whose distribution ranges and populations are being depleted as a result of climate change and who are unable to colonize new suitable habitats naturally, (4) targeted introduction should be encouraged. (5) The effects of climate change on conservation goals and protected habitats and species must also be taken into account in forest nature conservation. Aspects of biodiversity conservation associated with tree species selection have already been discussed in Chapter 4.1. To be able to monitor the effects of climate change and adaptation measures on biodiversity, approaches for representative biodiversity monitoring must also be developed (see Chapter 4.9). The recommendations in this area are largely based on the expert opinion "Approaches to efficient forest nature conservation in Germany" of the WBW and the Scientific Advisory Council on Biodiversity and Genetic Resources (*WBBGR*) published in 2020. More specifically, the following measures are recommended:

1. Preserve, expand and develop valuable forest biotopes, habitats, and ecosystems: Measures to adapt forests to climate change can be both passive (for instance protection of natural processes) and active (for instance habitat management) in nature. In general, it is important to develop, expand and secure as many forest biotopes, habitats and ecosystems as possible that are of value for nature conservation in such a way that they possess a high degree of survivability in climate change. To this end, strategies for forest nature in forests must be further developed and coordinated with climate change adaptation strategies (see Chapter 4.1). Especially in public forests, it makes sense to involve stakeholders in these strategy and planning processes.

2. Develop goals and scenarios for forest ecosystem restoration: To facilitate the future-oriented restoration of forest ecosystems, the goals and models for future forests must first be developed based on an understanding of the interrelations among forest structure, habitat availability, ecosystem functions, and ecosystem services. This understanding, which was inadequate up to now, must be further developed through research and monitoring. Restoration should begin first in high-risk stands and forests already damaged by climate change (see Chapters 4.1 and 4.3).

3. Ensure permeability and connectivity of forest ecosystems: Forest ecosystems must possess both permeability and connectivity to enable climate change-

induced shifts in species and communities and genetic exchange between populations across the landscape. In the future, when designating priority nature conservation areas, including those outside forests, greater attention should be paid to their connectivity and also to their contribution to connectivity, for instance, hedges, hedge banks, tree-lined avenues, parks, etc.

4. Introduce and translocate species expediently: To support biodiversity, the expedient introduction and translocation of species can be encouraged. This applies to species with low mobility and those that can make an important contribution to the structure and habitat creation and the functionality and performance of ecosystems.

5. Use protected areas to study passive forest adaptation: Protected areas, where the protection of natural processes is the primary conservation goal, will be valuable laboratories for the study of passive forest adaptation to climate change. In protected areas in which the maintenance of specific habitats and species is the primary conservation goal, climate change may threaten or compromise the achievement of these goals. In protected areas as specified in the Fauna-Flora-Habitat (FFH) Directive, whose designation was primarily oriented towards natural plant communities under steady site conditions, an account will also have to be taken of degradations in habitat structures, in the habitat-typical species inventory and other climate change-related modifications in the future. Approaches need to be developed here to clearly distinguish between management-related and climate change-related degradations, and to adjust reference systems such as habitat-typical species inventories.

4.5 Protect soil and water

The conservation of forest areas means protecting the soil, water, and nutrient cycles. At the same time, soil protection promotes forest vitality and resilience. Carbon storage in forest soils makes a decisive contribution to the climate mitigation effect of forests. Forest soils and their water storage capacity are crucial when it comes to compensating for prolonged periods of drought and avoiding the associated drought stress or damage to forests. The loose storage and intensive rooting of topsoils are the precondition to their functioning as water stores. Both this water storage capacity and access by trees to groundwater must be preserved and promoted in the face of the growing number of dry spells. At the same time, forests mitigate negative impacts on soils and their microbial communities, a function that is crucial for forest nutrition.

To this end, (1) site-specific decision-making bases are to be provided, (2) the negative effects of forestry activities on carbon, nutrient, and water balances are to be averted, (3) soil compaction is to be avoided and (4) contamination is to be prevented, (5) drainage is to be reduced where possible and (6) groundwater extraction under forests is to be limited.

More specifically, the following measures are recommended:

1. Provide site-specific decision-making bases: Forest site mapping is an important foundation for management decisions, from tree species selection to soil protection. Site-specific recommendations and guidelines are essential for tree species selection and for assessing climate risks to soil and water. Consequently, forest site mapping should be further enhanced by incorporating new research approaches. Approaches that take into account the dynamics of site characteristics are particularly important. Funds must be made available for site mapping to close mapping gaps, and to update and further develop old maps, especially for private and municipal forests and in a digitalized form. For adaptation to drought, raising the level of knowledge about the spatial distribution of the water storage capacity of forest soils is of great importance (including skeletal content, soil depth, wetting inhibition, and interflow in sloping sites). Many of the measures listed below must be implemented in a manner appropriate to the specific site. This is only possible based on this site-specific information.

2. Avoid the negative effects of forestry measures on the carbon, nutrient, and water balance: Tree species selection must take into account the long-term impact on soils and groundwater recharge (nutrient availability, pore volume, humus content). For this purpose, existing

knowledge should be used in forestry planning and extended where necessary. To minimize the possible risks of tree species with unknown influences on soils and water (for instance influence on the N balance, proton balance, humus balance, wetting inhibition, and soil microbial community), their proportion in mixed stands should be limited, and only gradually increased in line with the knowledge gained.

From the perspective of soil and groundwater protection, we recommend promoting forests with a rich structure. Their ecosystem compartments, such as deadwood, distinct herbaceous layer, stand gaps, or humus layer, promote carbon storage, groundwater recharge, or water retention in the stand.

Soil risks (negative nutrient balance, soil compaction or erosion, humus depletion) and negative influences on the water balance (wetting inhibition of forest soils in the event of dehydration, increase in surface runoff, reduction in infiltration capacity and storage of water available to plants), should also always be taken into account in forestry planning (silviculture, timber harvesting, road construction, etc.).

After natural or direct anthropogenic disturbances (windthrow, drought damage, mass propagation of harmful organisms, fire), the humus layer should be disturbed as little as possible and the vegetation cover quickly restored to prevent soil erosion and surface runoff of water. If there are conflicting decisions, priority should be given to protecting the soil and water balance (for instance by planting nurse crops), otherwise irreversible damage to forests and water bodies may occur.

To reduce the export of organic matter, no full-tree harvesting should be undertaken. The wood below the compact wood limit should be left in the forest provided this does not conflict with aspects of forest protection. Leaving bark in the forest can be encouraged by using harvester heads with debarking capacities, for instance through the BMEL "Forest Investment Programme". Appropriate retrofitting measures for harvesters should be promoted. In the medium term, this should be made standard practice wherever possible and appropriate. These measures also promote nutrient sustainability and reduction of forest protection risk.

3. Avoid soil compaction: Promote the technical advancement of off-ground methods of timber harvesting (for instance cable crane systems). In conjunction with low-impact, mechanized timber harvesting that protects the soil, support should be given to enterprises, for instance through incentive systems (for example premiums) for forest owners and forest entrepreneurs. Significant contributions to soil protection can be made not only through appropriate technical equipment, but above all through the improved organization of the use of forestry technology. The development of soil-weather models with local references could be helpful here.

By digitalizing extraction lines and creating information platforms, existing forest access could be used permanently and expediently, even in the aftermath of areal disturbances such as windthrow. This would mean that no new access ways would have to be created. The drawing up of digital maps for the future use of harvesting machinery and skidders and likewise the use of Global Positioning Systems (GPS) should therefore be promoted in private and corporate forests.

4. Prevent contamination: The chemical status of soils is critical for resilience in climate change. Therefore, protection from material contamination is also essential for the climate adaptation of forests. In this context, it is important to reduce nitrogen inputs and avoid the pollution of forest ecosystems by organic pollutants. Nitrogen inputs from adjacent, primarily agricultural systems must be further reduced. For this, the corresponding regulations must be in place in agriculture.

The discharge of organic loads (phenols, insecticides to protect wood piles from bark beetles) must be borne in mind when constructing wood storage areas to avoid damage to soils and groundwater. For machine interventions, the use of biodegradable operating materials should become the standard.

5. Reduce drainage where possible and maintain and improve the water storage function: Greater consideration should be given in stands to the impact of drainage on the water balance of sites, water catchment areas, and feed into receiving water bodies. Where this measure does not reduce forest stability or threaten partial habitats of endangered species (for example amphibians), drainage ditches in the stand should be removed. Enterprises should also consider water storage conservation in their planning.

In the course of forest development, efforts should be made to maintain or increase water retention capacity, i.e. water from drainage ditches constructed to protect infrastructure should be returned to the forest or used to feed small water bodies, ponds, and fire ponds. For these measures, some thought should also be given to optimizing the ecological potential of this kind of infrastructure (for example short-lived micro-water bodies as spawning grounds).

Financial incentives are needed to protect and restore forest peatlands to increase the carbon content of the soils or to preserve peatlands as an ecosystem and water store (in coordination with other ecosystem services).

6. Restrict groundwater extraction under forests: The harmful intensification of groundwater extraction under forests should be avoided. Under no circumstances should this lead to such extensive, area-wide lowering of the groundwater level that the capillary connection of the tree roots of affected stands to the groundwater is interrupted. It is particularly important to bear this in mind when the drought risk of forests is high. In this case, groundwater extraction may have to be adapted to climatic conditions and then reduced. Since groundwater extraction by agriculture, industry, and private consumption increases especially during dry, hot spells, cross-sector regulations are needed here.

4.6 Promote sustainable timber use

Changes in productivity, tree species composition, categories, and the proportion of incidental uses necessitate adjustments in the downstream wood-based industry and timber use. To establish and expand the sustainable use of wood, value chains should be established on time that optimizes the economic and climate-effective use of domestic unprocessed wood and thus significantly supports the transformation to a bioeconomy. Accompanying incentive systems should focus more on the material than on direct energy recovery. Timber construction in particular is a key, directly available technology for carbon storage (1). Its share in building structures nationwide can be significantly increased by 2050 through the immediate construction of as many timber buildings as possible for multi-storey residential, commercial, office, and industrial use.

To supply the required quantities and qualities of wood from domestic forestry, (2) responsive and receptive markets as well as appropriate logistics and storage structures must be created, especially for maintaining the value of logs from disturbance events and, if necessary, semi-finished wood products. (3) Technical procedures for the more flexible processing of different timber categories that were difficult to market up to now (calamity timber, large-dimensioned coniferous wood, hardwood) are to be introduced. (4) A sufficient proportion of climate-adapted coniferous species is required to maintain the proportion of coniferous wood needed by industry. (5) Efforts to establish the prerequisites for the future generation of new sources of mechanical pulp from recovered and waste wood must move ahead to be able to partially replace declining coniferous softwood categories and (6) to tap into the existing opportunities for bioeconomic timber use. This also includes addressing conflicting goals between timber use and nature conservation in communications (see Chapter 4.11). More specifically, the following measures are recommended:

1. Continue the support for constructive timber construction, hammer out the details, and improve incentives: Increasing the timber construction quota by immediately erecting as many timber buildings as possible for multi-story residential, commercial, office, and industrial use by 2050 is a proactive climate mitigation service that involves material substitution and increased carbon storage in long-lived products. Here, in terms of resource efficiency, the goal should be to create as much living or usable space as possible from the volume of timber used. A limitation of greenhouse gas emissions for buildings, demonstrated by standard-compliant documentation of the CO_2 balance, should be combined with funding on this basis (for example the Building Energy Act [*GEG*] with due consideration of material-related CO_2 emissions over the life cycle).

Increasing carbon storage in buildings should be remunerated using incentive schemes, for instance, an additional eligibility criterion for support for carbon storage in buildings from the Finance Corporation for Reconstruction (*KfW*).

2. Create responsive and receptive markets, logistics, and storage structures, and maintain storage capacity to accommodate fluctuations in the timber market: As a basis, forecast models of resource availabilities and raw material potentials (quantity- and time-resolved material flows from primary and secondary production) are to be provided by the specialist units of the federal state governments. Wood supply scenarios with disturbance influences are to be supplemented by research. This could mitigate the strong price reactions after the calamity years.

In addition to increasing wet storage capacity for recently felled timber (see Chapter 4.3), similar support instruments should be established for setting up storage capacities for semi-finished products such as lumber in enterprises in the usage chain.

Transportation logistics should brace themselves for an increase in unplanned uses as a result of disturbances, for instance by promoting the maintenance or reestablishment of loading stations for the rail transport of calamity timber. "Cabotage," i.e. transportation services within a country provided by foreign carriers, should be possible. EU legal requirements must be complied with to avoid price and wage dumping.

3. Develop and introduce technical processes for more flexible material processing of different wood categories: Efforts should be made to widen the product categories of hardwood, too. Support centers should, therefore, be set up as public-private partnerships and investment incentives should be further developed for the switching over of production from coniferous to hardwood technologies in the wood-processing industry.

In the short term, technologies and processes must be established for the material processing of the existing stocks of large-dimensioned timber in timber construction products. To this end, the private sector should set up regional infrastructures and technologies for the combinable use of coniferous and hardwood logs in construction products. In addition, pilot and demonstration plants for regional wood product plants, including the necessary infrastructure and logistics, should be established using public incentive schemes. Active cross-cluster innovation management for the use of the digested wood components (cellulose, lignin) of native wood species in previously non-wood technology sectors (chemistry, pharmaceuticals, energy storage, electronics) should be practiced through federal states specific economic development. Promote a start-up culture in the wood-based industry by establishing a venture capital fund to finance it.

4. Lay the foundations for the future supply of the required wood categories: Forest conversion strategies to promote resilient and adaptive mixed stands should consider the low-risk cultivation of climate-adapted conifer species.Research the properties and uses of alternative tree species.

5. Generate new wood pulp sources from waste wood: For the comprehensive material use of recovered and waste wood in the timber-based material industry, private sector incentives are needed for efficient renaturation, processing, cleaning, and sorting processes with pollutant removal. To ensure the necessary supply of sufficient quantities, the provisions of the Ordinance on the Management of Waste Wood (AltHolzV) must be adapted.

The recycling-friendly development and use of wood products and wood structures are to be extended through adapted product and connection design along the lines of "Design for Reuse/Recycling".

6. Identify potentials and challenges of the wood-based bioeconomy in dialogue with different stakeholder groups: Development of scientifically sound information material on the potentials and challenges of the wood-based bioeconomy with the involvement of broad interest groups (especially nature conservation, public administrations, planners, and decision-makers). This can be accomplished using the example of timber used in construction (best practices) and existing ecological "safeguards".

4.7 Develop forests as places for recreation, sports, and tourism

In order for forests to be locations that are well suited for recreational and leisure use, even under the conditions of climate change, the ecosystem changes that are expected or are already being experienced must be addressed in the same way as societal demands and changes. To this end, (1) information on recreational and leisure use should be available nationwide so that it can be systematically integrated into forest management planning, (2) local recreational planning and communication with forest visitors should be based on sociological monitoring and dialogue with user groups, (3) forest owners' services should be remunerated and new responsibility relationships established, and (4) recreational infrastructure should be adapted to changing needs and expected extreme events.

More specifically, the following measures are recommended:

1. Collect information on the cultural ecosystem services provided by forests on a widespread basis to be able to integrate this information into forest management planning: Especially in urban forests and forests used extensively for recreation, sports, health, and tourism, there is a need for systematic recording of recreational and leisure use. In this way, user perspectives can be processed for forest management planning and conflicts of interest can be resolved early on. Thus, in addition to forestry and nature conservation data, information on the societal or cultural dimension of forest use will become the third source of information for forest management and adaptation planning. In this context, it must be clarified how the surveys and coordination processes can be easily integrated into forest management and who will cover the increased costs of involving forest visitors outside state forests.

The collection of data on the use of forests for sport and recreation will also serve as a technical and argumentative basis for the appropriate remuneration of the cultural ecosystem services provided by forests (see point 3). In particular, it will highlight qualitative and quantitative trends of development and facilitate a spatial differentiation in the estimation of the burdens borne by forest owners or their corresponding efforts to provide these services.

2. Base local recreation planning and communication with forest visitors on sociological monitoring and dialogue with users: The proactive management of conflicts between individual recreational and leisure uses, as well as between forest adaptation, management, and recreational uses, requires systematic monitoring to generate data as a basis for communication, decision-making, and evaluation. Sociological monitoring can be used to map patterns of user behavior, describe how they change, and identify recreation conflicts early on (see also Chapter 4.9). This monitoring should not be seen as an additional task of forest enterprises but as a public task. It should be stressed that the recording of utilization claims is not associated with any guarantee of implementation by forest owners or forest enterprises.

The monitoring of activities and expectations will also create the basis for the – ideally digitally supported – steering of visitor behavior. It will likewise identify target groups and content for communication between forest enterprises and visitors.

Given the strong identification of people with forests close to their homes and the increased demand overall for a right to have their say, dialogue processes between those responsible for the forest on the ground and other forest users must be strengthened in public forests. In this way, classic technical expertise can be expanded to include the users' local experiential knowledge. The different ownership structures in forests should also be touched on to prevent the carry-over of the demands made on public owners of forests to private forests. Dialogue processes can also address how to deal with uncertainty and change (for example concerning harmful and pathogenic agents), and how to manage use conflicts.

3. Remunerate the services provided by forest owners and establish new responsibility contexts: The considerable additional expenses and reduced proceeds for owners resulting from the recreational use of forests should be tax-funded to compensate for the more complex management caused by climate change and an increased operating risk coupled with growing demand. New remuneration models could be refined technically and justified on policy grounds. They could be based on the proposals of the federal platform "Forest – Sport, Recreation, Health" (*WaSEG*) and the model for the regionalization of economic values of forest services (*ReWaLe*) developed by the Thünen Institute.

The mapping of current recreational and leisure uses and sociological monitoring systems can generate databases for a regionally differentiated area-based premium related to the intensity of use.

Like *WaSEG*, the WBW also opposes the funding of everyday recreation in forests solely by users ("forest toll") and rather advocates the two-tiered funding of recreation-related costs. The first stage includes flat-rate cost compensation that indemnifies forest owners for general forest access rights depending on the respective local visitor frequency. This premium could be integrated into the structures of the Joint Task for the Improvement of Agricultural Structures and Coastal Protection (*GAK*). The second stage will serve to create specific incentives for voluntary additional services to improve the recreational impact of forests. They would then have to be remunerated primarily by the specific users or their communities of interest (for example, through membership fees of associations, crowdfunding, and sponsoring) on a contractual basis.

4. Adapt recreational infrastructure to changing needs and the expected extreme events: The right of access derived from forest and nature conservation laws should be harmonized across the federal states to make it easier for forest visitors to familiarise themselves with the laws and to increase the chance that they will behave accordingly (WaSEG 2019). This goal is served by

generally comprehensible, well-founded, and similar regulations for all federal states. In cases of doubt, they should also be backed by sanctions in the interest of property, nature conservation, and species protection.

Urban green spaces and forests close to towns should be more closely interlinked through regional recreation planning. In this context, it is important to overcome disciplinary and administrative boundaries, for example between green spaces departments or parks departments and forestry administrations.

Traditionally, aesthetics have been seen as an important benchmark in the design and management of forests and green spaces close to towns. Forests, particularly those that prioritize recreation over other uses, can cater to the well-known preferences of visitors, for example by offering moderate structural diversity, loose canopy closure, curved forest edges, open spaces, and mature trees.

Recreational infrastructure is essentially based on the existing forest path network that should include barrier-free options in each region. Infrastructure planning and maintenance must factor in more frequent extreme weather events and be designed to avoid increased water runoff from forests.

4.8 Remunerate ecosystem services

The WBW thinks that the biggest problem facing forest policy is that forests will no longer be able to provide important ecosystem services such as climate change mitigation, water protection, nature conservation, and recreation to the extent desired by society in the future unless there is increased investment in forest adaptation. It will mean a loss of revenue or additional costs for forest owners. However, the income of forest enterprises is based almost exclusively on revenue from timber sales. The services relating to climate change mitigation, water protection, nature conservation, recreation, etc., which are also important for society, are scarcely remunerated at all.
Against this backdrop, the consequence could be social mismanagement (market failure) due to a lack of funding and incentives. This problem is significantly exacerbated by the current crisis with long periods of drought and widespread, massive forest damage, developments that are to be expected in the long term as a consequence of climate change. There is, therefore, an urgent need for the public sector to give its backing to financing and business models that provide forest enterprises with long-term plannable revenues in return for the provision of ecosystem services. More specifically, the following measures are recommended:

1. Clarify responsibilities for remunerating societal services and develop implementable mechanisms: The remuneration of services that have a supra-regional impact and for which the federal government also has a performance obligation vis-à-vis others (as a rule, the international community of states) should be regulated on a uniform federal basis. This primarily includes services to protect the global climate through CO_2 sequestration in forests, wood products, and by substitution, as well as services to protect biodiversity or nature conservation.

However, there are also ecosystem services for which there is regional demand, for instance, the recreational services provided by forests. In their case, predominantly local remuneration mechanisms are to be put in place. The responsibilities will be positioned accordingly at the district, or municipal level.
More particularly, for the remuneration of services with a supra-regional impact, remote sensing-based monitoring systems need to be developed in addition to existing national inventory systems such as the National Forest Inventory or the National Forest Soil Inventory. They will facilitate the elaboration of robust indicators for the respective criteria such as climate mitigation performance, adaptability, or the presence of certain forest structures for nature conservation, and will do away with the need for costly terrestrial surveys (cf. Chapter 4.9). The necessary technical infrastructure and processing capacities are to be specifically supported by the federal government and, if available, used for performance assessments.

2. Remunerate climate mitigation performance and forest adaptation: CO_2 pricing is an important climate policy instrument. To achieve the desired internalization of the negative external effects, the CO_2 price for all activities must be increased until it mirrors the societal costs. The CO_2 price makes substitute products such as steel, concrete, aluminum, coal, or petroleum more expensive than wood, a raw material associated with lower CO_2

emissions. This creates overall incentives for sustainable forest management and timber use. Consequently, the WBW welcomes the introduction and planned adjustment of a CO_2 price. The federal government has now introduced this CO_2 pricing in the Act on National Certificate Trading for Fuel Emissions (BEHG) to supplement the European Emission Trading System.

Since both forests and their climate mitigation function are threatened by climate change, some of the federal government's revenues from the CO_2 levy should be used to adapt forests to climate change thereby safeguarding the climate mitigation performance of forests and sustainable timber use. With this in mind, the federal government introduced the "forest sustainability premium" in 2020/21 with funding to the tune of EUR 500 million. As part of the economic stimulus package for the conservation and sustainable management of forests, it must be further developed and attributed to permanent status.

Currently, a lively discussion is ongoing in the political arena of alternative concepts for remunerating ecosystem services. The development and implementation of such a concept, which would place forestry in Germany on a new financial footing, is dependent on clear policy targets and financing concepts that are viable in the long term, too. Furthermore, a concept of this kind must be easy to implement and not encumbered with excessive transaction costs. The intention with a concept of this kind is not to replace the specific GAK support measures but to supplement them in a meaningful way.

The WBW believes one fundamental way of doing this is to reward the adaptability or adaptedness of forests to climate change. This will then serve as the basis for the future provision of all ecosystem services. Here, the rationale is to use public funds to maintain and safeguard the public good of climate change mitigation. To clearly distinguish this type of remuneration from support under the Joint Task for the Improvement of Agricultural Structure and Coastal Protection (GAK), it is not the individual measures that increase adaptive capacity (for example, forest conversion) that would be remunerated, but the result or condition. Forest enterprises would thus receive ongoing remuneration for the part of their forests that can be deemed sufficiently resilient and adaptable based on the latest findings available. For this kind of system, some degree of differentiated remuneration based on the degree of adaptedness or adaptability would be possible. For example, this could take the form of a tiered system for forests that, based on current knowledge, can be deemed to be largely resilient and adaptive, those that are moving in this direction through forest conversion measures, and those that are currently classified as at-risk forest cover. To provide an incentive for a low-threshold entry into forest adaptation, some remuneration could also be paid for those stands for which there is already a binding adaptation plan, for instance in the context of forest management. Valid, standardized indicators for the quantification of the criteria resilience and adaptability would have to be developed on a sound scientific basis by a broadly-based working group (representatives of science, forestry practice from the federal government and federal states, and certification bodies), and suggested to the BMEL as the representative of the federal government.
Forest areas that have been stocked with tree species or provenances for which, by their very nature, no reliable experience is yet available on their suitability under climate change, should also be included in this remuneration instrument. One option would be to classify them in a similar way to forest stands already in the process of conversion.

As long as the use of timber for energy generation does not lead to a reduction in the average biomass stocks of forests and only releases the CO_2 captured from the atmosphere, the combustion of timber from sustainable forestry should continue to be exempt from CO_2 levies (as is currently specified in the Fuel Emissions Trading Act, BEHG). Compared to the direct combustion of wood, however, a higher climate mitigation performance is achieved through cascade use with energy recovery at the end. Incentives should, therefore, be developed to use wood as far as possible and reasonably for material recycling first, before it is combusted (see Chapter 4.6).

3. Develop and use instruments for remunerating nature conservation services in forests: The climate adaptation of our forests can also be effectively promoted by remunerating nature conservation services. First, it can be assumed that forests with higher biodiversity will also be more resilient to climate change. Second, remuneration for nature conservation services (for example rewetting) in forests would also help forest enterprises to finance the necessary measures for the climate adaptation of their forests.

Furthermore, nature conservation is another ecosystem service provided by forests that is important for society. In a joint expert opinion "Approaches to efficient forest nature conservation in Germany", the two Scientific Advisory Councils on Forest Policy, Biodiversity and Genetic Resources, submitted proposals to the BMEL detailing what an instrument for remunerating forest nature conservation should entail (see WBW and WBGR 2020).

Based on this and other available proposals, policymakers should develop and implement concrete instruments for the long-term financing of conservation services in forests. Given the major importance of nature conservation, the large area-based impact of the EU Fauna-Flora-Habitats (FFH) Directive on forest enterprises and the level of their economic burdens, the remuneration of nature conservation services in forests should also include, more particularly, the eligible areas and habitat types specified in the EU FFH Directive. For this purpose, FFH monitoring must be further developed in such a way that its results can be used as a basis for remuneration. As already mentioned in Chapter 4.4, it is important to distinguish between modifications in conservation status caused by climate change and those caused by management changes.

4.9 Optimise monitoring

Forest monitoring constitutes an essential basis for the perception and assessment of risks and their impact, forest developments, ecosystem services, and the verification of the effectiveness of forestry measures. It, therefore, occupies a key position in the strategies for adaptation to climate change. Any need for action on, among other things, the development of silvicultural strategies, support measures, research topics, and legislative amendments stems from such observations. In many instances, present-day forest monitoring no longer meets the current and future requirements for spatial and temporal resolution.

By building on the current level of environmental forest monitoring in Germany and the large number of indicators recorded, the informative value of forest monitoring is to be enhanced and further developed into a transparent instrument for risk analysis. To this end, measures are proposed that facilitate area-based statements, ensure the connectivity of as many elements of forest monitoring as possible, accelerate the provision of information, and widen the species spectrum of target organisms. More specifically, the following measures are recommended:

1. Provide up-to-date, nationwide risk assessments for storms, forest fires, insect mass outbreaks, and drought stress: To improve both existing monitoring concepts and preventive measures nationwide, regularly updated risk assessments for storms, forest fires, insect mass outbreaks and drought stress should be conducted, for instance by the forest experimental stations. This assessment (risk maps) could then be used to prioritize and, if necessary, redirect monitoring points, plots, and measures. These up-to-date risk assessments could serve as the basis for adapted preventive measures, for instance adapted vegetation management along critical infrastructures such as roads, railroads, or energy lines.

2. Review the effectiveness of silvicultural adaptation and preventive measures and their impact on ecosystem services: Current forest monitoring does not include observation of the impact of silvicultural activities, for instance, on the intensity of use (frequency and intensity of interventions) or tending and protective measures (such as cleaning of stands or fencing). Information on this is provided by forestry experimentation and natural forest research (see Chapter 4.14). At the ecosystem level, the development dynamics of the managed forests and the ecosystem services provided should be observed, in addition to appropriate experiments, in the long term too in line with the methodological monitoring principles, for example, under the aegis of the forest experimental stations. The forest development types for managed forests and the network of unmanaged forests are an important foundation for this (natural forest reserves, protected forests). Broadly designed forest monitoring based on a more advanced Forest Enterprise Monitoring Network can also make an important contribution here.

Up to now, the quantification of ecosystem services has been largely ignored in environmental forest monitoring. To remedy this, appropriate concepts must be developed in cooperation between science, the forestry sector, certification bodies, forest owners, and the consumers of ecosystem services (see Chapter 4.13).
The spectrum of tree species recorded to date in forest monitoring should be widened to include potentially more climate-tolerant species. Both monitoring levels (1 and 2) of environmental forest monitoring focus on just a few main tree species. For the indicators, vitality, growth, and fructification, the tree species spectrum that is to be monitored must be widened at the auto-ecological level, especially concerning potentially more climate-tolerant species (for example hornbeam, Douglas fir, red oak, maple species). Representative monitoring concepts must be elaborated for this purpose. Since this can hardly be done by densifying the grids, representative monitoring populations must be selected for this purpose.

3. Link up monitoring data and data provision to increase understanding of complex forest changes at the ecosystem and landscape levels: Given the different sub-objectives, the established monitoring procedures run largely in parallel, with different responsibilities and partly on displaced grids (for example the National Forest Inventory and the Forest Condition Survey). This makes it difficult to link up data and results in a loss of information. To improve understanding of complex forest changes at the ecosystem and landscape levels, the various monitoring results must be placed concerning each other. This necessitates early and ongoing coordination with the development of monitoring initiatives by other departments (agriculture, nature conservation). To this end, the necessary structures must be developed across departments at country and state levels.

4. Extend and apply remote sensing methods to obtain area-based statements: The current supra-regional forest monitoring is mainly based on terrestrial sample-based inventories with a widely-meshed grid to generate statements for large strata (Forest Soil Condition Survey, Forest Condition Survey, National Forest Inventory). The derivation of statements for concrete forest areas based on point data comes with a relatively large degree of uncertainty. Terrestrial methods should, therefore, be supplemented by remote sensing methods (for instance free satellite images) with different spatial and temporal resolutions to (1) estimate forest conditions annually nationwide, (2) quantify event-based disturbances such as fire, storm, drought, or insect mass outbreaks promptly and (3) provide additional plot information (for example tree species, biomass, structural diversity) for the purpose, for instance, of quantifying the degree of adaptation. To this end, the competencies and infrastructure in the field of remote sensing and statistics must be further enhanced and bundled within the responsible institutions (for instance forest experimental stations, Thünen Institute, forest planning offices, and national parks).

In addition, monitoring data must be made freely available for the calibration and validation of remote sensing methods to improve the procedures.
Since remote sensing is not a direct measurement method applied to the subject in hand, it always comes with a certain degree of uncertainty. This should always be quantified when presenting results by applying the uncertainty measures commonly used in practice.

5. Build on competencies for the early detection of disturbances, and provide information on time: The timescales from occurrence to comprehensive recognition and assessment of disturbance events (forest fires, storms, insect outbreaks, etc.) need to be shortened further, particularly to rapidly notify decision-makers. The forest experimental stations of the federal states play a key role in the carry-over of new procedures and research methods into a routine application. They must be equipped with the human and technical resources required to carry out this task.

This involves, among other things, the upscaling of forest fire monitoring to include the early detection of forest fires. This is the key to reducing the scale of damage with the aid of modern terrestrial and satellite-based remote sensing.
A uniform nationwide forest protection monitoring and reporting system are to be put in place, specifically for harmful organisms that have an economic impact. This system (1) will compare species-specific threshold values such as local population densities at monitoring points, and (2) will quantify the scale of damage (for example leaf loss, mortality on the whole area) caused by biotic pests using, for instance, remote sensing techniques. A federal government – federal state -working group could be the driver of this concertation.

Against the backdrop of global propagation paths, forestry personnel needs to undergo further training which will enable them to detect new harmful organisms, too, at an early stage. In addition, the experimental stations need to be equipped with resources that will enable them to use state-of-the-art methods as well such as the DNA barcoding of insects and pathogens in routine procedures.
Stable communication channels and standardized recording procedures for large-scale disturbance incidents must be developed or extended at the country and state levels.

6. Adapt indicators of existing monitoring procedures to new requirements: By definition, any monitoring will rely on the repeated recording of target variables using identical procedures to ensure time series. However, over time, monitoring objectives may change and new methods may be developed. This throws up the challenge of adapting monitoring procedures to the identification of new risks and, at the same time, of continuing existing, valuable time series. Against this backdrop, the WBW recommends supplementing intensive forest monitoring (ICP Forests Level II) with reaction indicators (for example physiological and genetic markers). This concept was developed as a result of the forest damage in the 1970s-1980s and is based, among other things, on accumulation indicators (for example, nitrogen, sulfur, aluminum). This is the only way of determining cause-effect relationships and developing early warning systems in the context of climate change and the changing abiotic influencing factors (for instance drought, heat, and storms) (see point 5). Costs can be saved on the previous accumulation indicators, for example, by lengthening the recording intervals.

7. Include forest regeneration, biodiversity, and the genetic structure of populations in monitoring: Current forest monitoring mainly focuses on selected indicators of the main stands of the main tree species. Nationwide, there is a lack of information (at shorter time intervals than in the National Forest Inventory) on forest regeneration and species diversity outside protected biotopes. Browsing damage monitoring (or the browsing and bark-peeling damage inventory), carried out up to now in the federal states with different objectives and procedures, is to be refined as forest regeneration monitoring with standardized recording procedures in concertation between the federal government and the federal states.

Point-, specialist- and department-based surveys of the occurrence and population dynamics of plant, animal and fungal species should be developed into landscape-level biodiversity monitoring. This will require nationwide interdepartmental design and coordination (for example at the National Biodiversity Monitoring Centre in Leipzig).

The genetic monitoring of beech and spruce was developed in several projects in Germany. It looks at the impact of climatic variables on the genetic system (pollination, flowering, fructification) and the genetic structure of populations. This program must be continued beyond the project status as a permanent task and extended to include other tree species.

8. Establish social monitoring to map usage patterns and conflicts

Climate change will modify the way people interact with forests. Proactive conflict management is dependent on monitoring to generate data as a basis for communication, decision-making, and evaluation. This also includes social monitoring which maps, for instance, patterns of usage and behavior conflicts in the taking up of various ecosystem services (see Chapter 4.7).

9. Ensure monitoring of the economic situation of forest enterprises: The measures proposed in this report to adapt forests to climate change, including related measures for biodiversity conservation, soil and water protection, conflict resolution, and communication, will mainly be implemented at the forest enterprise level. To do this, the enterprises must have a high level of technical expertise which must be continuously upgraded. In addition, the operational effort required to implement the measures is expected to be considerable. To be able to recognize promptly whether the forest enterprises can sustain this effort – the precondition for the implementation of the measures proposed here – there is an urgent need for monitoring the economic situation of the forest enterprises as well. Against the backdrop of the drastic decline in the number of participants in the BMEL Forest Enterprise Monitoring Network, concepts for further development or viable alternatives for the comprehensive and representative economic monitoring of forest enterprises should be elaborated without delay and also implemented by the federal government and the federal states.

4.10 Adapt institutional structures

Two developments exacerbate the existing problems in forest management, especially in small-parcel private and corporate forests. First, under climate change, revenues from traditional forest management focusing on raw timber production will decline as a consequence of increasing risks and the necessary modifications of tree species. Second, additional costs will arise from adaptation measures in forest conversion, forest maintenance, and forest protection, including traffic safety, which will necessitate more activities and people on the ground. For this reason, there is an urgent need for the creation of institutional structures that are financially secure in the long term, especially in small-scale private and corporate forests. The WBW already pointed this out in June 2018 in its expert opinion "Management advice and financial support in small-scale private and corporate forests". Specifically, the following actions are recommended to improve the institutional environment for non-state forests.

1. Establish long-term stable structures for the stewardship of non-state forests: The indirect support for private and corporate forests has mainly been provided by the state forestry administrations of the federal states as low-cost or free services. It is currently being restructured in the federal states as direct support in compliance with the requirements of antitrust and state aid law. In the long run, this will necessitate the undiminished, non-bureaucratic provision of corresponding public funding (see WBW 2018).

Given the societal importance of forest conservation, forest tending, and timber use for the area-wide provision of ecosystem services, the community stewardship, and management of (small-structured) private and municipal forests must be financially secured in the long term. In this context, the guiding principle of "temporary help for self-help", which has so far determined funding policy regarding "forest self-help institutions" (forest management associations) for non-state forests, should be abandoned. This is also necessary because it will become increasingly difficult for forest owners to "manage everything themselves" in woodland areas anyway. The reasons for this are urbanization, advancing mechanization, and technical specialization, coupled with the rapid erosion of acquired insights and the uncertainties due to climate change.
Forest enterprise associations and other forms of inter-enterprise forestry cooperation, for instance, cooperative forest management, should be supported by publicly financed, long-term forest tending, timber mobilization, or ecosystem service premiums for the establishment and maintenance of personnel and organizational structures. This is an essential prerequisite for the development of adaptable forests in small-scale private woodland.
The establishment and maintenance of information platforms for non-state forest owners is also an important task to be co-financed by the public sector in the long term. For instance, the continuation of the Internet platform "Forests become mobile" (“*Wald wird mobil”*), a non-profit limited liability company founded in 2007 as a public-private partnership for the mobilization of small private forests, is currently at risk following the expiry of project funding. A foundation model could also be considered here perhaps to ensure long-term institutional security.

2. Create organizational and financial incentives for the transfer of forest management: Organisational and financial incentives should be created that enable "inactive" forest owners to transfer forest management to third parties in the longer term, for example, through forest leases or forest tending contracts. Appropriate incentives could include, for example, their exemption from paying contributions to the employer's liability insurance association.

3. Make support for forestry more efficient: Forestry support in Germany should be made more effective and efficient through more consistent regulations, more exchange and coordination between the federal states on best practices (regarding support content and organizational processes), and the simplification and standardization of contents and administrative procedures.

Public funding should focus primarily on the societal benefits of the ecosystem services provided by forests. In this context, timber production through its contribution to climate change mitigation, employment, regional value creation, etc. is a very important factor, too. Other aspects of relevance for public welfare include, for instance, adapting forests to climate change, protecting forests from large-scale disturbances, or protecting biodiversity.
Funds should be provided to cover the respective costs of not only the measures but also the organizational side. In addition, the funding should be made more attractive for forest owners, for example, by lowering their contributions and reducing the repayment risks (for instance, in the event of failure to achieve the regeneration targets through no fault of their own).

The group of beneficiaries of forestry support should also be extended to include, for instance, forest service companies. If it is worth their while for entrepreneurs to take the initiative in forests for conversion, protection (calamity timber), tending, etc., then these activities will be implemented in concertation with the landowners. This could also be helpful, for instance, when it comes to implementing nature conservation measures in forests such as the creation and care of forest edges, flower strips in forests, etc.

4.11 Communicate adaptation strategies, structure conflict management

Forests enjoy a high standing in our society. Changes in and disturbances to forest ecosystems, especially if they affect popular excursion destinations, are therefore sometimes accompanied by strong emotional reactions in the public or the affected user groups. Societal demands on forests have increased. Spending time in forests, which have a climate-balancing effect, will continue to grow in popularity. In line with this increased importance, the need for laypersons interested in forests to have a say in the design and management of forests has also grown in recent years. As is the case in expert circles, the opinions of societal groups regarding the adequate adaptation of forests to climate change differ in the balancing act between passive and active adaptation through management.
To defuse any ensuing conflicts and come up with viable concepts for adapting forests to climate change, there is a need for increased communication on this subject in public and the proactive structuring of conflict resolution processes. This also includes actively conducting a societal debate that incorporates both technical expertise, current research approaches, and usage demands from various societal groups.
The goal of this communication in the public domain that also fosters social cohesion should be (1) to develop new models of forests and forestry adapted to climate change and to formulate key communication messages on them, (2) to anchor communication on the adaptation of forests to climate change in forestry education and training, (3) to promote wide-ranging public relations work and communication, (4) to initiate dialogue processes on forest adaptation, especially at the municipal or regional level, and (5) to facilitate civic engagement in forests.
To this end, the following strategies and measures are recommended:

1. Dynamize models, elaborate key communication messages: Communication by the public authorities responsible for the topic of climate change and forests and by associations actively engaged in this field should be adapted to the dynamics of the socio-ecological processes currently taking place. It should take up the following contents and translate them into communication messages: Climate change encompasses all forest ecosystem services. The public debate on climate change in forests is currently dominated by individual issues, such as the search for tree species that will be suitable in the future or strategies for dealing with increased disturbances. Information and communication must adopt a broader approach and stress that climate change affects all forest ecosystem services and threatens their availability for future generations.

Develop dynamic models for forests and forestry The public's image of forests and forest ecosystems is dominated by images of forests and nature that will not be able to keep pace with climate-induced changes (for example "beech country Germany", the definition of static conservation statuses in protected areas, the dichotomy of native and non-native or natural in the sense of yesterday/uninfluenced and not natural in the sense of influenced by humans, forest management as timber harvesting, etc.). These familiar mindsets should be replaced by dynamic models that also address issues of ignorance and uncertainty in a positive way. The antagonism between the forestry sector and nature conservation that has been fuelled for decades should be revisited as a constructive debate about future forest images and turned into something useful. Backward-looking focuses of the forestry sector on the history of forests and forestry must also be overcome and aligned with the progressive dynamics of natural processes (motto: "Forests develop dynamically - so do we"). At the same time, it is necessary to develop and communicate criteria that guide actions and communication in dynamic processes, too. In this context, a key communication task is to contrast the sometimes negative public perception of forest management with the importance of functioning forest enterprises for forest conservation and climate adaptation, the provision of ecosystem services, and the role of forests and timber in the context of climate change mitigation. This can be done, for example, by showcasing progress in adapting forest enterprises to climate change and by talking about good practices.

Communicate the connectivity and trade-offs of climate adaptation measures Climate adaptation measures for forests are not located solely in the forests themselves. Through changes to the actions taken by the socio-ecological system in which forests are embedded, the main preconditions for the success of climate adaptation can be put in place. Examples include reducing the use of groundwater, preventing the introduction of harmful organisms through the movement of goods, or regulating hoofed game populations to facilitate forest regeneration. These systemic effects and links need to be communicated, as do competitions and trade-offs between other ecosystem services and climate adaptation.

Talk about the emotional significance of forests in communication: forests also furnish important cultural ecosystem services. They provide habitats, spaces for retreats, and meeting places. Communication about forest-related environmental and climate change should, therefore, address the shift in these emotional references due to climate impacts or climate adaptation measures, and show appreciation for the emotional attachment of people to forests.

2. Anchor communication on the adaptation of forests to climate change in forestry education and training: People who work in forests are the first port of call for forest visitors. They should be able to credibly convey the key messages outlined above. To this end, formats such as a series of seminars on improving communication in everyday forestry work have been launched in recent years. They should be further developed and established permanently (see also Chapter 4.12).

3. Promote public relations and communication across the board: The preparation and communication of complex knowledge interrelationships in the context of climate and forests come under the state's educational mandate. These are time-consuming tasks and need dedicated support. The communication activities of not only state forestry institutions, and independent education providers, but also forest and environment research institutes can be supported by promoting such offers in forests and on Internet platforms, in information campaigns, or competitions. This involves, more particularly, working with online offerings and social media to reach younger generations more readily, both in and out of school, while also "leading them into the woods". Alliances with stakeholders from the field of education for sustainable development, "forestfluencers" or climate conservationists can be just as helpful here as establishing media partnerships.

4. Launch dialogue processes on forest adaptation at the municipal or regional level: At the municipal or regional level, forest dialogues can be a suitable medium for addressing the different demands of various interest groups and user groups, for instance, regarding timber harvesting methods and timelines. Furthermore, they can be used to inject life into forest developments and discuss them with interested groups amongst the public at large. These dialogues can also explain the measures that are necessary as a consequence of climate change, such as restricted access to forest areas due to inadequate traffic safety. Here, familiar formats can be used, for instance, the discussion of forest issues at local council meetings, classic participatory components of forest planning, or during excursions with forest rangers. At the same time, forest dialogues can also act as a sounding board for people's emotional relationships with the forests around them and as an opportunity for a more intensive exchange between forestry professionals and laypeople before a potential conflict can even arise.

5. Enable societal engagement in forests: A direct link between the local population and a forest can increase understanding of the changes in forest ecosystems. Suitable formats worthy of support include forest sponsorships, new forms of ownership such as forest cooperatives, and opportunities for the private financing of measures in forests, for instance, under the heading of forest climate projects as part of voluntary carbon markets. The attention of interested groups in the population could be captured through planting campaigns for the reforestation of dead forests or activities in the field of citizen science such as biodiversity monitoring.

4.12 Realign education and lifelong learning

The half-life of our knowledge is steadily decreasing. However, traditional concepts of forest protection and management are deeply entrenched. Practical illustrations work only to a limited extent in the face of rapidly changing climatic and site conditions. Consequently, empirical management that relies on traditional "evidence-based" approaches may not evolve quickly enough to generate effective future management options. Due to the acceleration of climate change and its impact on forest ecosystems, forest management, and processes such as digitalization, this loss of relevance of experiential knowledge is gaining additional momentum. At the same time, the many problems to be solved are becoming increasingly complex. Therefore, the capacity to acquire new knowledge quickly and to solve problems in an interdisciplinary way takes on far more importance compared to factual and experiential knowledge or purely disciplinary approaches to problems. Training courses must, therefore, focus more on developing these skills than they have in the past. New knowledge must also be disseminated and assimilated more quickly and effectively in the institutions that deal with forest management, taking into account the knowledge gained from experience. This will enable the stakeholders to adapt their competencies on an ongoing basis, too. At the same time, the need for lifelong learning in forestry professions is an opportunity to make them more attractive.

To this end, (1) the curricula of forestry courses should be geared even more than before towards research competencies, methodological knowledge, interdisciplinarity, and problem-solving skills, (2) further training and qualification schemes for specialist staff in forest enterprises, relevant specialist authorities (nature conservation, hunting, water, etc.), forest owners and forestry experts should be significantly increased, (3) aspects of digitalization and communication should be integrated more than before into the training of forest managers, (4) dealing with uncertainties and knowledge gaps should be explicitly integrated into education and further training programs and in consultancy services. More specifically, the following measures are recommended:

1. Align the curricula of forestry courses at universities with current competence requirements: In addition to aspects of climate change and adaptation, the content of forestry courses at universities should focus even more on research skills, methodological knowledge, interdisciplinarity, and problem-solving skills. To this end, there has to be an intensive exchange between forestry practice and universities, concerning the requirement profiles for graduates.

2. Extend further training and qualification schemes for forest enterprises, specialized authorities, forest owners, and forestry experts: Capacities and competencies (for instance didactics) in this field have to be extended to offer further training and qualification schemes for specialized personnel in forest enterprises, relevant specialized authorities (nature conservation, hunting, water, etc.), forest owners and forest experts.

The regular participation of staff in further training should be intensified through appropriate motivation and recognition by the institutions concerned. A rapid expansion of these schemes could be achieved through an improved division of labor and connectivity at the supra-regional level, especially through the use of new media. Not every topic needs to be developed in-house by all the institutions. To enable people to take advantage of such schemes, previous barriers such as state limitations on schemes and participation must be removed.

3. Integrate aspects of digitalization and communication more than before in the training and continuing education of specialist staff: Due to the increasing forest damage and the obvious transformation of forests, communication between foresters working in woodland areas and forest visitors and an informed public is becoming increasingly important (see Chapter 4.11). This also requires more training of technical forestry personnel in this area.

As digital and sensor-based technologies are increasingly used in the detection and monitoring of climate change-related hazards and changes, as well as in new work processes, the relevant competencies must be taught in the education and training programs for skilled personnel along the entire value chain.

4. Establish education and training programs and guidance on dealing with uncertainties: One of the major challenges facing forest management in climate change is dealing with uncertainty and a lack of knowledge. This applies to the research, planning, and execution levels. These aspects should, therefore, be given appropriate space, especially in education and continuing education programs. At a time when even experts are confused, many forest owners, especially of small private forests, no longer know what to do. As the adaptation of forests and their management rarely take place in a climate of major uncertainty, the outcome is frequently the cessation of management. Consequently, dealing with uncertainties, particularly when advising forest owners, should also play an important role.

4.13 Strengthen and reorient research capacities and improve connectivity

To structure research on the adaptation of forest ecosystems, the forest sector, the wood-based industry, and other sectors of relevance to climate change effectively and efficiently, a refocusing of research on forest sciences, forest and wood products is recommended not only concerning new research content but also for (1) the strategic development of new research approaches, (2) the creation of long-term infrastructures and capacities, (3) networking and cooperation, including the sharing of infrastructures, and (4) the exchange of data and information and the promotion of synthesis work; see also Isermeyer et al. (2021). The alignment of research content with current problem areas is ongoing anyway and is not, therefore, touched on in these recommendations. The recommendations aim to supplement but not replace existing programs such as the Forest Climate Fund or the funding programs of the Agency for Renewable Resources (*FNR*) or of the federal states. More specifically, the following measures are recommended:

1. Formulate new research approaches: Many of the challenges of climate change and adaptation are not limited to individual sectors. Consequently, research programs are needed that facilitate the promotion of trans-sectoral projects, for instance, agriculture, forestry, and nature conservation. The often pressing need for adaptation is also dependent on the close networking of researchers with decision-makers and other actors and stakeholders in transdisciplinary projects to enable a rapid transfer between science and practice and the application of knowledge in practice-relevant solutions. The promotion of interdisciplinarity between the natural sciences, technical sciences, social sciences, and humanities as well as transdisciplinarity in research projects all necessitate a novel form of peer review and indicators for evaluating success that differs from those in classic, disciplinary projects.

In addition, many questions about adaptation to climate change can only be answered through long-term research (for example identification of appropriate tree species and provenances through cultivation trials, impacts of adaptation measures on biodiversity, and the provision of ecosystem services). Consequently, options for funding longer-term collaborative research projects (similar to the collaborative research areas of the German Research Foundation (*DFG*), should be included in the relevant country and federal states research programs.

2. Increase research capacities: In many forestry and wood science disciplines, which play a key role in elucidating future research questions, there are only a few up-and-coming scientists (for example pathology, forest protection, forest genetics, forest plant breeding). First, this has to do with the fact that there have been no vacant professorships at universities in some of these areas for long periods. Second, there are very limited opportunities for young scientists to develop or reliably plan scientific careers due to the paucity of subject-specific positions in most forestry disciplines. In the short to medium term, this problem could be attenuated using the dedicated funding of junior researcher groups in areas of particular importance for research on forest adaptation to climate change. In this way, the required disciplines can be built up again and developed through staff capacities. Additional capacity is also urgently needed in the area of research infrastructure. In particular, this includes long-term collaborative trials and observation areas with a uniform design and comparable instruments for supra-regional evaluation. Support for this infrastructure must be made possible beyond the establishment phase or short-term project periods, similar to the network for long-term ecological research (*LTER*). Opportunities for cooperation between the federal government and the federal states should be used to reach agreements on jointly funding cross-regional research on climate change adaptation. Questions that could and should be dealt with in this way are outlined in the next section.

3. Improve networking and cooperation: Due to the federal structure and organization of state forests, application-based forestry research has also traditionally been oriented towards the federal states which gives it a regional connection.

For joint issues, there have already been cases in the past where collaborative, coordinated test facilities undertook joint evaluations. Currently, there is a lack of coordinated collaborative tests on key forest adaptation issues with a design that permits joint evaluation. More particularly, the identification of suitable tree species and provenances should be carried out in parallel by as many stakeholders in research as possible to identify site-based variation as comprehensively as possible, and to spread the considerable costs for the setting up and long-term running of the tests. Other questions of relevance for nationwide coordinated collaborative trials include, for instance, the performance of mixed stand types and spatial configurations of mixtures concerning ecosystem services or the impact of management intensity on biodiversity and resilience to extreme events. In addition to jointly developed test facilities, innovative and complex methods for forest conditions and forest development monitoring should also be elaborated in effective research alliances.

Networking and cooperation on the pressing issues of adapting forests and forest management to climate change are not limited to Germany. The knowledge gain and the necessary cooperation would be greatly spurred on if funding in the important national research programs of the FNR and the Forest Climate Fund were also to be made available for international collaborative projects on issues relevant to Germany, for instance, work on the genetic resources of European tree species or on coping with disturbances.

4. Improve the exchange, synthesis, and visibility of data: The exchange and joint evaluation of data constitute an important basis for networking and cooperation. Collaboration on the analysis of large, shared data sets has so far only taken place within Germany to a limited degree and on a project-by-project basis. Data exchange and availability (including data collected with public funds) are often hampered by competitive concerns and a lack of trust. The agencies that finance research do not stipulate that the datasets collected in externally funded projects have to be made available and published. Joint analyses and syntheses based on existing data could be encouraged by the systematic publication or accessibility of data collected by research institutes thanks to public funding. Since there are innumerable older data sets, some of which are not yet available in databases or have not been sufficiently quality-checked, the preparation of these data for specific evaluation goals would have to be given the corresponding backing. In this context, the providers of external funding should also give their explicit support to synthesis projects that aim to evaluate existing data. The financing of research projects from public funds should always be dependent on compliance with the FAIR principles (Findability, Accessibility, Interoperability, and Reuse of digital assets) in research data management.

In many cases, important research results from research institutes are "only" published in German, non-scientifically peer-reviewed literature ("grey literature"), or are not published at all. Since this lack of visibility and findability considerably hinders general knowledge gain, clear preconditions for the publication of results and data should be attached to research funding. Knowledge and information for practitioners should be posted on proven, well-known platforms (for instance Information Service Wood, Forest Knowledge) instead of creating additional, parallel platforms.

Literature

The literature cited is listed in the bibliography of the original document. (German version)

https://www.bmel.de/SharedDocs/Downloads/DE/_Ministerium/Beiraete/waldpolitik/gutachten-wbw-anpassung-klimawandel.html