Concepts, objectives and values in German forest conservation – a comparative analysis, an assessment of practicability and future prospects

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*There is grandeur in this view of life,
with its several powers, having been
originally breathed into a few forms or
into one; and that, whilst this planet
has gone cycling on according to the
fixed law of gravity, from so simple a
beginning endless forms most
beautiful and most wonderful have
been, and are being, evolved.*

- Charles Darwin -

For my family!

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Glossary

Term	Definition	German equivalent
Biotope	Derives from the German *Biotop* and originates from Greek *bios* = life and *topos* = place. "Combines the physical environment (habitat) and its distinctive assemblage of conspicuous species" (Olenin and Ducrotoy 2006). Subject is a biocoenosis, a biological community limited to a narrow environment.	Biotop
Conservation object	Concrete biotic and abiotic protected goods of biodiversity, such as species, habitats, structures, soil, water and climate.	Schutzgut der Biodiversität
Conservation objective	Combination of a physical object of conservation, e.g. organisms, habitats, soil or water resources and the properties of its desired state (target, goal).	
Forest development type	Long-term vision of how the species composition and the structure of existing and new forest stands are expected to develop through a suitable choice and mixture of tree species.	Wald-entwicklungs-typ
Habitat	Originates from Latin *habitāre* = to inhabit / to hold / to have. Defined "according to geographical location, physiographic features and the physical and chemical environment" (Olenin and Ducrotoy 2006). Subject is a population that is not confined to a geographical area.	Lebensraum/ Habitat
Habitat continuity	Synonym: Ecological continuity. Refers to physical or structural continuity of habitats in the landscape (Kemp 2008) and to habitats that make an important contribution to the region's natural and cultural heritage by having evolved their typical biodiversity over a long period of time.	
Habitat types	Represent types of environment identified according to abiotic conditions, physiognomic characteristics of vegetation and species composition of flora and fauna, and include site, structure and use characteristics (Schaefer 2003; Drachenfels 2012).	Biotoptypen
Habitat types of the Habitats Directive or of Community interest	Habitat types "are in danger of disappearance in their natural range; have a small natural range following their regression or by reason of their intrinsically restricted area; present outstanding examples of typical characteristics of one or more of the five biogeographical regions" (European Commission 1992)	FFH-Lebens-raumtypen
Need for protection	Degree of threat as a result of adverse effects of land-use and environmental changes.	Schutz-bedürftigkeit
Social-ecological system	A "coherent system of biophysical and social factors that regularly interact in a resilient, sustained manner that is defined at several spatial, temporal, and organisational scales, which may be hierarchically linked" (Redman et al. 2004).	
Worthiness of protection	Contribution to the preservation of characteristic species, habitats and gene pools in natural or semi-natural landscapes or ecosystems.	Schutz-würdigkeit

Summary

The global biodiversity crisis is, along with climate change, the greatest challenge facing mankind. To ensure the long-term protection of biodiversity, conservation objectives must be agreed upon by all stakeholders, defined in concepts, and appropriate actions taken. This involves considering the often contrasting needs of nature and people and examining ethical-moral issues about the value of nature as well as different approaches to nature conservation. In this thesis, conservation objectives and values in German forest conservation concepts, considering ecological, political and social aspects are analysed in an interdisciplinary approach. The present state of forest conservation in Germany is discussed and current and future challenges are described. Based on this assessment of needs new methods for the classification of conservation objectives and for the assessment of forest conservation objects are presented and possible changes in conservation responsibility in view of climate change are proposed.

Forests support a significant proportion of global biodiversity and provide essential ecosystem services, and their long-term conservation and sustainable use is becoming more important than ever in the face of climate change. Due to the diverse demands for conservation and use, a consensus on the objectives is necessary in forest conservation. Only a transparent system based on consistent objectives and measures is likely to be sufficiently accepted and implemented. Therefore, a hierarchical framework for the classification of nature conservation objectives was developed in Chapter 2 of this thesis. Within higher-level target areas, desired target properties were assigned to conservation objects, which are to be achieved through certain measures. Using this framework, the contents of biodiversity and forest conservation concepts were examined for commonalities and differences. A broad consensus on conservation objectives was found in the concepts across different stakeholder groups and spatial scales, with the conservation of species, ecosystems and structures in forests rated as particularly important. Deficits were identified with regard to genetic diversity, abiotic resources and social-cultural objectives, as well as a mismatch in the transfer of knowledge. The reasons for these inconsistencies in forest conservation include conflicting objectives, lack of coordination across scales and inadequate implementation of objectives.

In private forests, which make up half of the German forest area, the implementation of nature conservation measures is a particular challenge. Private forest owners often have reservations about sovereign nature conservation regulations and are less willing to participate due to the financial expenses involved. In order to ensure higher acceptance, forest conservation measures

should be financially compensated. However, the contractual agreement of nature conservation services and financial remuneration (= contract-based nature conservation) has so far found limited application in private forests. Since the successful implementation of contract-based forest conservation requires a system of reasonable measures, the conservation objects identified in Chapter 2 (forest habitat types, structures and processes in forests) were assigned a conservation value in Chapter 3 on the basis of the need for, and the worthiness of, protection. Oak and mixed oak forests, dry-warm beech forests, historical forms of forest use (coppice forests or wood pastures) and natural structures such as deadwood (deciduous tree species, standing and lying) or habitat trees have a high nature conservation value. Based on the initial value and the expected value development, it was assessed whether conservation or restoration measures within the framework of contract-based forest conservation with varying durations are suitable. Contract-based forest conservation is particularly suitable for conservation objects with a high initial value if a loss of value can be avoided and if a high increase in value can be expected. It is not suitable for low initial values and a low restoration potential. With this framework, private forest owners can easily assess which nature conservation measures are suitable in their forest, increasing the likelihood that they will apply contract-based forest conservation in the future.

Climate change and its predicted effects in terms of intensity and frequency of disturbances require an adaptation of silvicultural management. In Germany, silvicultural planning tools such as forest development types are often only related to the economic productivity function, while nature conservation demands are given little consideration. Therefore, the framework developed in Chapter 3 for the conservation value assessment of forest habitat types was adapted in Chapter 4 to the economically relevant tree species (beech, oak, pine, spruce, fir, Douglas-fir and larch) and further developed for application in forest stands according to the potential natural vegetation of the location. With the new framework, the nature conservation impacts of silvicultural planning and future tree species composition in forest stands can be spatially-explicitly assessed. Certain silvicultural combinations of tree species can lead to a reduction in the initial nature conservation value, which is determined by the forest habitat type naturally occurring there. The highest nature conservation value can be achieved if the planned tree species are both autochthonous and a natural component of the respective forest habitat type. The framework was trialled to assess planned forest development types using a Germany-wide transect. In most cases, the forest development type combinations led to a reduction of the initial nature conservation value, as the restricted tree species selection of the forest development types did not correspond to the diverse species composition of the natural forest habitat types. With this evaluation framework, forest planning can also be assessed in terms of nature conservation and be adapted to a tree species composition that is as close to nature and site-specific as possible.

The uncertainties of climate change and the associated changes in environmental conditions also pose new challenges for nature conservation and may require an adaptation of the conservation objectives and justifications. Chapter 5 therefore investigated whether the favourable conservation status of forest habitat types of the Habitats Directive remains a well-founded objective when confronted with climate change. In this context, both the question of the conservation justification and an assessment of the future development trend of the conservation status of forest habitat types of the Habitats Directive were addressed. It was shown that current niche and species distribution models of habitat types and tree species indicate that a climate change-induced increase in drought can lead to losses in area of forest habitat types such as the subalpine sycamore-beech forest and the montane-alpine soil-acid spruce forest. In the case of bog woodland and alluvial forests, successful restoration should be the first priority before future development can be assessed. Forest habitat types on secondary sites, such as mixed oak forests, will probably continue to require active management measures to restore and secure a favourable conservation status in the long term. The distribution models for beech forest habitat types showed increasing uncertainty regarding future distribution, and for the most part no significant negative change could be identified, even under climate change. Flexibilisation and adaptation of conservation objectives should therefore only take place on the basis of evidence and within the framework of adaptive management. Overall, no clear indications is found to abandon the favourable conservation status of forest habitat types under climate change as a well-founded objective of nature conservation.

This thesis discusses the importance of forest conservation concepts in today’s world and the difficulties that can arise in the classification and implementation of forest conservation objectives. Furthermore, the challenges that may arise in the conservation value assessment of conservation objects and tree species as well as in future implementation of forest conservation measures are identified. It was found that the systematic analysis of conservation objectives has gained importance in conservation research and that there is a broad consensus on the objectives of forest conservation in Germany. Nevertheless, there is a considerable need for more specification, especially with regard to the implementation of contract-based nature conservation in private forests. The frameworks presented for the derivation of nature conservation values can be helpful in turning abstract properties such as nature conservation values into a simplified and comprehensible system. Forestry and nature conservation stakeholders can thus be sensitised to the conservation value of forest biodiversity. In order to reduce existing prejudices between stakeholders, it is also necessary to further revise the funding system in Germany with regard to its financial scope and the effectiveness of conservation measures, and to provide practical recommendations for action based on scientific findings.

This thesis underlines that a constant adaptation of forest management strategies is necessary for forest conservation and silviculture to cope with the challenges of climate change. For forests to maintain their diverse functions and ecosystem services in the future, semi-natural, species-rich resilient mixed forests composed of predominantly native tree species should be favoured and the existing objectives in nature conservation should not be abandoned without reason. Only in this way can forest conservation in Germany and also worldwide be successful in the long term.

Zusammenfassung

Die globale Biodiversitätskrise stellt neben dem Klimawandel die größte Herausforderung für die Menschheit dar. Um den Schutz der Biodiversität langfristig zu garantieren, sind zwischen allen beteiligten Akteuren abgestimmte Ziele zu vereinbaren, in Konzepten festzulegen und geeignete Naturschutzmaßnahmen zu ergreifen. Dabei sind divergierende Bedürfnisse von Natur und Menschen zu berücksichtigen und ethisch-moralische Fragen über den Wert der Natur sowie unterschiedliche Ansätze zum Naturschutz zu untersuchen. In dieser Dissertation werden Ziele und naturschutzfachliche Werte in deutschen Waldnaturschutzkonzepten in einem interdisziplinären Ansatz unter Berücksichtigung ökologischer, politischer und gesellschaftlicher Aspekte analysiert. Dabei werden der derzeitige Zustand des Waldnaturschutzes in Deutschland bewertet sowie aktuelle und zukünftige Herausforderungen beschrieben. Die Dissertation stellt neue Methoden zur Klassifizierung von Naturschutzzielen und zur Bewertung von Schutzgütern im Wald vor und erörtert mögliche Veränderungen der Naturschutzverantwortung vor dem Hintergrund des Klimawandels.

Der langfristige Erhalt sowie eine nachhaltige Nutzung der Wälder sind angesichts des Klimawandels wichtiger denn je geworden, denn Wälder leisten einen wichtigen Beitrag zum Schutz der Biodiversität und erbringen zahlreiche Ökosystemleistungen. Aufgrund der vielfältigen Schutz- und Nutzungsanforderungen ist im Waldnaturschutz ein Konsens über die Ziele erforderlich. Nur ein auf übereinstimmenden Zielen und Maßnahmen beruhendes transparentes System dürfte ausreichend akzeptiert und umgesetzt werden. Daher wurde in Kapitel 2 dieser Dissertation ein hierarchisches System zur Klassifikation von Naturschutzzielen entwickelt. Innerhalb von übergeordneten Zielbereichen wurden Schutzgütern angestrebte Zieleigenschaften zugeordnet, die durch bestimmte Maßnahmen erreicht werden sollen. Anhand dieses Systems wurden die Inhalte von Biodiversitäts- und Waldnaturschutzkonzepten auf Gemeinsamkeiten und Unterschiede untersucht. In den Konzepten wurde ein breiter Konsens hinsichtlich der Schutzziele über verschiedene Interessensgruppen und räumliche Bezugsebenen hinweg festgestellt, wobei die Erhaltung von Arten, Ökosystemen und Strukturen in Wäldern als besonders wichtig eingestuft wurde. Im Hinblick auf die genetische Vielfalt, abiotische Ressourcen und soziokulturelle Ziele wurden Defizite festgestellt, ebenso wie eine skalenbedingte Inkonsistenz beim Wissenstransfer. Als Ursachen für diese Divergenzen im Waldnaturschutz können Zielkonflikte, eine mangelnde Abstimmung über Skalenebenen hinweg und eine unzureichende Umsetzung der Ziele identifiziert werden.

Im Privatwald, der die Hälfte der deutschen Waldfläche ausmacht, ist die Umsetzung von Naturschutzmaßnahmen eine besondere Herausforderung. Privatwaldbesitzer haben oftmals Vorbehalte gegenüber hoheitlichen Naturschutzauflagen und aufgrund des finanziellen Aufwands eine geringere Teilnahmebereitschaft. Um für mehr Akzeptanz zu sorgen, sollten Naturschutzmaßnahmen im Wald finanziell ausgeglichen werden. Die vertragliche Vereinbarung von Naturschutzleistung und finanzieller Gegenleistung (= Vertragsnaturschutz) findet im Privatwald jedoch bisher wenig Anwendung. Da die erfolgreiche Umsetzung des Waldvertragsnaturschutzes ein System sinnvoller Maßnahmen erfordert, wurde den in Kapitel 2 identifizierten Schutzgütern (Waldbiotoptypen, Strukturen und Prozessen im Wald) in Kapitel 3 ein naturschutzfachlicher Wert auf Grundlage der Schutzbedürftigkeit und der Schutzwürdigkeit zugeordnet. Einen hohen Naturschutzwert haben Eichen- und Eichenmischwälder, trocken-warme Buchenwälder, historische Waldnutzungsformen (Mittel- oder Hutewälder) und natürliche Strukturelemente wie starkes Totholz (Laubbaumarten, stehend und liegend) oder Habitatbäume. Auf Grundlage des Ausgangswertes und der erwarteten Wertentwicklung wird abgeschätzt, ob Erhaltungs- bzw. Wiederherstellungsmaßnahmen im Rahmen von Vertragsnaturschutz mit unterschiedlichen Laufzeiten sinnvoll sind. Vertragsnaturschutz ist besonders bei Schutzgütern mit einem hohen Ausgangswert geeignet, wenn damit ein Wertverlust vermieden werden kann und wenn mit einer hohen Aufwertung zu rechnen ist. Bei niedrigem Ausgangswert und geringer Aufwertungswahrscheinlichkeit ist Vertragsnaturschutz nicht sinnvoll. Mit diesem Bewertungssystem können Privatwaldbesitzer überprüfen, welche Naturschutzmaßnahmen in ihrem Wald geeignet sind und damit in Zukunft zu einer erhöhten Anwendung des Waldvertragsnaturschutzes beitragen.

Der Klimawandel und seine prognostizierten Auswirkungen hinsichtlich Intensität und Häufigkeit von Störungen erfordern eine Anpassung der waldbaulichen Bewirtschaftung. Waldbauliche Planungsinstrumente wie Waldentwicklungstypen (WET) sind in Deutschland oft nur an der wirtschaftlichen Produktivitätsfunktion orientiert, während naturschutzfachliche Anforderungen wenig Berücksichtigung finden. Daher wurde das in Kapitel 3 entwickelte System zur naturschutzfachlichen Bewertung von Waldbiotoptypen in Kapitel 4 an die wirtschaftlich relevanten Hauptbaumarten (Buche, Eiche, Kiefer, Fichte, Tanne, Douglasie und Lärche) angepasst und für die flächendeckende Anwendung im Waldbestand entsprechend der potenziellen natürlichen Vegetation des Standortes weiterentwickelt. Mit dem neuen System können naturschutzfachliche Auswirkungen der waldbaulichen Planung und zukünftigen Baumartenzusammensetzung in Waldbeständen räumlich-explizit eingeschätzt werden.

Bestimmte forstliche Baumartenkombinationen können dabei zu einer Verschlechterung des naturschutzfachlichen Ausgangswertes führen, welcher durch den dort natürlicherweise vorkommenden Waldbiotoptyp bestimmt wird. Der höchste Naturschutzwert kann erhalten werden, wenn die geplanten Baumarten sowohl autochthon als auch natürlicher Bestandteil des spezifischen Waldbiotoptyps sind. Anhand eines deutschlandweiten Transekts wurde die naturschutzfachliche Bewertung von zukünftig geplanten WET erprobt. In den meisten Fällen führten die WET-Kombinationen zu einer Verschlechterung des ursprünglichen Naturschutzwertes, da die eingeschränkte Baumartenwahl der WET nicht die vielfältige Artenzusammensetzung der natürlichen Waldbiotoptypen widerspiegelte. Mit diesem Bewertungssystem lässt sich die Waldbauplanung auch naturschutzfachlich einschätzen und auf eine möglichst naturnahe und standortheimische Baumartenzusammensetzung ausrichten.
Die Unsicherheiten des Klimawandels und die damit verbundenen Veränderungen der Umweltbedingungen stellen auch den Naturschutz vor neue Herausforderungen und können eine Anpassung von Zielen und Schutzbegründungen erforderlich machen. In Kapitel 5 wurde daher untersucht, ob der günstige Erhaltungszustand von FFH-Waldlebensraumtypen angesichts des Klimawandels ein gut begründetes Ziel bleiben kann. Dabei wurde sowohl auf die Frage der Schutzbegründung eingegangen als auch eine Einschätzung des zukünftigen Entwicklungstrends des Erhaltungszustandes von FFH-Waldlebensraumtypen vorgenommen. Es konnte gezeigt werden, dass aktuelle Nischen- und Artverbreitungsmodelle von Lebensraumtypen und Baumarten darauf hindeuten, dass eine Klimawandel-bedingte Zunahme der Trockenheit für Waldlebensraumtypen wie den subalpinen Bergahorn-Buchenwald sowie den montan-alpinen bodensauren Fichtenwald zu Arealverlusten führen kann. Bei Moor- und Auenwäldern sollte zunächst eine erfolgreiche Renaturierung im Vordergrund stehen, bevor eine zukünftige Entwicklung abgeschätzt werden kann. Waldlebensraumtypen auf Sekundärstandorten wie Eichenmischwälder benötigen wahrscheinlich weiterhin aktive Pflegemaßnahmen, um einen günstigen Erhaltungszustand wiederherzustellen und langfristig zu sichern. Bei den Verbreitungsmodellen für Buchenwaldlebensraumtypen konnte eine zunehmende Unsicherheit bezüglich der zukünftigen Verbreitung festgestellt werden und es ließ sich auch unter Klimawandel überwiegend keine deutlich negative Veränderung erkennen. Eine Flexibilisierung und Anpassung von naturschutzfachlichen Zielsetzungen sollte demnach nur evidenzbasiert und im Rahmen eines adaptiven Managements erfolgen. Insgesamt ergeben sich vorerst keine eindeutigen Hinweise darauf, den günstigen Erhaltungszustand der Waldlebensraumtypen unter Klimawandel als ein gut begründetes Ziel des Naturschutzes aufzugeben.

In dieser Dissertation werden die Bedeutung von Waldnaturschutzkonzepten in der heutigen Zeit und die Schwierigkeiten, die bei der Einordnung und Umsetzung von Waldnaturschutzzielen auftreten können, diskutiert. Ferner werden die Herausforderungen, die sich bei der naturschutzfachlichen Bewertung von Schutzgütern und Baumarten sowie bei der zukünftigen Umsetzung von Waldnaturschutzmaßnahmen ergeben können, identifiziert. Dabei wurde festgestellt, dass die systematische Analyse von naturschutzfachlichen Zielsetzungen in der Naturschutzforschung an Bedeutung gewonnen hat und ein insgesamt breiter Konsens über die Ziele im Waldnaturschutz in Deutschland herrscht. Trotzdem besteht ein erheblicher Präzisierungsbedarf, insbesondere im Hinblick auf die Umsetzung des Vertragsnaturschutzes im Privatwald. Die vorgestellten Systeme zur Ableitung von Naturschutzwerten können insofern hilfreich sein, als dass abstrakte Eigenschaften wie Naturschutzwerte in ein vereinfachtes und nachvollziehbares System eingeordnet wurden. Forstliche und naturschutzfachliche Akteure können damit für den Naturschutzwert der Wälder sensibilisiert werden. Um bestehende Vorurteile zwischen den Akteuren abzubauen, ist es zudem notwendig, das Fördersystem in Deutschland im Hinblick auf den finanziellen Umfang und die Wirksamkeit von Naturschutzmaßnahmen weiter zu überarbeiten sowie praktische Handlungsempfehlungen auf der Grundlage wissenschaftlicher Erkenntnisse zu geben.

Diese Dissertation unterstreicht, dass eine ständige Anpassung der Waldbehandlungsstrategien für den Waldnaturschutz und Waldbau notwendig ist, um die Herausforderungen des Klimawandels zu bewältigen. Damit Wälder ihre vielfältigen Funktionen und Ökosystemleistungen auch in Zukunft erhalten können, sollten naturnahe, artenreiche und aus überwiegend heimischen Baumarten aufgebaute resiliente Mischwäldern bevorzugt und die bestehenden Ziele im Naturschutz nicht ohne Grund aufgegeben werden. Nur so kann Waldnaturschutz in Deutschland und auch weltweit langfristig erfolgreich sein.

CHAPTER 1

General Introduction

1.1 Concepts and frameworks in European nature conservation

Biodiversity loss is one of the greatest challenges facing humankind in the 21st century (Lorey 2002; Rands et al. 2010; Pereira et al. 2012; Ceballos et al. 2015; IPBES 2019). Biodiversity in the form of genes, species, ecosystems and landscapes is the foundation for diverse ecosystem services and thus the basis for human existence (MEA 2005; Rands et al. 2010). However, the stability and resilience of biodiversity is threatened by accelerating climate and land use change (Côté and Darling 2010; Streitberger et al. 2017; IPBES 2019). Environmental changes such as temperature increases, changes in the soil water balance and an increase in the frequency of extreme weather events can lead to habitat transformation, loss of species and shifts in biotic communities, limiting their local and geographical distribution (Tilman et al. 2017; WWF 2020). Human activity, as the main driver of these changes (Pereira et al. 2012; Young et al. 2016; IPBES 2019), has even led to an entire epoch being named after its global impact, the Anthropocene (Hayward 1997; Crutzen 2006). To retard or even halt biodiversity loss, increased global efforts in the form of international conventions and frameworks with adaptable objectives and measures are needed.

The Convention on Biological Diversity (CBD), adopted in 1992 and signed so far by 196 contracting parties, 168 states and the European Union, is the first and most important international agreement to ensure the conservation of biodiversity, the sustainable use of all its components and the fair and equitable sharing of benefits arising from genetic resources (United Nations 1992a). Thirty years after the entry into force of the CBD, discussions about its objectives, their achievability and their implementation have not abated and have even become more important in the face of the global biodiversity crisis (IPBES 2019). With the commencement of the CBD, the Parties agreed to develop national and regional strategies and legislation for the protection and conservation of their native biodiversity. In 2002, the international community reaffirmed the targets of the CBD and committed to reducing the alarming rates of current biodiversity loss by 2010 (CBD 2006). However, the Parties failed to achieve these targets (Mace and Baillie 2007; Butchart et al. 2010; CBD 2010). In response, the Strategic Plan for Biodiversity 2011-2020 and its Aichi Biodiversity Targets were developed (CBD 2010), which were initially welcomed as SMART (specific, measurable, ambitious, realistic and time-bound), but then criticised for shortcomings such as missing thresholds, scant quantifiable elements and an insufficient base of scientific evidence (Mace and Baillie 2007; Perrings et al. 2011; Maxwell et al. 2015; Butchart et al. 2016). Despite all ambitions towards successful implementation, the Aichi Biodiversity Targets were still not achieved by the end of 2020 (CBD 2020). Therefore, the Post-2020 Biodiversity Framework was developed in 2021 as a stepping stone towards the 2050 vision of living in harmony with nature. The aim is that "by 2050, biodiversity is valued, conserved, restored and wisely used, maintaining ecosystem services, sustaining a healthy planet and delivering benefits essential for all people" (CBD 2021: 4). Whether this objective will be achieved is yet to be seen.

Whilst the CBD itself is not legally binding, ratification needs to be first implemented in binding national laws. One of the most important tools towards reaching the goals of the CBD in the European Union (EU) is the establishment of the Natura 2000 protected areas network in 1992 (European Commission 1992). The Habitats and the Birds Directives 92/43/EEC and 2009/147/EC are the basis of this comprehensive system of protected areas, which aims to guarantee the transnational protection and conservation of endangered wild species and their habitats (EU 2020). In Germany, 5,200 Sites of Community Importance and Special Protected Areas are currently registered, covering 15.5% of the terrestrial national territory (BfN 2019). The necessary conservation and development measures are set out in the management plans. The Annexes of the Habitats Directive list the rare and endangered animal and plant species as well as habitats for which comprehensive conservation concepts and management plans are to be developed. For Germany, Annex 1 of the Habitats Directive identifies 92 habitat types for which there is a special responsibility for protection and conservation. In Natura 2000 sites, forestry and agricultural use is not generally excluded. However, it must be ensured that the management does not lead to a deterioration of the conservation status of the species and habitats. At the same time, it strives to consider the economic, social and cultural conditions as well as the local contexts in the framework of sustainable development (European Commission 1992; Meyer 2013a; Tiebel et al. 2021a). Whether the objectives of favourable conservation status of the habitat types of the Habitats Directive will remain valid in the face of climate change is currently being intensively discussed and requires review (Hendler et al. 2010; Cliquet 2014; DVFFA 2019).

In addition to the Natura 2000 protected areas network, the EU is also contributing to its CBD commitments through the adoption of its Biodiversity Strategy to 2020. Given the uncertainties of future climatic developments (Kunreuther et al. 2014; Streiberger et al. 2017) and constantly changing environmental conditions, as well as the increased occurrence of threats to biodiversity (Tilman et al. 2017; WWF 2020), international and national conservation strategies and frameworks for biodiversity protection need to be constantly adapted. Thus, as part of the European Green Deal, the European Union has revised its 2020-Biodiversity Strategy and adapted targets and measures for the EU Biodiversity Strategy 2030 (European Commission 2020b). The new strategy focuses even more on identifying and tackling the main drivers of biodiversity loss, such as land use intensification, pollution, overexploitation of natural resources, and aims to integrate sustainable biodiversity management into economic measures. However, even with this new, adapted strategy, it remains to be seen whether it will prove successful. This again highlights the need to define nature conservation objectives for biodiversity protection as precisely as possible, including valuable conservation objects and quantifiable measures of success, and as cost-effectively as possible (Salafsky et al. 2002; Christie et al. 2021). However, without knowing the conservation value of the respective conservation objects, it can be difficult to prioritise these objectives.

1.2 Nature conservation objectives and the value of biodiversity

The valuation of nature or biodiversity is related to ecological, ethical, cultural and economic questions (Piechocki 2010; Treves et al. 2021). Discussions about protecting nature for intrinsic values, for aesthetic or religious motives and by valuing the benefits and services that people gain from protecting biodiversity have been shaping nature conservation for more than a century (e.g. Soulé 1985; Swart et al. 2001; Schmoll 2005; Vucetich et al. 2015; Mölder et al. 2017). This is also reflected in the CBD: the preamble states that the Parties are "conscious of the intrinsic value of biological diversity and of the ecological, genetic, social, economic, scientific, educational, cultural, recreational and aesthetic values of biological diversity and its components" (United Nations 1992a: 1).

The assessments of what is worth protecting are made by humans, and the resulting decisions and measures therefore often anthropocentric (Piechocki 2010; Kopnina et al. 2018). Humans, aware that they themselves are part of nature, can make decisions as responsibly and sustainably as possible to the best of their knowledge and conscience (Redman et al. 2004; Bruley et al. 2021; Treves et al. 2021). However, they can only observe and try to assess the status and development of biodiversity as well as its reactions to land use and environmental changes and initiate measures accordingly (Flores and Clark 2001). Representatives of science, politics, society and nature conservation must conscientiously evaluate which conservation objects are worth protecting, where urgent threats occur and whether there is a conservation responsibility (Ammer et al. 2018). Objectives and measures in nature conservation should therefore be based on reliable and sound arguments, ensuring a high level of transparency and evidence (Tear et al. 2005; Christie et al. 2021). However, they are often controversial and influenced by different stakeholders, which can make it difficult to reach consensus on the objectives and implementation of the measures (Demant et al. 2019; Treves et al. 2021). Nature conservation strategies and objectives require close collaboration and the combination of various field-tested adaptive and evidence-based approaches (Sutherland et al. 2004; Mupepele et al. 2016; Christie et al. 2021). The protection of conservation objects is usually approached by defining specific targets or indicators, with the aim of achieving a favourable conservation status to be restored and/or maintained by sensibly chosen conservation measures (Alberdi et al. 2019). These measures can either be developed on the basis of scientific knowledge (evidence), or be based on many years of expert experience and the knowledge gained from it (expertise, Hofer 2016). It may be the case that measures are not based on scientific-objective findings, but can be subjectively-emotionally influenced (Matthews 1975; Wei 2021). As a consequence, human needs may be prioritised over the needs of nature (Bruley et al. 2021).

The concept of typical assemblages of species is relevant to biodiversity conservation at a landscape or ecosystem level. The objective of a purely quantitative maximisation of species diversity can conflict with the preservation of the typical biodiversity of the natural landscape (Lindenmayer and Hunter 2010). Simply increasing the number of species above typical levels can lead to a homogenisation of natural areas as well as a loss of biodiversity at higher spatial scales (Meyer 2013b). Depending on the frame of reference, the species composition of an ecosystem can be considered typical or atypical. In this context, typical means "embodying a (certain) type [and] exhibiting its characteristic features in a pronounced form" or "being characteristic, distinctive, indicative of a certain type, of something, someone specific" (Duden online 2022). Typical biodiversity can refer to different spatial (e.g. single tree, forest stand, forest ecosystem, landscape patterns) and temporal (short- to long-term development) scales. However, this variability in scales may require different management approaches to meet the many conservation needs of biodiversity (Carvalho et al. 2020). In this context, mismatches in knowledge transfer, in different perceptions of values and in the application of measures at different spatial and temporal scales may arise (Paloniemi et al. 2012; Guerrero et al. 2013).

In environmental ethics, discussions about the value of nature or biodiversity can be traced back to the questions whether nature is to be protected solely for reasons of use and human interest (instrumental value, German: "Nutz-/Gebrauchswert"), whether nature is ascribed its own cultural, aesthetic, spiritual, symbolic value by humans (eudemonic intrinsic value, "Eigenwert"), or whether nature is to be protected for its own sake, regardless of how humans value it (moral-intrinsic or inherent value, "Selbstwert", Soulé 1985; Eser and Potthast 1999; Eser et al. 2011; Vucetich et al. 2015). These different perspectives on value can be further developed into four basic types of environmental ethical justification for nature conservation (Gorke 2010; Piechocki 2010):

- Anthropocentrism: only humans have an intrinsic value, which is why a moral responsibility to protect can only be justified in relation to humans.
- Pathocentrism: in addition to humans, all higher living beings capable of suffering are ascribed an intrinsic value.
- Biocentrism: all living beings have an intrinsic value or a moral status.
- Holism: all living and non-living things on earth have a moral right to exist and are worth protecting for their own sake.

There are divergent ideas about conservation values and what is worthy of protection (e.g. Piechocki 2010; Vucetich et al. 2015; Doorn 2017; Areendran et al. 2020; Treves et al. 2021). According to Naveh (1994) a holistic approach can be meaningful when it comes to conservation responsibility and value discussions to ensure comprehensive protection of biodiversity (Lindenmayer and Hunter 2010). Anthropocentric or instrumental values are often equated with the economic value when it comes to quantifying the indirect or direct use value of biodiversity, creating a cascade from biodiversity to ecosystem functions to ecosystem services to economic values (Potschin and Haines-Young 2011; Hanley and Perrings 2019; Paul et al. 2020). Ecosystem functions describe the transfer and exchange of energy, information, material, processes and structures between ecosystem components (Jax 2005; Meyer et al. 2015c). Ecosystem services, in particular provisioning, regulating, cultural and supporting services, are the benefits that people gain from ecosystems (MEA 2005). They can also be described as the (active and passive) contributions to human well-being provided by ecosystem functions (Fisher et al. 2007; Burkhard et al. 2012). The Conceptual Framework of the Intergovernmental Platform on Biodiversity and Ecosystem Services (IPBES) distinguishes, among other things, the "intrinsic value of nature", "nature's benefits to people" and "a good quality of life" as the main elements connecting nature and society (Díaz et al. 2015). One approach to standardise and harmonise the assessment and mapping of ecosystem services was the development of the Common International Classification of Ecosystem Services (CICES). CICES aims at translating between different ecosystem service classification systems (Haines-Young and Potschin-Young 2018). The international initiative The Economics of Ecosystems and Biodiversity (TEEB) aims to assess the economic benefits and value of biodiversity and highlights the costs that arise from biodiversity loss and ecosystem degradation (TEEB 2010).

To reward the benefits that people gain from protecting ecosystem services and functions, incentives can be paid to landowners in exchange for certain voluntary actions. These payments for ecosystem services can be used to increase the willingness of landowners to protect and conserve ecosystems and biodiversity. So far, a variety of definitions and differing interpretations of the concept of ecosystem services have been published, as summarised by Bruley et al. (2021). Despite these differences, the concept links sociological and ecological systems and has already found its way into political decision-making processes (Rüdisser et al. 2020). The decline in biodiversity and the associated impairments of ecosystem functions in the past decades have reduced nature's ability to contribute to people's quality of life (Brauman et al. 2020). Since protecting ecosystem structures and functions is crucial for the provision of ecosystem services, nature conservation should focus even more on maintaining these ecosystem capacities, also by improving financial compensation opportunities and sufficient integration and transfer of knowledge to link the multiple demands in social-ecological systems (Berkes et al. 2003; Redman et al. 2004; Reyers et al. 2018; Bixler 2021). This also applies to German nature conservation. Because even there, insufficient consideration is given to the different needs of the various stakeholders, which makes it difficult to achieve nature conservation objectives.

1.3 Nature conservation in German forests

Nature conservation in Germany has a long tradition and the term "Naturschutz" in its current meaning was first mentioned by Philipp Leopold Martin in 1871 (Hachmann and Koch 2015; Hachmann et al. 2021). In addition to Martin, who focused more on the need to protect wildlife, another pioneer of nature conservation in Germany was Ernst Rudorff, who emphasised more the aesthetic aspects of nature (Hachmann and Koch 2015). Both founders of the idea of nature conservation experienced the increasing industrialisation in the 19th century as a threat to nature and homeland. The orientation and focus of German conservation has evolved from a former understanding of homeland and natural monument conservation as well as forest protection (in the sense of bird and habitat tree protection), to today's species, ecosystem, environmental and general biodiversity conservation (Schmoll 2004; Sukopp et al. 2006; Piechocki 2010; Mölder et al. 2020). According to Meyer et al. (2016a: 497), nature conservation can be understood as "an element of land use systems that modifies, restricts or can completely exclude certain areas of land use type and intensity with regard to biological diversity". In contrast to ecology, nature conservation can be a social field of action that is influenced and guided by values and norms (Lindenmayer and Hunter 2010; Piechocki 2010). However, it is dependent on the scientific findings and results of ecology and other natural and social sciences, which form the basis for value judgements (Haber 2004).

The first developments of genuine nature conservation in forests in Germany took place a few decades after Martin and Rudorff at the beginning of the 20th century. Driven by the constantly increasing loss of forests since the Middle Ages, Hugo Conwentz was the first to speak out for the preservation of natural forest stands in 1907, and in the same year, together with the painter Theodor Rocholl, he campaigned for the designation of the (former) pasture woodland “Urwald Sababurg” in Hesse as one of the first nature reserves in Germany (Conwentz 1914; Schmidt and Rapp 2006; WBW and WBBGR 2020). It was not until the 1960s and 1970s that the idea of forest conservation became considerably more widespread in Germany. With the designation of the first strict forest reserves in course of the first nature conservation year in 1970 in West Germany and the establishment of a representative system of protected areas in East Germany, the value of unmanaged forests for research purposes was also highlighted (Meyer 2009a; Meyer et al. 2011; Meyer et al. 2022). Further important development impulses for forest conservation resulted from the adoption of the CBD in 1992 and of the German National Biodiversity Strategy in 2007 (Petereit et al. 2019). Nowadays, there is a whole range of publications, guidelines, and concepts from various stakeholders (e.g. politics, provincial forestry enterprises, nature conservation agencies, non-governmental organisations) that deal with the topics of nature conservation in forests as well as a sustainable and a semi-natural forest management (Demant et al. 2019; Petereit et al 2019).

The principle of sustainability or sustainable land use has accompanied human development and various cultures for thousands of years (Spindler 2013), even though there are different understandings and interpretations of sustainability (Ott and Döring 2011). The concept of sustainability in modern forestry was coined by Hans Carl von Carlowitz, a chief miner active in Saxony the 18th century. For von Carlowitz, sustainability meant nothing other than that no more timber should be removed from a forest than would grow back naturally, or through reforestation in the same period of time (Carlowitz 1713). According to today’s anthropocentric understanding, sustainability can be understood as ensuring that the satisfaction of the needs of future generations is not restricted by the current use of natural resources, or as defined in the Brundtland Report sustainable development is development that meets the “needs of the present without compromising the ability of future generations to meet their own needs” (WCED 1987: 15). The intended needs do not only refer to material goods, but encompass the entire spectrum of ecosystem services, which ultimately rely on biodiversity (Costanza et al. 1997; Brockerhoff et al. 2017). In nature conservation, sustainability or sustainable land use is understood as a system that does not overburden the resilience of biological diversity, i.e. its capacity for restoration, and its ecological stability (Holling 1973; Meyer et al. 2016a).

According to an evaluation of the map of the potential natural vegetation, almost 99% of the German land area would be naturally forested or characterised as forested land (Suck and

Bushart 2010). Due to historical settlement, agricultural and forestry use and the associated intensive deforestation, the forested area in Germany has declined sharply in the Middle Ages and had its lowest level (20%) in the 14^{th} century (Mutke and Quandt 2018). To date, the proportion of forested area has risen again to around 30%, with coniferous forests of spruce and pine still accounting for the largest share at 60% (Polley et al. 2016). Naturally, however, more than 70% of Germany’s forests would consist of beech and mixed beech forests (Suck and Bushart 2010).

With the establishment of the Natura 2000 network of protected areas, Sites of Community Importance were also designated in Germany’s forests, and management plans were developed for the conservation and development of the existing 17 forest habitat types. The most widespread forest habitat types are Luzulo-Fagetum beech forests (9110) and Asperulo-Fagetum beech forests (9130) with a share of about 70% (568,000 ha), followed by oak forest habitat types with a share of about 12% (Rosenkranz et al. 2012). As listed in Annex 1 of the Habitats Directive, forest habitat types represent the "(sub)natural woodland vegetation comprising native species forming forests of tall trees, with typical undergrowth, and meeting the following criteria: rare or residual, and/or hosting species of Community Interest" (European Commission 2013: 13). Specific requirements for the forestry and nature conservation management of forests in Natura 2000 areas apply with regard to an appropriate proportion of veteran trees and dead wood, the protection or development of habitat trees, a predominantly standing stem harvesting, the promotion of light demanding tree species, a mosaic of different forest development phases and a proportion of habitat type-typical tree species of more than 70% (Sippel 2004; MU and ML 2019).

The conservation state of forests in Germany is assessed as relatively favourable compared to agricultural ecosystems (Meyer et al. 2016a). The indicator for species diversity and landscape quality confirms a slightly positive trend in the development of selected bird species relevant to forests from 1970 to 2016 (Destatis 2021). Other forest biodiversity-relevant indicators also show positive developments, such as an increase in the proportion of deadwood, veteran trees and deciduous forest area, a more semi-natural forest management (e.g. site-specific tree species selection, promotion of natural forest regeneration, and preserving forest edges), as well as an increase in the proportion of naturally developing forests (e.g. Meyer 2013b; NLF 2016; Polley et al 2016; Engel et al. 2019; BMU 2021).

Forest conservation in Germany faces the challenge of both protecting and restoring the historically evolved typical cultural landscape, such as the rare traditionally managed coppice-with-standards and wood pastures, and at the same time preserving the typical natural forest communities (e.g. autochthonous beech forests, Demant et al. 2019; WBW and WBBGR 2020). In order to ensure the protection of this typical forest biodiversity, it is important to consider the worthiness of, and the need for, protection of conservation objects (Demant et al. 2020). A forest conservation object is worthy of preservation if it is a component of natural or semi-natural forest ecosystems in Central Europe. Conservation objects may also need protection if they are (indirectly) endangered by land use, changes in use or indirect anthropogenic environmental changes (Demant et al. 2020). In order to further promote and improve forest conservation, there should be as much consensus as possible among stakeholders involved (Lindenmayer and Hunter 2010). Against the background of the ongoing conflicts of interests and discussions on what is worthy of, and in need of, protection, consensual conservation objectives and feasible conservation measures become even more important (Demant et al. 2019).

Half of the forest area in Germany is privately owned (Polley et al. 2016), which can lead to difficulties in implementing conservation measures. Since the implementation of nature conservation measures in forests can result in reduced income, opportunity costs and considerable additional expenditure for forest owners (Sotirov 2017), this can lead to acceptance problems, especially in privately-owned forests (Seintsch et al. 2018; Tiebel et al. 2021a, 2021b). One possible instrument for implementing nature conservation measures in private forests can be contractually regulated individual agreements (contract-based conservation). The contract should specify the type and scope of certain nature conservation measures, be mutually terminable, and provide information on fair and adequate compensation payments (Demant 2018; Lutter and Paschke 2018). So far, in Germany, forest conservation measures are largely implemented through regulatory instruments and sometimes through voluntary commitments. For this reason, politics and science have been calling for a strengthening of contract-based forest conservation for some years now (Güthler et al. 2005; BMUB 2007; Franz et al. 2018b; Miljand et al. 2021). In 2021, the Federal Government in Germany adopted a new edition of the funding principles of the Joint Task Improvement of Agricultural Structure and Coastal Protection (BMEL 2021b). The Joint Task is the most important national funding instrument for supporting agriculture and forestry, developing rural areas as well as improving coastal and flood protection. With regard to forests, various measures and actions are promoted with federal funds. In addition to promoting measures to cope with the consequences of extreme weather events, semi-natural forest management, forestry infrastructure and initial afforestation, this now includes the funding of contract-based forest conservation (BMEL 2021b). However, contract-based forest conservation in privately-owned forests in Germany is still not common and successful implementation is linked to certain prerequisites, such as a solid foundation of trust, the involvement of committed intermediaries, result-based payments, success bonuses as well as the identification of suitable indicators (Franz et al. 2018a). The reasons for this insufficient consideration of contractually agreed nature conservation services in private forests and their financial compensation are manifold and require closer examination.

1.4 Forest management and conservation in Germany facing climate change

Forest management should as its best should be ecologically, economically and socially sustainable, and should thereby ensure the long-term provision of ecosystem functions and services (Lindenmayer and Hunter 2010). The principle of modern multifunctional and sustainable forestry is to be understood as a concept in which many, possibly even competing services of forests are provided on the same area and at the same time (Sutherland and Huttunen 2018). A multifunctional forest should offer a range of services such as timber supply, conservation of forest biodiversity, recreation and tourism, carbon storage and water retention (Benz et al. 2020).

Future forest conservation management depends, on the one hand, on the willingness of forest owners to implement and value nature conservation measures in their forests and, on the other hand, on the availability of suitable compensatory payment schemes. In addition, the uncertainties of future climatic developments pose increasing challenges, e.g. in forest conversion and tree species selection. Climate change is expected to cause an increase in extreme climatic conditions, such as an increase in disturbance size, severity, and frequency (e.g. Turner 2010; Seidl et al. 2017; Senf and Seidl 2021a). An ecological disturbance is “any relatively discrete event in time that disrupts ecosystems, community, or population structure and changes resources, substrate availability, or the physical environment” (Pickett and White 1985: 7). Disturbances can alter ecosystem services and are important drivers for a sustainable and semi-natural forest management (Thom and Seidl 2016; Kuuluvainen et al. 2021). The importance and value of natural disturbances for forest biodiversity is widely recognised (e.g. Lindenmayer and Hunter 2010; Beudert et al. 2015; Thom and Seidl 2016; Thorn et al. 2018, 2020; Seidl et al. 2019). Natural and anthropogenic disturbances (e.g. drought, fire, wind throw, insect outbreak, and logging) can create early-successional forest ecosystems that are characterised by a high species and structural diversity and therefore are of high ecological importance (Swanson et al. 2011).

The need to protect forests globally in the face of the looming climate crisis is widely recognised. At the UN Climate Change Conference of the Parties (COP26) in Glasgow in 2021, the member states reaffirmed their commitment to the Paris climate protection agreement to limit global warming to a maximum of 1.5 degrees Celsius compared to the pre-industrial levels, and agreed to revise their respective climate protection targets by 2030 (United Nations 2021). To reduce the greenhouse gas emissions the Parties also agreed to halt and reverse deforestation and land degradation. Some went even further, with 141 countries emphasising "the critical and interdependent roles of forests of all types, biodiversity and sustainable land use in enabling the world to meet its sustainable development goals; to help achieve a balance between anthropogenic greenhouse gas emissions and removal by sinks; to adapt to climate change; and to maintain other ecosystem services" (UKCOP26 2021). Even though the Parties do not specify how exactly they intend to halt and reverse forest losses in particular, this agreement underlines the importance of global forest conservation in the face of climate change. At the international level (e.g. Bolte et al. 2009; FAO 2013; Lindner et al. 2014; Keenan 2015; Krumm et al. 2020; Mauser 2021), but also at the German level (e.g. LWF 2007; BMEL 2019b; DVFFA 2019; BfN 2020; DNR 2021; WBW 2021), a large number of stakeholders have been addressing forest management in the face of climate change in recent years. These concepts and guidelines, in general, call for a future forest management that

- does not overburden the natural resilience of forests,
- promotes their stress resistance and adaptability to future changes,
- preserves natural biodiversity and genetic diversity,
- ensures the continuous provision of ecosystem functions and services of forests, also in the long term for future generations as a provision of existence,
- promotes mixed forests with a site-specific choice of tree species,
- and ensures a high proportion of native tree species where possible.

The elaboration of these objectives and the specific derivation of practical recommendations for action are implemented in forest stand planning. Depending on the site conditions, silvicultural management plans provide indications on the composition, mixture and choice of tree species and define corresponding long-term economic yield goals. A nature conservation assessment of this economically oriented silvicultural planning has not been carried out so far. Given the uncertainties of climate change, this is all the more important in order to maintain the resilience and adaptability of tree species and forests in the long term. Semi-natural, species-rich mixed forests with site-suitable native tree species have proven to be particularly adaptable to extreme climatic conditions such as droughts and storms (BfN 2020; BMEL 2021a).

Therefore, an adaptation of silvicultural planning with regard to the nature conservation impacts of tree species selection is urgently needed. In addition, more financial incentives and support systems should be created to reward the socially important ecosystem services for climate protection, water conservation, nature conservation and recreation. It is undisputed that forests will have to cope with new climatic conditions in the future and at a rate that may exceed their natural development and adaptation capacities. In view of the climate challenges, it may be necessary to review and, if necessary, adapt the justifications and validity of existing protection concepts and conservation objectives. However, this should only be done with sufficient scientific evidence, so that existing conservation objectives are not carelessly abandoned, which requires careful consideration as this is still subject to great uncertainties.

Given the climatic uncertainties and the related challenges in future silvicultural planning, spatial niche and species distribution models are a helpful tool for predicting the species composition of forests or suitable areas for the occurrence of forest tree species (e.g. Kölling 2007; Hickler et al. 2012b; Beierkuhnlein et al. 2014; Walentowski et al. 2017; Mette et al. 2021). However, these models often have limited explanatory power because, in addition to abiotic environmental variables, they have often only been validated based on the current distribution of species and thus usually do not cover the entire spectrum of the species' possible distribution ranges (Ferrier and Guisan 2006; Beierkuhnlein et al. 2014). Nevertheless, these species distribution models are used in spatial conservation planning and in the designation of protected areas networks (Lawler et al. 2011; Domisch et al. 2019). Therefore, their importance is increasing, especially in discussions and debates on the maintenance and justification of existing conservation objectives, such as within Natura 2000 protected areas and their associated habitat types (Dempe et al. 2012; Sofaer et al. 2019).

1.5 Thesis structure and problems addressed

The aim of this doctoral thesis is to compare and analyse objectives and values in German forest conservation concepts, using an interdisciplinary approach that takes into account aspects of ecology, politics and society. The practicability and feasibility of their application were assessed and potential uncertainties were identified to improve their informative value and validity. The thesis provides an evaluation of the state of nature conservation in forests in Germany and assesses the current and future challenges for nature conservation. It presents new methods for the classification of nature conservation objectives and for the assessment of conservation objects in forests. Therefore, I have identified and discussed existing problems in the implementation of nature conservation measures in forests and have provided revised assessment frameworks using several examples. Finally, I have discussed possible changes in conservation responsibility in the face of climate change.

Conservation objectives can only be achieved and measures implemented successfully if there is as much consensus as possible among stakeholders involved in forest conservation. **Chapter 2** therefore examines whether there are differences between stakeholders with regard to conservation objectives and objects, and whether there is sufficient knowledge transfer between the various actors and scales. For this purpose, a reference framework of German forest conservation objectives is developed in order to classify objectives, to systematically analyse contemporary conservation concepts in terms of completeness and consistency, and to search for commonalities and differences between the concepts.

In order to achieve established forest conservation objectives, it is useful to define forest conservation objects and assess their nature conservation value. Since half of the forest area in Germany is privately-owned, the implementation of forest conservation objectives in private forests is not a matter of course and is tied to financial compensation, for example within the framework of contractually agreed forest conservation services. This challenge requires a comprehensive system of suitable measures. **Chapter 3** therefore deals with the question of how forest conservation objects can be assessed in terms of their nature conservation value, in particular, with regard to their need for, and worthiness of, protection. Furthermore, this chapter examines which forest conservation objects are suitable for effective contract-based conservation in privately-owned forests, and over which contractual periods should measures reasonably be funded.

The protection of forest biodiversity cannot be achieved solely through specifically defined nature conservation objectives and measures. Rather, regular forest management must be as nature conservation-compliant as possible, in particular in times of climate change, and protect forest biodiversity through semi-natural silvicultural management. The choice of tree species and the derivation of stand-specific forest development types are particularly important in this context. As nature conservation aspects are usually given less consideration in this silvicultural planning, improvements are needed here. **Chapter 4** therefore determines the nature conservation value of tree species and predetermined forest development types and draws conclusions for future forest management.

In times of climate change, existing conservation concepts and objectives in forest conservation may be confronted with the question of whether their conservation justification can be maintained or whether they need to be adapted. It is therefore be necessary to review the validity of conservation objectives also within established protected area systems such as the European

Natura 2000 protected areas network. This problem is addressed in **Chapter 5** and it is examined whether the favourable conservation status of selected forest habitat types of the Habitats Directive remains a valid nature conservation objective faced with the existing uncertainties of climatic developments. The present conservation justification is discussed and a possible future trend development of the conservation status of Natura 2000 forest habitat types is given.

The last **Chapter 6** summarises the main results of the previous four chapters of this doctoral thesis on the state of nature conservation in German forests, on diverging nature conservation value assessments and on the problems in implementing nature conservation measures in forests. Possible consequences for forest and nature conservation, but also for politics and society are discussed. Furthermore, the new findings are compared with results from interdisciplinary conservation sciences and placed in a wider context. The chapter ends with a comprehensive conclusion and explains possible future prospects for sustainable forest conservation management that preserves the values of forest biodiversity even in the face of climate change uncertainties.

CHAPTER 2

Seeking consensus in German forest conservation: An analysis of contemporary concepts

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2.1 Abstract

Setting operational conservation objectives is a major challenge for effective biodiversity conservation worldwide. To analyse forest conservation objectives in Germany in a transparent manner and to achieve a consistent and consensual framework, we systematically classified conservation objectives suggested in concepts by different stakeholders. We analysed 79 biodiversity and forest conservation concepts of different stakeholder groups at various scales and applied textual content analysis and Dirichlet regression to reach a high degree of transferability and applicability. Our analysis revealed a broad consensus concerning forest conservation across stakeholders and scales, albeit with slight differences in focus, but we detected a scale-related mismatch. A wide array of conservation objectives covered social, biotic and abiotic natural resources. Conservation of species, ecosystems and structural elements in forests were found to be of primary importance across stakeholders and scale levels. Shortcomings in the conservation concepts were found in addressing genetic diversity, abiotic resources and socio-cultural objectives. Our results show that problems in forest conservation may be rooted in trade-offs between aims, targeting mismatch across scale levels and insufficient implementation of objectives.

Keywords:
biodiversity, conservation concepts, conservation objectives, Dirichlet regression, forest conservation, stakeholders, spatial scales, scale mismatch, targets

2.2 Introduction

Twenty-five years after coming into force, the targets of the Convention on Biological Diversity (CBD) are yet to be reached. National and international strategy papers on nature conservation and sustainability have proliferated in the meantime (Hagerman and Pelai 2016; BMU 2018). However, implementation is often controversial and not all measures have been successful in achieving CBD targets. There is general agreement amongst conservationists, that biodiversity and its services to human well-being are still at high risk and that many actions have not succeeded in reducing these risks. For instance, Tittensor et al. (2014) concluded that, by 2020, the pressures affecting biodiversity will still be increasing and Ripple et al. (2017) warned that the global state of biodiversity conservation is more than worrying. Human-induced biodiversity loss is a matter of concern for all societal groups and from global to local levels (Masood 2018). It is beyond doubt that biodiversity decline is driven chiefly by unbridled habitat destruction and land use intensification (MEA 2005; CBD 2010; Tittensor et al. 2014; Vellend et al. 2017).

Effective conservation needs a consistent and comprehensive framework of conservation objectives. Such a framework should aim at preserving wildlife species, as well as ecosystems as a whole. Moreover, the sustainable production and use of natural products such as food, timber, minerals and other resources for human needs, as well as the non-material benefits of recreation, amenity, culture and science, are to be considered (Harley 1977). Perrings et al. (2011) emphasised that frameworks should indeed reflect and consider human well-being and the benefits people enjoy and gain by protecting biodiversity and securing its ecosystem services. To enhance biodiversity-friendly land use, it is crucial to develop nested knowledge systems (Cornell et al. 2013), which are harmonised across scales and groups of stakeholders (Peterson et al. 2018).

The limited success of nature conservation efforts can also be attributed to scale mismatches within frameworks of conservation objectives (Guerrero et al. 2013). Scale mismatches (temporal, functional or spatial) arise when social-ecological functions are disrupted across the scales of the managing social and environmental organisations and when environmental problems are the result of mismatches between the scales of human responsibility and natural resources (Lee 1993; Cumming et al. 2006). Within stakeholder groups (e.g. administrations, conservation associations, forest enterprises), conservation objectives should ideally be nested and harmonised across scales, enabling unimpeded conceptual transfer and exchange of knowledge. As ecological processes and ecosystem functions vary across scales (Peterson et al. 1998), overcoming scale mismatches is of particular importance for the successful implementation of conservation objectives (Ahlborg and Nightingale 2012; Paloniemi et al. 2012). It is essential to reveal framework inconsistencies and whether conservation objectives deviate amongst stakeholders and between spatial scales and, if so, in which respect (Guerrero et al. 2013). Several studies found that insufficient definitions of objectives and inconsistencies in frameworks are major obstacles for effective nature conservation (Tear et al. 2005; Kapos et al. 2008; Heink and Kowarik 2010; Marquard et al. 2013; Stafford-Smith 2014; Maxwell et al. 2015; Butchart et al. 2016; Meyer et al. 2016a). Different stakeholder expectations may be a major reason for such deficiencies. This study aims at bridging these obstacles by providing a conceptual contribution to the ongoing debate in nature conservation.

Multiple approaches exist to frame nature conservation, provide tools and justify actions (Mace 2014). The People and Nature approach tries to encompass ideas and disciplines by interrelating the protection of nature with the services it provides for human well-being (Carpenter et al. 2009; Mace 2014). In contrast, the Nature's Contribution to People approach, developed by the Intergovernmental Platform on Biodiversity and Ecosystem Services (IPBES), the Provisioning, Regulating and Maintenance and Cultural Ecosystem Services (CICES; Haines-Young and Potschin-Young 2018), look at nature conservation in a more utilitarian way. These approaches have a wider focus than the general ecosystem service framework (MEA 2005), as they also include social and cultural standards (Díaz et al. 2018).

In fulfilment of the obligations of CBD, article 6, Germany adopted a National Strategy on Biological Diversity, comprising 330 targets and around 430 measures (BMUB 2007), many of them involving forest ecosystems. Subsequently, individual German federal states as well as state forestry enterprises and non-governmental organisations published separate regional biodiversity and nature conservation concepts. In Germany, where forests cover approximately one third of the land area, close-to-nature forest management and sustainable use of forest products are priority components of these concepts. With respect to forest conservation, our overall objectives were

(1) to derive a comprehensive and conceptual reference framework of German forest conservation objectives based on contemporary concepts to classify and systematically analyse the conservation objectives in terms of completeness and consistency;
(2) to reapply the results to conservation concepts in search of commonalities and differences and to examine the comprehensive nature of concepts.

Assuming a wide range of different interests, we hypothesised considerable variation between the conservation concepts and objectives provided by different stakeholders but, nevertheless, scale-independent consensus (meaning a balanced knowledge transfer) within particular groups of stakeholders. Another aim was thus to verify unimpeded conceptual transfer of knowledge within stakeholder groups across scales.

2.3 Methods

2.3.1 Deriving a reference framework of conservation objectives

We define a conservation objective (CO hereafter) as the combination of a physical object of conservation, e.g. organisms, biotopes, soil or water resources and the properties of its desired state (target). We derived a comprehensive reference framework of CO by referring to the CBD (United Nations 1992a) and the German Nature Conservation and Landscape Management Act (BNatSchG, as amended on 29 July 2009). The BNatSchG, in its Article 1 (1), defines the purpose of nature conservation and landscape management as to "permanently safeguard (1) biological diversity, (2) the performance and functioning of the balance of nature, including the ability of natural resources to regenerate and lend themselves to sustainable use and (3) the diversity, characteristic features and beauty of nature and landscape, as well as their recreational value" (BMU 2010: 7). According to both CBD and BNatSchG, biological diversity is defined as the variability amongst living organisms, terrestrial, marine and freshwater and the ecological complexes of which they are part; this includes interactions within species, between species and communities, ecosystems and biotopes (United Nations 1992a).

For each objective, we defined six levels of potential hierarchical classification depth of COs (Table 1). Relationships between levels of COs were understood as functions and indicated separately. Each single observation within the framework of COs was described as a target. For instance, the target "forest bog ecosystem" was described by the cross-connected code NBEF(NAC), as bogs are ecosystems functioning as important long-term carbon sinks (Moore and Knowles 1989), hence contributing to climate protection. With this approach, we identified and described even rather complex and interlinked relationships, reflecting multi-layered environmental patterns and processes. Each single target received a code (a combination of letters) representing a certain level of the framework of COs.

At the first level of differentiation (general field of conservation), COs were classified into the categories socio-political (e.g. recreation, enhancement of tourism, stimulating financial funding for conservation, legal issues, awareness-raising) or nature conservation *sensu stricto*. For socio-political CO, no further differentiation was deemed necessary, but cross-connections were possible (Supplement S1). COs of nature conservation *sensu stricto* were grouped into abiotic and biotic objectives. The latter were further grouped to cover genetic, species and ecosystem diversity (in accordance with the CBD) and landscape diversity, as this is stressed in the BNatSchG. Our differentiation of abiotic and biotic natural resources is compatible with the CICES themes and classes of ecosystem services: provisioning, regulating and maintenance and cultural (Haines-Young and Potschin 2011; Haines-Young and Potschin-Young 2018).

Table 1: Classification framework of conservation objectives (for a detailed list see Supplement S1).

Level	Conservation objective	Specification	Code
1	General field of conservation	Socio-political	S
		Nature conservation *sensu stricto*	N
2	Field of natural resources	Abiotic environment	A
		Biotic environment	B
3	Mainly abiotic targets	Soil	S
		Water	W
		Climate	C
	Mainly biotic targets	Genetic diversity	G
		Species	S
		Ecosystems and biotopes	E
		Landscapes	L
4	Categories of natural resources	Processes	P
		Structures, elements	S
		Functions = cross-connecting various levels	F
5	Qualities and properties of natural resources	Diversity	D
		"Typicalness"	T
		Completeness, integrity	C
6	Management dependency	Self-sustaining	S
		Management-dependent, culture-bound	M

To give each objective more detail, we developed further levels concerning categories of natural resources, qualities and conditions of existence (Table 1). We distinguished between CO related to processes, structures or functions and further, by CO addressing diversity as such, typical features or integrity/intactness. At the final level, we differentiated between self-sustaining and management-dependent systems.

A specific code was assigned to each CO (Supplement S1). However, as the classification system had to deploy an operational level, some specific targets fall under the same generalised category and could not be detected separately. The code NBESTS, for example, comprises all targets concerning self-sustaining ecosystem structures.

Finally, individual target keywords were added to address more specific cases. For instance, the code NBESCS, addressing the integrity of self-sustaining ecosystems, was further detailed by the target keyword "protection of beech forest ecosystems". A detailed list of all target keywords and their assigned codes can be found in Supplement S2.

2.3.2 Textual content analysis

We conducted textual content analyses of 79 biodiversity and forest conservation concepts (for a detailed list of concepts, see Supplement S3). The concepts were collected via web-based literature research on the websites of different stakeholders. We selected and gathered all current concepts and strategies published until 2016, covering all relevant stakeholder groups. Single forest owners or private forest enterprises were not analysed, as they did not develop their own valid forest conservation concepts. Furthermore local or municipal groups were excluded as well to ensure comparability amongst all stakeholders.

We classified the stakeholders into three pre-defined groups; administrative institutions (e.g. ministries), nature conservation NGOs and state forestry enterprises (Table 2). Furthermore, each concept was assigned to a specific concept type: general nature and biodiversity conservation related concepts; specific forest conservation concepts; concepts addressing forest management and silviculture; general forest programmes; and specific concepts addressing veteran tree and deadwood management.

In terms of scale, the concepts were referable to international, national (Germany) or regional (federal states) levels (Table 2). For the definition of scale, we refer to Gibson et al. (2000) and Cash et al. (2006), who state that scale has many different dimensions (e.g. spatial, temporal, jurisdictional, institutional), each having different levels, “units of analysis that are located at different positions on a scale” (Cash et al. 2006). The international, national and regional levels refer to the jurisdictional scales (administrations, Cash et al. 2006).

Textual content analysis was used to identify and interpret the CO. Content analysis is a standard research method in social sciences and is used to gather and scrutinise text, the content of which “can be words, meanings, pictures, symbols, ideas, themes or any communicated message” (Neuman 2014: 371). Qualitative (descriptive) and quantitative (numerical) content analyses can be distinguished and the former may be “defined as a research method for the subjective interpretation of the content of text data through the systematic classification process of coding and identifying themes or patterns” (Hsieh and Shannon 2005: 1278). To ensure scientific transparency and reproducibility throughout the process of content analysis, all concepts were read twice. During that second stage, falsely assigned COs were reassigned to another code and neglected ones were newly described. Each identified CO was categorised according to the classification system.

Table 2: Categorisation of concepts with their abbreviations (Abbr.) and numbers of concepts per stakeholder group and jurisdictional scale level (Int = International, Nat = National, Reg = Regional).

Stakeholder	Abbr.	Concept type	Int	Nat	Reg
			Jurisdictional scale levels		
Concepts published by administrative or governmental institutions (e.g. ministries)	Instit	Biodiversity	3	2	14
		Forest conservation	1	-	2
		Forest management	-	-	3
		Forest programme	-	1	4
		Veteran trees and deadwood	-	-	-
Concepts originated under the leadership of state forestry enterprises	StateF	Biodiversity	-	-	-
		Forest conservation	-	-	10
		Forest management	-	-	14
		Forest programme	-	-	2
		Veteran trees and deadwood	-	-	6
Concepts published by environmental and nature conservation NGOs	NGO	Biodiversity	-	1	1
		Forest conservation	-	8	4
		Forest management	-	1	-
		Forest programme	-	-	1
		Veteran trees and deadwood	-	-	1

3.2.3 Data analysis

For each concept, all individual CO code assignments were treated as single observations and each hierarchical level of classification (Table 1) was analysed separately. The relative importance of a certain objective was determined by dividing the number of targets assigned to the CO by the overall sum of targets registered in the concept. This procedure generates vectors of shares of targets, distributed along the CO. Each vector contains non-independent elements and must be treated as one observation per concept. We used Dirichlet distribution as a statistical model suitable for describing the mechanisms underlying such observations. Dirichlet regression (Maier 2014) is a statistical method for working out differences in the expected composition of such vectors – that is, the collection of expected values (EV) of the vector elements – according to differences in explanatory variables. Presented results are based on the estimated EV and their uncertainties quantified in uncertainty intervals. If one of the observed vectors – belonging to one specific CO – contains an element that has a value of zero, this CO had no target mentioned in a concept. As all concepts in this study are related to nature conservation, we assumed that each of these underlie minimal shares of concern for each CO. Based on this assumption, we treated zero observations as "rounded zeros" (Martín-Fernández et al. 2003), which enabled us to lift zero values up to small positive values based on the transformation proposed by Maier (2014). This makes the use of Dirichlet regression possible, as it requires values between 0 and 1. We ran the Dirichlet regression model (Maier 2014) with concept type as categorical explanatory variables. All analyses were performed using the STAN Bayesian inference environment (Carpenter et al. 2017). For technical details of the model fitting process, see Sennhenn-Reulen (2018). Of the several prior choices described by Sennhenn-Reulen (2018), we used the N (0.5) prior for all model coefficients. Results are displayed as posterior means (Jaynes 2003) in percentages. With this standardised method, the relevance for forest conservation of each CO level was ensured for all concepts. Furthermore, the motivation for protecting and securing forest biodiversity of each stakeholder group could be assessed and evaluated.

With respect to orthogonality, it is critical that not all stakeholders are represented on all jurisdictional levels (Table 2). Thus, the analysis of the effect of the stakeholder group was conducted only at the regional level, reducing the sample size to 62 concepts. To analyse the effect of scale, only administrative concepts were assessed, reducing sample size to 30. In this stakeholder group, we expected content-related harmonisation across the levels.

To further analyse the degree of specification within the stakeholder group of administrative institutions, a level-of-detail-analysis was conducted. To allow for sufficient specification, we restricted the analysis to biotic COs (genes, species, ecosystems and landscape, see Table 1) at the third level. The level of detail was equal to the maximum hierarchical level reached (Table 3). The analysis was conducted for each biotic CO separately and mean specification degrees were calculated for each concept. For the analysis of the keywords, counts or mentions (presence/absence) per concept were calculated.

Table 3: Specification degree of conservation objectives.

Conservation objective	Level of Detail
No further specification of biotic objective	0
Categories of natural resources	1
Qualities and properties of natural resources	2
Management dependency	3

2.4 Results

2.4.1 Commonalities and differences between conservation concepts

The textual content analysis of 79 concepts revealed a broad range of single CO. In total, 170 individual targets (keyword combinations) were detected, with between 14 and 85 (mean 50) targets per concept. On average, a single concept covered 30% of the overall number of targets.

All stakeholders clearly prefer nature conservation *sensu stricto* instead of socio-political CO (Table 4). The EV for the social-political targets ranged between 8% and 11%. The highest values were found in the concepts of nature conservation NGOs (NGO) and administrative-governmental institutions (Instit), the latter significantly differing from state forestry enterprises (StateF). The highest percentages, albeit insignificant, of socio-political targets were found in national and international concepts.

Table 4: Proportions (expected values, in %) of the first and second classification level of conservation objectives.

		General field of conservation			Natural resources		
		Socio-political	**Nature conservation**	*****	**Abiotic**	**Biotic**	*****
Regional stakeholder	Instit (n=23)	10.3	89.7	*a*	8.0	92.0	*a*
	NGO (n=7)	11.1	88.9	*ab*	6.3	93.7	*a*
	StateF (n=32)	7.6	92.4	*b*	6.5	93.5	*a*
Jurisdictional scale	Int (n=4)	13.7	86.3	*a*	14.2	85.8	*a*
	Nat (n=3)	13.1	86.9	*a*	11.6	88.5	*ab*
	Reg (n=23)	9.5	90.6	*a*	6.9	93.1	*b*

Instit = Administrative-governmental institutions, NGO = Non-governmental organisations or nature conservation associations, StateF = State forestry enterprises, Int = International, Nat = National, Reg = Regional * = different letters indicate significant differences between stakeholder groups and between scale levels.

Our results show that COs consider protecting the biotic environment generally more important than abiotic resources (Table 4). Even though biotic targets are pursued at all spatial scales, regional institutions have significantly higher percentage values than international institutions. Ecosystem and species diversity are the main biotic COs in all analysed concepts, followed by, but with considerably lower percentages, the protection of landscape elements (Figures 1 and 2). In contrast, the protection of genetic diversity and of all elements of abiotic resources (soil, water and climate) is considered as of minor relevance. Within regional stakeholders (Figure 1), Instit had significantly lower proportions for the most frequently mentioned targets (protection of ecosystem and species diversity) than NGO and StateF. Regarding the protection of landscape diversity, Instit concepts had significantly higher values than the other stakeholder groups. Targets for the protection of soil, water, climate and genetic diversity were scarcely mentioned by all stakeholder groups, with EV mainly lower than 5%. Apart from soil-related COs, where Instit had lower proportions than the other two groups, no significant differences were found between the stakeholder groups. However, this difference is based on lower sample size and not discussed further.

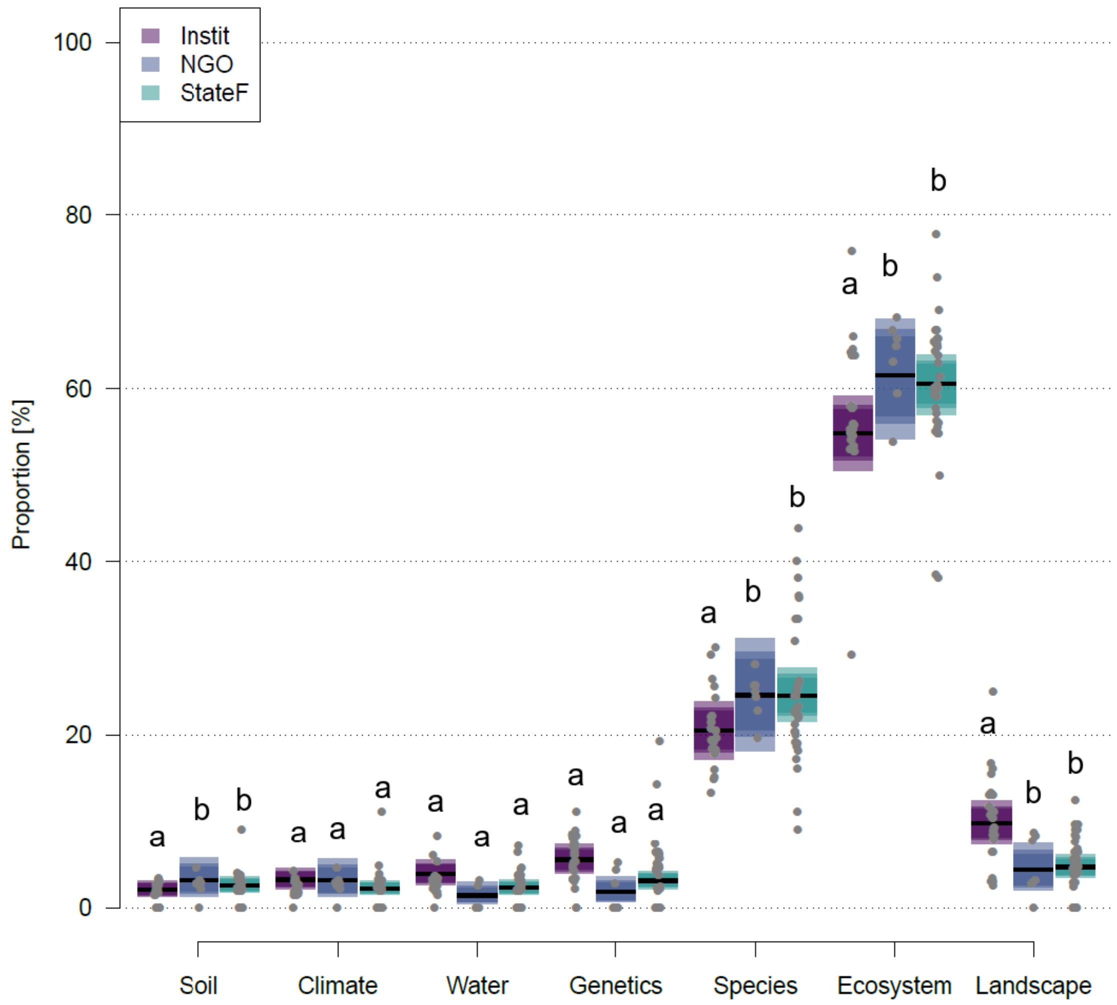

Figure 1: Stakeholder impact – posterior means for the third level of COs for the three stakeholder groups (n = 62). Different letters indicate significant differences between stakeholder groups (Instit = administrative-governmental institutions, NGO = environment or nature conservation NGOs, StateF = State forestry enterprises). Displayed are the expected value (black line), the 99% (light), the 95% (medium) and the 90% (dark) uncertainty intervals.

Regarding the scale effect, regional concepts exhibited a smaller range than the other levels (Figure 2). For international institutions, the protection of ecosystems turned out to be significantly less important than for national and regional institutions. Species and ecosystem protection were similarly relevant in international concepts, whereas in national or regional concepts, the protection of species was less frequently mentioned. The protection of landscape elements was found to be of minor importance at all levels. With decreasing scale level, the necessity for protecting genetic diversity and abiotic resources was noted decreasingly, although this effect was not significant.

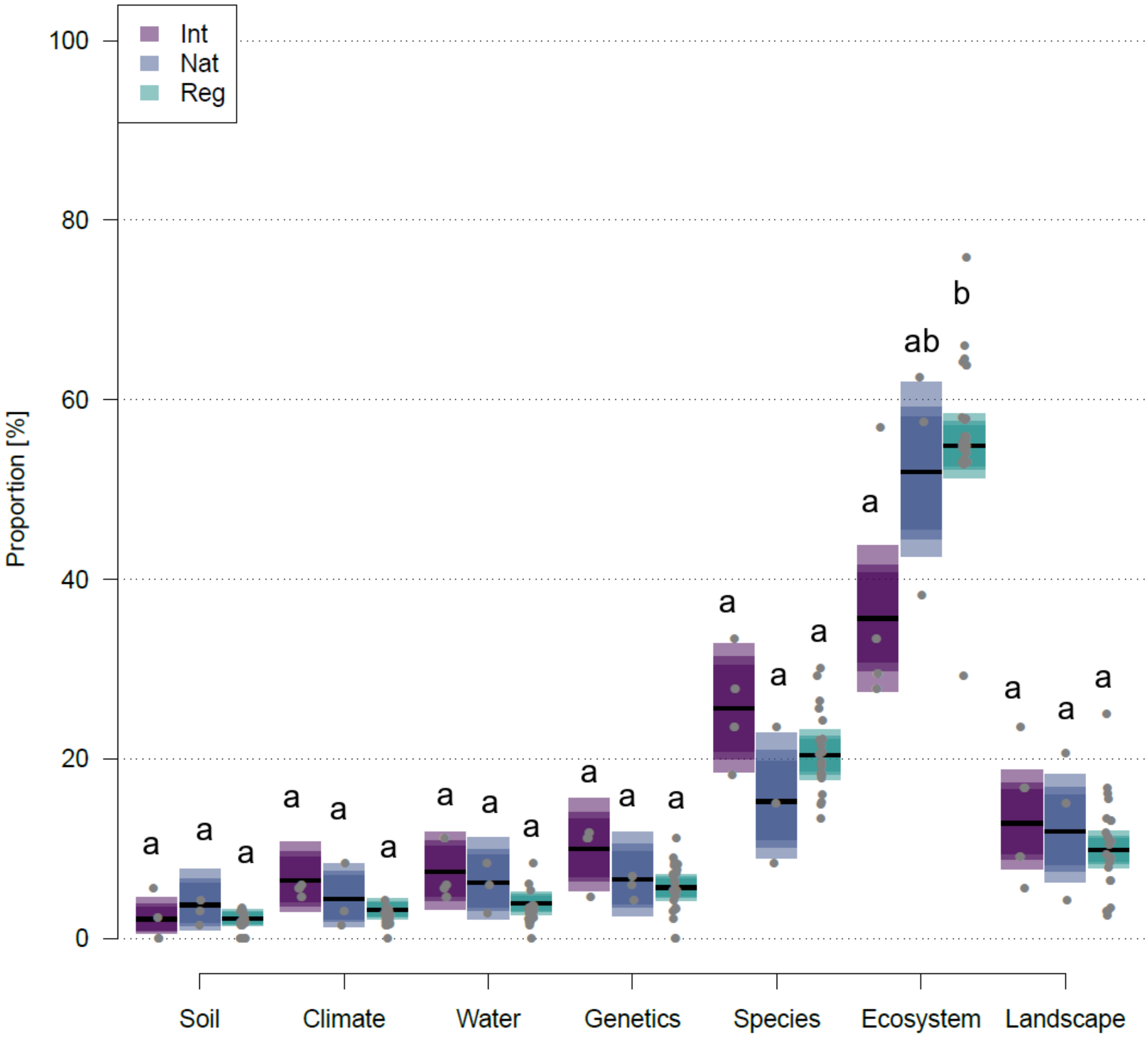

Figure 2: Jurisdictional scale effect – posterior means for the third level of COs for the three spatial scales (n = 30). Different letters indicate significant differences between scales (Int = International, Nat = National, Reg = Regional). Displayed are the expected value (black line), the 99% (light), the 95% (medium) and the 90% (dark) uncertainty intervals.

The results concerning the category (Table 5), quality (Table 6) and conditions of existence (Table 7) showed that the general focus in all concepts – regardless of the specific stakeholder group or scale level – lies in protecting diverse and naturally self-sustaining structures of forest ecosystems. Targets for the protection of processes or natural dynamics (fourth level: e.g. natural forest cycles; natural forest regeneration; habitat continuity) were the least mentioned by the stakeholders, with NGO having significantly higher percentage values than Instit and StateF (Table 5). For international institutions significantly lower values regarding natural dynamics protection were found than for regional ones.

The significantly highest percentages of targets with functions/cross-connections to other CO levels were found in international concepts. Cross-connections were either in relation to socio-political targets (e.g. a social responsibility to protect species; forest habitats as a place for recreation and tourism) or to abiotic targets (e.g. preservation or development of climate-resilient forest stands; water supply by forests). Here, StateF had significantly lower percentages than NGO. In general, protecting particular elements and structures (e.g. specific forest or species communities; habitat trees; biotope types; single species) plays a major role across almost all stakeholders and levels. However, StateF and Instit emphasise the protection of structural elements significantly more than NGO. This was also true at the regional level and partly so at the national level.

Table 5: Proportions (EV, in %) of the fourth level to describe the categories of conservation objectives.

		Functions/ cross-connections	*	Processes	*	Structures, elements	*
Regional stakeholder	Instit (n=23)	24.7	*ab*	14.0	*a*	61.3	*a*
	NGO (n=7)	28.3	*a*	20.8	*b*	50.9	*b*
	StateF (n=32)	22.6	*b*	13.9	*a*	63.5	*a*
Jurisdictional scale	Int (n=4)	49.4	*a*	3.3	*a*	47.4	*a*
	Nat (n=3)	30.3	*b*	12.3	*ab*	57.5	*ab*
	Reg (n=23)	25.0	*b*	14.6	*b*	60.4	*b*

Instit = administrative-governmental institutions, NGO = environmental and nature conservation NGOs, StateF = State forestry enterprises, Int = International, Nat = National, Reg = Regional, * = different letters indicate significant differences between stakeholder groups and between scale levels.

The fifth level describes particular qualities of COs (Table 6), focusing either on diversity (e.g. habitat or species diversity), qualitative characteristics (particular forms or features) or on attempting completeness, integrity or intactness of the CO. Such targets were commonly mentioned in all concepts. Significant differences were found between scale levels but not between stakeholder groups. At the international level, the main target was to protect a maximum degree of diversity. At national and regional levels, significantly lower percentages of this target were found. Generally, the aim to protect typical or complete qualities of COs was found to be of relatively low priority at all levels, with the significantly lowest EV at the international level (Table 6).

Table 6: Proportions (EV, in %) of the fifth level to describe the qualities of conservation objectives.

		Diversity	*	"Typicalness"	*	Completeness	*
Regional stakeholder	Instit (n=23)	53.6	*a*	40.7	*a*	5.6	*a*
	NGO (n=7)	47.2	*a*	49.5	*a*	3.3	*a*
	StateF (n=32)	56.2	*a*	39.9	*a*	3.9	*a*
Jurisdictional scale	Int (n=4)	76.7	*a*	20.7	*a*	2.6	*a*
	Nat (n=3)	46.5	*b*	43.1	*a*	10.5	*b*
	Reg (n=23)	53.6	*b*	40.6	*a*	5.8	*b*

Instit = administrative-governmental institutions, NGO = environmental and nature conservation NGOs, StateF = State forestry enterprises, Int = International, Nat = National, Reg = Regional, * = different letters indicate significant differences between stakeholder groups and between scale levels.

On the sixth level, protecting self-sustaining biodiversity features was given priority across all stakeholders and scales (Table 7). This was particularly true for concepts by NGOs or at international level, which had the significantly highest percentage (EV) values. The maintenance of culture-bound and management-dependent systems was considered particularly important for Instit and StateF. Within institutions, it is more often addressed at the national and regional than at international level.

Table 7: Proportions (EV, in %) of the sixth level to describe the conditions of existence of conservation objectives.

		Management-dependent	Self-sustaining	*
Regional stakeholder	Instit (n=23)	22.2	77.9	*a*
	NGO (n=7)	9.2	90.9	*b*
	StateF (n=32)	20.5	79.5	*a*
Jurisdictional scale	Int (n=4)	7.4	92.6	*a*
	Nat (n=3)	25.2	74.8	*b*
	Reg (n=23)	21.5	78.5	*b*

Instit = administrative-governmental institutions, NGO = environmental and nature conservation NGOs, StateF = State forestry enterprises, Int = International, Nat = National, Reg = Regional, * = different letters indicate significant differences between stakeholder groups and between scale levels.

2.4.2 Degree of specification for administrative concepts

We assumed that the degree of specification would increase from the international to the regional level. However, this was not the case for COs related to genetic diversity and only weakly so for species and landscape diversity (Figure 3). Here, levels of detail mainly remained at the fifth overall level (Table 1). A clear, scale-dependent increase of specification could only be confirmed for the CO ecosystems. With respect to the CO landscape, the range is prominently higher at the regional than at the national and international levels.

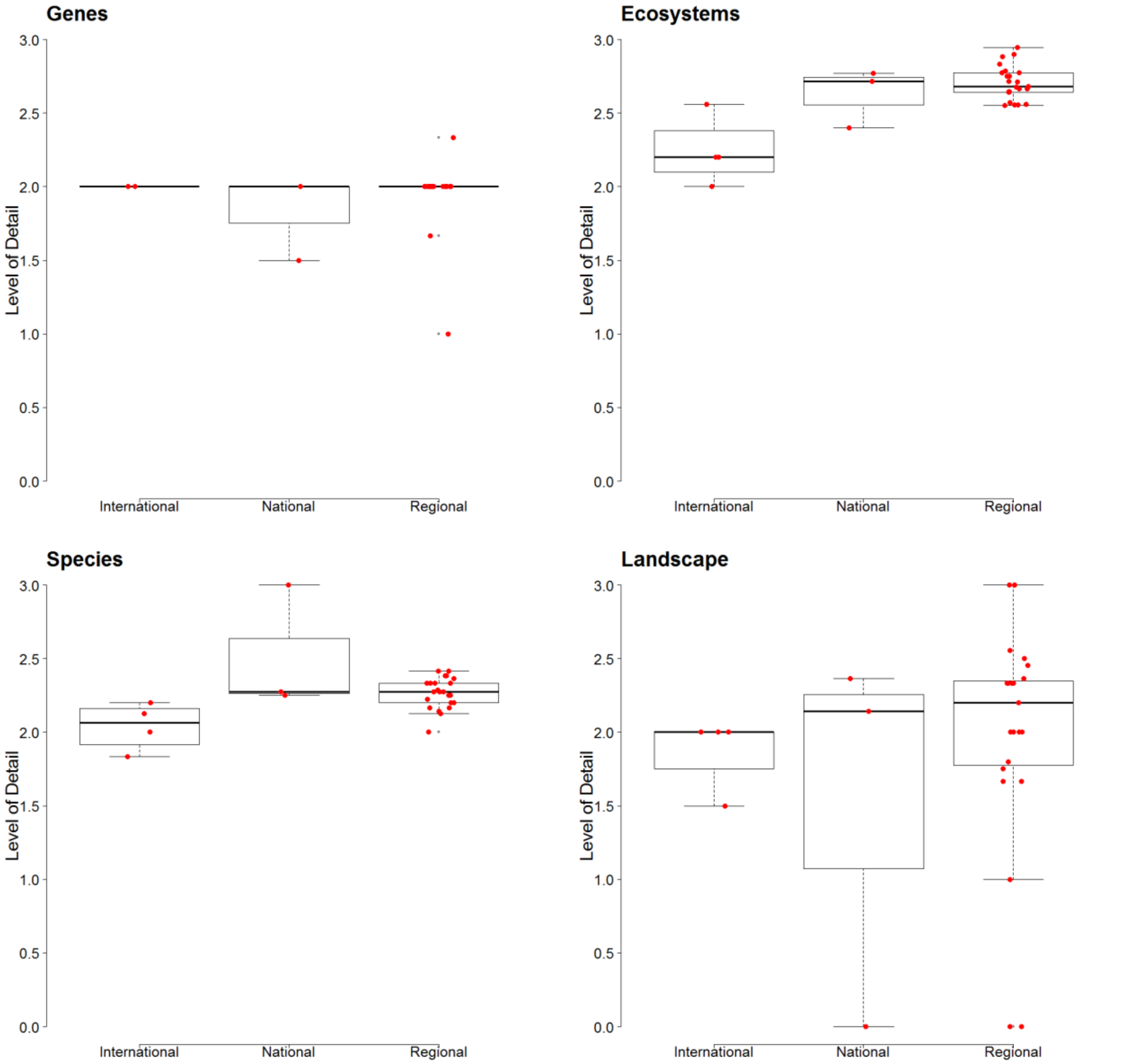

Figure 3: Level of detail (specification degree) for the four elements of biodiversity, genes, species, ecosystems and landscape, in relation to their scale levels (international n = 4, national n = 3 and regional n = 23).

2.4.3 Assessment of forest conservation target keywords

We distinguished a total of 107 target keywords in the concepts (Supplement S3). While concepts of international administrations cover only 18% of all possible keywords, national ones included 40% and regional ones 44%. NGO and StateF generally cover about 30% and Instit 44% of all possible keywords. The protection of habitats was the most frequently mentioned target included in all concepts (Table 8). Targets such as the maintenance of deadwood in forest ecosystems, sustainable forestry, the social obligation to protect and secure species habitats, the implementation of a close-to-nature forest management and the protection of habitat trees were also very frequently mentioned. With on average approximately 60 mentions, the preservation of protected areas, as well as of habitats and species in the EU Natura 2000 network of conservation areas, also played a major role in the concepts. Keywords concerning the protection of particular forest biotopes (e.g. wooded heathland or fir forests) and of forest attributes with carbon sink functions (e.g. deadwood and old-growth forests) were comparatively rarely mentioned.

Table 8: Absolute and percentage frequency of the most important keywords for all concepts, for administrative-governmental concepts at all levels and for regional concepts of all stakeholder groups, respectively (only keywords with > 40 mentions for all concepts are listed).

Keyword	All concepts (n = 79)	%	Administrative concepts (n = 30)	%	Regional concepts (n = 62)	%
Habitat protection	75	94.9	28	93.3	59	95.2
Deadwood in forest ecosystems	67	84.8	24	80.0	53	85.5
Sustainable forestry	65	82.3	27	90.0	50	80.6
Social obligation for habitat protection	65	82.3	21	70.0	51	82.3
Close-to-nature forestry	63	79.7	23	76.7	52	83.9
Habitat trees	63	79.7	20	66.7	52	83.9
Protected areas	62	78.5	26	86.7	46	74.2
Natura 2000 habitats	61	77.2	25	83.3	49	79.0
Natura 2000 species	59	74.7	24	80.0	47	75.8
Semi-natural forests	59	74.7	24	80.0	46	74.2
Rare species	59	74.7	20	66.7	46	74.2
Forest structures	58	73.4	19	63.3	48	77.4
Naturally developing forests	58	73.4	20	66.7	46	74.2
Natural regeneration	54	68.4	19	63.3	45	72.6
Hunting	53	67.1	22	73.3	43	69.4
Natural forest reserves	52	65.8	18	60.0	42	67.7
Biotope network	51	64.6	26	86.7	40	64.5
Wetlands	51	64.6	20	66.7	41	66.1
Deadwood-dependent species	49	62.0	15	50.0	42	67.7
Forests developing stages	49	62.0	17	56.7	42	67.7
Old-growth forest	49	62.0	16	53.3	39	62.9
Species stepping stones	49	62.0	20	66.7	37	59.7
Forest edges	48	60.8	16	53.3	39	62.9
Beech forests	46	58.2	16	53.3	37	59.7
Mixed forests	46	58.2	22	73.3	41	66.1
Rare tree species	45	57.0	16	53.3	38	61.3
Bogs	44	55.7	21	70.0	38	61.3
Riverine systems	44	55.7	24	80.0	36	58.1
Traditional forest management	44	55.7	16	53.3	36	58.1
Certification	42	53.2	19	63.3	32	51.6
Forest conservation financing	42	53.2	18	60.0	28	45.2

Certain differences between administrative-governmental concepts (found at all scale levels) and between regional concepts (found in all different stakeholder groups) are worth mentioning. Regional concepts pay more attention to the protection of specific forest elements, such as habitat trees, deadwood-dependent species and old-growth forests. Administrative-governmental concepts, on the other hand, stress the importance of landscape- and connection-related elements, such as biotope networks, species stepping stones and riverine systems, while emphasising the need to finance forest conservation. Although not shown in Table 8, some keywords were non-exclusively claimed by all members of a specific stakeholder group or scale level. International institutions invariably mentioned habitat protection, sustainable forestry and ecosystem services. Likewise, national institutions all claimed sustainable forestry, biotope networks and the maintenance of protected areas, wildlife species and semi-natural forests. All NGOs pursue the purpose of habitat protection, protecting natural forest development and designating protected areas. Regional concepts emphasise specific forest conservation related keywords of local scope, such as the protection of deadwood and habitat trees, as well as close-to-nature forestry. This was particularly true for StateF and NGO. In the concepts of regional institutions, more general nature conservation statements were made, such as protecting Natura 2000 habitats and expanding biotope networks.

2.5 Discussion

2.5.1 Deriving and applying frameworks of conservation objectives

Many researchers examined and reviewed nature conservation concepts in general and the implementation of nature and forest conservation objectives in particular (Pullin et al. 2004; Sutherland et al. 2004; Pullin and Stewart 2006; Moilanen et al. 2014; Morales-Hidalgo et al. 2015; Ulloa et al. 2018). Amongst their findings was that it requires interdisciplinary collaboration, the integration of all fields of biodiversity research and a unifying frame of reference to be effective in conservation. As there is no review of forest conservation that could be used as a generalised reference frame, the framework of forest COs we derived may serve as such a reference system and moreover contribute to an improved communication of this often emotionally discussed topic (Scherzinger 1996; Winkel et al. 2005; Meyer 2013a).

The framework proved suitable in reviewing 79 concepts of different stakeholder groups and across different scale levels. Universal validity with respect to German nature conservation in forests is achieved due to the fact that our analysis is firmly based on the common ground of the CBD and the BNatSchG. The frame may be used to encompass all possible objectives in nature conservation and cultural and natural objectives alike. It may be adopted in various fields of conservation science, despite its presently narrow focus on German forests. Our framework is in line with the initially-mentioned approaches to widely conceive nature conservation (CICES, People and Nature, Nature's Contribution to People). It is, however, constrained to an overall level, requiring further implementation in practice.

The assignment of keywords helps to acquire higher degrees of detail and to overcome the disadvantage of abstraction and is important in specifying CO, making the framework more applicable. Nevertheless, some constraints remain, as further implementation also means setting priorities and identifying synergies or trade-offs between single CO and hierarchical levels. This process, however, defies generalisation, as additional criteria need to be evaluated, such as the local or regional conservation status or the level of protection already gained. Thus, priority setting and the identification of trade-offs are not included in our framework of COs. However, the functional relationships can be regarded as an indication of existing synergies.

2.5.2 Commonalities and differences amongst forest conservation concepts

Our analyses of forest COs show that, in general, there is a broad consensus concerning forest conservation amongst different stakeholders in Germany. A wide variety of targets was found, covering social, biotic and abiotic natural resources. All stakeholder groups emphasised the protection and maintenance of diverse and self-sustaining structures, forest ecosystems, species and natural forest elements. Genetic diversity, landscape elements and abiotic resources are less considered. However, apart from this detected consensus amongst stakeholders and across scales, some differences in prioritising conservation objectives were identified, which do not fully accord with a comprehensive approach to nature conservation. The preamble of the CBD in 1992 already recognised the importance of comprehensive nature conservation concepts in postulating that the contracting parties are "conscious of the intrinsic value of biological diversity and of the ecological, genetic, social, economic, scientific, educational, cultural, recreational and aesthetic values of biological diversity and its components" (United Nations 1992a: 1).

National and international administrations take more account of social demands and the protection of abiotic resources. Since abiotic resources and their regulating services are an essential part of the natural environment (Dewulf et al. 2015), their protection and maintenance is crucial for the sustainable development and use of global biodiversity, including all elements of ecology, economy and society (United Nations 1992b). As the conservation of abiotic natural resources is scarcely mentioned by most stakeholders, conservation efforts in this field could be intensified. For internationally orientated concepts, the percentages found at the third level of CO (climate, soil, water, genes, species, ecosystems and landscape) were more balanced, underlining their more encompassing scope and validity. Although regional stakeholders consider the protection of landscape diversity more than others, COs concerning the protection of landscape and its components were rarely represented. Our results, concerning the under-representation of landscape protection and social-political requirements in the concepts, are in accordance with Petereit et al. (2017), who analysed the implementation of nature conservation in public forests in a manner analogous to ours. Their findings show that the main forest conservation target in concepts was the maintenance of biodiversity in general and that targets for the protection of natural resources were of marginal importance. Securing landscape and recreational values were the least claimed targets.

On the whole, concepts with a wider scale level turned out to be more balanced and consider functional relations. Regional concepts focus on concerns to be tackled by approved forest conservation methods and are more aware of management-dependent systems. Nevertheless, our results demonstrate that there is a lack of focus on the maintenance of culture-bound and management-dependent COs (e.g. cultural heritage and management-related habitat tradition). Even state forestry enterprises focus on natural and self-sustaining ecosystems, although initially we assumed they would pay more attention to management-dependent systems.

For an effective forest biodiversity conservation, it is important to identify synergies and trade-offs (Perrings et al. 2010; Di Marco et al. 2016). Our analyses of biodiversity and forest conservation objectives showed that COs with functions/cross-connections to other levels of COs, while indeed common in some concepts, could be more frequently considered by regional stakeholders. Providing and addressing these synergies is essential for fostering biodiversity protection. Our degree-of-specification analysis within administrative-governmental concepts confirmed the expected increase in specific COs with decreasing scale level for ecosystems only. The weaker response of species and landscape COs can be neglected, as the protection of ecosystem diversity was, with few exceptions, the most common COs in the concepts. Lindenmayer and Franklin (2002) stated that preventing species loss can be achieved by preventing ecosystem loss through maintaining habitat connectivity, landscape heterogeneity and stand structural complexity. Therefore, it seems wise to lay the primary focus on the conservation and restoration of forest ecosystem diversity, which simultaneously contributes to some extent to the protection of species and genetic diversity and serves the purpose of carbon storage in forest ecosystems.

The most frequently mentioned forest conservation keywords (e.g. protecting deadwood in forest ecosystems) reflect topics recently discussed amongst forest conservationists in Germany. The differences between the concepts concerning the frequency of specific keywords are, with few exceptions, not very pronounced, supporting the detected consensus amongst stakeholders in terms of forest conservation.

2.5.3 Knowledge transfer within stakeholder groups and across scales

As ecosystem functions, species and ecosystem processes occur at different temporal and spatial scales (Peterson et al. 1998; Paloniemi et al. 2012), the political and societal challenges are to consider these complex and multi-dimensional processes during governmental decision-making and biodiversity conservation planning (Lee 1993). Our analysis revealed that COs considering societal obligations, e.g. environmental education for effective biodiversity conservation, are under-represented in most concepts, especially surprisingly at the regional level. This imbalance is the more astonishing, as regional stakeholders, in particular, should be aware of what is needed to reconcile the local population with nature conservation. International administrative institutions follow more general nature conservation goals and differ markedly from regional administrations. The challenging transferability of national or regional level CO, on the one hand and broader scales (Europe or worldwide) on the other, can lead to an implementation mismatch.

The detected imbalance in target-consistency prompts us to reject our hypothesis that frameworks of COs within stakeholder groups are scale-independently consensual and confirms rather a slight scale mismatch indicating possibly insufficient transfer and exchange of knowledge. One-to-one transmissions of CO set at the international level may be problematic (Guerrero et al. 2013). The EU Habitats Directive, for example, has a broad spatial range of validity and aims at the conservation of species and habitats of Community concern, many of which are vulnerable. It is implemented at the local or regional level, though, with possible bottom-up consequences (Paloniemi et al. 2012). To overcome trade-offs between aims and targeting inconsistency across scale levels, stakeholders need to stress their conceptual clarity and facilitate an unimpeded transfer and exchange of knowledge.

2.6 Conclusions

Paloniemi et al. (2012) put in a nutshell where nature conservation needs to improve on: "analysing, understanding, and overcoming […] ecological scale-sensitivities requires combining ecological knowledge with information, awareness and experience of actors at various governance levels thus directly bridging science and policy discourses". Furthermore, it requires addressing the importance of protecting all types of ecosystems and their services within nature conservation concepts (Faith 2011; Perrings et al. 2011) as focal species and ecosystems differ in their response towards environmental changes and land-use management intensities at different scales (Nilsson 2009). Our study confirms the importance of integrating the various stakeholders, instruments and scales into conservation practices, taking into account their specific needs and requirements. With the increasing complexity of successfully implementing conservation actions across scales and different stakeholder groups, our framework of COs might qualify as a common basis for conservation priority targeting even beyond the context of German forest conservation and can help to manifest a consensual, precedential and long-term forest conservation.

Our analysis identified shortcomings concerning the unbalanced design of the concepts, where social-cultural demands and societal obligations, as well as the protection of landscape, genetic diversity and abiotic resources are not always covered adequately. These objectives might have been considered as subsidiary COs, implemented per se in the wake of ecosystem and species diversity conservation (umbrella effect). This study suggests to stakeholders that they reassess their conservation concepts in these fields. Improving the awareness of biodiversity and its values is essential to convince residents and other people concerned of the ecological and economic justification and the necessity and consequences of conservation actions.

Forest stakeholder concepts describe the purpose of conservation and restoration measures, such as to secure veteran and habitat trees, forest soil care, management of protected biotopes and species conservation programmes. The next step, specifying how to implement the measures, was taken only in 48 out of 79 concepts which provided information to this effect for certain forest COs. Without practical how-to recommendations, however, even well-founded objectives run the risk of remaining wishful thinking, a long way from implementation.

If, as our results indicate, stakeholders largely agree on the conservation objectives, the question remains why there are still considerable discrepancies in German forest conservation. Implementing forest conservation measures usually involves various stakeholders (owners, inhabitants, users, nature conservationists, administrators) with diverse and sometimes incongruent requirements. Therefore, the procedure of integrating all parties, which is so essential for the successful conservation and sustainable use of forest biodiversity, is to be improved. Mutual respect should be strengthened.

2.7 Author contribution

LD and PM conceived the presented idea and developed the theoretical background of the framework. LD carried out the framework implementation and performed the data analysis. HSR designed and run the statistical model. LD wrote the manuscript with support from PM, HW and EB. All authors discussed the results and contributed to the final manuscript.

2.8 Acknowledgements

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2.9 Supplementary materials

Framework for conservation objectives and its application.

ame	Position	Specification	Abbreviation	Code	Continue with p
eneral field of onservation		Socio-political	S	S	S*
		Nature conservation *sensu stricto*	N	N	N*
ocio-political	S*	Tourism, recreation	T	ST	Keyword or cros connection (N**
		Financial funding to protect biodiversity	F	SF	
		Legal issues or law	L	SL	
		Consciousness for and knowledge of biodiversity-values	C	SC	
		Role model function	M	SM	
		Biological education	E	SE	
		Sustainability	S	SS	
		Social obligation for habitat protection	O	SO	
ature conservation target field of natural resources	N*	Biotic target (protection of the living environment)	B	NB	NB*
		Abiotic target (protection of the lifeless environment)	A	NA	NA*
biotic targets	NA*	Protection of soil	S	NAS	keyword or cross connection (NB*
		Protection of climate	C	NAC	
		Protection of water	W	NAW	
iotic targets	NB*	Protection of genetic diversity	G	NBG	NB**
		Protection of species	S	NBS	
		Protection of ecosystems	E	NBE	
		Protection of landscapes	L	NBL	
ategories of natural esources	NB**	Processes	P	NB*P	NB***
		Structures, elements	S	NB*S	
		Functions = cross-connection to other levels	F	NB*F(***)	
ualities and properties of atural resources	NB***	Diversity	D	NB**D	NB****
		Characteristic typical form	T	NB**T	
		Completeness, integrity	C	NB**C	
anagement dependency	NB****	Self-sustaining	S	NB***S	keyword
		Management dependent, culture-bound	M	NB***M	

st of all target keywords, their German equivalent and their assigned codes according to the framework of conservation objectives.

	German equivalent	Cross-connection/specification	Code
ts	Buchenwälder		NBESTS
ts with climate protection function	Buchenwälder	Klimaschutzfunktion	NBEF(NA
work	Biotopverbund		NBL***
works for genetic exchange	Biotopverbund	Genetischer Austausch	NBGPD*
works with climate protection function	Biotopverbund	Klimaschutzfunktion	NBLF(NA
tection	Lebensraumschutz		NBLS**
es	Biotoptypen		NBEST*
	Moorwälder		NBESTS
	Moore		
limate protection function	Moore	Klimaschutzfunktion	NBEF(NA
ests	Hang- und Schluchtwälder		NBESTS
n	Zertifizierung		NBE***
ure forestry	Forstwirtschaft	Naturnah	N**F(S)
ure forestry for climate protection	Naturnahe Forstwirtschaft	Klimaschutzfunktion	NBEF(NA
ers	Binnen- und Küstengewässer		NBESTS
n of genetic populations	Genetischer Populationserhalt		NBGP**
itage	Kulturerbe		NB***M
dependent species	Totholz	Artenschutz	NBSSDS
n forest ecosystems	Totholz	Ökosystemschutz	NBESDS
with climate protection function	Totholz	Klimaschutzfunktion	NBEF(NA
services	Ökosystemdienstleistungen		NBE***
stepping stones	Wildtierkorridore und -trittsteine in Ökosystemen		NBEPDS
ecies	Endemische Arten		NBSST*
nt of new forest for climate protection	Waldneubegründung	Klimaschutzfunktion	NBEF(NA
nding of forest conservation	Waldnaturschutz	Finanzielle Förderung	NB*S(SF)
	Tannenwälder		NBESTS
forests	Auwälder		NBESTS
	Auen		NBES*S
with climate protection function	Auen	Klimaschutzfunktion	NBEF(NA
with water protection function	Auen	Wasserschutzfunktion	NBEF(NA
oping stages	Waldentwicklungsphasen		NBEPDS
mics	Walddynamik		NBEPDS
s	Waldränder		NBLSDM
ows	Waldwiesen		NBESDS
ction	Waldschutz		NBE***

ontinued

	German equivalent	Cross-connection/specification	Code
ctures	Waldstrukturen		NBESD
recreation	Wälder	Erholungsfunktion	NBEF(S
h climate protection function	Wälder	Klimaschutzfunktion	NBEF(I
h flood protection function	Wälder	Hochwasserschutzfunktion	NBEF(I
h immission protection function	Wälder	Immissonsschutzfunktion	NBEF(I
h soil protection function	Wälder	Bodenschutzfunktion	NBEF(I
h water protection function	Wälder	Wasserschutzfunktion	NBEF(I
rotection	Heimisches Pflanz- und Saatgut		NBGSD
ntinuity	Habitatkontinuität		NBEPT
tection	Schutz der Artenlebensräume		NBSS*
es	Habitatbäume		NBES*
sts	Heidewälder		NBEST
	Wildbesatz/Jagd		NBESC
es	Binnendünen		NBEST
mosaic	Landschaftsmosaik		NBLST
ected areas as surrogates for sustainability	Großschutzgebiete	Modellregionen für Nachhaltigkeit	N**F(S
ndent forest species	Lichtwaldarten		NBS*D
ndent tree species	Lichtbaumarten		NBS*D
ppropriate forests	Standortgerechte Wälder und Baumarten		NBEST
ppropriate forests for climate protection	Standortgerechte Wälder und Baumarten	Klimaschutzfunktion	NBEF(I
tats	Mikrohabitate		NBES*
sts	Mischwälder		NBESD
sts with climate protection function	Mischwälder	Klimaschutzfunktion	NBEF(I
forests	Bergwälder		NBEST
ional forestry	Forstwirtschaft	Multifunktional	N**F(S
ed forests	Mehrschichtige Wälder		NBESD
species	Standortheimische Baumarten		NBEST
species for climate protection	Standortheimische Baumarten	Klimaschutzfunktion	NBEF(I
0 habitats	Lebensraumtypen der Flora-Fauna-Habitat Richtlinie		NBES*
0 species	Arten der Flora-Fauna-Habitat und Vogelschutz Richtlinie		NBSS*
eiduous forests	Natürliche Laubwälder		NBEST
est communities	Natürliche Waldgesellschaften		NBEST
eneration	Waldnaturverjüngung		NBEPT
est reserves	Naturwaldreservate		NBEST
ests	Naturwälder		NBEST

ntinued

	German equivalent	Cross-connection/specification	Cod
age	Naturerbe		NB*
veloping forests	Wälder mit natürlicher Entwicklung		NBI
veloping forests role model function	Natürliche Waldentwicklung auf 10 % der Waldfläche der öffentlichen Hand	Vorbildfunktion	NBI
rming forestry	Forstwirtschaft	Naturgemäß	N**
forests	Naturnahe Wälder		NBI
	Eichenwälder		NBI
forest	Alte Wälder		NBI
forests for climate protection	Alte Wälder	Klimaschutzfunktion	NBI
apes	Offene Landschaftselemente		NBI
orest	Dauerwald		NBI
	Kiefernwälder		NBI
unities	Pflanzengesellschaften		NBS
ervation	Prozessschutz		NBI
eas	Schutzgebiete		N**
ommunities	Seltene Waldgesellschaften		NBI
	Seltene Arten		NBS
ecies	Seltene Baumarten		NBS
e communities	Regionaltypische Waldgesellschaften		NBI
s	Urwaldreliktarten		NBS
forests	Standorttypische Wälder und Baumarten		NBI
tree species	Standortgemäße Baumarten		NBI
ation for beech forests protection	Buchenwälder	Erhaltungsverantwortung	NBI
ation for habitat protection	Lebensräume	Erhaltungsverantwortung	NB*
ping stones	Wildtierkorridore und -trittsteine		NBS
ts	Fichtenwälder		NBI
nes for genetic exchange	Wildtierkorridore und -trittsteine für den genetischen Austausch		NBC
tems	Fließgewässer		NBI
forestry	Forstwirtschaft	Nachhaltig	NB*
sts	Sumpf- und Bruchwälder		NBI
orest management	Traditionelle Waldbewirtschaftung (Hute-, Mittel- und/oder Niederwälder)		NBI
diversity	Baumartenvielfalt		NBI
ed forest area	Unzerschnittene Waldfläche		NBI
ed landscape	Unzerschnittene Landschaft		NBI

German equivalent	Cross-connection/specification	Keyword
Stillgewässer		NBES*S
Feuchtgebiete		NBES*S
Wildnis		NBE*TS
Wildtierarten		NBSS*S

List of all concepts analysed in this study with their names, references, type of concept, assigned stakeholder group, jurisdictional scale level allocat
lication.

	Reference	Concept type	Stakeholder group	Scale leve
nservation - BUND Position 59	BUND -Association for the Environment and Nature Conservation Germany e.V.	Biodiversity concept	Associations and NGO´s	National
ty Conservation in Germany 2014 - ve Country Analysis for the Protection of ty	BUND -Association for the Environment and Nature Conservation Germany e.V. and NABU - Nature Conservation Association Germany e.V.	Biodiversity concept	Associations and NGO´s	Regional
lan for Biodiversity 2011–2020 and the ets	Secretariat of the Convention on Biological Diversity	Biodiversity concept	Institutions/ administrations	Internatio
ersity Strategy to 2020	European Commission	Biodiversity concept	Institutions/ administrations	Internatio
Agenda for Sustainable Development	United Nations	Biodiversity concept	Institutions/ administrations	Internatio
t for the Protection of Nature - BNatSchG, d on 29th of July 2009	Federal Ministry of Justice and Consumer Protection	Biodiversity concept	Institutions/ administrations	National
ational Strategy on Biodiversity	German Federal Ministry for the Environment, Nature Conservation, Building and Nuclear Safety	Biodiversity concept	Institutions/ administrations	National
n Strategy for the conservation of biological	Ministry of Agriculture, Forestry, Environment and Nature Conservation Thuringia	Biodiversity concept	Institutions/ administrations	Regional
tegy on Biodiversity	Senate Department for Urban Development Berlin	Biodiversity concept	Institutions/ administrations	Regional
f measures Biological Diversity rg	Ministry of Rural Development, Environment and Agriculture of the country Brandenburg	Biodiversity concept	Institutions/ administrations	Regional
on Strategy of the State of Baden- berg	Ministry of Rural and Consumer Protection Baden-Wuerttemberg	Biodiversity concept	Institutions/ administrations	Regional
iodiversity strategy and Bavarian y program 2030	Bavarian Ministry of the Environment and Consumer Protection	Biodiversity concept	Institutions/ administrations	Regional
odiversity strategy	Hessian ministry for environment, climate protection, agriculture and consumer protection	Biodiversity concept	Institutions/ administrations	Regional
ersity - Quality of the City of Hamburg, or the Development of Biodiversity	Free and Hanseatic City of Hamburg	Biodiversity concept	Institutions/ administrations	Regional
on and development of biological diversity nburg-Vorpommern	Ministry of Agriculture, Environment and Consumer Protection Mecklenburg-Vorpommern	Biodiversity concept	Institutions/ administrations	Regional
ty Strategy of the State of North Rhine- a	Ministry for Climate Protection, Environment, Agriculture, Nature and Consumer Protection of the State of North Rhine-Westphalia	Biodiversity concept	Institutions/ administrations	Regional

continued

	Reference	Concept type	Stakeholder group	Scale leve
ity strategy for Rhineland-Palatinate	Ministry of the Environment, Agriculture, Food, Viticulture and Forestry Rhineland-Palatinate	Biodiversity concept	Institutions/ administrations	Regional
ion 2020 - 20 points for the natural Schleswig-Holstein	Ministry of Agriculture, Environment and Rural Areas of Schleswig-Holstein	Biodiversity concept	Institutions/ administrations	Regional
biodiversity strategy	Ministry of Environment and Consumer Protection Saarland	Biodiversity concept	Institutions/ administrations	Regional
on biological diversity in the Free State of	Saxon State Ministry of Environment and Agriculture	Biodiversity concept	Institutions/ administrations	Regional
ity Strategy of the State of Saxony-Anhalt	Ministry of Agriculture and Environment of Saxony-Anhalt	Biodiversity concept	Institutions/ administrations	Regional
urope´s Forests	Ministerial Conference on the Protection of Forests in Europe	Forest conservation concept	Associations and NGO´s	Internation
ests - BUND Position 57	BUND -Association for the Environment and Nature Conservation Germany e.V.	Forest conservation concept	Associations and NGO´s	National
t plan for the forest of the future	BUND -Association for the Environment and Nature Conservation Germany e.V. and NABU - Nature Conservation Association Germany e.V.	Forest conservation concept	Associations and NGO´s	National
020 Perspectives and requirements from of view of nature conservation	NABU - Nature Conservation Association Germany e.V.	Forest conservation concept	Associations and NGO´s	National
s international responsibility: protecting ests in a network	Greenpeace e.V.	Forest conservation concept	Associations and NGO´s	National
he old beech forests	Greenpeace e.V.	Forest conservation concept	Associations and NGO´s	National
re conservation in the forest	NABU - Nature Conservation Association Germany e.V.	Forest conservation concept	Associations and NGO´s	National
sition: natural forest development until	NABU - Nature Conservation Association Germany e.V.	Forest conservation concept	Associations and NGO´s	National

ntinued

	Reference	Concept type	Stakeholder group	Scale level	Y
in private forests	NABU - Nature Conservation Association Germany e.V.	Forest conservation concept	Associations and NGO´s	National	2
s for the citizen forest in the 21st century	BUND - Nature Conservation in Bavaria e.V. and Greenpeace Bavaria	Forest conservation concept	Associations and NGO´s	Regional	2
ower Saxony's forests from the point of D, Greenpeace and NABU	BUND, Greenpeace and NABU Lower Saxony	Forest conservation concept	Associations and NGO´s	Regional	2
forests for Bavaria	Greenpeace e.V. and BUND -Association for the Environment and Nature Conservation Germany e.V.	Forest conservation concept	Associations and NGO´s	Regional	2
conservation in the forest - NABU calls t strategy for North Rhine-Westphalia	NABU - North Rhine-Westphalia	Forest conservation concept	Associations and NGO´s	Regional	2
th Rhine-Westphalia, our valuable ge	Ministry for Climate Protection, Environment, Agriculture, Nature and Consumer Protection of the State of North Rhine-Westphalia	Forest conservation concept	Institutions/ administrations	Regional	2
habitat protection in Natura 2000 state leswig-Holstein	State Office for Agriculture, Environment and Rural Areas Schleswig-Holstein	Forest conservation concept	Institutions/ administrations	Regional	2
Action for Species and Habitat Natura 2000 Forest Areas	Schleswig-Holsteinische Landesforsten	Forest conservation concept	State forestry departments	Regional	2
in the forests of North Rhine-Westphalia	Landesbetrieb Wald und Holz NRW	Forest conservation concept	State forestry departments	Regional	2
concept of the Bavarian State Forests	Bayerische Staatsforsten	Forest conservation concept	State forestry departments	Regional	2
iodiversity: Genetic Diversity in the uide to Forest Management in North halia	Landesbetrieb Wald und Holz NRW	Forest conservation concept	State forestry departments	Regional	2

S 3: continued

	Reference	Concept type	Stakeholder group	Scale level
versity in the forests	Landesforsten Rheinland-Pfalz	Forest conservation concept	State forestry departments	Regional
ting instruction: Forest nature conservation in ndesbetrieb Forst Brandenburg	Landesbetrieb Forst Brandenburg	Forest conservation concept	State forestry departments	Regional
ll concept of forest nature conservation	Landesbetrieb ForstBW	Forest conservation concept	State forestry departments	Regional
rvation Guideline	Landesbetrieb HessenForst	Forest conservation concept	State forestry departments	Regional
resters- 49 Species	Landesforstbetrieb Sachsen-Anhalt	Forest conservation concept	State forestry departments	Regional
nal biodiversity strategy and Beech forest am	SaarForst Landesbetrieb	Forest conservation concept	State forestry departments	Regional
erber Manifesto - Protection of Biodiversity gh Integrative Forest Management	FAUN -Initiative Forest Conservation Integrative	Forest handling concept	Associations and NGO´s	National
vision 2030: Objectives and principles of the gical forest management Brandenburg	Ministry of Infrastructure and Agriculture of the State of Brandenburg	Forest handling concept	Institutions/ administrations	Regional
ll concept for ecological forest management of ate forest in North Rhine-Westphalia	Ministry of Environment, Spatial Planning and Agriculture North Rhine-Westphalia	Forest handling concept	Institutions/ administrations	Regional
Strategy 2050 for the Free State of Saxony	Saxon State Ministry of Environment and Agriculture	Forest handling concept	Institutions/ administrations	Regional
line for the management of the state forest and ine for the Promotion and Conservation of versity in the State Forest of Saarland	SaarForst Landesbetrieb	Forest handling concept	State forestry departments	Regional
tive and principles of ecological forest gement	Landesbetrieb Forst Brandenburg	Forest handling concept	State forestry departments	Regional
to the management of the state forest of y-Anhalt under nature conservation aspects	Landesforstbetrieb Sachsen-Anhalt	Forest handling concept	State forestry departments	Regional
line for the Implementation of Goals and ples of Natural Forestry Mecklenburg- ommern	Landesforst Mecklenburg-Vorpommern	Forest handling concept	State forestry departments	Regional

continued

	Reference	Concept type	Stakeholder group	Scale level
E program of Lower Saxony	Niedersächsische Landesforsten	Forest handling concept	State forestry departments	Regional
or the management of forests in Schleswig- n ecological aspects	Schleswig-Holsteinische Landesforsten	Forest handling concept	State forestry departments	Regional
ral forestry	Landesanstalt für Wald und Forstwirtschaft	Forest handling concept	State forestry departments	Regional
e principles of the Bavarian State Forests	Bayerische Staatsforsten	Forest handling concept	State forestry departments	Regional
nagement guideline "Gruener Ordner" urg	Landesbetrieb Forst Brandenburg	Forest handling concept	State forestry departments	Regional
for the management of the Hessian state forest	Hessian ministry for environment, energy, agriculture and consumer protection	Forest handling concept	State forestry departments	Regional
and guidelines for the natural economy in the ate forest	Landesbetrieb HessenForst	Forest handling concept	State forestry departments	Regional
e principles for the state forest of Saxony	Saxon State Ministry of Environment and Agriculture	Forest handling concept	State forestry departments	Regional
Instructions WALDBAU	Schleswig-Holsteinische Landesforsten	Forest handling concept	State forestry departments	Regional
e principles for the state forests of Thuringia the treatment guidelines of the main tree species	Thuringian Ministry of Agriculture, Nature Conservation and the Environment	Forest handling concept	State forestry departments	Regional
apers Schutzgemeinschaft Deutscher Wald	Protection of German Forests Bavarian Association e.V.	Forest program	Associations and NGO´s	Regional
ational Forest Strategy 2020	Federal Ministry of Food, Agriculture and Consumer Protection	Forest program	Institutions/ administrations	National
n Forestry Program 2000-2001	Thuringian Ministry of Agriculture, Nature Conservation and the Environment	Forest program	Institutions/ administrations	Regional
Forest 2014 in Saxony-Anhalt	Minister of Agriculture and Environment Saxony-Anhalt	Forest program	Institutions/ administrations	Regional
ransition - a chance for Thuringia	Ministry of Agriculture, Forestry, Environment and Nature Conservation Thuringia	Forest program	Institutions/ administrations	Regional
gram Brandenburg	Ministry of Infrastructure and Agriculture of the State of Brandenburg	Forest program	Institutions/ administrations	Regional

	Reference	Concept type	Stakeholder group	Scale level	Year
ervice of the general public	Staatsbetrieb Sachsenforst	Forest program	State forestry departments	Regional	2008
xony-Anahlt - tics and administration	Landesbeirat Holz Sachsen-Anhalt	Forest program	State forestry departments	Regional	2011
l and dead wood	NABU - Nature Conservation Association Germany e.V. National Association Saarland e.V.	Old and deadwood concept	Associations and NGO´s	Regional	2014
leswig Holstein Landesforsten	Schleswig-Holsteinische Landesforsten	Old and deadwood concept	State forestry departments	Regional	2010
iotope trees, old trees and n Rheinland-Pfalz	Landesforsten Rheinland-Pfalz	Old and deadwood concept	State forestry departments	Regional	2011
obius North Rhine-Westphalia	Landesbetrieb Wald und Holz NRW	Old and deadwood concept	State forestry departments	Regional	2014
romotion of biotope trees and st of Brandenburg -	FORSTBrandenburg	Old and deadwood concept	State forestry departments	Regional	2016
and dead wood shares in the	Landesforst Mecklenburg-Vorpommern	Old and deadwood concept	State forestry departments	Regional	2002
pt	Landesbetrieb ForstBW	Old and deadwood concept	State forestry departments	Regional	2010

CHAPTER 3

Suitability of contract-based nature conservation in privately-owned forests in Germany

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3.1 Abstract

The successful implementation of contract-based nature conservation in privately-owned forests requires a framework of reasonable operational measures. Our study aimed at developing such a framework by; 1) defining forest conservation objects including structures, processes, and habitat types, 2) assessing their conservation value based on the need for, and worthiness of, protection, 3) reviewing the suitability of contract-based measures for conservation. Overall, we defined 67 conservation objects, with 8 of them used as case studies: deadwood, habitat trees, natural succession after large-scale disturbance, coppice-with-standards, bog and fen woodlands, dry sand pine forests, and beech forests. We considered contract-based conservation suitable if, within the contract period, outcomes of measures resulted in ecological upgrading or avoidance of value loss. We identified contract-based conservation suitable for 42 combinations of objects and measures. Our approach of assessing the potential of contract-based measures for forest conservation is novel with regards to its broad range of objects, defined criteria, and various contract periods. It can help to progress conservation and improve outcomes of measures especially in privately-owned forests in Germany. Further prerequisites are sufficient financial resources, effective administration, consultancy and the mid- to long-term stability of funding programs.

Keywords

Forest conservation objects, funding, nature conservation value, suitability assessment, need for protection, private forests, worthiness of preservation

3.2 Introduction

In the European Union (EU-28), about 60% of the forested area is privately owned, with huge differences among the member states (Eurostat 2018). Germany, which lies slightly below the EU-28 average with about half of the forest area being privately-owned (Polley et al. 2016), may serve as an example to highlight the problems and opportunities for nature conservation in private forests. Implementing conservation measures in private forests may cause additional costs or expenses for forest owners (Sotirov 2017). At present, forest conservation measures in private forests are implemented in Germany primarily through regulations, rather than through subsidies. In stark contrast to agriculture, contractual agreements and funding instruments to compensate for economic losses caused by the implementation of nature conservation measures are rarely used in German forestry (Güthler et al. 2005; Franz et al. 2018b). However, German legislation indicates that the country grants voluntary agreements preference over legal regulations and constitutes in § 3(3) of the German Federal Nature Conservation Act that "… priority shall be given to reviewing whether the intended purpose could also be achieved via contractual agreements" (BMU 2010: 10). Contract-based agreements are assumed to have a higher acceptance among private forest owners than purely regulatory measures (Franz et al. 2017). The National Strategy on Biological Diversity calls to "promote contract-based nature conservation in 10% of privately-owned forest land" (BMUB 2007: 32), but this target is still far from being achieved, not least because the conditions for contract-based forest conservation have not yet been met (Franz et al. 2018a). Furthermore, overall funding frameworks, for instance for the implementation of Natura 2000, are lacking (Geitzenauer et al. 2017; Sotirov 2017). In contrast to regulations, contract-based nature conservation strives to achieve a consensual, bilateral agreement. In Germany, such voluntary agreements are usually contracted between private forest owners and funding bodies such as the country, federal states, foundations, or private investors. Context-specific conservation measures, referring to specific conservation objects, funding periods and amounts as well as possible monitoring to verify success are contractually agreed upon. A broad consensus among different stakeholders in Germany with respect to conservation objectives (Demant et al. 2019) may further promote the implementation of contract-based conservation in private forests.

A prerequisite for the implementation of nature conservation measures in forests is the identification of an operational catalogue of forest conservation objects covering all aspects of forest habitat and biodiversity conservation. An approach using conservation objects accounts for temporal context-specifity and spatial variability, if there is a broad selection of widely accepted and properly defined objects and consensus about suitable preservation measures. At present, the most commonly addressed conservation objects in private forests are habitat trees, deadwood, and historical types of forestry use, such as coppicing or wood pasture (Franz et al. 2018b). However, numerous further objects may be taken into consideration in order to fully tap the potential of private and other forests for the restoration and preservation of biodiversity. The aim of our study was to develop a comprehensive catalogue of forest conservation objects and measures eligible for contract-based funding. We built on the framework of conservation objectives suggested by Demant et al. (2019) and focussed on forest habitat types, structural elements, and developmental processes as the most relevant conservation objects. We identified the conservation value of the objects by assessing the need for protection (owing to threat, endangerment) and the worthiness of preservation. The guiding questions for our study were:

(1) How can forest conservation objects be assessed in a way that reflects their nature conservation value, particularly in terms of their need for, and worthiness of, preservation?
(2) Which forest conservation objects are suitable for effective contract-based conservation measures and over which contractual periods should measures reasonably be funded?
(3) What consequences for nature conservation practitioners and forest owners can be derived?

3.3 Methods

3.3.1 Assessment of the nature conservation value of forest conservation objects

To assess the nature conservation value of a forest conservation object, we considered the initial value (before conservation measures were implemented) and the conservation value achieved after application of a measure over varying time periods. According to Frenz and Müggenborg (2016), worth of preservation alone is not enough for an object to justify a legal priority protection setting, conservation objects must also be (potentially) threatened. Thus, we differentiated between the two components "worthy" (contributing to the preservation of characteristic species and gene pools in natural or semi-natural landscapes or ecosystems) and "need" or "urgency" (degree of threat as a result of adverse effects of land-use and environmental changes) to assess the conservation value of the objects (Figure 4).

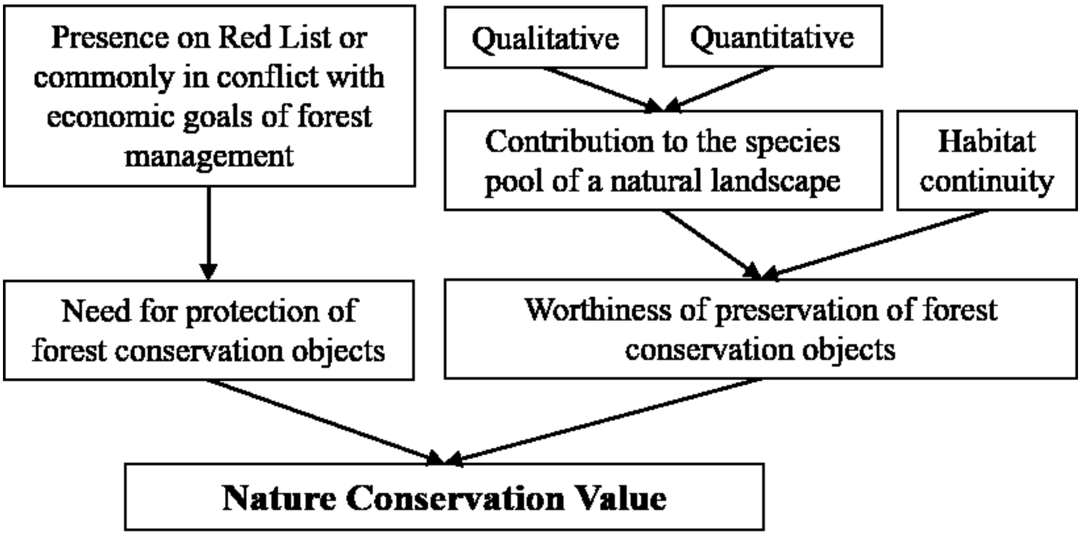

Figure 4: Assessment of the nature conservation value of forest conservation objects.

We based the assessment of the need for protection on the national and the European Red List status categories (Janssen et al. 2016; Finck et al. 2017) translated into an ordinal scale (Table 9). The Red List status categories encompass long-term threat (assessed at national and regional levels), the current trend (stable, increasing, decreasing), rarity, and the ability to regenerate (Finck et al. 2017). Threats are "human activities or processes that have impacted, are impacting, or may impact the status of the taxon being assessed" (IUCN 2013: 1).

Table 9: German Red List categories of habitat types and their translation into numerical and verbal reference values.

Red List category	Description	Need for protection	Value
0	collapsed	very high	5
1!	critically endangered (acutely)	very high	5
1	critically endangered	very high	5
1-2	endangered to critically endangered	high	4
2	endangered	high	4
2-3	vulnerable to endangered	moderate	3
3	vulnerable	moderate	3
3-V	near threatened to vulnerable	low	2
V	near threatened	low	2
*	no current risk of loss trend (least	very low	1
#	classification not meaningful, or no risk	no	0

The forest structures and processes that we assessed have a high urgency for protection. For example, the retention of deadwood and a natural forest development are commonly in conflict with the economic goals of forest management.

Based on an assumption that the maintenance of core ecosystem functions was of high value we selected forest conservation objects, whether they represent structures, processes, or habitat types, as worthy of preservation if they are integral parts of natural self-sustaining, or semi-natural, managed forest ecosystems (Frenz and Müggenborg 2016). We also assumed that higher value would be placed on objects with a greater importance for a region's natural and cultural heritage. The longer the habitat continuity, i.e. the period in which a conservation object has evolved its typical biodiversity, the more important it is to preserve it (Nordén et al. 2014). As the habitat continuity increases, so, too, does the responsibility of preserving the conservation object to meet "the needs of the present without compromising the ability of future generations to meet their own needs" (WCED 1987: 15). Wood-pastures, for example, have a centuries-long habitat continuity (Bergmeier et al. 2010; Plieninger et al. 2015), and are regarded as being part of the European cultural-natural heritage (Leuschner and Ellenberg 2017).

Apart from habitat continuity, other factors determining the worth of a conservation object were the quantitative (absolute number of species) and qualitative (relative to a desired reference state) contribution of a conservation object to the species pool of a natural landscape. For example, intact peat bog woodlands may have a relatively low absolute number of species, but a high qualitative contribution to the typical diversity of the natural landscape. We based our assessment of the worthiness on expert valuations and distinguished six levels in a qualitatively ranked ordinal scale (Table 10).

Table 10: Variables for the evaluation of the worthiness of preservation.

Habitat continuity (HC)		**Quantitative contribution (Q1)**		**Qualitative contribution (Q2)**		**Worthiness = [HC+ ((Q1+Q2)/2)]/2**
very long	5	very high	5	very high	5	5
long	4	high	4	high	4	4
medium	3	moderate	3	moderate	3	3
short	2	low	2	low	2	2
very short	1	very low	1	very low	1	1
none	0	none	0	none	0	0

Q1 = quantitative (absolute) contribution, Q2 = qualitative contribution to the typical biodiversity of the natural landscape unit.

For example, dry oak-hornbeam forests (*Galio-Carpinetum*) have a Red List status of 1-2 (Endangered to Critically endangered, Finck et al. 2017) which means their need for protection was high (4). Furthermore, they have a very long habitat continuity (HC = 5), a high quantitative (Q1 = 4), and a very high qualitative (Q2 = 5) contribution to the diversity of the natural landscape. Their worthiness of preservation resulted in “very high” ([5+ ((4+5)/2)]/2 = 4.75). We assert that structures and processes, as essential components of natural forests, are highly worthy insofar as they allow maintenance of key ecosystem functions (Walentowski and Winter 2007). The final nature conservation value resulted from the calculation of the mean values of the two protection criteria, worthiness and need, with the classes 0 = no, 1 = very low, 2 = low, 3 = moderate, 4 = high, and 5 = very high conservation value. In the example above the final conservation value is high ((4.75+4)/2 = 4.375).

3.3.2 Forest conservation objects

The nature conservation value assessment was carried out for eight forest structural elements, four processes, and 55 forest-related habitat types (Finck et al. 2017; see Table S 4). In the main body of the present paper, representative assessments for 8 out of 67 forest conservation objects were made, characterised in Table 11.

Table 11: Characteristics of 8 case study forest conservation objects.

Conservation object	**Characteristics**	**Possible conservation measure during contract period**	**References**
Deadwood	Key structure in forest ecosystems, variable in terms of amount, decay stages, size classes, wood diameters, microclimatic conditions, and tree species.	Retention of dead trees or logging residues; supply ring-barking, crown cutting, felling or knocking-over of trees.	Harmon et al. 1986; Davies et al. 2008; Lassauce et al. 2011; Lindenmayer et al. 2012; Agnew and Rao 2014; Seibold et al. 2015
Habitat trees	Characterised by various tree-related microhabitats (e.g. hollows or dead branches), indication habitat continuity; important for countless species supported by dieback structures of old-growth forest stages.	Protection of existing habitat trees and retention of potential once; creation of structures by breaking-off branches, making bark injuries or bark-removal, constructing cavities, dendrothelms (water-filled tree hollows).	Winter and Möller 2008; Fedrowitz et al. 2014; Kraus et al. 2016; Larrieu et al. 2018; Asbeck et al. 2019; Gustafsson et al. 2019; Mölder et al. 2020

Table 11: Continued

Conservation object	Characteristics	Possible conservation measure during contract period	References
Natural forest development	Characterised by typical regional and local-scale old-growth forest structures and associated biodiversity. With ongoing cessation of forestry interventions, typical developmental and structural features gradually develop over long periods of time.	Continuation of natural forest development initiated several decades ago, recent decommissioning of semi-natural commercial forests. Minimum standards as defined by Engel et al. (2016, p. 38) apply.	Meyer and Schmid 2008; Vandekerkhove et al. 2011; Kraus and Krumm 2013; Paillet et al. 2015
Natural succession after large-scale disturbance	Natural disturbances (e.g. by wildfires, windstorms, or insect infestations; intensity and frequency are expected to increase under climate change) are important drivers of forest dynamics and associated biodiversity. They contribute to maintaining pioneer species and habitats, enhance structural heterogeneity, and make forests more resilient to future disturbances.	Allowing and supporting natural development in early-successional stages	Runkle 1989; Franklin et al. 2002; Lindenmayer et al. 2008; Swanson et al. 2011; Seidl et al. 2017; Thorn et al. 2018; AK Waldökologie GfÖ 2019; Müller et al. 2019
Coppice-with-standards	Two-layered stands with an upper story consisting of mature trees (standards) used for timber and fruit setting. Even-aged understory regrowth (coppice) consists of multi-stemmed trees cut at a 20-30-year rotation cycle. Offer a mosaic of habitats and structures favourable for light-demanding and thermophilic species due to conditions of alternating shade and light. Abandoned coppice-with-standards with all trees left uncut (“overstood”, stems having the size of mature forest stands) are commonly converted to high forests (even-aged forest stands).	Continuation and resumption of coppice-with-standard management.	Barnthöl 2003; Groß and Konold 2009; Kirby et al. 2017; Meyer et al. 2018; Unrau et al. 2018

Table 11: Continued

Conservation object	Characteristics	Possible conservation measure during contract period	References
Bog and fen woodlands	Ecosystems of coniferous or broadleaved trees and shrubs on low-productive peaty soils with high water level. When intact, they contribute to climate protection, if drained, they emit greenhouse gases at high rates. Habitats for many specialised, rare and endangered species and highly threatened by hydrological changes caused by forest management and drainage.	Restoration of degraded bog and fen woodlands by raising the water level, regeneration of the acrotelm, the active peat zone containing living plants, removal of non-native tree species and renouncement of peat extraction.	Moore and Knowles 1989; Joosten 2012; EEA 2013; Joosten et al. 2015; EEA 2019
Dry sand pine forests	Lichen-rich dry pine forests on nutrient-poor, acidic sands with low shrub, herb, and litter cover. Being the result of historical land use (mainly litter raking and sod cutting) they depend on nutrient removal to accommodate typical epigeous (growing on the soil surface) lichen species. They are highly endangered, mainly due to discontinuation of litter raking and by nitrogen deposition caused by agriculture and traffic emissions and have both high historic-cultural and biodiversity significance	Protection of extant lichen-rich pine forests and restoration of degraded lichen-poor sand pine forests through litter and topsoil removal.	Heinken 1990; Heinken 2008; Fischer et al. 2009; Fischer et al. 2014; Brackel and Brackel 2016; Stefańska-Krzaczek et al. 2018
Beech forests	Naturally self-sustaining ecosystems dominated by beech (*Fagus sylvatica*), but commonly managed as productive high forests.	Prolonging of rotation cycles beyond conventional harvesting age, thus preserving old-growth-associated biodiversity, and enhancing natural regeneration.	Kroiher and Bolte 2015; Meyer et al. 2015a; Winter et al. 2016

3.3.3 Suitability assessment scheme

We assessed the suitability of contract-based funding for forest conservation objects by comparison of the initial and final conservation value (Figure 5). The initial conservation value of the conservation object was scaled between very low (0) and high (5). After projecting the expected development and outcomes over a contract length, we calculated a final conservation value, again scaled between very low and high (Figure 5). As relevant development periods differ greatly among conservation objects, we considered three potential contractual periods: short-term (< 10 years), mid-term (10-30 years), and long-term (> 30 years).

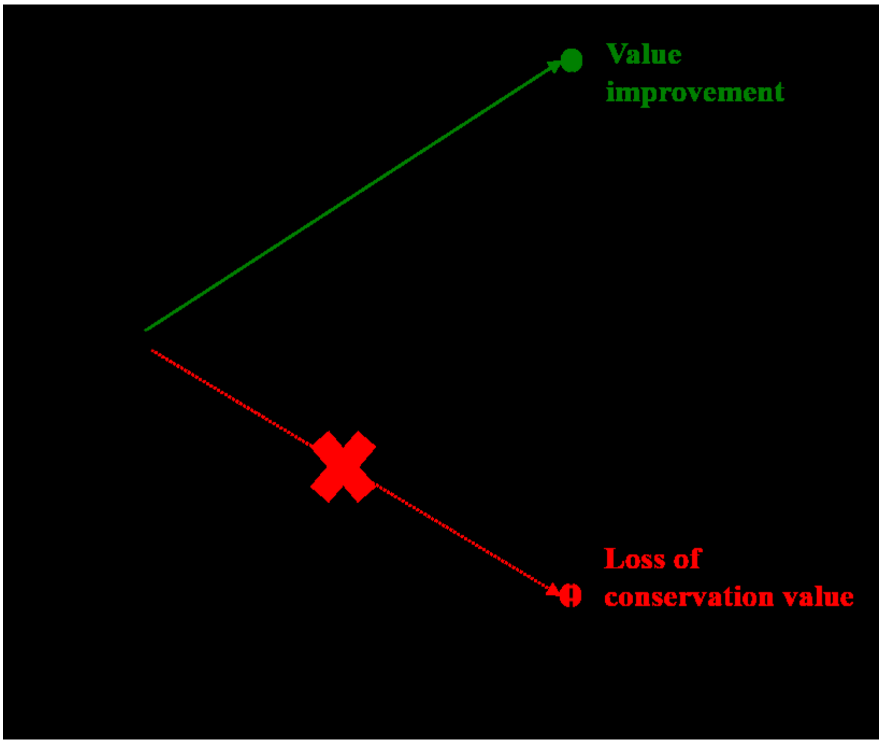

Figure 5: Development pathways of the initial nature conservation value.

The assessment of the worthiness of, and need for, protection of forest conservation objects resulted in a single nature conservation value, although each individual variable may have different values (Table S 5). Conservation objects may achieve a high value when preservation measures have been implemented and have produced positive results, when degraded objects have been restored successfully (restoration measures), or when the objects have been newly created. A high conservation value towards the end of a contractual period indicates an improvement of an initially lower conservation value, or the prevention of value loss of an initially high value.

Contract-based funding would be particularly suitable for conservation objects with high initial conservation value that would suffer value loss in the absence of conservation measures, or for objects with rather low initial value but considerable restoration potential to achieve a higher final value. If the conservation value of a newly created conservation object (initial value = 0) was likely to increase over a given contract period, contract-based funding of conservation measures was also considered reasonable. If both initial value and restoration potential were low, contract-based conservation was deemed inappropriate. The suitability assessment is depicted as a four-level colour scheme, reflecting the final value (Table 12).

Table 12: Description and assignment of the final nature conservation value (NCV) to the suitability assessment of conservation measures and the corresponding colour in Table 7 and Supplement S1.

Final nature conservation value	Description	Suitability of conservation measures	Colour
0	No NCV	not suitable	Red
1	Very low NCV	not suitable	Red
> 1 - 2	Low NCV	not suitable	Red
> 2 - 3	Moderate NCV	moderately suitable	Yellow
> 3 - 4	High NCV	suitable	Light green
> 4 - 5	Very high NCV	very suitable	Dark green

3.4 Results

3.4.1 Initial nature conservation value of forest conservation objects

More than 82% of all conservation objects were assessed as being highly or very highly worthy of preservation. However, only 39% had a high to very high need for protection and these were found exclusively within the group of objects of high to very high worthiness. Thus, some conservation objects can be regarded as very valuable, but are not seriously threatened, such as mesic beech forests or riparian alluvial forests (Table S 4). Forest structures and processes made up only a small proportion of all conservation objects. For forest structures, the proportion of low-value and non-threatened objects was higher than that of highly valuable and threatened ones, since many structures are being developed or newly implemented (e.g. the active supply of deadwood, or the designation of potential habitat trees).

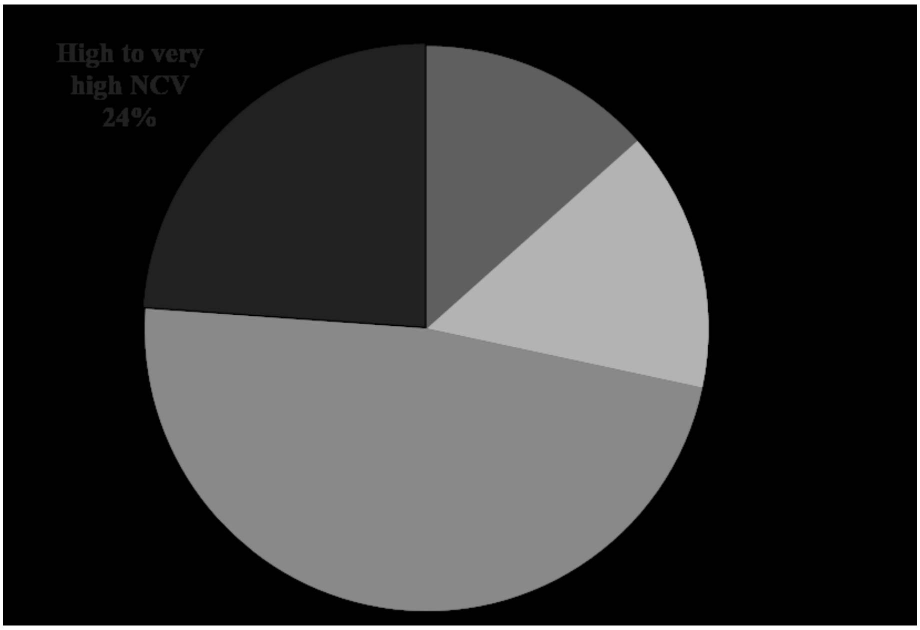

Figure 6: Initial nature conservation value (NCV) of all 67 forest conservation objects analysed.

One quarter of all forest conservation objects were assessed as having a high to very high initial nature conservation value (Figure 6). The conservation objects coppice-with-standards, wood pastures, intact bog and fen woodlands, continuation of natural forest development, natural succession after large-scale disturbance, deadwood retention, eyrie tree protection (nesting sites for birds of prey) and protection of habitat trees were assessed as having very high conservation value. About three quarters of all conservation objects were ascribed a moderate to very high initial conservation value. Habitat types, comprising 55 out of the 67 identified forest conservation objects, made a major contribution to high conservation-value objects (initial value higher than 3; Table 13).

Table 13: Distribution of the shares of the initial nature conservation value (NCV) classes for all 67 forest conservation objects.

Description	NCV	Habitat types	Structures	Processes
No to low NCV	0 - 2	3	5	1
Low to moderate NCV	> 2 - 3	9	0	1
Moderate to high NCV	> 3 - 4	32	0	0
High to very high NCV	> 4 - 5	11	3	2

3.4.2 Suitability of contract-based forest conservation

As many as 42 out of 67 forest conservation objects proved suitable for contract-based conservation measures (Table S 4). Most of the assessed forest structures and processes were considered suitable or very suitable for contract-based conservation, irrespective of the contract period. For forest habitat types, accounting for the largest part of all assessed conservation objects, the findings are more nuanced. Short-term contracts (<10 years) were found to be very suitable for 15 out of 67 forest conservation objects (3 process-related, 4 structural and 8 habitat types; Table 14 and Table S 4). The conversion of forest stands of non-native trees, the continuation of traditional forest management (wood pastures, coppice-with-standards), and the retention of deadwood belong in this category. Mid-term contracts (10-30 years) were found to be very suitable for 31% of all conservation objects, including the resumption and continuation of traditional forest management, the restoration of degraded habitat types, the active creation of habitat trees, micro-habitats, as well as the conservation management of high-valued habitat types (Table S 4). Long-term contracts (>30 years) were assessed as being very suitable for about 33% of all conservation objects, mostly the same as for mid-term contractual periods, though with a few exceptions, such as the continuation of a natural forest development, or the retention of potential habitat trees. Contract-based agreements were rated not suitable for 34%

of all conservation objects, regardless of the contractual period. This category includes almost exclusively habitat types, chiefly because they are either legally protected habitats (Box 1) or low-valued pioneers.

For most suitable conservation objects (82%) contract duration was considered of little relevance. Nevertheless, longer funding durations are to be preferred. This would not apply, however, for wind-throws or other large-scale disturbances left to natural succession, because here, the early succession stages are the intended objective.

Table 14: Suitability assessment proportions of forest conservation objects for different contract terms (years).

Suitability	**Contract duration (years)**	**Forest conservation object group**		
		Structures (8)	**Processes (4)**	**Habitat types (55)**
Not suitable	<10	1	0	22
	10-30	0	0	23
	>30	0	0	23
Moderately suitable	<10	0	1	3
	10-30	1	0	2
	>30	0	1	2
Suitable	<10	3	0	22
	10-30	0	2	18
	>30	1	0	18
Very suitable	<10	4	3	8
	10-30	7	2	12
	>30	7	3	12
Total proportion [%]		**11.9**	**6.0**	**82.1**

ability assessment of representative forest conservation objects and conservation measures for different contract duration periods. For the nature conservation value (NCV), based on worthiness of preservation and need for protection see Tables 9, 10 and 12.

conservation	Possible conservation measure during contract period	Period (years)	Initial NCV: Worthiness	Initial NCV: Need	Final NCV: Increase in value **with** contract-based conservation	Final NCV: Loss of value **without** contract-based conservation	Suitability contract-b conservati
ood	Active deadwood provisioning to ensure continuous supply of a certain amount	< 10	0	0	4	No	s
		10 - 30			5		vs
		> 30			5		vs
	Retention of naturally supplied or silvicultural routine deadwood	< 10	5	5	5	Yes	vs
		10 - 30					vs
		> 30					vs
trees	Retention of potential habitat trees	< 10	0	0	0-1	No	ns
		10 - 30			3		ms
		> 30			5		vs
	Initial creation of microhabitats	< 10	0	0	4	No	s
		10 - 30			5		vs
		> 30			5		vs
	Protection of habitat trees	< 10	5	5	5	Yes	vs
		10 - 30					vs
		> 30					vs
l forest ment	Recent semi-natural forest set-aside	< 10	3	3	3	Yes	ms
		10 - 30			4		s
		> 30			5		vs
	Continuation of natural forest development initiated several decades ago	< 10	5	5	5	Yes	s
		10 - 30					vs
		> 30					vs
l succession rge-scale ance	Sites of wind-throws or other disturbances in native forests left to itself	< 10	5	5	5	Yes	vs
		10 - 30			4		s
		> 30			3		ms

nservation value. Colours: red = not suitable (ns), yellow = moderately suitable (ms), light green = suitable (s), dark green = very suitable (vs). * = d habitat (§30 BNatSchG).

: Continued.

	Forest conservation object	Possible conservation measure during contract period	Period (years)	Initial NCV: Worthiness	Initial NCV: Need	Final NCV: Increase in value with contract-based conservation	Final NCV: Loss of value without contract-based conservation
woodland	**Coppice-with-standards**	Resumption of traditional coppice-with-standard management	< 10	4	3	3.5	Yes
			10 - 30			5	
			> 30			5	
		Continuation of coppice-with-standard management	< 10	5	5	5	Yes
			10 - 30				
			> 30				
	Intact bog and fen woodlands *	Renouncement of degrading measures	< 10	5	5	not assessable	No
			10 - 30				
			> 30				
	Degraded bog and fen woodlands	Restoration (rewetting)	< 10	4	3	4	Yes
			10 - 30			5	
			> 30			5	
	Intact lichen-rich dry sand pine forest (*Cladino-Pinetum sylvestris*) *	Conservation- and habitat-adapted management	< 10	5	4	4.5	Yes
			10 - 30				
			> 30				
	Degraded (lichen-poor) dry sand pine forest	Restoration through litter and topsoil removal	< 10	3	3	4	No
			10 - 30			5	
			> 30			5	
	Dry limestone beech forest (*Carici-Fagetum*) *	Conservation- and habitat-adapted management	< 10	5	4	4.5	Yes
			10 - 30				
			> 30				
	Mesic beech forest on base-rich sites (*Galio odorati-Fagetum, Mercuriali perennis-Fagetum*)		< 10	5	2	3.5	Yes
			10 - 30				
			> 30				

re conservation value. Colours: red = not suitable (ns), yellow = moderately suitable (ms), light green = suitable (s), dark green = very suitable (vs). * =
0 BNatSchG).

3.4.3 Forest conservation objects – case studies

Deadwood

Measures to actively supply deadwood were assumed to have a positive short- to long-term effect on the richness of saproxylic (depending on dead or decaying wood) organisms (Table 15). Therefore, short-term contracts were considered suitable. When contracting for mid-term periods, it should be considered that, due to decay, deadwood needs to be replenished to ensure continuous provisioning of different deadwood qualities (see deadwood estimation tool, Meyer et al. 2009b). With further contractual period extension, the conservation value is expected to increase, provided that a continuous deadwood supply is guaranteed. Natural deadwood, or silvicultural routine deadwood, has a very high initial conservation value, making even short-term contracts very suitable. Mid- to long-term contracts to secure continuous deadwood supply would result in a very high conservation value.

Habitat trees

We considered trees with trunk diameter far beyond the typical harvest size (DBH > 80 cm for deciduous trees on normal sites, for oaks > 90 cm), and/or the site-specific harvesting age (e.g. beech > 200 a, oak > 300 a), as well as trees rich in microhabitats and/or with very large crowns or low crown bases, to be particularly qualified to become habitat trees (Table 15). As the natural formation of tree microhabitats was assumed to take >50 years at minimum (Larrieu et al. 2012), only long-term contracts qualify. Trees with microhabitats created through management measures have no initial object-specific conservation value (Table 15), but this may increase soon, making even short-term contracts reasonable. Mid- to long-term contracts were considered very suitable to achieve very high conservation value.

Natural forest development

Forests with long habitat continuity, where forestry ceased many decades ago, contribute considerably to the biodiversity of the natural landscape. Therefore, their worthiness was rated very high (Table 15). Due to their low presence in German forests (only 2.8% of the total forest area; Engel et al. 2019), their need for protection is also very high. The continued protection of forests with a long-lasting natural development was recommended for all contractual periods. Semi-mature forests that have been recently decommissioned have a moderate need for protection. Positive effects on biodiversity of such forests may only be measurable after many years or decades. Therefore, contract-based decommissioning of forests was assumed to be suitable for mid- to long-term periods only. Follow-up contracts were recommended for prolonged natural development.

Natural succession after large-scale disturbance

Natural forest succession after major disturbance events requires silviculturists to refrain from salvage logging, deadwood removal and replanting. Untouched early-successional stages are rarely found in privately-owned forests and are thus regarded as highly vulnerable (Table 15). As such pioneer habitats support numerous warmth- and light-dependent species, they are worthy and, consequently, of high initial conservation value. As disturbed areas decrease in object-specific conservation value over time, mid-term contracts were considered particularly suitable. Long-term contracts would only be meaningful if non-disturbed, surrounding stands are simultaneously targeted beyond the given conservation object.

Coppice-with-standards

Traditional coppice-with-standards woodlands can be protected from being transformed into high forests by continuing their specific management. As coppice-with-standards contribute much to the biodiversity of the natural landscape, they were granted a very high worthiness (Table 15). Due to their extreme rarity (less than 0.4% of the forest area in Germany; Albert and Ammer 2012) and susceptibility to management change, they were also assessed as having a very high need for protection and risk of value loss. Therefore, all contract terms were considered suitable, with long-terms preferred.

Abandoned and “overstood” coppice-with-standards may be restored by resuming the former management. As a moderate loss of habitat continuity and species richness was assumed, their worth of, and need for, protection were given medium ratings (Table 15). Since one rotation cycle usually takes 20-30 years, short-term contracts do little to increase the conservation value of “overstood” coppice-with-standards. More suitable contract periods are mid- to long-term.

Bog and fen woodlands

As part of the landscape’s natural vegetation, intact bog and fen woodlands have a very long habitat continuity and, consequently, very high worthiness. Due to their high level of endangerment, they also have an urgent need for protection (Table 15). Intact bog and fen woodlands have been protected under the Federal Nature Conservation Act. As mere preservation is not compensable (Box 1), contract-based conservation was considered unsuitable, unless combined with additional measures. As remnant or slightly degraded bog and fen woodlands may still contribute to the biodiversity of the natural landscape, they have been assigned medium to high worthiness and medium need for protection (Table 15). Because the restoration of slightly degraded bog and fen woodlands promptly leads to a value increase, even short-term contracts were deemed to be adequate.

Box 1: Legally protected habitat types.

Special case: Legally protected habitat types

Some German forest habitat types are legally protected according to § 30 BNatSchG. These are primarily natural and self-sustaining habitat types that do not require management, and include among others fen and bog woodlands, riparian forests, forests of ravines, slopes and screes, and xerothermic forests and shrub lands. Destruction or actions with significant adverse effects are prohibited by law. Forest owners are obliged to protect and maintain these habitats and to refrain from destruction or considerable impairment. Private land owners cannot be compensated for fulfilling these legal obligations. In contrast, for habitat types that rely on active conservation measures, such as mixed oak forests derived from coppicing, financial compensation appears reasonable.

Likewise, for restoration of degraded habitat types, such as drained swamp forests, financial compensation is possible. The successful restoration of degraded habitats may result in permanent restriction of the forest owner's right of disposal once the status of a legally protected habitat is reached. Franz et al. (2018a) argued that, for reasons of fairness, this permanent use restriction should be permanently compensated.

Dry sand pine forests

The qualitative contribution of lichen-rich dry sand pine forests to the biodiversity of the natural landscape was top-rated and, consequently, their worthiness was also high (Table 15). Being endangered, they have a very high need for protection. However, as a legally protected habitat type, forest owners cannot be compensated for its mere preservation (Box 1). Contract-based maintenance was therefore considered unsuitable unless combined with extra measures, such as rotational litter and topsoil removal.

For degraded forms, if still restorable and credited with medium conservation value, financial compensation for measures to initiate recolonization of characteristic lichen species was recommended. Short-term contracts were considered suitable, although long-term contracts rendered higher conservation value.

Beech forests

A long habitat continuity and high relevance for the biodiversity of the natural landscape were assumed to result in very high worthiness (Table 15). Our assessment is that financial compensation for preservation-friendly management of dry and mesic beech forest complexes is highly recommendable, whatever the contractual period, if it clearly extends beyond regular forestry practice.

3.5 Discussion

3.5.1 Assessing the nature conservation value of forest conservation objects

By means of various indicators or criteria, evaluating conservation objects may be understood as the transfer of factual knowledge to a valuation scheme (Plachter 1991; Schultze et al. 2016). This valuation approach has formed the basis of many studies that have applied scoring techniques (Usher 1994; Gastauer et al. 2013; Capmourteres and Anand 2016; IUCN 2016), and we used it to develop our framework of reasonable and operational measures to assess the nature conservation value of forest conservation objects.

Our conservation valuation comprises different attributes, with single summarised scores, to allow for its country-wide application. With contextual modifications such as other Red List levels to specify the need for protection, the approach may be applicable in yet other regions. By including forest structures, processes, and habitat types, we tried to cover relevant attributes of forest biodiversity. The selected conservation objects are representative for forest conservation management and include those in urgent need of conservation actions. They are particularly relevant in times of climate change, as they encompass short-term objects (e.g. wind-throw sites), climax habitat types (e.g. beech forests), habitats of carbon sink relevance (bog and fen woodlands), habitats with climate-sensitive species (e.g. dry pine forests), and habitats with considerable economic potential for financial risk spreading (coppice-with-standards).

3.5.2 Contract duration to safeguard forest conservation objects

We showed that contractual agreements can be appropriate to support conservation measures in forests. The evaluation of 67 forest conservation objects showed that contract-based conservation agreements prove suitable for 42 objects, albeit with different contract durations. Short-term contracts are less suitable for the retention of habitat trees and for decommissioning semi-mature forests, while long-term contracts are not recommended for funding natural succession after large-scale disturbance. Contract-based conservation is particularly suitable for high-valued objects, such as coppice-with-standards, that depend on active conservation measures to prevent deterioration. Even short-term contracts may be adequate in cases of objects with low to medium initial conservation value if a prompt value increase is to be expected, e.g. newly created habitat trees. In contrast, short-term contracts are less meaningful for conservation objects with low initial conservation value and slow value improvement.

Permanent compensation and long-term agreements would be required for private owners of forests under permanent statutory use restriction (e.g. in bog and fen woodlands). A short contract duration, covering only initial investment expenses but no further maintenance measures, would fail to produce a return on landowner's investment. However, if there is a general willingness of forest owners to accept follow-up contracts, and if suitable funding resources are available, short-term contracts are better than no agreement.

3.5.3 Consequences for nature conservation and forestry practice

As far as forest habitat types are concerned, our conservation objects are in line with the EU Habitats Directive (Natura 2000) and the European Nature Information System (EUNIS) classification (Table S 6) and our approach may help to improve the mandatory assessment of the conservation status. In the EU Natura 2000 network, the preservation of diverse forest structures (e.g. deadwood, habitat trees) is a necessary element for a particular forest habitat type to achieve favourable conservation status (Winkel et al. 2015; Alberdi et al. 2019). Since a high proportion of European forest habitat types have been assigned an unfavourable conservation status (European Commission 2015), enhancing these forest structures helps to improve their conservation status.

Our suitability assessment revealed that the conservation or restoration of forest conservation objects may have synergetic effects and simultaneously result in the protection and improvement of other objects. These synergies should be given special consideration (Margules and Pressey 2000; Cimon-Morin et al. 2013). Potential trade-offs and competing objectives across conservation objects should be weighed in the light of the conservation objectives, site conditions and the expected value development. For instance, natural forest development and coppice-with-standards management cannot be implemented in the same site. In general, forest owners cannot meet all possible conservation objectives in a single stand. A contract usually covers a single conservation object and the necessary measures (setting, extent, feasibility, financial framework), but several contracts may be concluded for different objectives in the same forest stand.

Given an underlying value structure that aims to protect typical regional forest biodiversity, the responsibility to protect can only be justified for native species appropriate to the site and location, long-term natural and semi-natural processes and structures, and the cultural development history (Meyer 2013b). Consequently, management in privately-owned non-cultural types of forest should be committed to close-to-nature forestry (extension of rotation periods, deadwood provisioning, and tree retention). Since this paradigm shift may cause additional costs for forest owners, suitable compensation structures are needed.

However, financial incentive systems in privately-owned forests are as yet lacking in Germany (Seintsch et al. 2018). Other countries successfully developed their own subsidy programmes, such as the English Woodland Grant Scheme introduced in 2005 (Forestry Commission 2010; Fuentes-Montemayor et al. 2015), replaced in 2015 by Countryside Stewardship grants. Such a country-wide system can lead to more transparency and acceptance among forest owners to support forest biodiversity conservation. Although some German federal states have developed their own incentive instruments, there is substantial variability in requirements and capacity for funding across states. For instance, the Bavarian contract-based forest conservation program supports the conservation of coppice-with-standards woodlands, the preservation of habitat trees and deadwood. In Hesse, forest conservation measures are funded by the Natura 2000 Foundation, but only within the Natura 2000 network. Additional funding options with differing requirements and payment amounts exist in Germany, yet none of these have nation-wide applicability (BMEL 2019a; European Commission 2020a). Unfortunately, the operational implementation of these general systems has by no means reached the individual private forest owner. Franz et al. (2018a) pointed out that there is an urgent need for action and to create the prerequisites for contract-based conservation in privately-owned forests, such as a solid foundation of trust, the involvement of committed intermediaries, result-oriented payments, success bonuses, as well as the identification of suitable indicators. Our comprehensive catalogue of forest conservation objects and measures eligible for contract-based funding is valid throughout Germany and in line with the Federal Compensation Directive (BMU 2020) just published. It does not, however, explain the possible trajectories between initial and final conservation values of objects. Forest owners are encouraged to use our catalogue for their conservation intentions. Given that they know the tree species composition and structural characteristics of their forest stands, they can easily identify conservation objects such as potential habitat trees, and choose a reasonable contract duration. The biggest challenge yet for contract-based nature conservation is to find suitable funding options, which vary between the German federal states. Authorities, nature conservation agencies, or NGOs might assist on this point. Therefore, while this paper provides a rationale and an objective-related design for contract-based nature conservation on forests, it cannot guide private forest owners towards an operational implementation. Such a guidance, generalised at the level of administrative units or federal states, remains yet to be elaborated.

3.6 Conclusions

The nature conservation value assessment of forest conservation objects provided in this paper enables forest owners to assess the conservation value of objects in their forest stands and to consider options for contract-based nature conservation, specifically in privately-owned forests in Germany. We also touch upon the much-discussed topic of conservation responsibility. We believe that the comprehensive catalogue of forest conservation objects and measures may be applicable in a wider Central European context. Furthermore, the nature conservation value assessment can help to improve the conservation status of Natura 2000 forest habitat types. We showed the suitability of many conservation objects to financial incentives and advocate conservation object-dependent variation in contract duration. We noticed a particular need for action in the case of conservation objects susceptible to an imminent loss of value in the absence of conservation measures.

Currently, however, a general framework for successful implementation of contract-based forest conservation, including factors such as legal security, fairness, continuity, and flexibility, is not available. The reference framework presented here and the considerable number of combinations of objects and measures found suitable for contract-based conservation, together with the recommendations for a forest conservation funding system given by WBW and WBBGR (2020), may help to enhance this implementation process. For the sake of diversified nature conservation in forests, politicians and stakeholders at all governmental levels should rethink and revise benefit payment programmes towards mid- to long-term contracts (Gemeinholzer et al. 2019), and thus encourage private forest owners to acknowledge biodiversity-related funding.

3.7 Author contribution

LD: Methodology, Formal analysis, Investigation, Writing- Original draft preparation, Visualization

EB: Writing - Review & Editing

HW: Writing - Review & Editing

PM: Conceptualization, Project administration, Supervision

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3.9 Supplementary materials

e **S 4:** Suitability assessment of forest conservation objects and conservation measures for different contract duration periods. For the scaling of the n
ervation value (NCV), based on worthiness of preservation and need for protection see Tables 9, 10 and 12. German Red List Status of threatened h
1! = critically endangered (acutely), 1 = critically endangered, 1-2 = endangered to critically, 2 = endangered, 2-3 = vulnerable to endangered, 3 = vulne
= near threatened to vulnerable, V = near threatened, * = no current risk of loss trend (least concern). Colours: red = not suitable (ns), yellow = mode
ble (ms), light green = suitable (s), dark green = very suitable (vs). # = legally protected habitat (§30 BNatSchG).

Forest ıservation object	Habitat type number (German Red List)	German Red List Status	Habitat type (Annex 1, EU Habitats Directive)	European Nature Information System (EUNIS) classification	Possible conservation measure during contract period	Period (years)	Initial NCV: Worthiness	Initial NCV: Need	Final NCV: Increase in value with contract-based conservation	Final NCV: Loss of value without contract-based conservation	Suitabi contrac conser
Deadwood					Active deadwood provisioning to ensure continuous supply of a certain amount	< 10	0	0	4	No	s
						10 - 30			5		v
						> 30			5		v
					Retention of naturally supplied or silvicultural routine deadwood	< 10	5	5	5	Yes	v
						10 - 30					v
						> 30					v
Eyrie trees					Establishment of artificial eyrie trees	< 10	0	0	5	No	v
						10 - 30					v
						> 30					v
					Protection of eyrie trees including their protection zones	< 10	5	5	5	Yes	v
						10 - 30					v
						> 30					v
Micro habitats and special structures					Creation of root plates, temporary ponds and others as species protection measures	< 10	0	0	4	No	s
						10 - 30			5		v
						> 30			5		v

ontinued

servation ect	Habitat type number (German Red List)	German Red List Status	Habitat type (Annex 1, EU Habitats Directive)	European Nature Information System (EUNIS) classification	Possible conservation measure during contract period	Period (years)	Initial NCV		Final NCV	
							Worthiness	Need	Increase in value with contract-based conservation	Loss of value without contract-based conservation
tat trees					Retention of potential habitat trees	< 10	0	0	0-1	No
						10 - 30			3	
						> 30			5	
					Initial creation of microhabitats	< 10	0	0	4	No
						10 - 30			5	
						> 30			5	
tat trees					Protection of habitat trees	< 10	5	5	5	Yes
						10 - 30				
						> 30				
ral forest lopment					Recent semi-natural forest set-aside	< 10	3	3	3	Yes
						10 - 30			4	
						> 30			5	
					Continuation of natural forest development that started several decades ago	< 10	5	5	5	Yes
						10 - 30				
						> 30				
tural cession r large-cale urbance				Early-stage natural and semi-natural forests and regrowth (T4-6)	Sites of wind-throws or other disturbances in native forests left to itself	< 10	5	5	5	Yes
						10 - 30			4	
						> 30			3	
ersion of rests					Conversion of non-native stocked forest stands into a habitat type with native tree species	< 10	0	0	Insert final values of the desired habitat type	No
						10 - 30				
						> 30				

ntinued

ion	Habitat type number (German Red List)	German Red List Status	Habitat type (Annex 1, EU Habitats Directive)	European Nature Information System (EUNIS) classification	Possible conservation measure during contract period	Period (years)	Initial NCV		Final NCV		Suita for co ba conse
							Worthiness	Need	Increase in value with contract-based conservation	Loss of value without contract-based conservation	
ice- h- ards	42.07.02	2-3		Broadleaved deciduous forest (T1)	Resumption of a coppice-with-standard management	< 10	4	3	3.5	Yes	
						10 - 30			5		
						> 30			5		
	42.07.01	1!			Continuation of a coppice-with-standard management	< 10	5	5	5	Yes	
						10 - 30					
						> 30					
od ures	42.04.02	1-2		Atlantic parkland (E7.1) and Sub-continental parkland (E7.2)	Resumption of a wood pasture management	< 10	4	4	4	Yes	
						10 - 30			5		
						> 30			5		
	42.04.01	1!			Continuation of a wood pasture management	< 10	5	5	5	Yes	
						10 - 30					
						> 30					
pice sts	42.05.02	1-2		Coppice and early-stage plantations (T4-7)	Resumption of a coppice forest management	< 10	4	4	4	Yes	
						10 - 30					
						> 30					
	42.05.01	1-2			Continuation of a coppice forest management	< 10	4	4	4	Yes	
						10 - 30					
						> 30					

ontinued

ervation object	Habitat type number (German Red List)	German Red List Status	Habitat type (Annex 1, EU Habitats Directive)	European Nature Information System (EUNIS) classification	Possible conservation measure during contract period	Period (years)	Initial NCV		Final NCV	
							Worthiness	Need	Increase in value with contract-based conservation	Loss of value without contract-based conservation
Subalpine pruce, larch-viss stone pine and larch woodland #	70.02, 70.03, 70.04	3-V	Alpine *Larix decidua* and/or *Pinus cembra* forests (9420)	Temperate subalpine *Larix, Pinus cembra* and *Pinus uncinata* forests (T3-4)	Conservation- and habitat-adapted management	< 10 10 - 30 > 30	4	2	n.a.	No
ubalpine (high montane) ycamore (*Acer eudoplatanus*)-eech woodland	70.01	2-3	Medio-European subalpine beechwoods with *Acer* and *Rumex arifolius* (9140)		Conservation- and habitat-adapted management	< 10 10 - 30 > 30	4	3	3.5	Yes
Scrub ommunities of e subalpine to alpine zone	69.	2-3	Bushes with *Pinus mugo* and *Rhododendron hirsutum* (Mugo-Rhododendretum hirsuti, *4070)		Conservation- and habitat-adapted management	< 10 10 - 30 > 30	4	2	3	Yes
ce/fir (mixed) t and spruce xed) forest n their natural range)	44.03	2-3	Acidophilous *Picea* forests of the montane to alpine levels (Vaccinio-Piceetea, 9410)	Temperate mountain *Picea* forests (T3-1) and temperate mountain *Abies* forests (T3-2)	Conservation- and habitat-adapted management	< 10 10 - 30 > 30	4	3	3.5	Yes
ry rocky pine forests #	44.02.01	3-V	Central European lichen Scots pine forests (91T0) and Sarmatic steppe pine forest (61U0)	Temperate continental *Pinus sylvestris* forests (T3-5)	Conservation- and habitat-adapted management	< 10 10 - 30 > 30	5	2	n.a.	No
imestone pine rest on gravel ank or alluvial cone #	44.02.02	2-3		Middle European *Pinus sylvestris* forests (T3-52)	Conservation- and habitat-adapted management	< 10 10 - 30 > 30	5	3	n.a.	No

nued

rvation	Habitat type number (German Red List)	German Red List Status	Habitat type (Annex 1, EU Habitats Directive)	European Nature Information System (EUNIS) classification	Possible conservation measure during contract period	Period (years)	Initial NCV		Final NCV		Su for con
							Worthiness	Need	Increase in value with contract-based conservation	Loss of value without contract-based conservation	
Intact hen-rich ry sand e forest #	44.02.03	1-2	Central European lichen Scots pine forests (91T0)	Subcontinental lichen *Pinus sylvestris* forests (T3-52112)	Conservation- and habitat-adapted management	< 10 10 - 30 > 30	5	4	4.5	Yes	
egraded hen-poor) ry sand ne forest		2-3			Restoration through litter removal	< 10 10 - 30 > 30	3	3	4 5 5	No	
tact bog nd fen odlands #	44.01	1-2	Bog woodland (91D0*)	*Picea* mire forests (T3-K) and *Pinus* bog forests (T3-J)	Renouncement of degrading measures	< 10 10 - 30 > 30	5	5	n.a.	No	
egraded g and fen odlands		2-3			Restoration of degraded bog or fen woodland (rewetting)	< 10 10 - 30 > 30	4	3	4 5 5	Yes	
eciduous mixed) ntations th native e species	43.09	*			Conservation- and habitat-adapted management	< 10 10 - 30 > 30	3	1	2	Yes	
h or ash- camore rest on amp site	43.07.01	2-3	Tilio-Acerion forests of slopes, screes and ravines (9180*)	Peri-Alpine mixed *Fraxinus - Acer pseudoplatanus* slope forests (T1-F3) and Acidophile ash-sycamore-lime ravine forests (T1-F12)	Conservation- and habitat-adapted management	< 10 10 - 30 > 30	5	3	4	Yes	

continued

conservation object	Habitat type number (German Red List)	German Red List Status	Habitat type (Annex 1, EU Habitats Directive)	European Nature Information System (EUNIS) classification	Possible conservation measure during contract period	Period (years)	Initial NCV		Final NCV	
							Worthiness	Need	Increase in value with contract-based conservation	Loss of valu without contract-based conservatio
Dry limestone beech forests (Carici-Fagetum) #	43.08.02, 43.08.03, 43.08.04	1-2	Medio-European limestone beech forests of the Cephalanthero-Fagion (9150)	Middle European dry-slope limestone *Fagus* forests (T1-741)	Conservation- and habitat-adapted management	< 10 10 - 30 > 30	5	4	4.5	Yes
Montane beech-fir/spruce forest (> 50% beech)	43.07.06	2-3	Luzulo-Fagetum beech forests (9110) and Asperulo-Fagetum beech forests (9130)	Western medio-European montane woodrush Fagus forests (T1-812)	Conservation- and habitat-adapted management	< 10 10 - 30 > 30	4	3	3.5	Yes
Mesic beech forest on base-rich sites (Galio odorati-Fagetum, Mercuriali perennis-Fagetum)	43.07.05	V	Asperulo-Fagetum beech forests (9130)	Medio-European woodruff and hairy sedge beech forests (T1-7112)	Conservation- and habitat-adapted management	< 10 10 - 30 > 30	5	2	3.5	Yes
Beech (mixed) forest on moist, base-deficient sites	43.07.04	3	Luzulo-Fagetum beech forests (9110) and Atlantic acidophilous beech forests with Ilex (9120)	Atlantic acidophilous forests (T1-82)	Conservation- and habitat-adapted management	< 10 10 - 30 > 30	4	3	3.5	Yes
Dry oak-hornbeam forest (Galio-Fagetum) #	43.08.01	1-2	Galio-Carpinetum oak-hornbeam forests (9170) and Pannonic woods with *Quercus petraea* and *Carpinus betulus* (91G0*)	Sub-continental *Quercus - Carpinus betulus* forests (T1-E16)	Conservation- and habitat-adapted management	< 10 10 - 30 > 30	4.7 5	4	4	Yes
Dry oak forest (Quercetalia pubescentis) #	43.08.05	2-3	Old acidophilous oak woods with *Quercus robur* on sandy plains (9190)	Acidophilous *Quercus* forest (T1-B)	Conservation- and habitat-adapted management	< 10 10 - 30 > 30	4.7 5	4	4	Yes

nued

ation	Habitat type number (German Red List)	German Red List Status	Habitat type (Annex 1, EU Habitats Directive)	European Nature Information System (EUNIS) classification	Possible conservation measure during contract period	Period (years)	Initial NCV		Final NCV		Sui con co
							Worthiness	Need	Increase in value with contract-based conservation	Loss of value without contract-based conservation	
-oak t on p to site	43.07.03	1-2	Sub-Atlantic oak-hornbeam forests (Stellario-Carpinetum, 9160)	Atlantic *Quercus robur* - *Betula* forests (T1-B1)	Conservation- and habitat-adapted management	< 10 10 - 30 > 30	4	4	4	Yes	
k-beam t on ogged st site ario-etum)	43.07.02	1-2	Sub-Atlantic oak-hornbeam forests (Stellario-Carpinetum, 9160)	Sub-Atlantic *Quercus* - *Carpinus betulus* forests with *Stellaria* (T1-E14)	Conservation- and habitat-adapted management	< 10 10 - 30 > 30	5	4	4.5	Yes	
ulder-cree #	43.06	3-V	Tilio-Acerion forests of slopes, screes and ravines (9180*)	Peri-Alpine mixed *Fraxinus* - *Acer pseudo-platanus* slope forests (T1-F3), Acidophile ash-sycamore-lime ravine f. (T1-F12)	Conservation- and habitat-adapted management	< 10 10 - 30 > 30	5	2	n.a.	No	
lluvial st #	43.05	1	Alluvial forests with *Alnus glutinosa* and *Fraxinus excelsior* (Alno-Padion, Alnion incanae, Salicion albae, 91E0*) and Riparian mixed forests (Ulmenion minoris, 91F0)	Atlantic *Alnus glutinosa* forests (T1-G22)	Renouncement of degrading measures	< 10 10 - 30 > 30	4	4	n.a.	No	
wood vial st #	43.04.03	1-2	Riparian mixed forests of *Quercus robur*, *Ulmus laevis* and *Ulmus minor*, *Fraxinus excelsior* or *Fraxinus angustifolia*, along the great rivers (Ulmenion minoris, 91F0)	Mixed *Quercus* - *Ulmus* - *Fraxinus* forest of great rivers (T1-31)	Renouncement of degrading measures	< 10 10 - 30 > 30	5	4	n.a.	No	

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onservation bject	Habitat type number (German Red List)	German Red List Status	Habitat type (Annex 1, EU Habitats Directive)	European Nature Information System (EUNIS) classification	Possible conservation measure during contract period	Period (years)	Initial NCV		Final NCV	
							Worthiness	Need	Increase in value with contract-based conservation	Loss of valu without contract-based conservatio
Softwood alluvial forest #	43.04.02	1-2	Alluvial forests with *Alnus glutinosa* and *Fraxinus excelsior* (Alno-Padion, Alnion incanae, Salicion albae, 91E0*)	Atlantic *Alnus glutinosa* forests (T1-G22)	Renouncement of degrading measures	< 10 10 - 30 > 30	5	4	n.a.	No
Degraded alluvial forests		3		Atlantic *Alnus glutinosa* forests (T1-G22) and Mixed *Quercus* - *Ulmus* - *Fraxinus* forest of great rivers (T1-31)	Restoration of natural flooding dynamics	< 10 10 - 30 > 30	4	3	4.5	Yes
iparian vial forests alder and ash #	43.04.01	3-V	Alluvial forests with *Alnus glutinosa* and *Fraxinus excelsior* (Alno-Padion, Alnion incanae, Salicion albae, 91E0*)	Atlantic *Alnus glutinosa* forests (T1-G22) and Riverine *Fraxinus* - *Alnus* forest, wet at high but not at low water (T1-21)	Renouncement of degrading measures	< 10 10 - 30 > 30	5	2	n.a.	No
egraded riparian vial forests alder and ash		3-V			Rewetting and removal of non-native tree species, if necessary initial planting	< 10 10 - 30 > 30	4	2	3.5	Yes
Stabile swamp forests #	43.03.01	2-.3		Broadleaved swamp forest on non-acid peat (T1-5) and Broadleaved swamp forest on acid peat (T1-6)	Renouncement of degrading measures	< 10 10 - 30 > 30	5	3	n.a.	No
Degraded swamp forests #	43.03.02	*			Rewetting and removal of non-native tree species, if necessary initial planting	< 10 10 - 30 > 30	4	1	4	Yes

nued

ervation t	Habitat type number (German Red List)	German Red List Status	Habitat type (Annex 1, EU Habitats Directive)	European Nature Information System (EUNIS) classification	Possible conservation measure during contract period	Period (years)	Initial NCV		Final NCV	
							Worthiness	Need	Increase in value <u>with</u> contract-based conservation	Loss of value <u>without</u> contract-based conservation
bile birch nd birch-lder carr oodland #	43.01, 43.02	1-2	Bog woodland (91D0*) and Alluvial forests with *Alnus glutinosa* and *Fraxinus excelsior* (Alno-Padion, Alnion incanae, Salicion albae, 91E0*)	Broadleaved swamp forest on non-acid peat (T1-5), Broadleaved swamp forest on acid peat (T1-6) and Coastal dune woods (B1.7)	Renouncement of degrading measures	< 10 10 - 30 > 30	4	4	n.a.	No
Degraded irch and rch-alder carr voodland		3-V			Rewetting and removal of non-native tree species, if necessary initial planting	< 10 10 - 30 > 30	4	3	4	Yes
Pioneer voodland (native shrub, ioneer and ermediate ee species) (#)	42.03	*		Early-stage natural and semi-natural forests and regrowth (T4-6)	Adapted nature conservation management in the direction of natural succession without massive acceleration	< 10 10 - 30 > 30	4	1	2.5 2 1	Yes
Voodland mantle #	42.01	2-3		Thermophile woodland fringes (E5.2) and Moist or wet tall-herb and fern fringes and meadows (E5.4)	Prevention of succession, promotion of light-loving tree and shrub species	< 10 10 - 30 > 30	4	3	3.5	Yes
st and nd fringe tion on ophic to c sites (#)	39.01.01	2-3	Hydrophilous tall herb fringe communities of plains and of the montane to alpine levels (6430)	Thermophile woodland fringes (E5.2) and Moist or wet tall-herb and fern fringes and meadows (E5.4)	Prevention of succession, promotion of light-loving tree and shrub species	< 10 10 - 30 > 30	4	3	3.5	Yes

continued

servation object	Habitat type number (German Red List)	German Red List Status	Habitat type (Annex 1, EU Habitats Directive)	European Nature Information System (EUNIS) classification	Possible conservation measure during contract period	Period (years)	Initial NCV: Worthiness	Initial NCV: Need	Final NCV: Increase in value <u>with</u> contract-based conservation	Final NCV: Loss of value <u>without</u> contract-based conservation
st and woodland ge vegetation on rtrophic sites (#)	39.01.02	*	Hydrophilous tall herb fringe communities of plains and of the montane to alpine levels (6430)	Thermophile woodland fringes (E5.2) and Moist or wet tall-herb and fern fringes and meadows (E5.4)	Prevention of succession, promotion of light-loving tree and shrub species	< 10 10 - 30 > 30	3	1	2	Yes
Stabile riparian herbaceous fringes or vegetation along water bodies #	39.04	2-3	Hydrophilous tall herb fringe communities of plains and of the montane to alpine levels (6430)	Moist or wet tall-herb and fern fringes and meadows (E5.4)	Renounceme nt of degrading measures	< 10 10 - 30 > 30	4	3	n.a.	No
Degraded riparian herbaceous fringes or vegetation along water bodies		3-V			Promotion of habitat type-characteristic species	< 10 10 - 30 > 30	3	2	3.5	Yes
Stabile seepage and marshy, pooling (limnocrenes) or flowing (rheocrenes) #	22.01, 22.02, 22.03	1-2	Petrifying springs with tufa formation (Cratoneurion, 7220*)		Renounceme nt of degrading measures	< 10 10 - 30 > 30	5	4	n.a.	No
Degraded seepage and marshy, pooling (limnocrenes) or flowing (rheocrenes)		2-3			Dismantling of sockets and drainage ditches, removal of non-native plant species	< 10 10 - 30 > 30	4	3	4.5	Yes

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ervation t	Habitat type number (German Red List)	German Red List Status	Habitat type (Annex 1, EU Habitats Directive)	European Nature Information System (EUNIS) classification	Possible conservation measure during contract period	Period (years)	Initial NCV		Final NCV		f c
							Worthiness	Need	Increase in value with contract-based conservation	Loss of value without contract-based conservation	
tural and i-natural ing waters #	23.01	1-2		Permanent non-tidal, fast, turbulent watercourses (C2.2), Eutrophic vegetation of slow-flowing rivers (C2.3), Tidal rivers, upstream from the estuary (C2.4) and Species-rich helophyte beds (C3.1)	Renouncement of degrading measures	< 10 10 - 30 > 30	5	4	n.a.	No	
ercourses bject to derate to severe ropogenic dification	23.02, 23.03	3-V		Permanent non-tidal, fast, turbulent watercourses (C2.2), Eutrophic vegetation of slow-flowing rivers (C2.3), Tidal rivers, upstream from the estuary (C2.4) and Species-rich helophyte beds (C3.1)	Removal of bank embankments, installation of flow control, cross-linking with side waters	< 10 10 - 30 > 30	2	2	4.5	Yes	
rmittently xposed tats below an water evel of rcourses #	23.08	1-2		Unvegetated or sparsely vegetated shores with soft or mobile sediments (C3.6), with non-mobile substrates (C3.7) and Inland spray- and steam-dependent habitats (C3.8)	Renouncement of degrading measures	< 10 10 - 30 > 30	5	4	n.a.	No	
tural and i-natural mporary rcourses #	23.09	1-2		Temporary running waters (C2.5)	Renouncement of degrading measures	< 10 10 - 30 > 30	4	4	n.a.	No	

continued

onservation bject	Habitat type number (German Red List)	German Red List Status	Habitat type (Annex 1, EU Habitats Directive)	European Nature Information System (EUNIS) classification	Possible conservation measure during contract period	Period (years)	Initial NCV		Final NCV	
							Worthiness	Need	Increase in value with contract-based conservation	Loss of valu without contract-based conservatio
Dystrophic standing waters/ peatland waters #	24.01	1-2	Natural dystrophic lakes and ponds (3160) and Depressions on peat substrates of the Rhynchosporion (7150)	Permanent dystrophic lakes, ponds and pools (C1.4) and Temporary lakes, ponds and pools (C1.6)	Renounce-ment of degrading measures	< 10 10 - 30 > 30	4	4	n.a.	No
Oligotrophic standing waters #	24.02	1-2	Oligotrophic waters containing very few minerals of sandy plains (Littorelletalia uniflorae, 3110), Turloughs (*3180), Oligotrophic to mesotrophic standing waters with vegetation of the Littorelletea uniflorae and/or of the Isoeto-Nanojuncetea (3130) and Hard oligo-mesotrophic waters with benthic vegetation of *Chara* spp. (3140)	Permanent oligotrophic lakes, ponds and pools (C1.1) and Temporary lakes, ponds and pools (C1.6)	Renounce-ment of degrading measures	< 10 10 - 30 > 30	4	4	n.a.	No
Mesotrophic standing waters #	24.03	1-2	Turloughs (*3180), Oligotrophic to mesotrophic standing waters with vegetation of the Littorelletea uniflorae and/or of the Isoeto-Nanojuncetea (3130) and Hard oligo-mesotrophic waters with benthic vegetation of *Chara* spp. (3140)	Permanent mesotrophic lakes, ponds and pools (C1.2) and Temporary lakes, ponds and pools (C1.6)	Renounce-ment of degrading measures	< 10 10 - 30 > 30	4	4	n.a.	No

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servation ect	Habitat type number (German Red List)	German Red List Status	Habitat type (Annex 1, EU Habitats Directive)	European Nature Information System (EUNIS) classification	Possible conservation measure during contract period	Period (years)	Initial NCV		Final NCV	
							Worthiness	Need	Increase in value **with** contract-based conservation	Loss of value **without** contract-based conservation
utrophic standing waters #	24.04	3-V	Natural eutrophic lakes with Magnopotamion or Hydrocharition -type vegetation (3150)	Permanent eutrophic lakes, ponds and pools (C1.3) and Temporary lakes, ponds and pools (C1.6)	Renouncement of degrading measures	< 10 10 - 30 > 30	4	2	n.a.	No
ermittently exposed bitats below ean water level of standing waters #	24.08	3-V	Oligotrophic waters containing very few minerals of sandy plains (Littorelletalia uniflorae, 3110), Oligotrophic to mesotrophic standing waters with vegetation of the Littorelletea uniflorae and/or of the Isoeto-Nanojuncetea (3130) and Depressions on peat substrates of the Rhynchosporion (7150)	Periodically inundated shores with pioneer and ephemeral vegetation (C3.5), Unvegetated or sparsely vegetated shores with soft or mobile sediments (C3.6) and with non-mobile substrates (C3.7)	Renouncement of degrading measures	< 10 10 - 30 > 30	4	2	n.a.	No
Degraded standing waters		2-3			Restoration of proper nutrient and oxygen content, desludging, reduction of external organic matter inputs	< 10 10 - 30 > 30	4	3	3-5	Yes

Table S 5: Proportions of the worthiness of preservation and need for protection of all forest conservation objects (FCO), and for each group.

			All FCO		Processes		Structures		Habitat types	
	Value	**Description**	**n**	**%**	**n**	**%**	**n**	**%**	**n**	**%**
Worthiness	0	No	6	9	1	25	5	62.5	0	0
	1	Very low	0	0	0	0	0	0	0	0
	2	Low	1	1.5	0	0	0	0	1	1.8
	3	Moderate	5	7.5	1	25	0	0	4	7.3
	4	High	30	44.8	0	0	0	0	32	54.5
	5	Very high	25	37.3	2	50	3	37.5	21	36.4
Need	0	No	6	9	1	25	5	62.5	0	0
	1	Very low	4	6	0	0	0	0	4	7.3
	2	Low	12	17.9	0	0	0	0	13	21.8
	3	Moderate	19	28.4	1	25	0	0	19	32.7
	4	High	18	26.9	0	0	0	0	18	32.7
	5	Very high	8	11.9	2	50	3	37.5	4	5.5

Table S 6: German Red List Status (1! = critically endangered (acutely), 1-2 = endangered to critically endangered, 2-3 = vulnerable to endangered, V = near threatened), Natura 2000 assignment and EUNIS (European Nature Information System) classification of the exemplary FCOs.

Forest conservation object	Red List Status	Habitat type (Annex 1, EU Habitats Directive)	European Nature Information System (EUNIS) classification	Relevant for Natura 2000 habitat type conservation status assessment
Coppice-with-standards	1!			-
Bog and fen woodlands	1-2	Bog woodland (Code 91D0*)	*Picea* mire forests (Code T3-K) and *Pinus* bog forests (Code T3-J)	-
Dry sand pine forests	1-2	Central European lichen Scots pine forests (Code 91T0)	Subcontinental lichen *Pinus sylvestris* forests (Code T3-52112)	-
Beech forests	V / 2-3	Asperulo-Fagetum (Code 9130) and Medio-European limestone beech forests of the Cephalanthero-Fagion (Code 9150)	Medio-European woodruff and hairy sedge beech forests (Code T1-7112) and limestone beech forests of the Cephalanthero-Fagion (Code 9150)	-
Deadwood	-	-		Yes
Habitat trees	-	-		Yes
Natural forest development	-	-		Yes
Natural succession after disturbance	-	-		Yes

CHAPTER 4

Transfer of nature conservation assessment into forestry practice – assessing the nature conservation value of forest tree species

Laura DEMANT

Unpublished manuscript

4.1 Abstract

The emering climatic changes and the uncertainties about the intensity and frequency with which these changes, such as disturbances, will occur in the future require adapted silvicultural management and consideration in silvicultural planning. In Germany, silvicultural planning tools such as forest development types are often only developed with regard to an economic productivity function and nature conservation aspects are less considered. A nature conservation assessment of tree species can help to ensure that the future species composition of forest stands is as semi-natural as possible and consists of mainly native tree species. Certain tree species combinations in silvicultural planning can, on the one hand, lead to a decrease in the initial conservation value (determined by the naturally occurring forest habitat type) or, on the other hand, to an improvement of a low initial value. With the presented nature conservation assessment framework, forest owners can not only orient their silvicultural planning towards maximum yield, but also try to consider the nature conservation needs of their forests, which represents progress.

4.2 Introduction

Natural disturbances caused by agents such as high wind speeds, insect infestations, droughts, or fires play a key role in forest dynamics and can make an important contribution to forest biodiversity (Franklin et al. 2002; Turner 2010). A changing climate will lead to an increase in the size, severity and frequency of disturbances due to an increase in extreme climatic events (Turner 2010; Seidl et al. 2017; Senf and Seidl 2018; Senf et al. 2018, 2021). It is therefore crucial to increase the resilience and resistence of forest ecosystems to disturbances (Seidl 2014; Johnstone et al. 2016; Senf and Seidl 2021b). Storm-related disturbances are the dominant disturbance type in European forests (Hanewinkel et al. 2011). With changing global climate conditions, the intensity of winter storms in Central Europe will most likely continue to increase (Mölter et al. 2016), although their spatial and temporal pattern will remain very heterogeneous (Jung and Schindler 2021). Facing these climate change-related challenges, future silvicultural concepts and the selection of suitable tree species that are better adapted to storms and other disturbances are becoming increasingly important. Forest planners in Germany are therefore confronted with the necessity to adapt future silvicultural stand planning. The primary objective should be to promote more climate-resilient forests and to consider semi-natural, species-rich mixed deciduous forests with site-specific, native tree species better adapted to extreme climatic conditions such as drought and storm (BfN 2020; BMEL 2021a).

These challenges were addressed within the MiStriKli-project: Minimising storm damage risk in forests being faced with climate change (German: Minimierung des Sturmschadensrisikos in Wäldern vor dem Hintergrund des Klimawandels). The aim of this research project, funded by the German Waldklimafonds, was to adapt the structure and tree species composition of forests in order to minimise the negative effects of future climate change-induced storm damage risk in German forests. The objectives of the MiStriKli-project were:

- the simulation of spatially high-resolution gust speed areas,
- the estimation of future damage potentials due to winter storms as a base for the selection of potential forest stands for the main economic tree species,
- the development and economic assessment of management strategies to minimise the negative impacts of future storm damage risk in forests,
- a nature conservation and forest ecology assessment of management strategies to minimise the negative impacts of future storm damage risk in forests,
- and finally, to optimise management strategies in the way of a robust, biodiversity-conscious and economically efficient forest management which takes storm damage risk and the uncertainty of climate change into account.

Within the MiStriKli-project forest development types were defined in order to identify tree species combinations that are better adapted to climate change-induced storm damage risks. The forest development types comprised the most common tree species in Central European commercial forests: beech, oak (with both European oak species, pedunculated and sessile oak), Scots pine, Norway spruce, silver fir, larch and Douglas fir). In work package 4 of the MiStriKli-project, the nature conservation and forest ecological effects of different management strategies on minimising negative impacts of storm damage risk were assessed with regard to forest stands, their structure and a possible management of disturbed forest areas. The present study, which is part of the work package 4, deals with the nature conservation assessment of forest stands. The aim was to develop an assessment framework for deriving a spatially-explicit nature conservation value at tree species level and thus to assess the forest development types planned throughout Germany in terms of to their nature conservation value. The central research objectives were:

- to assign a spatially-explicit reference to the nature conservation assessment of forest habitat types by Demant et al. (2020),
- to develop an assessment framework to assign a tree species-specific nature conservation value to silvicultural forest development types,
- and to investigate whether the specific tree species selection leads to a change in the initial nature conservation value, which is determined by the respective naturally occurring forest habitat type.

As natural forest habitat types usually consist of more than the main economic tree species analysed in this study, it is to be expected that the absence of certain secondary tree species within the forest development types, such as species of lime, maple and hornbeam, may lead to a change in the initial nature conservation value.

4.3 Methods

4.3.1 Forest development types

The nature conservation assessment of forest stands was conducted by assessing the nature conservation value of Germany-wide forest development types. Defining forest development types (German: *Waldentwicklungstypen*, WET) is a general practice in silvicultural planning and provides a long-term vision of how species composition and structure of forest stands are expected to develop through appropriate selection and mixture of tree species (Larsen and Nielsen 2007; Spencer and Field 2019). Forest development types establish a functional link between the initial condition and the desired target condition in forest stands and also include the most suitable silvicultural measures for achieving this target condition (Eisenhauer and Sonnenmann 2009; ForstBW 2014).

Table 16: Forest development types with their different mixture proportions. OLD = other long-lived deciduous tree species.

Forest development types	Mixture proportion (%)
Beech	100
Beech – Spruce	75 – 25
Beech – Spruce	50 – 50
Spruce	100
Spruce-Beech	75 – 25
Beech – Larch	75 – 25
Beech – Larch	50 – 50
Larch - Beech	75 – 25
Beech – Douglas fir	75 – 25
Beech – Douglas fir	50 – 50
Douglas fir – Beech	75 – 25
(Sessile and/or Pedunculate) Oak	100
Oak – Beech	75 – 25
Oak – Beech	50 – 50
Oak – Pine	75 – 25
Oak – Pine	50 – 50
Pine	100
Pine – Beech	75 – 25
Pine – Beech	50 – 50
Beech – Fir – Spruce	60 – 30 – 10
Fir – Beech – Spruce	60 – 30 – 10
Beech – Fir – Douglas fir	60 – 30 – 10
Fir – Beech – Douglas fir	60 – 30 – 10
Pine – Douglas fir – Beech	60 – 30 – 10
Beech - OLD	75 – 25
Beech – OLD	50 – 50
OLD – Beech	75 – 25

The forest development types selected in the MiStriKli-Project comprise main tree species in Central European commercial forests: beech (*Fagus sylvatica* L.), oak (which combines and not further differentiates within the forest development types between pedunculate oak (*Quercus petraea* (MATT.) LIEBL.) and sessile oak (*Quercus robur* L.)), Scots pine (*Pinus sylvestris* L.), Norway spruce (*Picea abies* (L.) H. KARST.), silver fir (*Abies alba* MILL.), European larch (*Larix decidua* MILL.) and Douglas fir (*Pseudotsuga menziesii* (MIRBEL) FRANCO). Further deciduous tree species, such as species of maple, lime, hornbeam and others, were grouped together as “other long-lived deciduous tree species”. Within the forest development types, the different tree species are combined and mixed with varying proportions (Table 16). A total of 27 different forest development types were defined, representing possible compositions of future commercial forest stands in Germany.

The aim of this MiStriKli-project-related compilation of forest development types is to give forest owners the opportunity to select certain tree species combinations in their future forest stands. In this context, individual objectives and motivations such as a conservation-oriented ecological and semi-natural forest structure, and/or the use of tree species that allow for the highest economic profit, and/or the consideration of tree species compositions that may lead to a reduction of storm damage risk are to be considered. As the storm-damage risk rating and the economical evaluation of the forest development types were carried out by other MiStriKli-project partners, they are not further addressed in the present study.

4.3.2 Nature conservation value assessment of forest development types

For the assessment of the nature conservation value of tree species and different forest development types, the concept of the nature conservation value assessment of forest habitat types by Demant et al. (2020) was applied and further developed. Demant et al. (2020) assessed forest habitat types according to their need for, and worthiness of, protection and distinguished six levels in a qualitatively ranked ordinal scale. The ordinal levels for the assessment of the need for protection were based on Red List categories of forest habitat types (Janssen et al. 2016; Finck et al. 2017). The assessment of the worthiness of protection of forest habitat types was based on habitat continuity. It was assumed that the longer a forest habitat type exists, the higher is its worth of preservation as part of a region's natural or cultural heritage. Further criteria for the assessment of the worthiness of protection were the quantitative (absolute number of species) and the qualitative (relative to a desired reference state) contribution of a forest habitat type to the species pool of a natural landscape. The final nature conservation value was obtained by calculating the mean value of the worthiness of, and the need for, protection with the classes 0 = no, 1 = very low, 2 = low, 3 = moderate, 4 = high, and 5 = very high conservation value (for a detailed methods description see Chapter 3, Demant et al. 2020).

The aim of the MiStriKli-project was to derive Germany-wide management strategies to minimise negative effects of future climate change-influenced storm damage risk at the level of forest stands by deducing suitable forest development types. Therefore, the main challenge in work package 4 was to carry out the nature conservation value assessment of the forest development types throughout Germany. However, since forest habitat types were not spatially-explicitly available, a Germany-wide reference system was needed. The concept of the Potential Natural Vegetation (PNV), first introduced by Tüxen (1956), describes the actualistichypothetical natural climax stage or the most highly developed state of vegetation units that a site could abruptly exhibit without human influence. Tüxen (1956) once specified the PNV "…is the vegetation that would finally develop if all human influences on the site and its immediate surroundings would stop at once, and if the terminal stage would be reached at once". The PNV can be used as a synonym for the final successional stage of vegetation based on real existing vegetation units, excluding future human influences or the effects of future climate change (Chiarucci et al. 2010). The PNV is usually presented in the form of maps at different spatial scales, which show the assumed distribution of the natural plant communities in terms of a final succession state under the current climatic and edaphic site conditions. For Europe, Bohn et al. (2003) depicted the PNV at a scale of 1:2,500,000. In the present study, the map by Suck et al. (2014) was used as reference for the new conservation assessment framework, which represents the PNV for Germany at a scale of 1:500,000.

Table 17: Assignment of the natural forest types (Engel et al. 2016) to the main vegetation unit (3rd level) of the PNV (according to Suck et al. 2014 and Engel et al. 2016). Explanation of codes of the 3rd level see Table S 7.

Natural forest type (short name)	Main vegetation units of the PNV (3rd level)
Birch-oak forest of fresh to moist sites (birch-oak forest fresh)	H1, H2, H3
Beech forest on base-rich and calcareous sites (beech forest rich)	Na1, Nb2a, Nc3, Nc4a, Nc4b, Nc5, Nc6, Nc7a, Nc7b, Nd3, Nd4, Nd5, Ne8a, Ne8b
Beech forest on acidic sites (beech forest poor)	La1, Lb2a,,Lb2b,Lb2c, Lb2d, Lb2e, Lc3a, Lc4, Lc5a, Lc5d, Lc6a, Lc6b, Ld3a, Ld4, Ld5, Ld6, Le7a, Le7b, Le8, Lf9
Beech forest on moderately rich calcareous sites (beech forest moderately rich)	Ma1a, Ma1b, Mb2, Mc3, Mc4, Mc5, Mc6a, Mc6b, Mc6c, Md3a, Md4, Md5, Md6a, Md6b, Me7, Me8, Me9
Oak-hornbeam forest on mesic to moist sites (oak-hornbeam forest fresh)	F1b, F2, F3, F4, F5, F6
Oak-hornbeam forest on warm-dry calcareous sites (oak-hornbeam forest dry)	Ga1, Ga2, Ga3, Gb5, Gb6, Gb7
Mixed oak forests on warm-dry calcareous sites (oak forest dry/rich)	K1a, K2a, K2b, K2c
Mixed oak forests on warm-dry acidic sites (oak forest dry/poor)	Ja1a, Ja1b, Jb2
Alder, swamp and fen woodlands (swamp and fen woodlands)	E1a, E1b, E3
Wet alder-elm, alluvial forest (wet alluvial forest)	E2, E4, E5, E7a, E7b
Montane spruce forest (spruce forest high)	S1a, S2, S4, T1, T2
Spruce forest on acidic sites (spruce forest)	
Bog and fen woodlands	C2a, C2b, C2c, D1a, D1b, D2, D3, D4a, D4b
Sand and silicate pine forests (pine forest)	P1a, P1b, P2a, P2b, P2c, Q1
Fir forest	R1, R2
Willow floodplain forests	E6a, E8

The PNV is subdivided into hierarchical levels of vegetation units, some of which are highly differentiated. As the direct assignment of forest habitat types to the PNV vegetation units was challenging, a linking framework was needed. Engel et al. (2016) assigned the PNV forest vegetation units to 16 "natural forest types" (Table 17). Since the lowest PNV unit has a high level of detail, the forest habitat types were linked according to the 3rd level of the PNV units.

Table 18: Assignment of the natural forest types (Engel et al. 2016) to the forest habitat types (Finck et al. 2017) with their nature conservation value assessment.

Natural forest type (short name)	Forest habitat type	Nature conservation value
Bog and fen woodlands	Birch bog woodland	4
Bog and fen woodlands	Bog and fen woodland	4
Alder, swamp and fen wood forests (swamp and fen wood forest)	Riparian alluvial forests of alder and ash	4
Alder-elm, alluvial and wet forest (alluvial and wet forest)	Alder carr woodland on nutrient rich sites	4
Alder-elm, alluvial and wet forest (alluvial and wet forest)	Hardwood alluvial forest	4
Willow floodplain forests	Softwood alluvial forest	4
Oak-hornbeam forest on fresh to moist sites (oak-hornbeam forest fresh)	Oak-hornbeam forest on waterlogged to moist site	4
Oak-hornbeam forest on warm-dry calcareous sites (oak-hornbeam forest dry)	Dry oak-hornbeam forest	4.5
Birch-oak forest of fresh to moist sites (birch-oak forest fresh)	Birch-oak forest on damp to moist site	4
Mixed oak forests on warm-dry acidic sites (oak forest dry/poor)	Dry oak forest on base-deficient sites	3
Mixed oak forests on warm-dry calcareous sites (oak forest dry/rich)	Dry oak forest on base-rich sites	4
Beech forest on acidic sites (beech forest poor)	Planar/montane beech forest on base-deficient sites	3
Beech forest on acidic sites (beech forest poor)	Montane beech-fir forest on base-poor sites (> 50% beech)	3
Beech forest on acidic sites (beech forest poor)	Montane beech-fir/spruce forest on base-deficient sites (> 50% beech)	3
Beech forest on moderate calcareous sites (beech forest moderately rich)	Beech (mixed) forest on base-deficient sites	3.5
Beech forest on base-rich and calcareous sites (beech forest rich)	Beech (mixed) forest on base-rich sites	3.5
Beech forest on base-rich and calcareous sites (beech forest rich)	Sedge-beech forest (orchid beech forest)	4
Beech forest on base-rich and calcareous sites (beech forest rich)	Montane beech-fir/spruce forest on base-rich sites (> 50% beech)	3.5
Sand and silicate pine forests (pine forest)	Dry pine forest	3
Fir forest	Montane fir-(spruce)-beech forest (> 50% coniferous)	3
Spruce forest on acidic sites (spruce forest)	Spruce plantations	1.5
Montane spruce forest (spruce forest high)	Spruce/fir (mixed) forest and spruce (mixed) forest (within their natural range)	3.5

In order to link the spatially-explicit vegetation units of the PNV with the forest habitat types, the natural forest types of Engel et al. (2016) were assigned to the forest habitat types assessed by Demant et al. (2020) in terms of their nature conservation value (Table 18). With this assignment, a spatially-explicit assessment of the nature conservation value for all forest habitat types could be derived for whole of Germany (Figure 7).

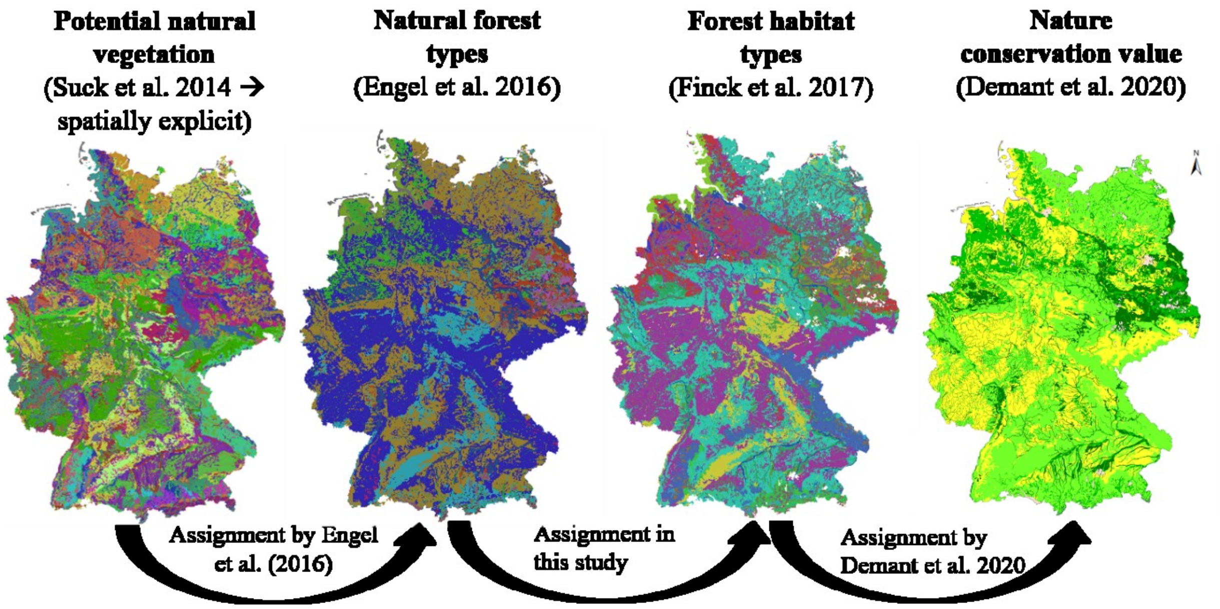

Figure 7: Schematic illustration of the assignment steps from the potential natural vegetation (Suck et al. 2014) to natural forest types (Engel et al. 2016) and to forest habitat types (Demant et al. 2020) with a finally available spatially-explicit nature conservation value for the whole of Germany.

In a next processing step, the forest development types (with their different tree species mixture proportions, Table 16) were assessed in terms of their nature conservation value. The assessment itself was carried out at tree species level. In order to derive a spatially-explicit nature conservation value for each forest development type, assessment rules were defined at coordinate point level (Table 19). The nature conservation value assessment of forest tree species was based partly on habitat continuity, expressed by the affiliation to the natural vegetation units and the degree of distinctiveness of the typical vegetation form. Subject of the habitat continuity assessment was whether the tree species is located within its Central European distribution range and is thus an autochthonous species. If this was the case, the nature conservation value existing at that spatial unit was not reduced. In addition to the assessment of habitat continuity, it was decisive for the avoidance of value losses that the tree species was part of the forest habitat type. Therefore, the highest nature conservation value of tree species could be maintained if they were both autochthonous and a natural component of the specific forest habitat type. If these conditions applied, the final nature conservation value of the forest development types corresponded 100% to the value of the forest habitat type existing at that spatial unit (multiplication factor = 1, Table 19).

The assessed forest habitat types represented the mapped PNV of each spatial unit and can thus be referred to the “understory reinitiation stage” (Oliver and Larson 1996), which represents a stable or mature climax vegetation community. However, belonging to a climax stage was not the only prerequisite for a one-to-one transfer to the nature conservation value of the forest habitat types. Since forest climax vegetation is commonly understood as a terminal state (Clements 1916) which often disregards or even excludes the different successional stages of forest disturbance dynamics, a succession parameter was included. If the tree species belonged to natural succession stages and in particular were pioneer tree species (in the present study this only applied to Scots pine), the species were treated as naturally belonging to the forest habitat type and the nature conservation value did not change (multiplication factor = 1, Table 19).

Table 19: Nature conservation value assessment expressed by the habitat continuity of the tree species of each forest development type. Numbers represent the multiplication factor for equation (1).

Species is within its natural distribution range	**Species belongs to the forest habitat type**		
	Yes, identical	No, but part of succession stages	No and no succession species
Yes	1	1	0.5
No, but European	0	0.5	0.25
No, introduced	0	0	0

If tree species were within their natural distribution range, but did not belong to the natural forest type and were not successional species, the initial nature conservation value was reduced by 50% (multiplication factor = 0.5, Table 19). This also applied, if it was a European tree species that was planned outside its natural distribution range and thus, did not belong to the forest habitat type, but was a successional tree species. However, if this last condition regarding the affiliation to a successional forest stage was not fulfilled either (in the present study this only applied to Norway spruce), the nature conservation value was reduced by 75% (multiplication factor = 0.25, Table 19). Introduced tree species (in the present study only Douglas fir) received a nature conservation value of zero, as they do not belong to the European natural or cultural landscape heritage. As foreign bodies in the coevolution of the Quaternary period of the last 2.6 million years, they have no conservation value.

Another assessment criterion was the degree of distinctiveness of the typical vegetation form (completeness). If the tree species composition of the forest development type did not fully correspond to the typical expression of the forest habitat type (certain tree species were missing), a further multiplication factor of 0.75 was applied. For example, if a forest development type with exclusively beech is planned on a site whose natural forest habitat type is a montane beech-fir-spruce forest, consequently silver fir and spruce are lacking, which leads to a reduction of the inital nature conservation value of 25% (multiplication factor = 0.75). Finally, the percentage of tree species in the respective forest development type was included in the calculation of the new nature conservation value of the forest development type, which was calculated according to equations [1] and [2]. First, the specific nature conservation value for each tree species of the forest development type ($NCV_{Species}$) was calculated (equation [1]). Secondly, the final nature conservation value for the forest development type (NCV_{FDT}) was calculated by summarising the nature conservation value of each tree species ($NCV_{Species}$) and dividing it by the number of tree species ($N_{Species}$) of the respective forest development type (equation [2]).

$$NCV_{Species} = NCV_{FHT} \cdot HC \cdot TE \cdot P_{\mathrm{FDT}} \qquad \text{equation [1]}$$

$$NCV_{\mathrm{FDT}} = \frac{(NCV_{Species1} + NCV_{Species2} + NCV_{Species3})}{N_{Species}} \qquad \text{equation [2]}$$

With:

$NCV_{Species}$ = nature conservation value of the tree species of the forest development type,
NCV_{FHT} = nature conservation value of the forest habitat type,
HC = habitat continuity factor,
TE = typical expression factor,
P_{FDT} = proportion of the forest development type,
NCV_{FDT} = nature conservation value of the forest development type,
$N_{Species}$ = number of all tree species of the selected forest development type.

Table 20 shows an exemplary nature conservation value assessment for five different forest development types and two forest habitat types. The final nature conservation values of each tree species ($NCV_{Species}$) and forest development type combination (NCV_{FDT}) were calculated separately (see equations [1] and [2]). The initial nature conservation values of both forest habitat types (3.5) could not be maintained for almost all forest development types. Only when considering pure beech stands in a beech forest on base-rich sites the value did not change. If only beech was considered in a mixed montane beech-fir-spruce forest, the condition for the degree of distinctiveness of the typical vegetation form (completeness) was not fulfilled (silver fir and spruce were missing). Consequently, the nature conservation value decreased by about one point to 2.6. Even if a forest development type consisting of beech and spruce was considered in this exemplary forest stand, the nature conservation value of the forest habitat type could not be maintained, because Silver fir was lacking. If Douglas fir was included, the value decreased considerably, since this species is introduced and does not receive any nature conservation value.

Table 20: Exemplary nature conservation value (NVC) assessment values for selected forest development types (FDTs) tree species combinations (FHT = forest habitat type, HC = habitat continuity, TE = typical expression, P = proportion).

FDT	Tree species	Forest habitat type	NCV_{FHT}	HC	TE	P_{FDT}	$NCV_{Species}$	NCV_{FDT}
Beech	Beech	Montane beech-fir-spruce forest on base-deficient sites	3.5	1	0.75	1	2.6	2.6
Beech – Douglas fir	Beech			1	0.75	0.75	2	1
	Douglas fir			0	0.75	0.25	0	
	Beech			1	0.75	0.5	1.3	0.7
	Douglas fir			0	0.75	0.5	0	
Beech – Spruce	Beech			1	0.75	0.5	2.6	2.6
	Spruce			1	0.75	0.5	2.6	
Spruce	Spruce	Beech forest on base-rich sites	3.5	0.5	-	1	1.8	1.8
Beech	Beech			1	1	1	3.5	3.5

4.3.3 Study area

In the MiStriKli-project, it was originally planned to carry out the nature conservation assessment of all forest development types within a 50 x 50 metre grid over the entire area of Germany, which would have resulted in a calculation of approximately 44 million tiles. Due to internal project challenges in data management, the respective project partners agreed that all analyses and calculations, including the nature conservation value assessment of the forest development types, would be be carried out at transect level. For this purpose, three Germany-wide transects were selected, containing 9,438 coordinates in one north-south and two east-west oriented lines (Figure 8). The results of the nature conservation assessment of the forest development types within this transect are presented in this study.

4.4 Results

4.3.1 Nature conservation value of forest development types

Within the Germany-wide transect, 14 forest habitat types were represented. Pure and mixed beech forests (beech (mixed) forest on base-rich soil sites and planar/submontane beech forest on base-deficient soils) were the most frequently represented forest habitat types, covering about 77% of all coordinate points. Mixed oak and oak-hornbeam forest habitat types accounted for around 10% and montane beech-fir-spruce forest habitat types for about 8%. Other forest habitat types were rarely represented with shares close to zero.

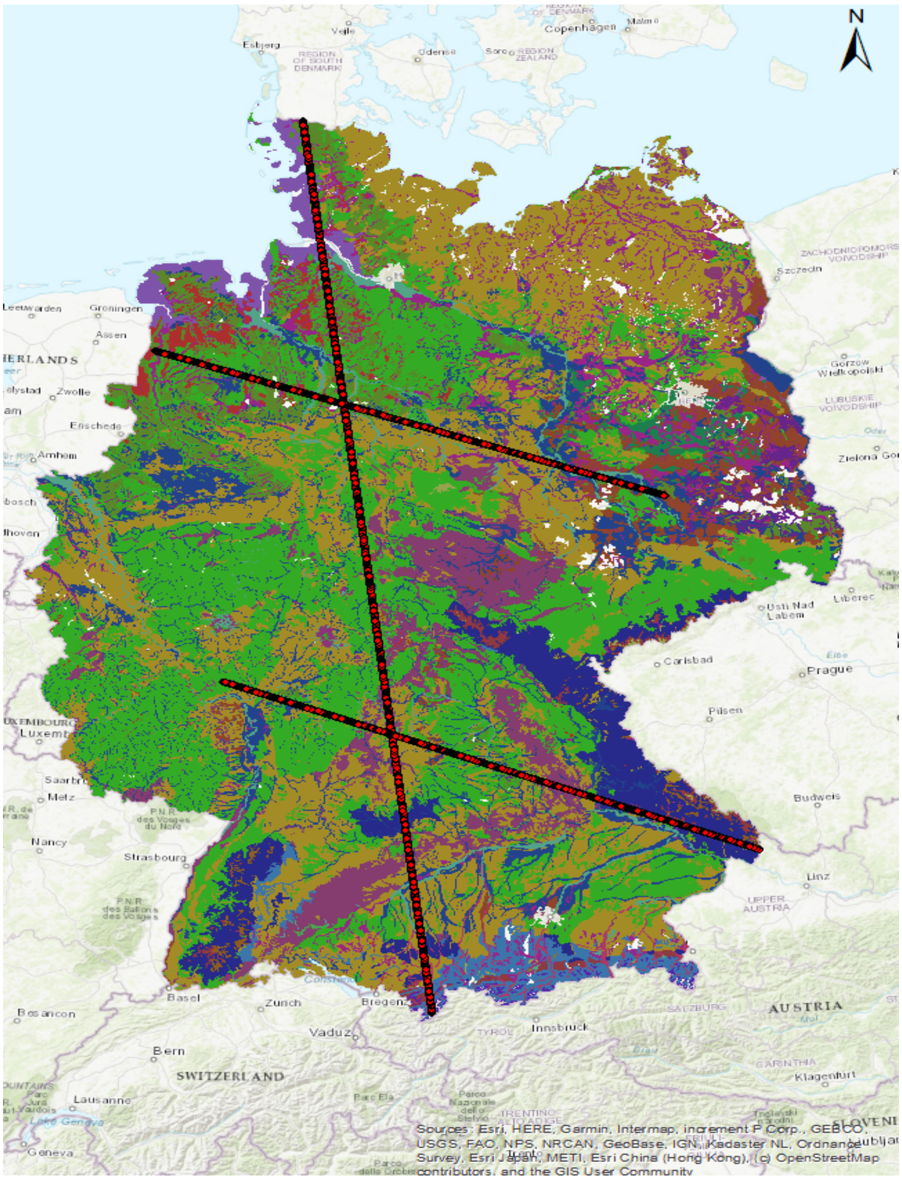

Figure 8: Germany-wide transect of 9,438 coordinates in north-south and east-west direction. Forest habitat types are shown in different colors.

e conservation values (NCV) of all 27 forest development types (FDTs) with different mixture proportions within the Germany-wide transect (NCV_{FDT}) and displayed
centage value losses in relation to the initial NCV of the FDTs. Very high value losses (≥90%) are displayed in darker red colours, high value losses (<90 to ≥70%) ar
ours, medium value losses (<70 to ≥50%) are displayed in yellow colours, lower value losses (<50 to ≥25%) are displayed in lighter green colours and very low valu
ed in darker green colours. Numbers in brackets behind the forest habitat types represent their initial nature conservation value. OLD = other long-lived deciduous tr

t t types	Mixture (%)	Forest habitat types: Birch bog woodland (4)		Bog and fen woodland (4)		Riparian alluvial forests of alder and ash (3)		Alder carr woodland on nutrient rich sites (4)		Hardwood alluvial forest (4)		Softwood alluvial forest (4)		Oak-hornbeam forest on waterlogged to moist site (4.5)		D horn
		NCV_{FDT}	% value loss	NCV_{FDT}	% value loss	NCV_{FDT}	% value loss	NCV_{FDT}	% value loss	NCV_{FDT}	% value loss	NCV_{FDT}	% value loss	NCV_{FDT}	/alue loss	NCV
.	100	1.5	62.5	1.5	62.5	1.1	62.5	1.5	62.5	1.5	62.5	1.5	62.5	1.7	62.5	1.7
pruce	75/25	1.3	67.2	1.5	62.5	1.0	67.2	1.3	67.2	1.3	67.2	1.5	62.5	1.5	67.2	1.5
pruce	50/50	1.1	71.9	1.5	62.5	0.8	71.9	1.1	71.9	1.1	71.9	1.5	62.5	1.3	71.9	1.3
e	100	0.8	81.3	1.5	62.5	0.6	81.3	0.8	81.3	0.8	81.3	1.5	62.5	0.8	81.3	0.8
Beech	75/25	0.9	76.6	1.5	62.5	0.7	76.6	0.9	76.6	0.9	76.6	1.5	62.5	1.1	76.6	1.1
arch	75/25	1.1	71.9	1.1	71.9	0.8	71.9	1.1	71.9	1.1	71.9	1.1	71.9	1.3	71.9	1.3
arch	50/50	0.8	81.3	0.8	81.3	0.6	81.3	0.8	81.3	0.8	81.3	0.8	81.3	0.8	81.3	0.8
eech	75/25	0.4	90.6	0.4	90.6	0.3	90.6	0.4	90.6	0.4	90.6	0.4	90.6	0.4	90.6	0.4
glas fir	75/25	1.1	71.9	1.1	71.9	0.8	71.9	1.1	71.9	1.1	71.9	1.1	71.9	1.3	71.9	1.3
glas fir	50/50	0.8	81.3	0.8	81.3	0.6	81.3	0.8	81.3	0.8	81.3	0.8	81.3	0.8	81.3	0.8
- Beech	75/25	0.4	90.6	0.4	90.6	0.3	90.6	0.4	90.6	0.4	90.6	0.4	90.6	0.4	90.6	0.4
	100	1.5	62.5	1.5	62.5	1.1	62.5	1.5	62.5	3.0	25.0	1.5	62.5	3.4	25.0	3.4
ech	75/25	1.5	62.5	1.5	62.5	1.1	62.5	1.5	62.5	2.6	34.4	1.5	62.5	3.0	34.4	3.0
ech	50/50	1.5	62.5	1.5	62.5	1.1	62.5	1.5	62.5	2.3	43.8	1.5	62.5	2.5	43.8	2.5
ine	75/25	1.5	62.5	1.9	53.1	1.1	62.5	1.9	53.1	2.6	34.4	1.9	53.1	3.4	25.0	3.4
ine	50/50	1.5	62.5	2.3	43.8	1.1	62.5	2.3	43.8	2.3	43.8	2.3	43.8	3.4	25.0	3.4
	100	1.5	62.5	3.0	25.0	1.1	62.5	3.0	25.0	1.5	62.5	3.0	25.0	3.4	25.0	3.4
ech	75/25	1.5	62.5	2.6	34.4	1.1	62.5	2.6	34.4	1.5	62.5	2.6	34.4	3.0	34.4	3.0
ech	50/50	1.5	62.5	2.3	43.8	1.1	62.5	2.3	43.8	1.5	62.5	2.3	43.8	2.5	43.8	2.5
Spruce	60/30/10	1.2	70.0	1.3	68.1	0.9	70.0	1.2	70.0	1.2	70.0	1.3	68.1	1.4	70.0	1.4
Spruce	60/30/10	1.0	75.6	1.1	73.8	0.7	75.6	1.0	75.6	1.0	75.6	1.1	73.8	1.1	75.6	1.1
ouglas fir	60/30/10	1.1	71.9	1.1	71.9	0.8	71.9	1.1	71.9	1.1	71.9	1.1	71.9	1.3	71.9	1.3
ouglas fir	60/30/10	1.0	75.6	1.1	73.8	0.7	75.6	1.0	75.6	1.0	75.6	1.1	73.8	1.1	75.6	1.1
fir – Beech	60/30/10	1.1	73.8	2.0	51.3	0.8	73.8	2.0	51.3	1.1	73.8	2.0	51.3	2.2	51.3	2.2
OLD	75/25	1.9	53.1	1.9	53.1	1.9	37.5	1.9	53.1	1.9	53.1	2.5	37.5	2.1	53.1	2.1
OLD	50/50	2.3	43.8	2.3	43.8	2.3	25.0	2.3	43.8	2.3	43.8	3.0	25.0	2.5	43.8	2.5
eech	75/25	2.6	34.4	2.6	34.4	2.6	12.5	2.6	34.4	2.6	34.4	3.5	12.5	3.0	34.4	3.0

: continued

Forest opment types	Mixture (%)	Forest habitat types											
		Birch-oak forest on damp to moist site (4)		Planar/montane beech forest on base-deficient sites (3)		Montane beech-fir/spruce forest on base-deficient sites (3.5)		Beech (mixed) forest on base-rich sites (3.5)		Sedge-beech forest (orchid beech forest) (4)		Autochthonous spruce-fir forest of the planar to colline zone (4)	
		NCV_{FDT}	% value loss	NCV_{FDT}	% value loss	NCV_{FDT}	% value loss	NCV_{FDT}	% value loss	NCV_{FDT}	% value loss	NCV_{FDT}	% valu loss
Beech	100	1.5	62.5	3.0	0.0	3.5	0.0	3.5	0.0	4.0	0.0	1.5	62
ech – Spruce	75/25	1.3	67.2	2.4	18.7	3.1	12.5	3.1	12.5	3.3	18.8	2.5	37
ech – Spruce	50/50	1.1	71.9	1.9	37.4	2.6	25.0	2.6	25.0	2.5	37.5	3.0	25
Spruce	100	0.8	81.3	0.6	81.2	1.3	62.5	1.3	62.5	0.8	81.3	4.0	0
ruce-Beech	75/25	0.9	76.6	1.3	56.2	2.2	37.5	2.2	37.5	1.8	56.3	3.5	12
ech – Larch	75/25	1.1	71.9	2.3	25.0	2.6	25.0	2.6	25.0	3.0	25.0	1.1	71
ech – Larch	50/50	0.8	81.3	1.5	50.0	1.8	50.0	1.8	50.0	2.0	50.0	0.8	81
rch - Beech	75/25	0.4	90.6	0.8	75.0	0.9	75.0	0.9	75.0	1.0	75.0	0.4	90
– Douglas fir	75/25	1.1	71.9	2.3	25.0	2.6	25.0	2.6	25.0	3.0	25.0	1.1	71
– Douglas fir	50/50	0.8	81.3	1.5	50.0	1.8	50.0	1.8	50.0	2.0	50.0	0.8	81
las fir – Beech	75/25	0.4	90.6	0.8	75.0	0.9	75.0	0.9	75.0	1.0	75.0	0.4	90
Oak	100	3.0	25.0	2.3	25.0	2.6	25.0	2.6	25.0	3.0	25.0	1.5	62
ak – Beech	75/25	2.6	34.4	3.0	0.0	3.5	0.0	3.5	0.0	4.0	0.0	1.5	62
ak – Beech	50/50	2.3	43.8	3.0	0.0	3.5	0.0	3.5	0.0	4.0	0.0	1.5	62
Dak – Pine	75/25	2.6	34.4	2.2	25.4	2.6	25.0	2.6	25.0	3.0	25.0	1.9	53
Dak – Pine	50/50	2.3	43.8	2.2	25.7	2.6	25.0	2.6	25.0	3.0	25.0	2.3	43
Pine	100	1.5	62.5	2.2	26.4	2.6	25.0	2.6	25.0	3.0	25.0	3.0	25
ne – Beech	75/25	1.5	62.5	3.0	0.0	3.5	0.0	3.5	0.0	4.0	0.0	2.6	34
ne – Beech	50/50	1.5	62.5	3.0	0.0	3.5	0.0	3.5	0.0	4.0	0.0	2.3	43
– Fir – Spruce	60/30/10	1.2	70.0	2.1	30.0	2.5	27.5	2.5	27.5	2.8	30.0	1.9	52
Beech – Spruce	60/30/10	1.0	75.6	1.4	52.5	1.8	50.0	1.8	50.0	1.9	52.5	1.6	60
Fir – Douglas fir	60/30/10	1.1	71.9	2.0	32.5	2.4	32.5	2.4	32.5	2.7	32.5	1.1	71
ech – Douglas fir	60/30/10	1.0	75.6	1.4	52.5	1.8	50.0	1.8	50.0	1.9	52.5	1.6	60
ouglas fir – Beech	60/30/10	1.1	73.8	2.1	31.1	2.5	30.0	2.5	30.0	2.8	30.0	2.0	51
eech - OLD	75/25	1.9	53.1	2.6	12.5	3.1	12.5	3.1	12.5	3.5	12.5	1.5	62
eech – OLD	50/50	2.3	43.8	2.3	25.0	2.6	25.0	2.6	25.0	3.0	25.0	1.5	62
LD – Beech	75/25	2.6	34.4	1.9	37.5	2.2	37.5	2.2	37.5	2.5	37.5	1.5	62

Table 21 shows the change in the initial nature conservation values of the forest habitat types for all 27 planned forest development types within the transect. Displayed are the final nature conservation value of the forest development types (NCV_{FDT}) and the percentage losses in value relative to the initial nature conservation value of the forest habitat types (NCV_{FHT}). The percentage losses are classified in a colour scale, with red colours representing higher value losses, yellow colours representing medium and green colours representing lower or no value losses (Table 21). As expected, almost all forest development types led to a reduction in the initial nature conservation value of the forest habitat types. In particular, this applied to forest habitat types and tree species that were not represented within the forest development types due to the project-related tree species restriction, such as bog woodlands, alluvial forests or oak-hornbeam forests. To avoid a strong loss of value in high valued bog and fen woodlands (high nature conservation value = 4), forest development types with pine or other long-lived deciduous tree species in combination with beech are preferred. On sites with hardwood alluvial forest habitat types, the most suitable forest development types were pure oak, oak with beech or pine, or beech and other long-lived deciduous tree species in combination.

In general, the forest development type beech with other long-lived deciduous tree species in mixture formed the preferred choice for riparian alluvial forests of alder and ash, softwood alluvial forest and most beech-dominated forest habitat types. No loss of value was observed for the forest development type pure beech, beech-oak or pine-beech on sites with pure beech or mixed beech forest habitat types. Selecting pine as a successional species did not lead to any reduction in nature conservation value within beech forest habitat types. Planning a pure spruce forest development type led to a considerable loss of value (~60-80%) for almost all forest habitat types, except when spruce was planted at higher altitudes within its natural distribution range. The highest value losses (~75-90%) were found in forest development types where Douglas fir and European larch have shares of 55-75%. In mixed broadleaf forest habitat types (in which beech is usually not dominant), the losses in nature conservation value are particularly high, if coniferous species such as spruce, larch and Douglas fir were part of the planned forest development types. Within the oak-hornbeam forest habitat types (very high nature conservation value = 4.5), the highest possible nature conservation value could be maintained if forest development types with pure oak, oak-pine, or pure pine (as a successional tree species) were planned (nature conservation value = 3.4, value loss: 25%).

4.5 Discussion

4.5.1 Assigning a spatial reference to forest habitat types

For the nature conservation assessment of forest stands to be developed in the future, this study refers to the nature conservation value assessment of forest habitat types by Demant et al. (2020). However, forest habitat types have not yet been mapped comprehensively for Germany. Therefore, in this study, an area-wide spatial reference was established for the forest habitat types, in order to be able to spatially-explicitly assess the forest development types, to be planned nationwide, in terms of their nature conservation value. The spatially-explicit reference was established using the potential natural vegetation (PNV). The use of the PNV-concept by Tüxen (1956) as a reference system is not without controversy. Welle et al. (2018) have critically summarised the difficulties that may arise in connection with the application and use of the PNV. The PNV has been criticised as being too static, as it does not consider the natural and successional dynamics of ecosystems, including uncertainties in the spatial and temporal variability of biological disturbances (e.g. Härdtle 1995; Zerbe 1998; Chiarucci et al. 2010; Loidi and Fernández-González 2012). Nevertheless, the PNV has also been used as a reference for naturalness (Reif 2000; Walentowski and Winter 2007; Engel et al. 2016). For example, Welle et al. (2018) used the PNV as a reference system in their nature conservation assessment of 22 forest types. As suggested by Somodi et al. (2012), the PNV was therefore used as a baseline reference in this study. The data used in this context from the PNV map by Suck et al. (2014) refer approximately to the turn of the millennium. Consequently, the nature conservation value assessments of forest habitat types, trees species and forest development types only reflect their current conservation condition. The assessment does not allow for predictions of future developments, as the PNV does not provide for climate change-specific dynamisation. The nature conservation assessment carried out in this study therefore only represents the present state of knowledge.

4.5.2 Nature conservation assessment of tree species and forest development types

For the nature conservation assessment of tree species and forest development types, habitat continuity was used in this study as an expression of the affiliation of tree species to natural vegetation units. Ecological habitat continuity means that a suitable habitat can persist over a long period of time and evolvs its typical biodiversity (Nordén et al. 2014; Mölder et al. 2021). The time factor is thus crucial and can vary depending on the condition of the habitat. At the local scale, habitat may refer, for example, to a single habitat structure of veteran trees, and at higher landscape scales to the general availability or suitability of landscape structures for species communities. Furthermore, habitat continuity also depends on connectivity, i.e. the spatial availability and closeness of habitats. This gives ecological habitat continuity a spatial dimension in addition to the temporal component (Nordén et al. 2014). Other important drivers describing habitat continuity are the distribution, the adaptive potential and the genetic composition of species (Fenberg and Rivadeneira 2019). In this study, a long (temporal) habitat continuity means that a tree species has existed in a (spatial) area for a long time and is thus located in its Central European distribution range and is therefore an autochthonous species. The longer the habitat continuity of a species, the more important it is to preserve it and does not lead to a loss of value of the forest habitat types in terms of nature conservation.

When assessing the tree species in terms of nature conservation, it must be considered that the MiStrikli-project restricted the selection of tree species of the forest development types. Therefore, it was not surprising that a large proportion of the forest development types studied resulted in a reduction of the nature conservation value for most forest habitat types. This is because the composition of the forest development types often did not fully correspond to the typical expression of the forest habitat types, as certain tree species were missing. For example, tree species that are characteristic or even eponymous for forest habitat types (e.g. hornbeam for oak-hornbeam forests, or alder for alder-carr-woodlands) were not assessed individually and combined into other long-lived deciduous tree species. A reduction in the nature conservation value of forest habitat types was therefore unavoidable. Consequently, the silvicultural establishment of wet forest habitat types was already excluded in advance. Nevertheless, the present nature conservation assessment of tree species and forest development types carried out in this study represents progress and offers divers possibilities for transfer and application. Since the nature conservation assessment of forest habitat types is in line with the Federal Compensation Directive of Germany (BMU 2020), which is also harmonised with the state-specifc habitat types and compensation guidelines, a derivation of the nature conservation value is possible at the federal state level. This supports the possibility for a nationwide application of the nature conservation assessment of forest development types in silvicultural planning.

Forest stand characteristics and silvicultural management standards are described in mostly regionally valid forestry frameworks or management plans, which are usually developed by the state forestry enterprises (e.g. MELV 2004; Eisenhauser and Sonnenmann 2009; SHLF 2011; LBHF 2016). Depending on the regional site and stocking conditions, they also describe specific forest conversion measures for the medium- and long-term development of site-specific forest stands (Deutscher Bundestag 2019). The plans include the assessment of the current forest condition (forest inventory), the control of the measures implemented in the previous management period and the medium-term planning for the following management period. Depending on the federal state and the forest owner, this management period can extend over 10 to 20 years. The forest development types used in this study are only applied in some German federal states such as Lower Saxony, Baden-Wuerttemberg and Saxony. Other federal states use different concepts instead, such as stand target types (= Bestandeszieltypen), and forest development targets (= Waldentwicklungsziele). However, the principles behind these concepts are more or less the same: the future definition of long-term silvicultural development and treatment plans for forest stands depending on tree species composition and stand structure. Forest development types (and similar concepts) are an important component of a mostly economically motivated silvicultural stand planning in which, depending on the site conditions, the highest timber production and thus the highest possible yield is aimed for. A comprehensive nature conservation assessment of these silvicultural stand development concepts does not yet exist. In forestry practice, forest habitat types have so far been little applied, as they are not a common element of silvicultural planning. The consideration of forest habitat types can be challenging, especially for private forest owners, as it cannot be assumed that they always know the natural species composition of forest habitat types and thus the nature conservation value. Simplified procedures and identification methods are therefore necessary to enable forest owners to apply the nature conservation assessment in their own forest stands. Transferring the nature conservation assessment of forest habitat types by Demant et al. (2020) to the level of tree species and forest development types can therefore help to close this knowledge gap and can be applied in all federal states. However, the assessment of forest development types carried out in this study does not provide information on possible silvicultural management strategies, or suggestions for concrete implementation in forest stands. In times of climate change, it can nevertheless help to assess the effects of a silviculturally determined tree species selection in future climate change-related forest conversion measures and to evaluate their consequences for nature conservation. In principle, the nature conservation assessment of forest stands depends not only on the tree species mixture of forest development types, but also on the current stand condition in terms of structure, the influence of silvicultural management and other anthropogenic impacts. These must also be considered in a holistic nature conservation assessment of forest stand conditions.

4.5.3 Consequences for future silvicultural stand planning

Numerous stakeholders have addressed climate-adapted tree species selection for forest stand establishment or forest conversion at the federal state level (e.g. Böckmann et al. 2019; MULE and NW-FVA 2020; NW-FVA 2020d, 2020e; STMELF 2020). The decisive factor is usually the future drought stress risk of tree species, which is often described in terms of a forestry production function and does not represent possible existence limits of the tree species' distribution ranges. There are already several modelling studies on the possible development of species ranges and distribution areas of forest communities under climate change (e.g. Kölling 2007; Hickler et al. 2012a, 2012b; Zimmermann et al. 2013; Beierkuhnlein et al. 2014; Fischer et al. 2019). However, the nature conservation assessment of a future distribution of forest tree species was not part of the present study and is discussed in more detail in Chapter 5.

The disturbances in Central European forests caused by droughts, storms and bark beetles infestations in recent years highlight the importance of forest conversion in the face of climate change. The way disturbed areas are managed is crucial for the development of the subsequent forest stand and the local biodiversity. The drought years 2018-2020 have in some cased led to a widespread loss of forest stands (NW-FVA 2020a - 2020c). Thus, by the end of 2020, a damaged wood area of around 277,000 hectares has accrued, with the share of damaged coniferous wood (around 156.5 million m^3) being almost 11 times larger than in hardwood (BMEL 2021a). Overall, about 2.5% of the entire forested area in Germany has been damaged by drought, storms and the associated extreme bark beetle calamities (Knoke et al. 2021). A formerly spruce-dominated forest conversion cultivation towards more climate- and disturbance-resilient mixed deciduous forest stands is advocated both by policy makers (BfN 2020; BMEL 2021a) and scientists (Bolte et al. 2009; Knoke et al. 2021). This includes leaving some of the recently disturbed forest areas to natural development and refraining from sanitary measures, in order to make a positive contribution to forest biodiversity (Swanson et al. 2011; Lindenmayer et al. 2017; Kuuluvainen et al. 2021; Thorn et al. 2020). Regarding the impacts of salvage logging on biodiversity, it is stated that a clearing of 50% of the disturbed forest areas would lead to a total species loss of 25%, while leaving 75% unlogged would preserve 90% of the species richness (Thorn et al. 2020). However, in forestry practice, recently disturbed forest areas are usually salvage-logged within short time after disturbance (Thorn et al. 2020). For example, Ipsen (2021) showed that in southern Lower Saxony, 92% of all areas disturbed by the severe winter storm in January 2018 had been salvage logged by September 2019.

On a large part of the disturbed forest areas in Germany, reforestation is to be carried out by artificial afforestation (BMEL 2021a). For future silvicultural stand establishment by sowing and/or planting, care should be taken to ensure sufficient genetic diversity of the material used. The origin (provenance) of the seed and planting material is of great importance. Whether, in the course of climate change in Germany, provenances from southern European regions should be increasingly cultivated, whose current climate could correspond to a possible future climate (Mette et al. 2021), cannot be cleary answered. Since the possible consequences for native biodiversity cannot yet be sufficiently assessed and comprehensive scientific results are lacking, such cultivation is not advisable from a nature conservation perspective. If cultivation trials with new varieties are nevertheless undertaken, it is recommended that they should be limited locally and accompanied by appropriate scientific monitoring.

4.6 Conclusion

Given the uncertainties of climate change, a rethink of silvicultural stand planning is needed to make forests more resilient and adaptable to potential changes such as future climate variability. In this context, primarily native and regionally adapted tree species should be selected to make an important contribution to the preservation of typical forest biodiversity. The present study has shown that in forest stands with a high nature conservation value, tree species and forest development types should be planned that do not lead to a reduction of this high value. Areas that have a lower initial nature conservation value due to previous non-site-specific silviculture, such as the cultivation of spruce stands on beech sites, can be converted into stands that are more valuable for protection through a suitable choice of tree species.

The final optimisation of management strategies in terms of robust, biodiversity-conscious and economically efficient forest management, taking into account the risk of storm damage and the uncertainty of climate change, has not yet been carried out by the partners of the MiStriKli-project. However, the present nature conservation assessment of forest development types at tree species level already provides an important contribution to derive nationwide management strategies for minimising the negative impacts of future climate change-induced storm damage risk. Furthermore, it is not only valid for German forests, but can be transferred to Central Europe forests with similar tree species compositions and provide indications for future forestry concepts.

4.7 Supplementary materials

Table S 7: Code and German description of the 3rd level of the potential natural vegetation units (Suck et al. 2014)

Code PNV Level 3	PNV Level 3 German description	Natural forest type (Engel et al. 2016)
C2a	Birken-Moorwälder	Moorwälder
C2b	Beerkraut-Kiefern-Birken-Moorwälder	Moorwälder
C2c	Latschen- und Spirken-Moorwälder	Moorwälder
D1a	Karpatenbirkenwälder	Moorwälder
D1b	Moorbirkenwälder	Moorwälder
D2	Torfmoos-Schwarzerlenwälder	Moorwälder
D3	Seggen-Schwarzerlenwälder	Moorwälder
D4a	Sumpfpippau-Schwarzerlenwälder	Moorwälder
D4b	Brennnessel-Schwarzerlenwälder	Moorwälder
E1a	Giersch-Eschenwälder	Erlen-Sumpf- und Bruchwälder
E1b	Kerbel-Eschenwälder	Erlen-Sumpf- und Bruchwälder
E2	Traubenkirschen-Schwarzerlen-Eschenwälder	Erlen-Ulmen-Auen- und Feuchtwälder
E3	Hainmieren-Schwarzerlen-Auenwälder	Erlen-Sumpf- und Bruchwälder
E4	Schuppendornfarn-Buchen-Bergahornwälder und Schuppendornfarn-Bergahorn-Schwarzerlenwälder	Erlen-Ulmen-Auen- und Feuchtwälder
E5	Giersch-Bergahorn-Eschenwälder	Erlen-Ulmen-Auen- und Feuchtwälder
E6a	Grauerlen-Auenwälder	Weiden-Auenwälder
E7a	Flatterulmen-Stieleichen-Auenwälder im Komplex mit Silberweiden-Auenwäldern	Erlen-Ulmen-Auen- und Feuchtwälder
E7b	Feldulmen-Eschen-Auenwälder im Komplex mit Silberweiden-Auenwäldern	Erlen-Ulmen-Auen- und Feuchtwälder
E8	Fahlweiden-Auenwälder	Weiden-Auenwälder
F1b	Sternmieren-Stieleichen-Hainbuchenwälder	Eichen-Hainbuchenwälder frischer bis feuchter Standorte
F2	Zittergrasseggen-Stieleichen-Hainbuchenwälder	Eichen-Hainbuchenwälder frischer bis feuchter Standorte
F3	Waldziest-Eschen-Hainbuchenwälder	Eichen-Hainbuchenwälder frischer bis feuchter Standorte
F4	Schwarzerlen-Stieleichen-Hainbuchenwälder	Eichen-Hainbuchenwälder frischer bis feuchter Standorte
F5	Ulmen-Hainbuchenwälder der Flussterrassen und Altauen	Eichen-Hainbuchenwälder frischer bis feuchter Standorte
F6	Ulmen-Hainbuchen-Hangwälder (Hochufer)	Eichen-Hainbuchenwälder frischer bis feuchter Standorte
Ga1	Waldreitgras-Winterlinden-Hainbuchenwälder	Eichen-Hainbuchenwälder trocken-warmer Standorte
Ga2	Knäuelgras-Winterlinden-Hainbuchenwälder	Eichen-Hainbuchenwälder trocken-warmer Standorte
Ga3	Leberblümchen-Winterlinden-Hainbuchenwälder	Eichen-Hainbuchenwälder trocken-warmer Standorte
Gb5	Wucherblumen-Eschen-Hainbuchenwälder	Eichen-Hainbuchenwälder trocken-warmer Standorte
Gb6	Leimkraut-Traubeneichen-Hainbuchenwälder	Eichen-Hainbuchenwälder trocken-warmer Standorte
Gb7	Weißseggen-Winterlindenwälder	Eichen-Hainbuchenwälder trocken-warmer Standorte
H1	Schwarzerlen-Moorbirken-Stieleichenwälder	Birken-Eichenwälder frischer bis feuchter Standorte
H2	Pfeifengras-Moorbirken-Stieleichenwälder	Birken-Eichenwälder frischer bis feuchter Standorte
H3	Pfeifengras-Buchen-Stieleichenwälder	Birken-Eichenwälder frischer bis feuchter Standorte

Table S 5: Continued

Code PNV Level 3	PNV Level 3 German description	Natural forest type (Engel et al. 2016)
Ja1a	Straußgras-Eichenwälder	Eichenwälder trocken-warmer bodensaurer Standorte
Ja1b	Drahtschmielen-Eichenwälder	Eichenwälder trocken-warmer bodensaurer Standorte
Jb2	Habichtskraut-Traubeneichenwälder	Eichenwälder trocken-warmer bodensaurer Standorte
K1a	Felsenahorn-Traubeneichenwälder	Eichenmischwälder trocken-warmer basenreicher Standorte
K2a	Berghaarstrang-Eichenwälder	Eichenmischwälder trocken-warmer basenreicher Standorte
K2b	Schwalbenwurz-Eichenwälder	Eichenmischwälder trocken-warmer basenreicher Standorte
K2c	Weißfingerkraut-(Trauben-)Eichenwälder	Eichenmischwälder trocken-warmer basenreicher Standorte
La1	Straußgras-Traubeneichen-Buchenwälder	Buchenwälder bodensaurer Standorte
Lb2a	Weißmoos-Buchenwälder	Buchenwälder bodensaurer Standorte
Lb2b	Drahtschmielen-Buchenwälder	Buchenwälder bodensaurer Standorte
Lb2c	Schattenblumen-Buchenwälder	Buchenwälder bodensaurer Standorte
Lb2d	Pfeifengras-Stieleichen-Buchenwälder	Buchenwälder bodensaurer Standorte
Lb2e	Blaubeer-Kiefern-Buchenwälder	Buchenwälder bodensaurer Standorte
Lc3a	Typische Hainsimsen-Buchenwälder	Buchenwälder bodensaurer Standorte
Ld3a	Hainsimsen-Tannen-Buchenwälder	Buchenwälder bodensaurer Standorte
Lc4	Flattergras-Hainsimsen-Buchenwälder	Buchenwälder bodensaurer Standorte
Ld4	Flattergras- und Waldschwingel-Hainsimsen-Tannen-Buchenwälder	Buchenwälder bodensaurer Standorte
Lc5a	Bergseggen-(gebietsweise Schattenseggen-)Hainsimsen-Buchenwälder	Buchenwälder bodensaurer Standorte
Ld5	Hainsimsen-Tannen-Buchenwälder im Komplex mit Wäldern auf Hangschutt und Felsen	Buchenwälder bodensaurer Standorte
Lc5d	Hainsimsen-Buchenwälder im Komplex mit Felsgehölzen sowie Wäldern auf Hangschutt	Buchenwälder bodensaurer Standorte
Lc6a	Rasenschmielen-Hainsimsen-Buchenwälder	Buchenwälder bodensaurer Standorte
Ld6	Hainsimsen-Tannen-Buchenwälder (oft Rasenschmielen- und Zittergrasseggen-Ausbildung); gebietsweise im Komplex mit Tannenwäldern oder sonstigen Wäldern auf Feucht- und Nassstandorten	Buchenwälder bodensaurer Standorte
Lc6b	Zittergrasseggen-Hainsimsen-Buchenwälder	Buchenwälder bodensaurer Standorte
Lc6b	Zittergrasseggen-Hainsimsen-Buchenwälder	Buchenwälder bodensaurer Standorte
Le7a	Wollreitgras-Fichten-Tannen-Buchenwälder	Buchenwälder bodensaurer Standorte
Le7b	Hainsimsen-Fichten-Tannen-Buchenwälder	Buchenwälder bodensaurer Standorte
Le8	Waldhainsimsen-Fichten-Tannen-Buchenwälder	Buchenwälder bodensaurer Standorte
Lf9	Hochmontane Fichten-Buchenwälder	Buchenwälder bodensaurer Standorte
Ma1a	Hainrispengras-Hainbuchen-Buchenwälder	Buchenwälder mäßig basenreicher Standorte
Ma1b	Knäuelgras-Hainbuchen-Buchenwälder	Buchenwälder mäßig basenreicher Standorte
Mb2	Flattergras-Buchenwälder	Buchenwälder mäßig basenreicher Standorte
Mc3	Hainsimsen-Waldmeister-Buchenwälder	Buchenwälder mäßig basenreicher Standorte
Md3a	Hainsimsen-Waldmeister-Tannen-Buchenwälder	Buchenwälder mäßig basenreicher Standorte
Mc4	Waldmeister-Buchenwälder	Buchenwälder mäßig basenreicher Standorte
Md4	Typische Waldmeister-Tannen-Buchenwälder	Buchenwälder mäßig basenreicher Standorte
Mc5	Bergseggen-Waldmeister-Buchenwälder	Buchenwälder mäßig basenreicher Standorte

Table S 5: Continued

Code PNV Level 3	PNV Level 3 German description	Natural forest type (Engel et al. 2016)
Md5	Waldmeister-Tannen-Buchenwälder im Komplex mit Wäldern auf Hangschutt und Felsen	Buchenwälder mäßig basenreicher Standorte
Mc6a	Hexenkraut-Waldmeister-Buchenwälder	Buchenwälder mäßig basenreicher Standorte
Md6a	Zittergrasseggen-Waldmeister-Tannen-Buchenwälder	Buchenwälder mäßig basenreicher Standorte
Md6b	Hexenkraut-Waldmeister-Tannen-Buchenwälder	Buchenwälder mäßig basenreicher Standorte
Mc6a	Hexenkraut-Waldmeister-Buchenwälder	Buchenwälder mäßig basenreicher Standorte
Md6b	Hexenkraut-Waldmeister-Tannen-Buchenwälder	Buchenwälder mäßig basenreicher Standorte
Mc6b	Rasenschmielen-Waldmeister-Buchenwälder	Buchenwälder mäßig basenreicher Standorte
Mc6c	Zittergrasseggen-Waldmeister-Buchenwälder	Buchenwälder mäßig basenreicher Standorte
Me7	Hochmontane Waldmeister-Fichten-Tannen-Buchenwälder	Buchenwälder mäßig basenreicher Standorte
Me8	Alpische Waldmeister-Fichten-Tannen-Buchenwälder	Buchenwälder mäßig basenreicher Standorte
Me9	Fichten-Bergahorn-Buchenwälder	Buchenwälder mäßig basenreicher Standorte
Na1	Bingelkraut-Hainbuchen-Buchenwälder	Buchenwälder basen-kalkreicher Standorte
Nb2a	Orchideen-Buchenwälder	Buchenwälder basen-kalkreicher Standorte
Nc3	Waldgersten-Buchenwälder	Buchenwälder basen-kalkreicher Standorte
Nc4a	Bergseggen-Waldgersten-Buchenwälder	Buchenwälder basen-kalkreicher Standorte
Nc4b	Christophskraut-Waldgersten-Buchenwälder	Buchenwälder basen-kalkreicher Standorte
Nd4	Christophskraut-Waldgersten-Tannen-Buchenwälder	Buchenwälder basen-kalkreicher Standorte
Nc5	Waldziest-Waldgersten-Buchenwälder	Buchenwälder basen-kalkreicher Standorte
Nd5	(Waldziest-)Waldgersten-Tannen-Buchenwälder im Komplex mit Wäldern feuchter bis nasser Standorte	Buchenwälder basen-kalkreicher Standorte
Nc6	Eschen-Buchenwälder	Buchenwälder basen-kalkreicher Standorte
Nc7a	Zwiebelzahnwurz-Buchenwälder basenreicher Silikatgesteine	Buchenwälder basen-kalkreicher Standorte
Nc7b	Alpenmilchlattich-Buchenwälder	Buchenwälder basen-kalkreicher Standorte
Ne8a	Hainlattich-Fichten-Tannen-Buchenwälder	Buchenwälder basen-kalkreicher Standorte
Ne8b	Alpenheckenkirschen-(Fichten-)Tannen-Buchenwälder	Buchenwälder basen-kalkreicher Standorte
P1a	Blaubeer-Kiefern-Traubeneichenwälder	Sand- und Silikat-Kiefernwälder
P1b	Waldreitgras-Kiefern-Traubeneichenwälder	Sand- und Silikat-Kiefernwälder
P2a	Krähenbeeren-Kiefernwälder	Sand- und Silikat-Kiefernwälder
P2b	Flechten-Kiefernwälder	Sand- und Silikat-Kiefernwälder
P2c	Preiselbeer-Kiefernwälder	Sand- und Silikat-Kiefernwälder
Q1	Buntreitgras-Kiefernwald	Sand- und Silikat-Kiefernwälder
R1	Beerstrauch-Tannenwälder	Tannenwälder
R2	Hainsimsen-Fichten-Tannenwälder	Tannenwälder
S1a	Wollreitgras-Fichtenwälder	Fichtenwälder bodensaurer Standorte
S2	Torfmoos-Fichtenwälder	Fichtenwälder bodensaurer Standorte
S4	Tieflagen-Fichtenwälder	Fichtenwälder bodensaurer Standorte
T1	Alpenlattich-Fichtenwälder	Montaner Fichtenwälder
T2	Alpendost-Fichtenwälder	Montaner Fichtenwälder

CHAPTER 5

Natura 2000 forest habitat types being confronted with climate change

Modified version of:

Laura Demant, Jonas Hagge, Andreas Mölder, Marcus Schmidt, Claudia Steinacker, Peter Meyer: *Bleibt der günstige Erhaltungszustand der FFH-Wald-Lebensraumtypen auch im Klimawandel ein sinnvolles Ziel?* BfN-Skripten (accepted)

5.1 Abstract

Climate change makes the assessment of the natural development of forest habitat types increasingly uncertain. This raises the question of whether the favourable conservation status of the forest habitat types of the Habitats Directive currently present in Germany remains a reasonable conservation objective in the face of climate change. In this paper, we address the question of conservation justification and provide an assessment regarding the future development trend of the conservation status forest habitat types. Flexibilisation and adaptation of conservation objectives should only be evidence-based and carried out within the framework of adaptive management. Our evaluation of current niche and species distribution models concerning range shifts of habitat types and tree species under climate change shows that for the subalpine sycamore-beech forest and the montane to alpine acidophilus Norway spruce forest, the increase in drought is likely to lead to area losses. In the case of bog woodlands and alluvial forests, successful restoration should be the first priority before future development can be assessed. On secondary sites of oak forest and lichen-rich Scots pine forest habitat types, active management measures are probably still necessary to restore a favorable conservation status and to secure them in the long term. In the case of beech forest habitats, the distribution models show considerable differences. For the time we did not find indications to abandon the favourable conservation status of forest habitat types under climate change as a well-founded conservation objective.

5.2 Introduction

The European Natura 2000 protected areas network aims at ensuring the transnational protection of endangered, typical and wild species and habitats, as well as to safeguard biodiversity by preserving natural habitats through the Habitats and Birds Directives 92/43/EEC and 2009/147/EC. EU member states are committed to achieving this objective by designating protected areas and implementing species protection measures outside of protected areas (Evans 2012). The overarching guiding principle in the Habitats Directive, adopted in 1992, is a favourable conservation status for the species, habitats and populations listed in the annexes. Within Natura 2000 protected areas, forestry and agricultural land-use management is by no means excluded. However, it must be ensured that management measures do not lead to a deterioration of the conservation status of the corresponding species and habitat types (European Commission 2015; Fischer-Hüftle 2020).

In the face of climate change, nature conservation is regularly confronted with the criticism of holding on to conservation objectives and targets that are insufficiently justified and too static (Marko et al. 2018; Eser 2021). In the context of the Habitats Directive, the question arises whether its objectives and guidelines, as well as the protected areas network, should be made more flexible (Vohland 2007; Hendler et al. 2010; Cliquet 2014; DVFFA 2019). Against this background, the following questions were examined using the example of the forest habitat types of the Natura 2000 Habitats Directive:

- How well justified is the conservation objective of a favourable conservation status for the forest habitat types of the Habitats Directive?
- Does the current state of knowledge about climate change and its effects on forest habitat types question this objective?

The validity of the present conservation justifications for the forest habitat types of the Habitats Directive is discussed and their possible future trend development of the conservation status is estimated. Thirteen forest habitat types relevant for Germany are described and their current conservation status is presented. The present and future impacts of climate change on forest habitat types are presented on the basis of a literature review and a prognosis about their future development is given. Finally, options for a suitable nature conservation management in times of climate change are discussed.

5.3 Conservation status of Central European forest habitat types of the Habitats Directive

5.3.1 Aggregation of the forest habitat types

Predominantly it is assumed that Central Europe is naturally densely forested and that beech and mixed beech forests take up the largest proportion of the natural vegetation (Ellenberg and Leuschner 2010). Forests unaffected by humans no longer exist in Germany (Sabatini et al. 2018, 2020). However, the degree of naturalness of current forest stands is heterogeneous, and natural forest habitat types are often found in a favourable conservation status (BMU and BfN 2020). In the course of land use that has lasted for thousands of years, forest habitat types worthy of protection have also developed beyond their natural habitats. There is now a consensus that these land-use-dependent forest habitat types can only be secured in the long term through active management (Ssymank et al. 2019). It is therefore reasonable to distinguish between naturally self-sustaining or natural and management-dependent or semi-natural forest habitat types. Within the former mentioned group, a distinction can be made between currently self-sustaining forest habitat types and those forest types that can only be classified as self-sustaining after the restoration of natural abiotic environmental conditions, such as bog woodlands and alluvial forests.

Eighteen forest habitat types of Annex 1 of the Habitats Directive occur in Germany (Ssymank et al. 1998; BfN 2021). The 13 most important forest habitat types in terms of area were considered in this study (Tab. 1). Currently self-sustaining forest habitat types include all types of beech forests, acidophilic spruce forests of the montane to alpine levels and mixed ravine and slope forests (see also Ssymank et al. 2019; LfU and LWF 2020). Forest habitat types may regain self-sustaining state after the abiotic environmental conditions have been restored. They include drained bog woodlands, alder-ash forests and softwood alluvial forests as well as oak-elm-ash alluvial forests on large rivers. If the original natural site conditions are restored and these forest habitat types can develop independently, all these forest habitat types can be classified as naturally self-sustaining.

The group of predominantly management-dependent forest habitat types includes oak and mixed oak as well as lichen-rich Scots pine forests. These forest types occur naturally under particular site conditions. For example, sub-Atlantic and Medio-European oak or oak-hornbeam forests of the *Carpinion betuli* are found on temporarily or permanently moist soils with high groundwater levels, which are difficult to be colonised by beech. *Galio-Carpinetum* oak-hornbeam forests can be found on alternately dry soils with warmer climatic conditions, where beech forests are also receding (Mölder et al. 2009; Ellenberg and Leuschner 2010). Old acidic oak forests include semi-natural birch-pedunculate oak forests and mixed beech-oak forests on sandy sites in the northwestern German lowlands (Drachenfels 2016; Ssymank 2016). Lichen-rich Scots pine forests naturally colonise very small areas on the most extreme sites at the drought and nutrient limits of acidophilic forests (Heinken 2008; Fischer et al. 2009).

All these forest habitat types have considerably increased their area by historical land-use practices, such as wood pastures, coppice and coppice-with-standards woodlands, and, in the case of lichen-rich pine forests, through litter use. Due to a transition to high forests that started in the 19th century and the cessation of litter use at the latest in the first decades after the Second World War, these historical forest use forms can nowadays only be found in relict stands (Bärnthol 2003; Fischer et al. 2014, 2015; Unrau et al. 2018). Many of these forest stands habour specific stress-tolerant, but competitively week species and particular structures (e.g. with spare canopy cover) and thus make an important contribution to the preservation of forest biodiversity. Like the naturally self-sustaining forest habitat types, they are part of our natural and cultural heritage (Ssymank 2016) and therefore have a high nature conservation value (Demant et al. 2020).

5.3.2 Nature conservation justification for forest habitat types

A major cause of conflicts between land use and nature conservation can be different concepts of values and ideals (Grodzinska-Jurczak and Cent 2011; Meyer 2013a). In order to identify this underlying cause, it is reasonable to present value concepts transparently and derive justifications for use and protection. With regard to values assigned to certain conservation objects, a distinction can be made between a moral-intrinsic or inherent value, a eudemonic intrinsic value (cultural-aesthetic value for people) and an instrumental use value (Eser and Potthast 1999; Eser et al. 2011). A completely consistent rationale for nature conservation cannot be derived from any of these values (Eser and Potthast 1999). However, it is undoubted that a restriction to the current instrumental usage value hardly meets the requirements of modern sustainability in the sense of intergenerational equity. According to today's understanding, sustainability can be understood in such a way that the satisfaction of the needs of future generations is not restricted by the current use of natural resources (WCED 1987). The intended needs do not only refer to material goods, but encompass the entire spectrum of ecosystem services, which ultimately rely on biodiversity (Costanza et al. 1997; Brockerhoff et al. 2017).

Complete and comprehensive conservation of biodiversity can therefore be derived directly from our understanding of sustainability. In order to ensure sustainable development and reduce conflicting goals in the protection of biodiversity, it can be beneficial to consider diverse societal understandings of nature conservation and concepts of values (Eser 2021). In a global context, the most comprehensive possible protection of biodiversity can best be achieved by assuming responsibility for the protection of the respective typical diversity of natural environments, i.e. historic-cultural and natural biodiversity (Lindenmayer et al. 2006; Lindenmayer and Hunter 2010). A purely quantitative maximisation of species diversity can run counter to the preservation of a natural and typical biological diversity. According to Meyer (2013b) simply increasing the number of species above the typical level can lead to a homogenisation of natural areas as well as a loss of biodiversity at higher spatial scales.

In this sense, the conservation responsibility for habitat types and species of the Habitats Directive is currently free of contradictions and well justified. However, it remains questionable to what extent climate change will lead to such major changes that safeguarding these conservation objects becomes futile.

5.3.3 Conservation status of forest habitat types

According to the Habitats Directive (Art. 17 paragraph 1), the EU member states are obliged to submit a report on the conservation status of habitat types and species of the annexes every six years (European Council 1992). A distinction is made between favourable, unfavourable-inadequate and unfavourable-bad conservation statuses, as well as between improving, stable or deteriorating trends (Table 22).

Most of the beech forest habitat types as well as mixed ravine and slope forests are in a conservation status which is more favourable in the Continental region than in the Atlantic region of Germany (BMU and BfN 2020). The trend of these forest habitat types is predominantly improving. Reasons for this positive trend can be the conversion to more natural forest management (Winkel and Spellmann 2019) and the associated increase in the proportion of valuable structures, such as veteran trees and deadwood (BMU and BfN 2020), as well as species characteristic of the habitat type (Meyer et al. 2016b). In both, the Continental and Atlantic regions, management-dependent habitat types, such as oak and mixed oak forests, have an unfavourable conservation status and their trend is partly stable, but partly deteriorating.

Alluvial forests, bog woodlands as well as lichen-rich pine forests show an unfavourable-bad conservation status, as well as a consistently deteriorating trend (BMU and BfN 2020). Reasons for this unfavourable-bad conservation status of alluvial forests and bog woodlands are primarily changes in hydrological conditions and drainage measures (Glaeser and Volk 2009; Härdtle et al. 2020). In the case of lichen-rich pine forests changes in species compositions due to natural succession as well as a lack of active management measures and the input of air pollutants, humus enrichment and soil eutrophication are the cause of this negative trend (Fischer et al. 2015). Acidophilous *Picea* forests of the montane to alpine levels have a favourable conservation status with a stable trend. Outside the Alpine region, however, their conservation status is unfavourable-inadequate.

Table 22: Conservation status (CS) in the reporting period 2013-2018 and the trend of the last 12 years of forest habitat types in Germany for the three biogeographical regions Atlantic, Continental and Alpine (changed according to BMU and BfN 2020).

Forest habitat type (Code)	Atlantic Region	Continental Region	Alpine Region	Group of forest habitat types
Luzulo-Fagetum beech forests (9110)	+ (yellow)	+ (green)	= (green)	CSS
Asperulo-Fagetum beech forests (9130)	+ (yellow)	+ (green)	+ (green)	CSS
Medio-European subalpine beech woods with *Acer* and *Rumex arifolius* (9140)	(grey)	- (yellow)	= (green)	CSS
Medio-European limestone beech forests of the *Cephalanthero-Fagion* (9150)	= (green)	= (green)	= (green)	CSS
Sub-Atlantic and medio-European oak or oak-hornbeam forests of the *Carpinion betuli* (9160)	- (yellow)	- (yellow)	(grey)	MD
Galio-Carpinetum oak-hornbeam forests (9170)	- (red)	- (red)	(grey)	MD
Tilio-Acerion forests of slopes, screes and ravines (9180)	(grey)	+ (green)	= (green)	CSS
Old acidophilous oak woods with *Quercus robur* on sandy plains (9190)	= (red)	- (red)	(grey)	MD
Bog woodland (91D0)	- (red)	- (red)	= (green)	AR-SS
Alluvial forests with *Alnus glutinosa* and *Fraxinus excelsior* (91E0)	= (red)	+ (red)	= (green)	AR-SS
Riparian mixed forests of *Quercus robur*, *Ulmus laevis* and *U. minor*, *Fraxinus excelsior* or *F. angustifolia*, along the great rivers (91F0)	= (red)	- (red)	(grey)	AR-SS
Central European lichen Scots pine forests (91T0)	- (red)	- (red)	(grey)	MD
Acidophilous *Picea* forests of the montane to alpine levels (9410)	(grey)	= (yellow)	= (green)	CSS

Red = unfavourable-bad CS, yellow = unfavourable-inadequate CS, green = favourable CS, grey = unknown. +: improving, =: stable, -: deteriorating trend. Groups of forest habitat types: CSS = currently self-sustaining, MD = management-dependent, AR-SS = after restoration self-sustaining.

5.4 Climate change and its consequences for forest habitat types

The stability and resilience of forest ecosystems is threatened by changes in land use, but also by climate change (Côté and Darling 2010; Streitberger et al. 2017; IPBES 2019). The resulting environmental changes can lead to a transformation of forest ecosystems, species loss and geographic shifts, as well as changes in biocoenoses (EEA 2017; Keeley et al. 2018). Despite uncertainties regarding the future climate development and a limited predictability of climatic variations (Vohland et al. 2013; Streitberger et al. 2017; BfN 2020), climate change-related impacts on ecosystems and species can already be observed today (Vohland 2007; Lindner et al. 2010; EEA 2017). In addition to changes in the distribution ranges of species and habitats, these also include phenological shifts and an extension of the vegetation period. These changes affect also the Natura 2000 protected areas network, and forest habitat types in Germany will increasingly face the impacts of climate change in the coming decades (Dempe et al. 2012). Climate change thus hampers the preservation of forest habitat types and their typical biodiversity in a given site (Nila et al. 2019).

As a result of climate change, temperatures are expected to rise and with them extreme weather conditions (IPCC 2012). The probability of dry and hot summers is increasing, but at the same time cold spells may continue to occur in winter (IPCC ibid.). The variability of precipitation events will increase, which may lead to longer periods of drought on the one hand, and extreme weather events with heavy rain and locally high wind speeds on the other (Mölter et al. 2016; Bahn et al. 2019). In the past centuries, there have always been fluctuations of extreme weather conditions with different optima to which tree species had to adapt (Erfurt et al. 2020). However, there is great uncertainty about the intensity and frequency of these fluctuations in the future, which makes it difficult to assess the stress tolerance and resilience of tree species (Wagner et al. 2014). Büntgen et al. (2021) showed that the five driest years in Europe in 2,100 years are in the period from 2014 to the present.

The extreme dry years from 2018 to 2020 have already led to increased dieback rates in forest trees species in Germany, especially in spruce forest stands (Schuldt et al. 2020). However, the intensity and effects differ regionally and locally (NW-FVA 2020a - 2020c). The mortality rate of beech trees has also increased significantly (NW-FVA ibid.). Such waves of mortality in beech stands after years of drought are well known from the past (Figure 9, cf. Wagenhoff and Wagenhoff 1975; Bonnemann 1984). Recent studies showed that beech is particularly sensitive to drought on dry, shallow soils, but its recovery potential seems to be greater compared to beech forests on more moist sites (Leuschner 2020).

The increase in extreme weather events due to climate change will be crucial for the endangerment and preservation of species and ecosystems (Jentsch and Beierkuhnlein 2008). The acceleration of climate change, the ongoing intensification of land use and the constant fragmentation of landscapes, as well as a tree species composition that has been altered and influenced by humans, reduce the adaptive capacity of tree species (Kölling 2014).

Furthermore, the local extinction of individual species and the immigration of neobiota will change the composition of ecosystems in the long term. Many native species cannot respond adequately to the consequences of climate change due to very slow migration rates and, in some cases, highly fragmented habitats (Beierkuhnlein et al. 2014). However, some species have already responded to the changing environmental conditions. For example, it has been observed that phenological leaf emergence has shifted by a few days and some species have extended their distribution ranges to more northerly regions (Essl and Rabitsch 2013). Furthermore, Lindner et al. (2010) observed an increase in thermophilic plant species. Other relevant factors for the ecophysiological adaptability to changing environmental conditions are the genetic constitution of species and phenological flexibility (Gugerli et al. 2016).

Figure 9: 140-year-old beech population in the Reinhardswald in 1891. Severe crown damage can be seen 35 years after the western edge has been cleared and a previous accumulation of dry years (1884, 1886 and 1887). Photo: archives forestry office Reinhardshagen.

Niche and distribution models can be used to estimate possible shifts in the distribution ranges of species and habitats under climate change. However, as these models are mostly based on the recent distribution of species (realised niche), they do not cover their entire possible range (fundamental niche, Ferrier and Guisan 2006; Hendler et al. 2010; Dempe et al. 2012; Beierkuhnlein et al. 2014). Furthermore, they are often only locally meaningful due to existing uncertainties regarding climatic developments (Fischer et al. 2019) and interpretation of the results is difficult due to limited data availability and quality (Steinacker et al. 2019). Furthermore, risk models exist to assess the suitability of tree species for silvicultural planning under climate change from a forestry perspective (Böckmann et al. 2019). However, these risk models do not allow predictions about the limits of tree species or forest habitat types under climate change.

For Lower Saxony economic forest, Böckmann et al. (2019) assume that not only spruce, but also beech will be exposed to a high risk of drought stress in the future. In contrast, a significantly lower risk is assumed for oak, Douglas fir and pine. Beierkuhnlein et al. (2014) modelled the influence of climate change on the distribution ranges of habitat types of the Natura 2000 Habitats Directive. The authors assume that beech forest habitat types will continue to be the predominant natural vegetation in Central Europe in the future. Hickler et al. (2012a) come to a similar conclusion. According to Kölling (2007), boreal and alpine tree species in particular will be affected adversely by an increase in mean annual temperature of about 2 °C. Beech, on the other hand, is expected to show only a slight change. An increase in mean annual temperature by 3 to 4 °C would lead to temperature and precipitation regimes that do not currently exist in Germany. This could exceed the adaptability limits of tree species (Kölling and Zimmermann 2014; Hohnwald et al. 2020; Heinrichs 2021). The modelling by Hickler et al. (2012b) shows hardly any changes in the distribution ranges for Central European deciduous tree species. Only in the case of very strong global warming do Hickler et al. (ibid.) assume that the most common tree species such as beech will be exposed to even greater stress factors in areas where they have already been displaced to their tolerance limits. While the probability of occurrence of beech in Central Europe decreases considerably under climate change, according to Hanewinkel et al. (2014). The modelling of Thurm et al. (2018) also comes to a comparable conclusion. Mette et al. (2021) estimate the effects of climate change on 23 European tree species using analogy areas. Under the climate scenario RCP 8.5, an increase is initially expected for beech by 2040 and a significant decrease by 2100. Under the more moderate scenario RCP 4.5, however, it remains an important natural tree species until 2100.

Fischer et al. (2019) modelled the distribution of potential natural vegetation in the form of 26 forest communities in Bavaria under climate change. All scenarios showed significant changes in environmental conditions and thus, also changes in the distribution of forest communities (shift of distribution ranges to higher altitudes, reduced areas). A temperature increase of 2 °C would result on one third of the area of Bavaria in site conditions that no longer correspond to the currently predominant forest communities. An increase of 4 °C would lead to unsuitable site conditions for the present forest communities on almost the entire area of Bavaria.

However, since the models of Fischer et al. (2019) were only parameterised based on the ecological conditions in Bavaria, they do not represent the actual limits of the forest communities. This restriction also applies to the modelling of natural forest communities by Starke et al. (2019) for Germany.

5.5 Discussion

5.5.1 Future development of forest habitat types

Taking into account the niche and distribution models listed in chapter 5.3 and the uncertainties of climate change, a possible natural development of the conservation status of forest habitat types with and without climate change was estimated (Table 23). The results are to be understood as aggregated hypotheses and are not the result of a formalised and representative expert assessment. The present assessment was compared with the results on climate sensitivity of Natura 2000 habitat types carried out by Petermann et al. (2007). Climate sensitivity was assessed on the basis of expert judgments and summarised in three sensitivity classes (1 = low, 2 = medium, 3 = high climate sensitivity). In many cases there was no agreement between the two assessments. This underlines the uncertainties in the evaluations and may also be due to the fact that conservation management measures were not include in the present assessment. In addition, the current status of species distribution modelling was considered.

For more than half of all forest habitat types, an estimation was hardly possible. In particular, there was much uncertainty for the widely distributed beech forest habitat types. Without climate change, these forest habitat types could develop positively and show an improved conservation status. With climate change, precise estimations become more difficult. Under warmer and drier climatic conditions, limestone beech forests of the *Cephalanthero-Fagion* could see an increase in area on calcareous sites at the expense of *Asperulo-Fagetum* beech forests. In the case of the more drought-tolerant oak forest habitat types, such as *Galio-Carpinetum* oak-hornbeam forests and old acidophilous oak woods with *Quercus robur*, climate change could indirectly lead to an improvement in conservation status due to a lower competitive strength of shade-tolerant tree species such as beech. In the case of the sub-Atlantic and Medio-European oak and oak-hornbeam forests of the *Carpinion betuli*, future management and the development of the groundwater balance are the decisive factors, so that an estimation is also subject to great uncertainties.

Table 23: Attempt to assess the possible natural development of the Natura 2000 forest habitat types with and without climate change, taking into account a need for restoration of the sites.

Forest habitat type	Need of restoration of site	CS under natural dynamics with and without climate change		Climate sensitivity
		without	with	
Luzulo-Fagetum beech forests (9110)	○	+	+ to –	2
Asperulo-Fagetum beech forests (9130)	○	+	+ to –	2
Medio-European subalpine beech woods with *Acer* and *Rumex arifolius* (9140)	○	+	–	1
Medio-European limestone beech forests of the *Cephalanthero-Fagion* (9150)	○	+	+	1
Sub-Atlantic and medio-European oak or oak-hornbeam forests of the *Carpinion betuli* (9160)	**o**	+ to –	+ to –	2
Galio-Carpinetum oak-hornbeam forests (9170)	○	= to –	+	1
Tilio-Acerion forests of slopes, screes and ravines (9180)	○	+	+ to –	3
Old acidophilous oak woods with *Quercus robur* on sandy plains (9190)	○	= to –	+	2
Bog woodland (91D0)	●	+	= to –	3
Alluvial forests with *Alnus glutinosa* and *Fraxinus excelsior* (91E0)	●	+	+ to –	3
Riparian mixed forests of *Quercus robur*, *Ulmus laevis* and *U. minor*, *Fraxinus excelsior* or *F. angustifolia*, along the great rivers (91F0)	●	+	+ to –	3
Central European lichen Scots pine forests (91T0)	●	–	–	3
Acidophilous *Picea* forests of the montane to alpine levels (9410)	○	+	–	3

Explanation of symbols: Need for restoration: ● = high, **o** = medium, ○ = low; future trend of the conservation status (CS) +: = negative trend (deterioration), =: medium trend (constant compared to today), –: positive trend (improvement). Climate sensitivity after Petermann et al. (2007): 1 = low, 2 = medium, 3 = high.

The situation is particularly unfavourable for Medio-European subalpine beech woods with *Acer* and *Rumex arifolius*, and acidophilous *Picea* forests of the montane to alpine levels. The same holds true for some subtypes of *Tilio-Acerion* forests of slopes, screes and ravines, which occur outside deeply incised gorges with independent internal microclimate but depend on cool and humid climate. Under climate change, exclusively negative development (deterioration) of the conservation status for these habitat types is assumed, as they react particularly sensitively to biotic and abiotic fluctuations and an increase in drought is likely to lead to a loss of area. Without climate change, however, these forest habitat types could develop positively under natural dynamics and show an improved conservation status. As the distribution range of the subalpine sycamore-beech forest is limited to high-montane to subalpine areas below the tree line (LWF 2009), there are only few possibilities to shift the distribution ranges to higher subalpine altitudes (Essl and Rabitsch 2013). Forests of slopes, screes and ravines also include more drought-tolerant block forests on sunny slopes, so the range of variation is larger here. A negative development is to be assumed for moist ravine or shady slope forests. Bog woodlands and alluvial and riparian forest habitat types are already in need of restoration. In the course of climate change, dry periods and the increase in evapotranspiration at higher temperatures are likely to negatively affect the conservation status. A reduced water supply is also likely to have a negative impact on alluvial and riparian forest habitat types. Lichen-rich Scots pine forests could only be preserved after successful restoration through resumption of litter use, regardless of climate change (Fischer et al. 2015). A possible area expansion at the expense of other sand Scots pine forests under dry-warm conditions remains speculative so far.

The assessment for *Galio-Carpinetum* oak-hornbeam forests is consistent with the results of Petermann et al. (2007), who described only a low climate sensitivity. Sub-Atlantic and medio-European oak or oak-hornbeam forests of the *Carpinion betuli* show a medium climate sensitivity. This is due to their strong dependence on groundwater, their susceptibility to invasive species and their lower regenerative capacity. The sensitivity analysis of Petermann et al. (2007) showed a medium climate sensitivity for old acidophilous oak woods with *Quercus robur* on sandy plains, since this forest habitat type showed a decline in area, which may also be an effect of management. *Tilio-Acerion* forests of slopes, screes and ravines had a high climate sensitivity, as they are difficult to regenerate, have limited distribution ranges, and include subtypes dependent on surface water regime. Acidophilous *Picea* forests of the montane to alpine levels also showed a very high climate sensitivity, as they are threatened by critical area losses and have only limited distribution ranges. This agrees with the results of the present assessment. The assessment of medio-European subalpine beech woods with *Acer* and *Rumex arifolius* is not consistent with Petermann et al. (2007), who attributed only low climate sensitivity to this forest habitat type. Alluvial and riparian forests, bog woodlands and lichen-rich Scots pine forests showed a high climate sensitivity (Petermann et al. 2007) which is consistent with the present assessment. In the case of alluvial and riparian forests and bog woodlands this was due to a high groundwater dependency, a strong decline in area and a high qualitative vulnerability. Lichen-rich Scots pine forests are particularly vulnerable by invasive species and have only a very small distribution range. Petermann et al. (2007) classified the climate sensitivity of the two most common beech forest habitat types (*Luzulo* and *Aperulo-Fagetum*) as medium. Medio-European limestone beech forests of the *Cephalanthero-Fagion*, on the other hand, have only a low sensitivity, as they are adapted to the expected dry-warmer conditions.

5.5.2 Nature conservation management planning for forest habitat types under climate change

The planning of nature conservation measures in Natura 2000 protected areas should be developed towards an adaptive management system (Meyer 2013a; Geyer et al. 2014; Meyer et al. 2017), which, in principle, includes the possibility of adjusting conservation objectives. However, a high evidence threshold must be set so as not to abandon well-founded conservation objectives. Monitoring and research in unmanaged forests should be an integral part of the management system to better assess the self-dynamic adaptation potential of forest habitat types (Meyer et al. 2017).

Changes in basic climatic conditions can have a direct influence on the development and persistence of Natura 2000 forest habitat types. Therefore, uncertainties and dynamic climate developments should be considered even more strongly in future management planning in Natura 2000 sites, and the respective protection justifications and conservation objectives should be adapted flexibly, if necessary (Vohland 2007; Cliquet 2014; Marko et al. 2018). Changes in native species and habitat diversity have always occurred in the course of global change. However, over the course of Earth's history, these changes have never happened as rapidly as in the recent past (Hobbs et al. 2009). There is therefore a risk that the speed of change will exceed the biological response capacity of species (Beierkuhnlein et al. 2014).

The assessment of thresholds ("tipping points", Thompson et al. 2009) at which irreversible changes occur is crucial for climate adaptation. Each ecosystem has its own natural range of variations. This "historical range of variability" (Morgan et al. 1994; Keane et al. 2009) describes the natural fluctuations that can occur within ecosystems without exceeding their ecological resistance and resilience. Only in the case of very strong changes in environmental conditions, species compositions and structures does a complete or even partial restoration towards a historical state no longer appear feasible (Figure 10, Hobbs et al. 2009). However, due to the resilience and restoration potentials of ecosystems, there is a broader range of possibilities within which restoration towards a historical state seems reasonable or at least partial restoration is possible. If conditions have changed to such an extent that it no longer corresponds to its original form and a return to its original state is also impossible, a so-called "novel ecosystem" (Hobbs et al. 2009) has developed. Existing management plans may need to be adapted due to the emergence of these novel ecosystems (Hobbs et al. 2009), so that future dynamic developments and changes in habitat conditions can be taken into account (Hermann et al. 2013; Marko et al. 2018).

A large proportion of native forests have a great potential to regenerate after disturbances, even without human assistance (cf. Senf et al. 2019). In addition, the adaptive capacity of forests to climate change must also be seen in the context of the many other anthropogenic environmental changes that affect forests, be it groundwater drawdown, (over)exploitation, the introduction of invasive or non-native species, pollutant inputs or increased clove-hoofed game populations.

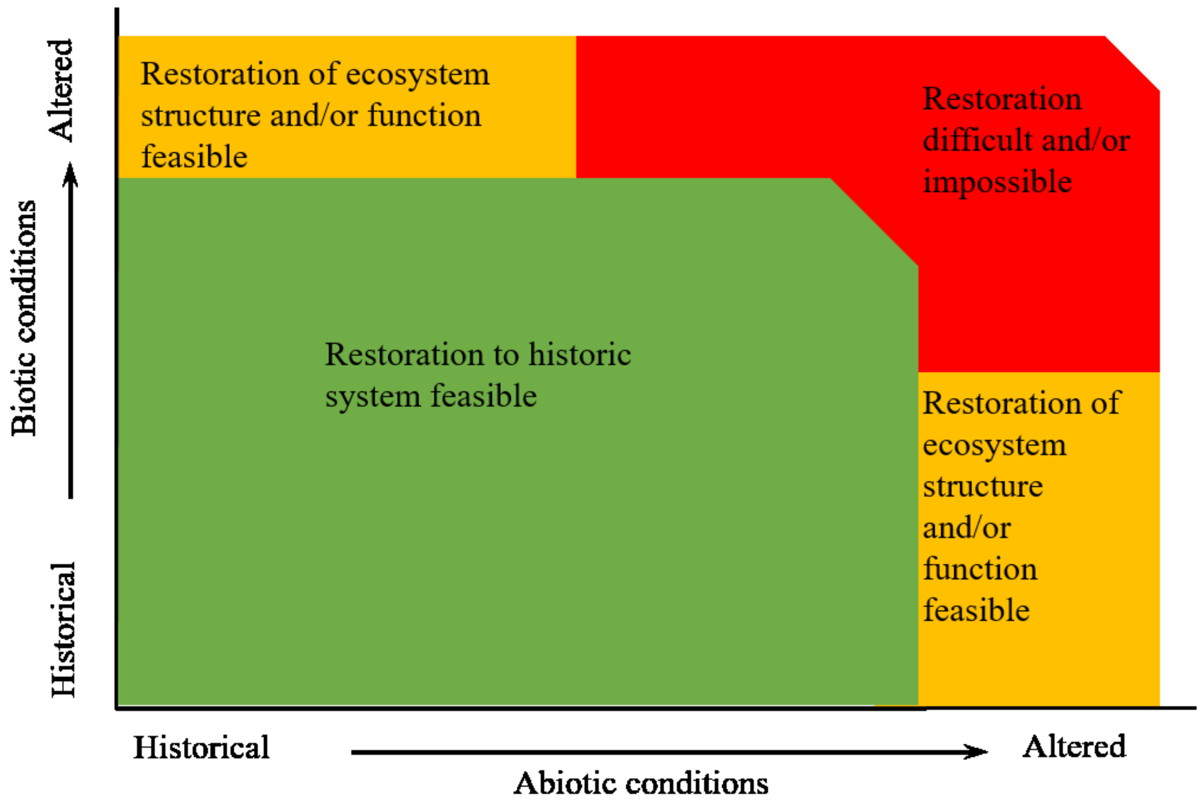

Figure 10: Restoration potential (range of variability) of ecosystems in terms of the type and manner of change in environmental conditions and species composition. Depending on the severity of the change, restoration of the ecosystems according to the historical model is feasible (green to yellow), or is difficult to realise (red). Biotic: loss or immigration of species; abiotic: climatic changes such as increasing drought or more intensive anthropogenic land use. Illustration according to Hobbs et al. (2009), modified.

The expansion and improvement of an effective habitat connectivity system and sufficient interconnectivity through the (increased) creation of corridors and stepping stones are further important measures to enable genetic exchange between populations and promote adaptation mechanisms to climate change (Mason and Zapponi 2015; Keeley et al. 2018; Schwenkmezger 2019). In this context, it is important to consider the current occurrence and dispersal potential of species characteristic to certain habitat types. In the case of isolated and small-scale occurrences of habitat types, there is a risk that species with low dispersal ability will not be able to respond to climate change through range shifts (Ewald 2009; Beierkuhnlein et al. 2014).

In contrast, more mobile species already show an adaptation of their distribution ranges (Essl and Rabitsch 2013).

In Natura 2000 protected areas, nature conservation and legal trade-offs may arise in the future, if the local populations of species or habitat types listed in the Annexes can no longer be maintained under the conditions of climate change (Hendler et al. 2010; Cliquet 2014). The disappearance of characteristic species and habitat types or the emergence of new species in habitat types may thus lead to the need to adapt current conservation objectives and measures (Möckel 2010; Bittner et al. 2011). The future distribution of forest habitat types and their conservation status will depend on the speed of climatic developments and how management and protection strategies are adapted in response. Predicting future development is therefore only possible to a limited extent. A further concentration of conservation efforts on forest habitat types would contribute to the protection of the native and typical forest biodiversity. In this context, it may be reasonable to also record forest habitat types outside of Natura 2000 sites and not to let conservation efforts end at the borders of protected areas.

5.6 Conclusion

The favourable conservation status of forest habitat types remains a well-founded objective of nature conservation, even under climate change. However, it is becoming increasingly urgent to adaptively coordinate land use and nature conservation in order to initiate necessary adjustments to the conservation objectives and thus ensure the diverse ecosystem functions and services in the long term. However, sufficient evidence is required for this.

For the forest habitat types under consideration, this evidence is available at best for medio-European subalpine beech woods with *Acer* and *Rumex arifolius* and acidophilous *Picea* forests of the montane to alpine levels. In the case of drained bog woodland and alluvial forests, restoration should be the first priority. On secondary sites of oak forests and lichen-rich Scots pine forest habitats, management measures are probably still necessary to restore a favourable conservation status and to secure them in the long term. Here, climate change could have a partially supportive effect on more warmth- and drought-tolerant forest habitat types. In the case of large-scale beech forest habitats, the distribution models available so far do not show any significant negative changes, even under climate change.

CHAPTER 6

Synthesis

6.1 Outline

In the previous chapters of this doctoral thesis, I have described and discussed in detail the importance of nature and forest conservation concepts in today's world and the difficulties that can arise in classifying and achieving forest conservation objectives. Furthermore, I have highlighted the importance of different perceptions of value in forest conservation and possible consequences for the protection of forest biodiversity. Using an interdisciplinary approach that spans ecology, politics and society, I have identified and scientifically analysed the challenges that can arise in the nature conservation value assessment of forest conservation objects and tree species as well as in the implementation of forest conservation measures. Finally, using selected forest habitat types of the Habitats Directive, I have discussed possible future justification of nature conservation in view of the uncertainties and challenges of climate change. All these aspects are now summarised, discussed and placed in a broader context in this final synthesis chapter.

6.2 Contemporary concepts and objectives in German forest conservation

Decades after intensive and ambitious conservation work, the global community has unfortunately still not succeeded in halting the loss of biodiversity (e.g. Butchart et al. 2010; Tittensor et al. 2014; IPBES 2019). Nevertheless, societal and political awareness of this crisis is growing and with it the willingness to work for the conservation of biodiversity (Leadley et al. 2022). In this context, consensus among stakeholders on the conservation objectives is a crucial factor in effective conservation (Demant et al. 2019). In Chapter 2, my co-authors and I discussed the challenges that can arise when specifying conservation concepts and objectives. Problems in this context can include overly ambitious objectives and disagreements among stakeholders regarding implementation of conservation measures. We have argued that for successful implementation of nature and biodiversity conservation initiatives, the development of comprehensive, comparable and feasible conservation objectives defined in nature conservation concepts and international frameworks is a key foundation (Demant et al. 2019).
The aim of our study in Chapter 2 was to analyse forest conservation objectives in Germany in a transparent way and to develop a consistent and consensual framework. We succeeded in deriving this comprehensive reference framework which systematically classifies and categorises conservation objectives with respect to German forest conservation. The framework has proven suitable in reviewing 79 biodiversity and forest conservation concepts of different

stakeholder groups at various scales and in applying textual content analysis. Since its rationale lies in the Convention on Biological Diversity and the German Federal Act for the Protection of Nature, it is based on common ground and is transferable to various fields of conservation. With our framework, forest conservation objectives can now be compared to search for commonalities and differences. Through its hierarchical structure, we have considered all important levels of nature and biodiversity conservation: socio-political and nature conservation objectives *sensu stricto*, abiotic and biotic objectives, as well as categories of natural resources, qualities and conditions of existence. We detected a general consensus among stakeholder groups and across jurisdictional scale levels. We identified the protection of ecosystems and species and, in particular, the preservation of diverse and self-sustaining forest structures (e.g. deadwood, habitat trees) as the most important objectives for forest conservation. However, our study has also indicated that social-political, genetic and abiotic objectives play only a minor role in the concepts so far. The low consideration of genetic diversity protection in nature conservation concepts and in the implementation of measures could also be confirmed by Klütsch and Laikre (2021). Although there is much scientific evidence for the need to conserve genetic diversity and the recognition of the genetic adaptation potential of species and populations, especially in the face of climate change and biodiversity loss, consideration of the resulting consequences in decision-making and practical environmental management falls short of expectations (Klütsch and Laikre 2021). This gap in integrating scientific knowledge into conservation practice is not limited to the field of genetics and is referred to as the knowledge-implementation gap in conservation science (summarised in Ferreira and Klütsch 2021).

We identified this knowledge-implementation gap in Chapter 2, where we discovered insufficient knowledge transfer from international to regional scales, particularly with regard to social-political objectives. Based on the distinction between social-political and nature conservation categories *sensu stricto*, we considered the societal challenges related to biodiversity conservation. In international concepts, the demand for holistic nature conservation that also addresses social needs and links people and nature, already seems to be given greater consideration (Colding and Barthel 2019). The integration and transfer of social knowledge across spatial-temporal scales and stakeholders is crucial as it can contribute to the resilience of social-ecological systems, i.e. the ability to cope with change, uncertainty, surprise and transformation, facing a changing climate (Berkes et al. 2003; Redman et al. 2004; Reyers et al. 2018; Bixler 2021). In a coherent social-ecological system, biophysical and social factors at spatial, temporal and organisational scales regularly interact in resilient and sustainable ways

(Redman et al. 2004). However, our study has shown that societal objectives such as recreation, tourism, financial compensation for nature conservation services, biodiversity education and environmental-awareness generally still play a subordinate role in the concepts studied. Stakeholders engaged in conservation politics and environmental decision-making need to intensify their efforts in this field and recognise the importance of multidisciplinary sources of knowledge such as science, practitioner experience, long-standing traditions or expert opinions (Cooke et al. 2018; Ferreira and Klütsch 2021). The scale mismatch we identified may be rooted in an insufficient integration of the preferences of multiple stakeholders involved in nature and forest conservation in Germany. In environmental decision-making, general agreements and requirements, such as the CBD or the EU Natura 2000 protected areas network are defined by transnational institutions or organisations and can sometimes be legally binding. These conventions and related measures developed by policy makers, researchers or governmental agencies at higher spatial scales, have consequences for individual land owners or practitioners operating at regional or even local scales, as the implementation of measures usually takes effect at this same level (Paloniemi et al. 2012; Guerrero et al. 2013; Jarvis et al. 2020).

In forests, however, successfully implementing these conservation measures mostly depends on the willingness and commitment of forest owners (Drescher et al. 2017; Mölder 2021). Without an operational and comprehensive catalogue of quantifiable forest conservation objects and measures, the defined objectives may not be achieved. To increase the motivation and commitment of forest owners, it might be beneficial to raise awareness of the intrinsic value and importance of their own forest biodiversity. Our frameworks for deriving a nature conservation value of conservation objects as well as forest tree species and forest development types, presented in Chapters 3 and 4, can be helpful in this respect. This is the first transferable framework to derive the nature conservation value of forest conservation objects and tree species (Demant et al. 2020).

6.3 Importance of nature conservation values for forest conservation

In assessing the nature conservation value of forest conservation objects (forest habitat types, structural elements in forests and development processes) and of forest tree species as well as forest development types, we have based our evaluation on the worthiness of, and the need for, protection. For forest habitat types, the need for protection was directly derived from Red List categories and translated into an ordinal scale. Red Lists for threatened species and habitat types are meaningful and widely used tools in nature conservation planning and management to set priorities for biodiversity conservation, but they have also been intensively debated in terms of their advantages and disadvantages (e.g. Rodrigues et al. 2006; Berg et al. 2014; Bennun et al. 2017; Betts et al. 2019). We did not consider the Red List status of single species because we believed that by considering selected forest habitat types and specific structures and processes in forests, species conservation can also be addressed. Our approach thus reflects a more holistic perspective on ecosystem conservation. Nevertheless, the importance of special species protection and assistance programmes should not be neglected, which are intended to ensure the long-term survival of many endangered and valuable species.

The worthiness of preservation assessment in Chapter 3 was not based on a consistent and universally valid indicator such as the Red List. Rather, we assumed that maintaining the core ecosystem functions is of high importance and therefore assessed forest conservation objects as worthy of preservation if they are integral parts of natural self-sustaining or semi-natural managed forest ecosystems (Frenz and Müggenborg 2016). Our evaluation of worthiness thus relates more to the nature of human perception. Designating a species, a certain structure or an entire ecosystem as worthy of protection means that it is perceived by humans as valuable, special, exceptional or important. In our understanding, conservation objects are worthy of preservation if they make an important contribution to the region's natural and cultural heritage by having evolved their typical biodiversity over a long period of time and thus exhibit a long ecological habitat continuity. As habitat continuity increases, so does the obligation of people to preserve conservation objects in the sense of sustainable and intergenerational responsibility (Demant et al. 2020). In Chapter 4, habitat continuity was used to assess the nature conservation value of forest tree species. Tree species achieved a higher value and a long (temporal) habitat continuity if they have existed within a region and thus within their Central European distribution range for a long time and can therefore be described as autochthonous.

As Central European forests were subject to continuous management and use for centuries or even millennia, habitats have evolved whose survival still depends on these former cultural management types, such as oak and mixed oak forests or, in particular, wood pastures or coppice forests (Bergmeier et al. 2010; Plieninger et al. 2015). In today's highly fragmented cultural landscape, these traditionally managed forests offer diverse structures and refuge opportunities for many specialised species and are therefore very worthy of conservation as social-ecological systems (Mölder et al. 2019; Demant et al. 2020). Such species-rich cultural forest landscapes are still dependent on active management today (Angelstam 2006). The long-term survival of these valuable forest ecosystems therefore depends on society's willingness to either commit to protecting the remaining habitats in the forest landscape or to restore them in suitable sites. With our reference framework of forest conservation objectives in Chapters 2 and in the assessment of the nature conservation value of forest conservation objects in Chapter 3, we considered the conservation importance of this social-cultural heritage and the associated biodiversity. Our studies thus make an important contribution to highlighting the ecological value for nature conservation of the habitat continuity of these cultural landscapes managed as social-ecological systems.

The continuous existence of conservation objects was not the only characteristic to achieve a high worthiness of protection. Other important criteria were the quantitative (absolute number of species = species richness) and qualitative (relative to a desired reference state = species composition) contribution that the conservation objects provide to the species pool of the natural landscape. Species richness, species composition or the relative abundance of species are important elements to describe the species diversity in a habitat or landscape, which we wanted to include when assessing the nature conservation value. A habitat can be species-poor (low species richness, low quantitative contribution), but its qualitative contribution can be very high because rare and endangered typical species can survive therein. This makes it a habitat worth protecting and contributes to a higher nature conservation value (Demant et al. 2020).

The final nature conservation value of the conservation objects was the combination of the separate values of worthiness of, and need for, protection, and comprised of six levels on a qualitatively ranked ordinal scale. Our approach resembles the method of Berg et al. (2014), who also developed a five- to six-level conservation value assessment framework to identify conservation priorities for plant communities. The authors derived their "need for action" from the assessment of endangerment (derived from Red Lists) and conservation value (relevance for species conservation, degree of naturalness and global relevance). Although their framework only considers plant communities, it would be of interest to find out whether their method can be combined with our nature conservation value assessment of habitat types, as both methods use Red Lists as a reference. When comparing our method with the concept of High Conservation Value introduced by Jennings et al. (2003), it becomes clear that their concept, in contrast to our approach, cannot be used to describe the conservation value of individual conservation objects such as forest habitat types or specific forest structures (e.g. deadwood, habitat trees), which highlights the advanced nature of our assessment framework. However, there are also similarities between the approaches, as the concept to assessing High Conservation Value forests also distinguishes criteria such as species diversity, habitat risks, landscape-level ecosystem mosaics, ecosystem services and cultural values (Brown et al. 2013; Areendran et al. 2019). In principle, our nature conservation valuation is comprehensible and easily transferable to other fields in nature conservation. Moreover, this simplified numerical value could contribute to making the nature conservation value of conservation objects more transparent and understandable for both the society and practitioners in conservation and forestry. Ideally, this would lead to greater social support for conservation measures. As there is no uniform and transferable system for deriving the nature conservation value of conservation objects in forests so far, our framework represents progress. However, as it is only based on the currently valid risk assessment of forest conservation objects, it cannot be estimated how the nature conservation value will change in the future given the uncertainties of climate change.

6.4 Importance of conservation values for silvicultural planning

Since climate change and the associated challenges pose new threats on future silvicultural planning, it is necessary to adapt silvicultural treatment strategies. Climate models provide predictions of the temperatures, precipitation amounts and likelihood of extreme events in the future. As described in more detail in Chapters 4 and 5, it can only be predicted with uncertainty to which climatic conditions tree species will be exposed in the coming decades and how they might react to these conditions with possible changes in their distribution ranges. Changes in climate can lead to changes in site conditions of forest stands and thus also have an influence on tree species composition. The extreme weather events of recent years have shown which climatic conditions may occur in the future. The dry periods of 2018-2020, in combination with an intensive bark beetle infestation, have led to widespread forest damage, especially in spruce stands (BMEL 2021a). It is expected that Central European tree species will be exposed to local changes such as higher temperatures, changes in the precipitation regime, longer dry periods especially in the summer months and heavy precipitation associated with extreme events (Collins et al. 2013). Chapter 4 noted that political decision-makers and individual forest managers have already recognised that such climatic changes are to be expected and that *business as usual* will not be meaningful in the future. Thus, current forest planning strategies are already abandoning the cultivation of pure coniferous stands in favour of the establishment of mixed forests rich in deciduous tree species. These mixed forests are more resistant and adaptable to increasing disturbances and provide a more stable biomass production (Schnabel et al. 2021; Senf and Seidl 2021b). Furthermore, they can cope with changing climatic conditions, are more resilient and adapt naturally to changing environmental conditions while maintaining their ecological functions and services (BMEL 2021a; Senf and Seidl 2021b).

Besides climatic challenges, the economic demands on forests will continue to influence the future choice of tree species in silvicultural planning. The main goal will remain to achieve the highest possible yield and to increase forest productivity, which is rarely compatible with the site-specific, native tree species mixture. So far, the consequences of forestry tree species selection for nature conservation have been given too little consideration. The methodology presented in Chapter 4 for the nature conservation value assessment of individual tree species and silvicultural forest development types overcomes this deficiency. For this purpose, the assessment framework developed by Demant et al. (2020) and presented in Chapter 3 was adapted for silvicultural planning and a spatially-explicit nature conservation value assessment method was developed at tree species level.

The basis for the assessment of the nature conservation value of tree species was the methodology presented in Chapter 3. However, since the habitat types were only considered and assessed as a whole unit, a direct tree species-specific evaluation was not possible and made it necessary to develop a further assessment framework. In silvicultural planning, usually only the economically relevant Central European tree species are planned in the forest stand with different proportions and compositions (= forest development types), which do not always correspond to the natural site-native tree species composition. The cultivation of tree species outside their natural distribution range, as was the case with spruce for decades, has led to these conifer monocultures being unable to react and adapt naturally to environmental changes.

An indication of which tree species can occur naturally at a site is given by the potential natural vegetation (PNV). Although, as described in Chapter 4, the concept of PNV must be viewed critically, it is currently the only reference system for the whole of Germany for the spatially-explicitly description of vegetation units or the potentially most highly developed vegetation composition of a site and establishes a relationship between the current abiotic site factors and the imagined present-day vegetation uninfluenced by humans (Tüxen 1956; Welle et al. 2018). Based on the PNV, the nature conservation value assessment of forest habitat types was spatially-explicitly adapted for Germany and refined at tree species level in Chapter 4. With the system presented, it is now possible to assess at each site in the forest stand what nature conservation effects the silvicultural selection of the main tree species in Central European commercial forests (beech, oak, spruce, pine, larch, fir and Douglas fir) will have. This involves assessing how the initial nature conservation value resulting from the naturally occurring forest habitat types may change as a result of the tree species selection and mixture. Depending on the silvicultural decision, the original nature conservation value of the forest habitat types at a site can be reduced, increased or maintained. However, since only the economically relevant tree species were assessed, there will often be a reduction in the nature conservation value, since the natural forest habitat types usually consist of additional secondary tree species. The WBW (2021) has also noted that in silvicultural planning and in forest environmental monitoring

mostly only the main tree species are used and a comprehensive consideration of all other tree species is missing. Therefore, with the framework presented, forest planners are provided with a practicable and applicable nature conservation value assessment tool.
The assessment approach described in Chapter 4 represents the current state of knowledge and gives forest managers the opportunity to better assess the conservation impacts of their own tree species choice in forest stands. As in Chapters 2 and 3, it is an attempt to depict the conservation value of forest biodiversity with the help of an artificial assessment system. Tree species are assigned a numerical ecological value to represent their nature conservation significance and to facilitate their comparison. Regardless of whether an ecological (ideal) or an economic (monetary) value is attributed to conservation objects, a valuation is always an attempt to fit an abstract characteristic, in the case of this thesis the nature conservation value, into a simplified and comprehensible system. There have already been numerous studies that address the economic valuation of biodiversity (e.g. TEEB 2010; Bartkowski et al. 2015; Hanley and Perrings 2019; Paul et al. 2020). Liang et al. (2016) found a positive biodiversity-productivity relationship in forests, noting that continued global species loss in forest ecosystems could reduce the global forest productivity, and consequently, the carbon absorption rate, which is crucial in the context of climate change. Since maximising biodiversity at ecosystem level does not generally lead to maximising economic and environmental values, this highlights the complex functional relationship between biodiversity and economic value which cannot be described by a single relationship pathway (Paul et al. 2020). The nature conservation evaluations carried out in this thesis provide an ethical-moral assessment and justification for the protection of forest conservation objects. However, further research is needed to draw conclusions about an economic value.

6.5 Ethical reasons for nature and forest conservation

The findings from Chapters 2, 3 and 4 have highlighted that it is crucial to improve the appreciation of biodiversity in order to convince decision makers of the necessity of conservation measures. As outlined in the general introduction to this doctoral thesis, questions regarding moral-ethical principles and motivations may arise in this context (Gorke 2010; Piechocki 2010; Vucetich et al. 2015). In developing our frameworks for analysing forest conservation objectives and assigning a conservation value to forest conservation objects and forest tree species, we have considered not only intrinsic values, but also moral-intrinsic or inherent values of nature (Soulé 1985; Eser and Potthast 1999; Eser et al. 2011; Vucetich et al. 2015). We did not consider instrumental or functional use value in our purely conservation-motivated assessment frameworks. However, protecting biodiversity for moral-intrinsic or aesthetic reasons can ultimately also lead to an instrumental benefit (Vucetich et al. 2015). This thesis supports the claims that nature should be valued and protected not only for its own sake, but also for cultural and aesthetic reasons. This means that basically every natural object on earth can be ascribed a value (Soulé 1985), which also justifies a broader definition of conservation objectives. We therefore take a more holistic approach to nature conservation, which in principle justifies the protection of all living and non-living beings (Gorke 2010; Piechocki 2010).

However, this cannot mean that everything can and must be protected always and everywhere, because there are many other aspects to be considered, such as nativeness, representativeness, naturalness/endemism, autochthony, site affiliation and endangerment status. Prioritisation in nature conservation is therefore necessary (Le Berre et al. 2019). As outlined in Chapters 2 and 3 and throughout this synthesis, semi-natural, cultural-historical forest biodiversity thus has an equally important conservation rationale for protection as natural, autochthonous forest biodiversity (Demant et al. 2019, 2020). This is all the more true as these historical forms of forest use could only develop in the past through extensive and diverse agricultural use, which created cultural landscapes rich in structure and species (Bergmeier et al. 2010; Plieninger et al. 2015; Mölder et al. 2019). However, they have been largely lost in the course of agricultural and forestry intensification (Angelstam 2006). We have tried to consider all these aspects in developing our frameworks for classifying nature conservation objectives and assessing nature conservation values. Since humans and nature have been shaping and changing each other for thousands of years, they can no longer be considered and evaluated separately in the Anthropocene (Reyers et al. 2018). Mankind has a responsibility towards its future generations to ensure that they preserve their natural and cultural heritage through a conscious and respectful approach to nature and its sustainable use (Díaz et al. 2019). It is therefore well justifiable that we also assign a very high conservation value to cultural-historical forest habitat types such as wood pastures or coppice forests (Angelstam 2006; Hartel et al. 2014).

The protection and improvement of forest biodiversity concerns all forest ownership types and should therefore be implemented across ownership boundaries (Mölder et al. 2021). Our frameworks for deriving a nature conservation value of conservation objects (Chapter 3) and of forest tree species in silvicultural stand planning (Chapter 4) can help to sensitise forest owners to the conservation value of their forest property. To ensure that forest owners actually decide in favour of conservation measures, incentive systems are necessary, as already described in

Chapter 3, to compensate for possible investments or opportunity costs and to increase the general acceptance of nature conservation measures in forests (Demant et al. 2020).

6.6 Can acceptance and practical implementation of forest conservation be improved through incentive schemes?

Agreements on forest conservation objectives and acceptance of conservation measures is crucial for successful and sustainable forest conservation (Demant et al. 2019, 2020). However, land users and conservationists do not always see eye-to-eye. Tiebel et al. (2021a, 2021b) underline the call already made by Franz et al. (2018a) for improved implementation and more adequate funding of forest conservation measures, especially in privately-owned forests. The forest conservation objectives and measures of the analysed concepts examined in Chapter 2 are implemented in Germany’s public forests mainly at the federal states level and are partly legally binding. However, they do not apply to privately-owned forests. For German private forests, there has so far been no catalogue of conservation measures suitable for contract-based forest conservation. The development of our framework in Chapter 3 for the suitability assessment of forest conservation objects and measures for contract-based forest conservation has now overcome this obstacle.

Our framework has proven useful in assessing suitability by analysing development periods through comparisons of initial and final nature conservation values. We considered different contractual periods (< 10 years, 10-30 years, and > 30 years) in order to achieve greater acceptance among private forest owners. Our assessment framework can be applied to all forest types, which is important because the challenges of the biodiversity and climate crises affect the entire forest, regardless of whether it is a public forest owned by the state, by a city, a municipality, or even the large-scale and small-scale private forest owners. Such different types of ownership and the associated management characteristics have shaped the structures and biodiversity of landscapes and forests for centuries, resulting in a diverse mosaic of habitats (Mölder et al. 2021). These different characteristics of forest landscapes (e.g. spatial connectivity of forests, species composition, and management systems) are often given too little consideration (Tinya et al. 2021).

Since half of the forest area in Germany is privately-owned, it would be a great step forward if our framework for the suitability assessment of contract-based forest conservation were to be applied more extensively in private forests. As already indicated in Chapter 3, the implementation of conservation measures is especially challenging there and incentives are needed to achieve forest conservation objectives (e.g. Seintsch et al. 2018; Demant et al. 2019, 2020; Juutinen et al. 2021; Tiebel et al. 2021a, 2021b; Baranovskis et al. 2022). In this context, there are also calls for stronger consideration of the individual needs of forest owners, such as increased integration into Natura 2000 processes, and the creation of a results-based incentive system for nature conservation measures (e.g. Burton and Schwarz 2013; Franz et al. 2017; Franz et al. 2018a; Herzon et al. 2018; Tiebel et al. 2021a). Contractual agreements on forest conservation measures and their financial compensation offer potential in this regard. In contrast to pure subsidies, the monetary benefit payment is always accompanied by a direct ecological performance (Wunder et al. 2008). Contract-based forest conservation or the remuneration of ecological services are part of the system of payments for ecosystem services and can create additional incentives to intensify activities to protect forest biodiversity and forest ecosystem services (Plieninger et al. 2013; Vedel et al. 2015).

Feil et al. (2018) and Franz et al. (2018b) discovered in surveys among private forest owners that they are in principle willing to implement forest conservation measures. However, direct interviews with private forest owners in the context of the WaVerNa-project and other studies have also shown that they are often more sceptical about “nature conservation” and in some cases have reservations that can lead to tensions and conflicts (Bergseng and Vatn 2009; Tiebel et al. 2021a; Baranovskis et al. 2022). Private forest owners fear that a voluntary contractual agreement on forest conservation measures imposes regulations on them and restricts their autonomy. Especially for forest owners, the protection of property and the sovereignty of individual decisions are a key issue (Sténs and Mårald 2020). Their forest is usually an economic resource and can mean a considerable financial income, especially for owners of large-scale private forests (Franz et al. 2018b). Small-scale private forest owners, on the other hand, are more heterogeneous in their motives and pursue not only an economic return, but also the conservation of their often very diverse personal property, which is valuable in terms of forest conservation (Schaich and Plieninger 2013; Mölder et al. 2021; Tiebel et al. 2021b). In a survey among small-scale private forest owners within Natura 2000 sites, Tiebel et al. (2021a) found that 90% theoretically consider biodiversity conservation very important, but only 45% actually implement forest conservation measures such as deadwood enrichment or habitat tree protection. To rectify this imbalance and to close the knowledge-implementation gap between theoretical willingness and practical implementation, our suitability assessment framework described in Chapter 3 could make an important contribution in the future.

In view of the heterogeneous debates and the challenges of meeting the different needs in implementing forest conservation measures in private forests, our catalogue can be of help to all forest owners to meet the responsibility of society (and thus also of private forest owners) for sustainable protection and conservation of forest biodiversity towards future generations. It can also provide guidance to the responsible ministries and authorities in selecting suitable measures and assessing their nature conservation development and applicability. Moreover, it can help to ensure that the objective called for in the National Strategy on Biological Diversity of "promoting contract-based nature conservation on 10% of privately-owned forest land" (BMUB 2007: 32) can also be achieved in the future.

The suitability assessment of contract-based forest conservation in Chapter 3 revealed that about 63% of the forest conservation objects and measures proved to be suitable. Short-term contracts are particularly suitable for objects with a low initial nature conservation value and where an immediate increase in value can be expected (e.g. actively created habitat trees), but are unsuitable for the retention of existing habitat trees. Long-term contracts, on the other hand, are generally recommended from a forest conservation perspective, except for funding natural succession after large-scale disturbances in forest (Demant et al. 2020). Particular attention should be placed on those objects where synergies arise and careful consideration should always be given to which forest conservation objective can be pursued on which forest area and then funded accordingly. For this purpose, it can be beneficial if forest owners are supported by trained advisors who know the funding possibilities in the respective federal state, can negotiate between the various stakeholders with their different needs and are also able to assess the conservation value of the forest conservation objects. The responsibility for promoting contract-based forest conservation cannot be imposed on forest owners alone. In their review, Mölder et al. (2021) confirm the importance of social-ecological systems within an integrative forest management, which considers the needs of nature and forest biodiversity on the one hand and social demands on the other. Uniform forest management concepts could otherwise lead to landscape homogenisation and habitat loss (Mölder et al. 2021). In times of limited financial and human resources, our frameworks can therefore help to set priorities for conservation measures and objectives that are specific and appropriate to the forest being analysed. Priority could be given to forest conservation objects with a high initial conservation value where an immediate loss of value is likely without active or passive conservation measures. These could be, for example, valuable deadwood and old-growth structures threatened by logging, or intact wood pastures and coppice forests threatened by acute cessation of use. Likewise, forest conservation objects with a low initial value could be selected with higher priority, if, for example, a considerable value increase can be expected through restoration measures (e.g. rewetting of degraded bog woodlands).

When the studies of the WaVerNa-project were conducted from 2015-2018, there was no nationwide funding programme for contract-based forest conservation in Germany. There were and are still considerable differences in the implementation and way of funding for forest conservation measures between the federal states. Often, no proper contracts are concluded, but decisions are made through a formal application procedure. A contract should be concluded on a voluntary basis, be terminable bilaterally, the conditions (benefits) be negotiated cooperatively-dialogically and be based on the agreement of service (nature conservation measure) and counter-service (financial compensation, cf. Lutter and Paschke 2018). Therefore, the development of a more harmonised approach is urgently needed. A first attempt was made within the framework of the Joint Task Improvement of the Agricultural Structure and Coastal Protection, where the topic contract-based forest conservation was added to the scope of funding (BMEL 2021b). However, implementation of the Joint Task lies in the responsibility of the federal states, which must develop their own guidelines. Nevertheless, a nationwide uniform legal basis for funding of forest conservation measures has been created, which, in addition to our catalogue of suitable forest conservation objects and measures, can contribute to achieving the federal government's goal of promoting contract-based forest conservation on 10% of the area in private forests in Germany. Whether the success factors identified by Franz et al. (2018a) such as legal security, fairness, continuity and flexibility, will be considered during implementation cannot yet be assessed and it remains to be seen whether this new instrument will achieve better acceptance among private forest owners with higher participation rates in the future.

6.7 Consequences for future forest conservation and management

Although we are still officially in the Holocene in terms of geological history, the Anthropocene is now considered as the current epoch due to the domination of humans (Hayward 1997; Crutzen 2006; Reyers et al. 2018; Lubbe and Kotzé 2019). More than three-quarters of the Earth's terrestrial surface is directly influenced by humans and can therefore be described as anthropogenic biomes (anthromes, Ellis and Ramankutty 2008). Pristine nature, completely unaffected by humans, probably no longer exists anywhere in the world, because humans have reached even the remotest parts of the earth with their harmful atmospheric emissions, where "anthropogenic climate change has already altered the natural world, from the timing of flowers opening in the spring to the whereabouts of animals" (Marris 2013: 85). Forests are particularly affected by this, with almost half of the world's native forests lost due to land-use changes and conversion to food crops, and the remaining forest area often intensively managed (Benz et al. 2020).

The profound changes in natural environmental conditions as well as the expected climatic changes also have significant impact on nature and forest conservation. For if everything around is changing, must forest and nature conservation also change by adapting their conservation objectives and measures? This question is addressed in Chapter 5 in relation to the validity of the conservation responsibility and justification of selected forest habitat types of the Habitats Directives. We have analysed whether the favourable conservation status of forest habitat types of the Habitats Directive remains a well-founded objective when faced with the uncertainties of climatic development. Furthermore, we have assessed the possible future trend development of the conservation status of these forest habitat types. For this purpose, we compared the predictions of different niche and species distribution models with regard to the future development of tree species and forest habitat types and discussed possible consequences for existing conservation objectives. As the various models differ considerably in their predictions of the future distributions of species and habitats, no generally valid conclusions can be given and a differentiated consideration for each forest habitat type is necessary.

We discovered that for some forest habitat types, climate change and the associated increase in droughts and changes in precipitation may lead to a possible shift in distribution ranges or even area losses. This concerns in particular the Medio-European subalpine beech woods with *Acer* and *Rumex arifolius*, the acidophilous *Picea* forests of the montane to alpine levels and the *Tilio-Acerion* forests of slopes, screes and ravines. For forest habitat types already in need of restoration, such as bog woodlands, riparian and alluvial forests, the effects of climate change, such as an increase in evapotranspiration and changes in groundwater levels, may increase the pressure on their already unfavourable conservation status. The focus of forest conservation measures should therefore be primarily on restoring their natural site conditions so that they can evolve a natural resilience to the climate change-related challenges.

With regard to the warmth-tolerant oak and oak-mixed forests, we observed that they could show an increase in area and their conservation status under climate change, mainly due to a higher drought tolerance of oak species (Härdtle et al. 2013; Zimmermann et al. 2015; Kasper et al. 2022). The proportion of oak has already declined sharply since the abandonment of cultural-historical forest use. For example, its proportion in the Solling forest has declined from about 30% to about 10% within 200 years (Reddersen 1934). In order for oaks and other warmth-favoured tree species to withstand competitive pressure, e.g. from beech, active management is necessary, especially on secondary sites (Meyer 2013a; Ssymank et al. 2019).

Oak regeneration requires open conditions, which can be created and maintained through active management and the resumption of cultural-historical management forms such as coppice forests and wood pastures (Meyer et al. 2018; Mölder et al. 2019). The importance of these special forest habitat types for forest biodiversity has already been highlighted in Chapters 2 and 3. Labour-intensive coppice management can lead to an improvement and stabilisation of oak-hornbeam forest habitat types and the associated habitat-typical structures and biodiversity (Meyer et al. 2018). In strict forest reserves, a positive development trend for forest stand maturation characteristics such as veteran trees, deadwood and more advanced forest development stages could be observed in beech and oak forests with a rather unfavourable initial condition (Meyer et al. 2016b). With regard to the completeness of the habitat-typical species inventory, a decreasing trend development was observed for oak as the main tree species, while a rather positive trend development was observed in beech habitat types (Meyer et al. 2016b). Thus, oak could either disappear from these forest stands in the long term, or it can use the opportunity of increased natural disturbances and withstand the competitive pressure of beech (Meyer and Mölder 2017). For Central European beech forest habitat types, there is still a great uncertainty about what impact climate change will have on the distribution ranges of these forests (Leuschner 2020). Although beech has an increased sensitivity to drought (Zimmermann et al. 2015; Leuschner 2020; Kasper et al. 2022) and the severe drought years 2018-2020 have led to vitality losses (Schuldt et al. 2020), scientists do not yet agree on whether or not beech will suffer significant range losses under climate change, as summarised by Antonucci et al. (2021).

However, forest habitat types are not only threatened by climate change-induced transformations described in Chapter 5. According to the reports under Article 17 of the Natura 2000 Habitats Directive for the period 2007-2012, anthropogenic land use requirements such as management and use of forests and plantations or, in the case of mountain forests, sports and recreation infrastructure are the main potential pressures and threats to forest habitat types (https://nature-art17.eionet.europa.eu/article17). It is therefore necessary to address not only whether existing conservation objectives for forest habitat types of the Habitats Directive need to be adapted due to climate change (Vohland 2007; Hendler et al. 2010; Cliquet 2014), but also how they can be better protected from anthropogenic disturbances and destruction. However, since the above-mentioned reporting period, pressures on forests have also continued to increase due to the intensification in natural and anthropogenic disturbances (Melo et al. 2019). The impacts of climate change and the resulting potential threats to forest habitat types and forest biodiversity must therefore not be neglected in future forest conservation and management planning. Despite the expected climatic changes and precisely because of the constant threat from anthropogenic land use, the favourable conservation status of forest habitat types of the Habitats Directive, as described in more detail in Chapter 5, thus remains a well-founded objective in nature conservation.

In addition to the projected climate change-induced shifts in abiotic and biotic environmental conditions, natural and anthropogenic disturbances are also expected to increase in frequency and intensity (Seidl et al. 2017; Danneyrolles et al. 2019; Senf et al. 2021). The spatial and temporal interplay of all these disturbances occurring in a landscape and their interactions, such as the type of disturbance, its frequency, severity and intensity, and the area size are described as the disturbance regime (Pickett and White 1985; Turner 2010). Considering the natural disturbance regime when planning silvicultural management strategies can improve forest resilience (BfN 2020; Senf and Seidl 2021a; BMEL 2021a). The conservation-oriented tree species selection described in Chapter 4 also has a significant effect, because the more natural the composition of the forest, the more likely it is that a natural disturbance regime will prevail. Furthermore, in order to emulate natural disturbance regimes as closely as possible, disturbance-based forest management practices should be integrated into regular forestry practice (Seymour et al. 2002; North and Keeton 2008; Kuuluvainen et al. 2021). The aim should be to adapt silvicultural management so that it corresponds as closely as possible to the natural development dynamics and the natural disturbance regime of forest ecosystems. Furthermore, forest ecosystem management before and after disturbances should focus on the long-term survival of native biodiversity that has developed under the local disturbance regime in order to enhance ecosystem functions (Newman 2019). As half of Europe’s forests, especially large old trees, may be more vulnerable to climate change-induced increases in disturbance in the future, the structural, physiological and mechanical properties of forests will be even more crucial for increased resilience to these disturbances (Forzieri et al. 2021).

When setting forest conservation objectives and planning conservation measures in the future following the principle of the “no-regret” strategies is sensible (Geyer et al. 2014). This means that well-founded conservation objectives should only be adapted on the basis of sufficient evidence. Otherwise, there is a risk that well-founded objectives, such as the favourable conservation status of forest habitat types of the Habitats Directive, are abandoned too carelessly. Only measures that "have an ecological, economic or societal benefit under today’s climate conditions, even if the actual reason for the measure taken does not occur to the extent expected" should be implemented (Westhauser 2020). Optimally, it should be possible to pursue the original conservation objective again. Dynamic planning of conservation objectives and measures in the context of adaptive management can better absorb future uncertainties of climate change, but this may come at the expense of predictability and certainty (Messier et al. 2013). Linking multiple conservation strategies at the same landscape scale can prove helpful (Meyer et al. 2016a), as it can create synergies to achieve the most comprehensive biodiversity protection possible (Lindenmayer et al. 2006). In this context, priority areas for nature conservation or for agricultural and forestry production can either be designated separately (segregative/land-sparing approach), or they can be implemented integratively by combining sustainable land use alongside priority areas for nature conservation (land-sharing approach, Green et al. 2005; Fischer et al. 2014; Meyer et al. 2016a; Kremen and Merenlender 2018; Grass et al. 2019). However, as an exclusively integrative land use approach is difficult to implement and does not meet the needs of comprehensive biodiversity conservation, and an exclusively segregative land use can lead to ethical conflicts between conservationists and land users, a combination of both approaches is considered promising (e.g. Kraus and Krumm 2013; Paul and Knoke 2015; Phalan 2018; Grass et al. 2019; Krumm et al. 2020; Grass et al. 2021). For forest conservation, this means that in addition to segregative elements such as national parks and strict forest reserves, integrative elements such as the protection and retention of habitat or veteran trees, particularly species-rich microhabitats or wildlife corridors within the managed forest area (cf. "biodiversity hotspots", Meyer et al. 2009a; Meyer et al. 2015b; Engel et al. 2018), can be or are already being implemented together in the landscape (Kraus and Krumm 2013; Mason and Zapponi 2015; Krumm et al. 2020). Our value assessment framework for forest conservation objects from Chapter 3 can be particularly helpful in classifying these integrative hotspots for biodiversity, especially in privately-owned forests.

Different conservation objectives, such as maximising biodiversity and species numbers, preserving naturalness of habitats, considering rarity and endangerment of individual species, and maintaining ecosystem services and all the benefits that mankind derives from ecosystem protection, cannot always be realised at the same landscape scale (Piechocki 2010). Careful consideration must therefore be given to which objective is to be achieved at which spatial scale. Particularly as, given the ongoing biodiversity and climate crisis, nature's ability to provide benefits to people is declining (Brauman et al. 2020). Future forest conservation and management across all ownership types must not only address the direct drivers of biodiversity decline (e.g. land use change, climate change, pollution, exploitation of natural resources), but intensify actions that address indirect drivers as well (e.g. socio-cultural challenges, economical imbalance, unequal distribution of resources) for precautionary reasons to ensure the well-being of future generations (MEA 2005; Pereira et al. 2012; Díaz et al. 2019).

An opportunity to better understand the natural processes in forests in this context is offered by natural forest research. Even if primeval forests have disappeared in Central Europe (Sabatini et al. 2018, 2020), we can use the existing naturally developing strict forest reserves to study the consequences of our forest management and derive possible conclusions. The importance of these forests for the conservation of biodiversity has received increasing attention and led to a further designation of natural forest research areas (Meyer et al. 2022). These new natural forests can be used as reference for natural development processes and serve as adaptive learning sites to study forest dynamics. Long-term ecological monitoring has already been able to demonstrate their self-regulated restoration potential after various disturbances (Meyer et al. 2022), from which consequences for future forest planning in Germany can be derived. Thus, not every damaged forest area must always be artificially reforested. Rather, natural and self-dynamic reforestation should be allowed on a large part. Should afforestation nevertheless be necessary, it would be a step forward if our framework for the nature conservation value assessment of tree species and forest development types would find application.

6.8 Concluding remarks

After the severe forest diebacks experienced in Germany in recent years, triggered by a cascade of disturbances (winter storms, summer drought and associated bark beetle outbreaks), discussions about future forest management have intensified. Unfortunately, these discussions are still far from the common consensus called for in Chapter 2. The difficulty of finding this consensus can be seen in the ongoing discussions and conflicts between forestry and nature conservation, such as the debate between different scientists and stakeholders on the climate change mitigation effect and carbon sink capacity of managed and unmanaged forests triggered by the study of Schulze et al. (2020a). This is a good example of how conflictual and in some cases even accusatory scientific exchange can be. The list of subsequent reactions and critical exchanges of scientific papers in this context is long (e.g. Bolte et al. 2020; Booth et al. 2020; Jacob 2020; Kun et al. 2020; Schulze et al. 2020b, 2020c; Welle et al. 2020a, 2020b; Irslinger 2021; Luick and Grossmann 2021; Schulze et al. 2021). Even though science itself needs such constructive exchange, the interpretation and communication of scientific results and facts as well as the recommendations for action derived from them should always be scientifically objective, comprehensible and evidence-based. Otherwise, the mismatch in the transfer of knowledge and in implementing nature conservation objectives and measures addressed in this doctoral thesis will never be overcome. The frameworks developed in the previous chapters of this thesis for the classification of nature conservation objectives and for the nature conservation assessment of conservation objects (forest structures and processes as well as forest habitat types) and forest tree species as well as forest development types can make an important contribution to rectifying this mismatch. The transfer and practical application of these scientifically obtained results is currently still the greatest challenge and can thus be assigned to the knowledge-implementation-gap already mentioned. For practitioners, our results and especially the frameworks for deriving nature conservation values might still be too abstract. To make the frameworks more accessible in everyday forestry management, these should be developed into user-friendly manuals or apps for mobile devices.

In the Anthropocene, it may also be necessary for to break new ground (“transformative change”, IPBES 2019; Leadley et al. 2022). Although nature has considerable potential for regeneration and restoration, one possibility in this context, as discussed in Chapter 5 and suggested by Marris (2013) and Hobbs et al. (2009), could be that conservationists in the future should refrain from trying to artificially restore biotic and abiotic conditions that no longer exist. Instead, this new wilderness should be embraced and accepted and its development monitored (Marris 2013). For forest management, this could mean, as already suggested, that after the intensive disturbance and damage events of recent years and the creation of diverse disturbance areas, some of these areas should be left to develop naturally while learning and observing what forests and biodiversity can accomplish, restore or even recreate on their own. In order to minimise the negative effects of post-disturbance management and salvage logging of recently disturbed areas, as described by Lindenmayer et al. (2017), it would be beneficial to record valuable structures and forest stands in advance in order to exclude these areas from salvage logging measures in the future after disturbances. These can be, for example, steep slopes or areas with easily erodible soils, in order not to further impair their water storage and soil stability. With the help of the nature conservation value assessment frameworks presented in this thesis, these high-valued areas and forest habitat types can be identified.

This thesis has highlighted that in order for forests to maintain their diverse structures, functions and ecosystems services in the future and provide suitable habitats for many different species, the development of semi-natural, resilient mixed forests consisting mainly of native tree species with high genetic adaptation potential should be pursued further. Only in this way can forests cope with the challenges to come, if they are managed wisely with a mixture of active interventions and passively leaving them in peace. At the same time, the existing objectives of nature conservation should not be lightly abandoned and a respectful approach as well as a cooperative dialogue between all actors involved should be further encouraged. For this is how forest conservation in Germany and worldwide can be more successful in the long-term.

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Academic Curriculum Vitae

Laura Demant

Born on 29th of September 1987 in Marburg, Germany

Education

2016-2022	PhD studies in the GAUSS (Georg-August-University School of Science) Basis Program Biology, Department Vegetation & Phytodiversity Analysis, Georg-August University of Göttingen, Germany and at the HAWK University of Applied Sciences and Arts Hildesheim/Holzminden/ Göttingen, Germany
2015	PhD studies at the at the Institute of Crop Sciences and Resource Conservation in the Department of Vegetation Ecology at the Rheinische Friedrich-Wilhelms-Universität Bonn, Germany
2011-2014	Master of Science 'Biodiversity, Ecology and Evolution' at the Georg-August-University of Göttingen, orientation: plant ecology, vegetation science and forest conservation. Topic of the Masters Thesis: Diversity of forests on the DBU Natural Heritage sites 'Reiterswiesen' and 'Lauterberg' in consideration of different management
2008-2011	Bachelor of Science 'Biodiversity and Ecology' at the Georg-August-University of Göttingen, orientation: botany and ecology. Topic of the Bachelors thesis (translated): Influence of topographic position on tree regeneration in canopy gaps in southern Ecuadorian mountain rainforest
1994-2007	Qualification for university studies (Abitur), Marburg, Germany

Work experience

2019-present	Research assistant at the Northwest German Forest Research Institute in the Department of Forest Nature Conservation in the field of natural forest research. Collaboration in the joint project 'MiStriKli: Minimising the risk of storm damage in forests against the background of climate change' and work on the sub-project 'Development of a nature conservation forest ecology assessment procedure for the worthiness and need for protection of forest development types

depending on location, protection status and management regime as well as storm-related disturbance areas and their management'.

2016-2022 Research associate at the Albrecht von Haller Institute for Plant Sciences in the Department of Vegetation Analysis and Phytodiversity at the Georg-August University of Göttingen. Collaboration in research and teaching. Leading botanical excursions and supervising theses.

2015-2018 Research assistant at the Northwest German Forest Research Institute Göttingen in the Department of Forest Growth and the subject area of Forest Nature Conservation and Natural Forest Research. Collaboration in the joint project "WaVerNa: Vertragsnaturschutz im Wald - Analyse der waldökologischen, ökonomischen und rechtlichen Optionen" and work on the sub-project "Naturschutzfachlich-waldökologische Analysen".

2015 Research associate at the Institute of Crop Sciences and Resource Conservation in the Department of Vegetation Ecology at the Rheinische Friedrich-Wilhelms-Universität Bonn, collaboration in research and teaching, doctoral thesis on "The heat-loving oak-hornbeam forests in western Central Europe and their history of use" – discontinued

2014-2015 Employed as a biologist at PLANB (project management, landscape and nature conservation planning, consulting) in Neu-Eichenberg. Tasks: Special species protection law assessments of projects and interventions, species protection expert contributions, GIS and biotope type mapping.

2014 Forest biotope mapping in Hessian natural forest reserves for Neckermann & Achterholt - ecological expertises, forest structure surveys, age estimates, stand mapping.

Forest biotope type mapping in Hesse for Simon und Widdig GbR, Büro für Landschaftsökologie, nature conservation assessment of various forest biotope types based on the compensation ordinance

2011-2014 Research assistant in the Department of Vegetation Analysis and Phytodiversity of the Georg-August-University Göttingen in the course *Applied Vegetation Ecology and Multivariate Analysis*

Research assistant in the Department of Botanical Systematics at the Georg-August-University Göttingen in the course *Botanical Identification Exercises* and in the basic practical course *Botany*

Student assistant in the Botanical Systematics Department of the Georg-August University Göttingen in the course *Botanical Identification Exercises*

Internships

2013	Three-month internship at the Deutsche Bundesstiftung Umwelt (DBU), vegetation field work and forest structure analyses on two DBU nature reserves in Bavaria.
2011	Seven-week internship at the State Bird Observatory for Hesse, Rhineland-Palatinate and Saarland in Frankfurt/Main
2010	Two-month tropical ecology internship at the Estación Cientifíca San Francisco in Ecuador
2007-2008	Voluntary social year in culture at the German Foundation for Musical Life in Hamburg

Scientific contributions

Articles in peer-review journals

2022	Jung, C., **Demant, L.**, Meyer, P., Schindler, D.: Highly resolved modeling of extreme wind speed in North America and Europe. Atmospheric Science Letters. Accepted.
2020	**Demant, L.**, Bergmeier, E., Walentowski, H., Meyer, P.: Suitability of conservation objects for contract-based nature protection in privately-owned forests in Germany. Nature Conservation 42: 89–112. https://doi: 10.3897/natureconservation.42.58173
2019	**Demant, L.**, Meyer, P., Sennhenn-Reulen, H., Walentowski, H., Bergmeier, E.: Seeking consensus in German forest conservation: An analysis of contemporary concepts. Nature Conservation 35: 1-23. https://doi.org/10.3897/natureconservation.35.35049

2019	Gemeinholzer, B., **Demant, L.**, Dieterich, M., Eser, U., Farwig, N., Geske, C., Feldhaar, H., Lauterbach, D., Reis, M., Weisser, W., Werk, K.: Artenschwund trotz Naturschutz. Noch immer Handlungs- und Forschungsbedarf. Biologie in unserer Zeit 49(6):444-455. https://doi.org/10.1002/biuz.201910689
2016	Meyer, P., **Demant, L.**, Prinz, J.: Landnutzung und biologische Vielfalt in Deutschland – Welchen Beitrag zur Nachhaltigkeit können Großschutzgebiete leisten? Raumforschung und Raumordnung. doi:10.1007/s13147-016-0427-2

Other publications

2022	**Demant, L.,** Hagge, J., Mölder, A., Schmidt, M., Steinacker, C., Meyer, P.: Bleibt der günstige Erhaltungszustand der FFH-Wald-Lebensraumtypen auch im Klimawandel ein sinnvolles Ziel? BfN-Skripten. Accepted.
2022	Meyer, P., Mölder, A., Feldmann, E., **Demant, L.,** Schmidt, M.: Neue Naturwälder in Deutschland – Hotspots für Forschung und biologische Vielfalt im Klimawandel. Geographische Rundschau 1/2-2022. 28-31.
2019	Engel, F., Meyer, P., **Demant, L.**, Spellmann, H.: Wälder mit natürlicher Entwicklung in Deutschland. AFZ/Der Wald 13: 22-25
2018	**Demant, L.**, Meyer, P., Spellmann, H.: Vertragsnaturschutz im Wald aus naturschutzfachlicher Sicht. AFZ-Der Wald 73(21): 16-19
2018	**Demant, L.**: Naturschutz im Privatwald im deutschlandweiten Vergleich – ausgewählte naturschutzfachliche Ergebnisse aus dem Waldvertragsnaturschutz-Projekt (WaVerNa). ANLiegen Natur 40 (2), 10 pp. Laufen. www.anl.bayern.de/publikationen
2018	**Demant, L.**, Meyer, P., Walentowski, H., Bergmeier, E.: Ziele und Maßnahmen im Waldnaturschutz in Deutschland - eine vergleichende Analyse relevanter Konzepte und Strategien. Treffpunkt Biologische Vielfalt XVI. Interdisziplinärer Forschungsaustausch im Rahmen des Übereinkommens über die biologische Vielfalt. BfN-Skripten 487: 42-49
2018	Demant, B., **Demant, L.**, Weißbecker, M.: Naturschutz und Forst im Gespräch: Schutz und Nutzung im Wald. Jahrbuch Naturschutz in Hessen Band 17 / 2018. 156-158

2018 Franz, K., Blomberg, M. v., **Demant, L.**, Dieter, M., Lutter, C., Meyer, P., Möhring, B., Paschke, M., Seintsch, B., Selzer, A. M., Spellmann, H.: Perspektiven für den Vertragsnaturschutz. AFZ-Der Wald 73(21): 30-33

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Declaration of originality and certificate of ownership

I, Laura Demant, hereby declare that I am the author of the present doctoral thesis entitled "Concepts, objectives and values in German forest conservation – a comparative analysis, an assessment of practicability and future prospects". All references and sources that were used in the thesis have been appropriately acknowledged and cited. I furthermore declare that this work has not been submitted elsewhere in any form as part of another thesis procedure.

Göttingen, February 2022

(Laura Demant)