CLIMATE CHANGE AND EUROPEAN FORESTS: IMPACTS, ADAPTATION, AND CONSEQUENCES FOR AESTHETICS

by

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Abstract

This dissertation investigates how European forests are affected by climate change, how forest practitioners perceive and respond to these impacts, and how adaptation and reforestation strategies shape the visual aesthetics of forest landscapes. By combining biophysical evidence, qualitative practitioner insights, expert assessments, and public preference assessments, the thesis develops a comprehensive understanding of forests as socio-ecological systems under increasing climate stress.

Across Europe, the 2018–2022 drought period caused widespread vitality loss, intensified pest outbreaks, and substantial tree cover decline, with Central Europe experiencing the most severe impacts. Damage patterns differed markedly among regions, yet even typically resilient or high-altitude forests showed signs of stress. Persistent effects in climatically average years highlight legacy effects of drought and heat events. These findings underline Europe's high forest vulnerability and the need for region-specific adaptation strategies.

Forest practitioners widely acknowledge drought as the dominant threat to forest health, citing its effects on mortality, regeneration, and pest susceptibility. Although there is broad consensus on the need to increase species and structural diversity for adaptation, substantial differences in preferred measures persist across practitioner groups. Economically oriented practitioners tend to favor active, conifer-based management, whereas those prioritizing protection and recreation advocate for native species and more naturalistic approaches. These contrasting strategies stem not from differing views on climate impacts but from divergent management philosophies and value orientations, illustrating that adaptation is as much a social negotiation as it is the management of ecological systems.

The dissertation further shows that climate change adaptation measures profoundly influence the aesthetic quality of forests—an often neglected but socially important dimension. Structural attributes such as tree size, height variation, understory density, and species composition strongly shape visual appeal. Measures that enhance structural diversity—mixed stands, multi-layered canopies, increased naturalness—tend to improve aesthetics. In contrast, interventions like leaving residues, using protective tubes, or uniform reforestation can temporarily reduce scenic quality, though many negative effects diminish as forests mature. Public preference analysis demonstrates significant temporal dynamics: reforestation strategies that appear unattractive shortly after implementation may become appealing decades later, while options that are initially appealing may lose their attractiveness over time. This highlights the importance of evaluating aesthetic outcomes across the full forest development cycle rather than at a single moment in time.

Taken together, the findings underscore that climate adaptation in forestry must integrate ecological risks, practitioner perspectives, and public aesthetic values. By recognizing forests as co-evolving socio-ecological systems, the dissertation provides a foundation for adaptation strategies that are not only ecologically effective but also socially acceptable and visually appreciated—essential conditions for sustaining multifunctional forests in a changing climate.

Zusammenfassung

Diese Dissertation untersucht, wie europäische Wälder vom Klimawandel betroffen sind, wie forstliche Praktiker diese Auswirkungen wahrnehmen und darauf reagieren und wie Anpassungs- und Wiederbewaldungsstrategien die visuelle Ästhetik von Waldlandschaften prägen. Durch die Kombination biophysikalischer Befunde, qualitativer Einblicke von Forstpraktikerinnen und -praktikern, Expertenbewertungen sowie Erhebungen öffentlicher Präferenzen entwickelt die Dissertation ein umfassendes Verständnis von Wäldern als sozial-ökologischen Systemen unter zunehmendem Klimastress.

In ganz Europa führte die Dürreperiode 2018–2022 zu weit verbreitetem Vitalitätsverlust, verstärkten Schädlingsausbrüchen und erheblichem Rückgang der Baumbedeckung, wobei Mitteleuropa am stärksten betroffen war. Die Schadensmuster unterschieden sich deutlich zwischen den Regionen, doch selbst typischerweise widerstandsfähige oder hoch gelegene Wälder zeigten Anzeichen von Stress. Anhaltende Folgen in klimatisch durchschnittlichen Jahren verdeutlichen Langzeiteffekte von Dürre- und Hitzeereignissen. Diese Ergebnisse unterstreichen die hohe Vulnerabilität der europäischen Wälder und den Bedarf an regionsspezifischen Anpassungsstrategien.

Forstpraktiker sehen Dürre als die dominierende Bedrohung für die Waldgesundheit an und verweisen auf die Folgen für Mortalität, Verjüngung und Schädlingsanfälligkeit. Obwohl ein breiter Konsens über die Notwendigkeit besteht, Arten- und Strukturvielfalt zu erhöhen, bestehen zwischen verschiedenen Praktikergruppen erhebliche Unterschiede, was die bevorzugten Maßnahmen betrifft. Praktiker die einen ökonomischen Schwerpunkt setzen, tendieren zu aktiver Anpassung und setzen weiterhin stark auf Nadelholz, während jene, die die Schutz- und Erholungsfunktion priorisieren, heimische Arten und natürliche Anpassungsmechanismen bevorzugen. Diese kontrastierenden Strategien resultieren nicht aus unterschiedlichen Einschätzungen der Klimafolgen, sondern aus divergierenden Managementphilosophien und Wertorientierungen – ein Hinweis darauf, dass Anpassung ebenso sehr ein sozialer Aushandlungsprozess wie die Steuerung ökologischer Systeme ist.

Die Dissertation zeigt zudem, dass Maßnahmen zur Klimaanpassung die Ästhetik von Wäldern tiefgreifend beeinflussen – eine oft vernachlässigte, aber gesellschaftlich bedeutsame Dimension. Strukturelle Attribute wie Baumgröße, Höhenvariation, Dichte der Strauchschicht und Artenzusammensetzung prägen die visuelle Attraktivität maßgeblich. Maßnahmen, die die strukturelle Vielfalt erhöhen – Mischbestände, mehrschichtige Kronendächer, gesteigerte Natürlichkeit – verbessern tendenziell die Ästhetik. Demgegenüber können Eingriffe wie das Belassen von Ernteresten, der Einsatz von Wuchshüllen oder gleichförmige Wiederaufforstung die Landschaftsqualität mindern, auch wenn viele negative Effekte mit der Zeit abnehmen. Die Analyse gesellschaftlicher Präferenzen zeigt deutliche zeitliche Dynamiken: Wiederbewaldungsstrategien, die kurz nach der Umsetzung unattraktiv erscheinen, können Jahrzehnte später an Attraktivität gewinnen, während Optionen, die zunächst attraktiv wirken, im Laufe der Zeit an Reiz verlieren können. Dies verdeutlicht die Notwendigkeit, ästhetische Folgen von Eingriffen über den gesamten Entwicklungszyklus eines Waldes hinweg zu bewerten statt zu einem einzelnen Zeitpunkt.

Zusammenfassend unterstreichen die Ergebnisse, dass die Klimaanpassung in der Forstwirtschaft ökologische Risiken, Sichtweisen der Praktikerinnen und Praktiker und ästhetische Wertschätzung der Öffentlichkeit gemeinsam betrachten muss. Durch die Betrachtung von Wäldern als sich mit der Gesellschaft mitentwickelnde sozialökologische Systeme schafft diese Dissertation eine Grundlage für Anpassungsstrategien, die nicht nur ökologisch wirksam, sondern auch gesellschaftlich akzeptiert und visuell geschätzt werden – wesentliche Voraussetzungen für den Erhalt multifunktionaler Wälder im Klimawandel.

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List of Abbreviations

CCAMs	Climate change adaptation measures
DCE	Discrete choice experiment
EFFIS	European Forest Fire Information System
ELC	European Landscape Convention
FPR	Prioritizing protection and recreation (practitioner group)
FPS LUCAS	CORDEX Flagship Pilot Study
FWP	Prioritizing wood production (practitioner group)
GRACE	Gravity Recovery and Climate Experiment
GW	Groundwater
IPCC	Intergovernmental Panel on Climate Change
NFI	Swiss National Forest Inventory
NAO	North Atlantic Oscillation
PES	Payments for ecosystem services
RCM	Regional climate model
SPEI	Standardized Precipitation Evapotranspiration Index
TCL	Tree cover loss
WII	Wood infected by insects

List of original articles with author contributions

Paper 1:

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1 Introduction

1.1 Motivation

Forests across Europe are increasingly affected by climate change, and Germany is no exception, facing complex challenges for its forest ecosystems and management. Rising average temperatures, altered precipitation patterns, and a growing frequency of extreme weather events—such as heatwaves, droughts and storms—(Bevacqua et al., 2024; Cardell et al., 2020; IPCC, 2021) are already transforming forest landscapes and will continue to do so in the decades ahead. These climatic changes intensify tree stress, increase vulnerability to pests and diseases (Frank, 2021; Hlásny et al., 2021), increase tree mortality (Haberstroh et al., 2022), and threaten the long-term viability of many native species (Martinez del Castillo et al., 2022). Accordingly, disturbances from storms, bark beetle outbreaks, and drought-triggered mortality are expected to become more frequent and severe (Hlásny et al., 2021), with dramatic ecological, economic, and social consequences for forest-dependent regions (Rosenkranz et al., 2023). Recent forest disturbances have highlighted these issues. In Germany alone, approximately 500 000 hectares of forest have been severely degraded since 2018, requiring reforestation (BMEL, 2025). These damages illustrate what will happen to forests mal-adapted to climate change, urging for a quick forest conversion of vulnerable forests. However, the precise strategies for reforestation, conversation of vulnerable forest stands and forest adaptation in general remain a matter of debate.

Against this backdrop, forest management is increasingly oriented toward maintaining a broad suite of ecosystem services—including timber production, carbon sequestration, habitat provision, and recreation—while simultaneously preparing forests for the diverse challenges posed by climate change (WBW, 2021). Adaptation requires not only technical interventions, such as the introduction of drought-tolerant species, adjustments of silvicultural systems, or the restoration of degraded sites, but also a broader understanding of which ecosystem services forests currently provide and can continue to provide in the future (WBW, 2021). It further requires a reconsideration of how these services are valued and prioritized, as well as mechanisms to appropriately compensate forest owners and managers for providing these services (Maier et al., 2021; WBW, 2021). In Germany, multifunctional forestry has long been embedded in national legislation and planning frameworks (FFA, 1975), reflecting a commitment to balancing ecological, economic, and social priorities. Consequently, forest practitioners and policymakers must navigate multiple, sometimes conflicting goals, including ecological resilience, timber supply, biodiversity conservation, and public acceptance (BMEL, 2021).

However, the provision of timber often remains central in adaptation planning, and much of the scientific literature continues to emphasize the biophysical and economic outcomes of forest adaptation (e.g. Fuchs, 2024; Kölling et al., 2010; Labarre et al., 2025; Rosenkranz et al., 2023). Alongside timber production, biodiversity conservation receives considerable attention (e.g. Augustynczik et al., 2020; Felton et al., 2016), whereas the impacts of climate change

adaptation on most other ecosystem functions remain comparatively underexplored (Lindner et al., 2010). In particular, the aesthetic quality of forests—especially as it evolves over time—has received relatively little attention in the adaptation discourse, despite its strong link to human well-being. Understanding how forest aesthetics respond to various adaptation measures is crucial for designing adaptation strategies that lead to landscapes that are not only resilient but also valued by the public, particularly in (sub-)urban areas where recreation is a key forest function (Lupp et al., 2016).

1.2 Aim and research questions

Adapting forests to climate change requires a comprehensive approach that integrates ecological resilience and the multiple ecosystem services provided by forests. This thesis contributes to this effort by investigating how forests are impacted by climate change, how foresters perceive these impacts and the resulting threats, what adaptation measures are used, and how climate-adaptive forest management and reforestation affect the aesthetic perception of forest visitors. The overarching aim is not to question the necessity of adaptation but to broaden the scope of decision-making by incorporating forest aesthetics, thereby supporting forest policies that are socially acceptable.

In detail, the following research questions are analyzed:

1. How do consecutive drought events impact European forests?
2. How do forest practitioners perceive the impacts of climate change and climate extremes on forest ecosystems and their work?
3. What are the most important climate change adaptation measures in forestry?
4. Which structural attributes of forests most strongly influence aesthetic perception, and what is the nature and strength of these relationships?
5. How do the most common climate adaptation measures influence the visual aesthetics of forests, and what can be done to counter negative impacts?
6. Concerning the treatment of damaged forests, which components of reforestation measures are appreciated by people, and to what extent?
7. What are the preferences for the aesthetic outcomes of reforestation measures at different points in time, and how do these temporal differences affect the choice of an optimal reforestation strategy?

1.3 Structure

To answer these research questions, the remainder of this thesis is structured as follows. Chapter 2 presents a succinct review of the empirical background and the current state of knowledge on the central topics of this thesis, thereby establishing the rationale for the research questions pursued. Chapter 3 outlines the methods employed in this thesis and links them to the research questions. Chapters 4 to 7 present the original articles. Chapter 4, addresses Research Question 1 by reviewing the impacts of the 2018-2022 drought period on European forests. Chapter 5 tackles Research Questions 2 and 3 by examining how forest practitioners perceive climate change impacts and how they adapt their forests to decrease climate change vulnerability. Chapter 6 complements the empirical findings of Chapter 5 with a literature-based perspective on Research Question 3. Furthermore, it provides an initial analysis of the effects of climate change adaptation on the visual aesthetics of forests by integrating insights from the literature and expert knowledge, thereby addressing Research Questions 4 and 5—identifying which structural forest attributes most strongly shape aesthetic perceptions and how common adaptation measures influence them. Chapter 7 extends this analysis to the specific context of reforestation following climate change–induced forest dieback. Using a large sample of potential forest visitors, this chapter addresses Research Questions 6 and 7 by evaluating how different aspects of reforestation influence the visual aesthetics of forests and how forest development over time affects the perceived attractiveness of reforestation measures. Chapter 8 first synthesizes the key findings of each paper to address the research questions individually, and then discusses the cross-paper implications for methodology, theory, and practice. Chapter 9 provides a brief conclusion and outlook.

2 Background and research gaps

This chapter provides a concise synthesis of the current state of knowledge on the key themes addressed in this thesis. Building on this overview, it identifies existing research gaps, that provide the rationale for the research questions pursued in this work. Moreover, by presenting the fundamental background relevant to central issues examined in this thesis, the chapter establishes the theoretical foundation necessary for understanding the analyses and arguments developed in the subsequent chapters.

The chapter begins by contextualizing the current state of European forests and the ecosystem services they provide. This is followed by a summary of the current state of climate change and the resulting impacts on forests. Subsequently, core conceptual considerations regarding adaptation to climate change in the forestry sector are presented. The chapter concludes with an introduction to the fundamental theories and concepts of landscape perception.

2.1 European forests and ecosystem services

2.1.1 Forest in Europe

European forests (in the sense of the Ministerial Conference on the Protection of Forests in Europe, 2020; excluding Russia) span over 227 million ha, which is 35% of the total continent's land area (Forest Europe et al., 2020). About 46% of these forests are predominantly coniferous, 37% are broadleaved and 17% are mixed (Forest Europe et al., 2020). The forest lands represent a complex mosaic of ecosystems shaped by biogeography, historical land use, and contemporary management regimes. Simplified, they are typically categorized into three major biogeographic zones: boreal, temperate, and Mediterranean (Jeanrenaud, 2001). Each zone exhibits distinct ecological characteristics and ecosystem service provision profiles. Growing timber stocks—which are fundamental for providing wood but also for CO_2 sequestration—are usually intermediate in boreal forests (~129 m^3/ha), highest in temperate forests (~250 m^3/ha) and lowest in Mediterranean forests (around 100 m^3/ha) (Forest Europe et al., 2020).

European boreal forests are located in northern regions such as Finland, Sweden, and the Baltic States, are largely composed of coniferous species such as Scots pine (*Pinus sylvestris*) and Norway spruce (*Picea abies*) and are intensively managed for wood production, often using clear-cutting (Gauthier et al., 2015; Yrjölä, 2002). These ecosystems are characterized by their relatively low species diversity but play a critical role in global carbon sequestration (Gauthier et al., 2015). In contrast, temperate forests, which are prevalent in central European countries including Germany, France, the UK, and Poland, today feature both broadleaf and coniferous species and mixtures thereof. Typical species are beech (Fagus sylvatica), oak (Quercus spp.), Scots pine (*Pinus sylvestris*) and Norway spruce (*Picea abies*) (Jeanrenaud, 2001; Spathelf & Ammer, 2015), although the latter two have mostly been planted outside their natural habitat (Jansen et al., 2017). These forests are increasingly managed with a multifunctional approach, integrating timber production with biodiversity conservation and recreational use. Mediterranean forests in southern Europe are adapted to arid climatic conditions with hot, dry summers and mild, wet winters and are typically composed of drought-resistant evergreen oaks

(e.g., *Quercus ilex*, *Q. suber*) and pines (e.g., *Pinus halepensis*, *P. pinaster*) alongside diverse shrubland characteristic of Mediterranean woodlands (Scarascia-Mugnozza et al., 2000). These forests often exhibit high biodiversity and provide key regulating services such as soil protection and watershed management, which are vitally important in erosion-prone landscapes (Nocentini et al., 2022). Although their biomass productivity is generally lower than that of temperate forests, timber production remains a central management objective (Nocentini et al., 2022).

2.1.2 Forest and ecosystem services

European forests provide a wide range of ecosystem services that are essential to human well-being. The multifunctionality of forests is increasingly recognized in forest management, as reflected by the widespread adoption of the ecosystem services framework as a central paradigm in forest management (Torralba et al., 2020). Ecosystem services are commonly categorized into provisioning, regulating, cultural, and supporting services (Figure 1). Provisioning services directly supply humans with raw materials, such as timber and wild food. These services are economically significant across Europe and have historically been the most widely acknowledged functions of forests (Lovrić et al., 2025). Timber and cellulose production play a key role for the forest-based sectors of countries such as Germany, Sweden, and Finland. In addition, non-wood forest products—including mushrooms, cork, and berries—contribute to local livelihoods and cultural practices.

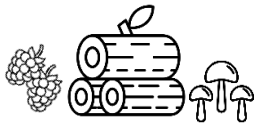
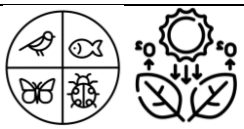
Provisioning services	**Regulating services**	**Cultural Services**	**Supporting services**
			
Timber, fiber, game, fruits, mushrooms…	Purification of air and water, carbon storage, erosion control…	Recreation, aesthetics, spirituality, education…	Habitats (Biodiversity), photosynthesis, nutrient cycling, soil formation…

***Figure 1**: Applying the Ecosystem Services Concept to Forests*
Based on Holzwarth et al. (2020)

Regulating services are those that moderate climatic and environmental extremes and help maintain living conditions that benefit humans. Among the most important regulating services provided by forests is carbon sequestration, which is particularly critical for global climate mitigation. Boreal and temperate forests, in particular, act as significant carbon sinks, storing large amounts of carbon in biomass and soils (Forest Europe et al., 2020; Gauthier et al., 2015; Seidl et al., 2017). In addition, forests play a central role in regulating water flows, purifying air and water, and stabilizing soils, thereby preventing erosion and rockfall. These functions are especially crucial in mountainous and Mediterranean regions, where landscapes are highly susceptible to drought, erosion, and extreme weather events (Seidl et al., 2019).

Cultural services provided by forests are increasingly recognized in forest policy and planning. Forest landscapes are highly valued for recreation and tourism, and they contribute to both mental and physical well-being. Practices such as forest bathing have gained popularity, and scientific studies demonstrate their positive effects on mental health (Siah et al., 2023). In

addition, forests possess cultural and historical significance, as exemplified by sacred groves, traditional land-use practices, and their role in shaping diverse forest landscapes (Agnoletti & Santoro, 2015; Ritter & Dauksta, 2013). Many cultural ecosystem services—particularly recreation and tourism—are strongly influenced by aesthetic qualities (Brown et al., 2019; Lee, 2020; Simkin et al., 2021), positioning forest aesthetics as a central component of cultural ecosystem services.

Supporting services provide the fundamental basis for all other ecosystem services, and their effects on humans are therefore more indirect, with changes typically manifesting over the long term (MEA, 2005). Among the most frequently discussed supporting services in forest ecosystems is biodiversity. Structurally diverse and mixed-species forests generally exhibit greater ecological resilience and higher conservation value compared to monocultural stands (Pardos et al., 2020), supporting the long-term provision of provisioning, regulating and cultural services.

2.1.3 Research gaps

Overall, forests cover a substantial portion of the European landscape and provide a wide range of essential ecosystem services. While provisioning and regulating services have been extensively studied and incorporated into management strategies, cultural ecosystem services—such as recreation, aesthetics, and heritage values—remain comparatively under-researched despite their recognized importance (Nesbitt et al., 2017; Torralba et al., 2020). This gap is particularly pronounced in the context of climate change adaptation measures (see Section 2.3), limiting our understanding of how such interventions affect human experiences and values associated with forests. Cultural services in post-disturbance forests are also poorly studied (see Section 2.2), even though they are expected to play an increasingly important role in shaping forest landscapes (Das et al., 2024).

2.2 Climate change and impacts on forests

This section first provides a concise overview of the current state of climate change, focusing on aspects most relevant to forests. It then highlights the associated impacts on forests and identifies the specific research gaps within this thematic area that are addressed in this thesis.

2.2.1 Current state of climate change

Global surface temperatures have risen sharply, with the year 2024 being the first with global temperature exceeding 1.5°C above pre-industrial levels and the five-year average exceeding 1.3°C (C3S & ECMWF, 2025). Europe is among the regions most affected, warming at roughly twice the global average. Mean annual temperatures across the continent have already exceeded 2°C above pre-industrial levels, and several recent years have set new regional records. 2024 marked the warmest year ever recorded in Europe, continuing a clear upward trend in both mean and extreme temperatures (C3S & WMO, 2025). Regional warming is particularly pronounced in parts of eastern and southern Europe (C3S & WMO, 2025), but also in Germany, where the yearly average temperature is already approaching 3°C above pre-industrial levels (see Figure 2). Alongside rising mean temperatures, heat extremes have intensified significantly in terms of frequency, intensity, and duration (IPCC, 2021).

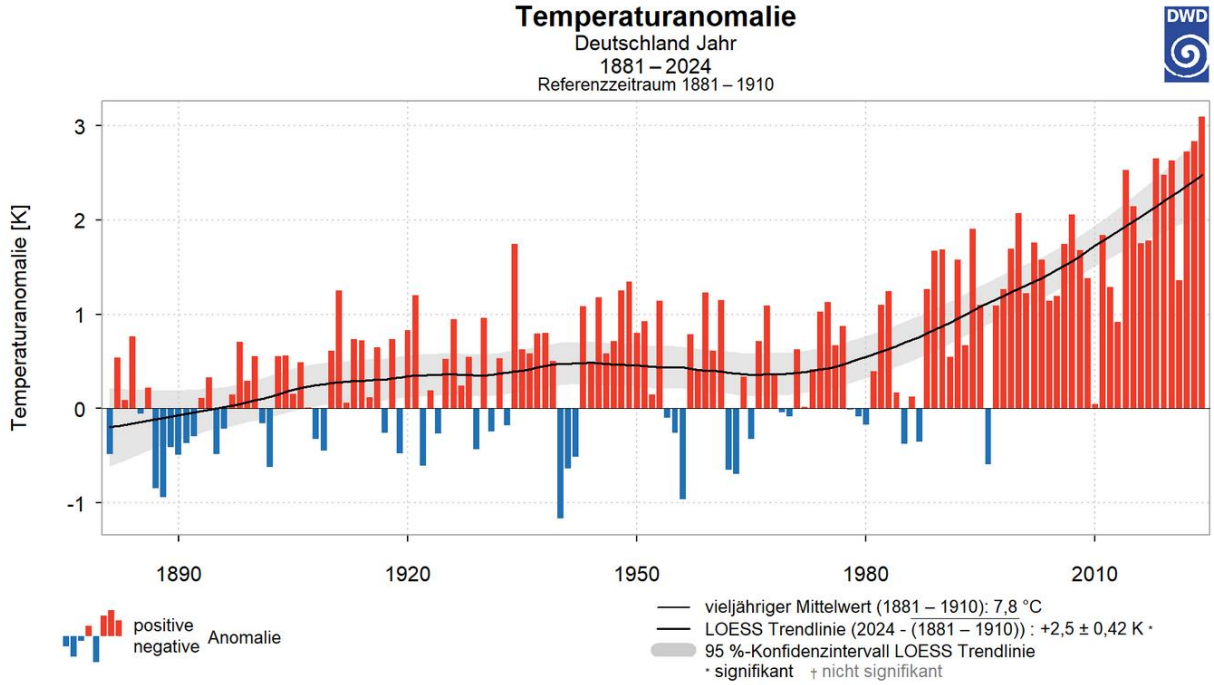


***Figure 2**:* Temperature anomaly in Germany 1881-2024.
DWD 2025

Precipitation trends across Europe are more complex and less uniform than temperature trends. In northern Europe, precipitation is projected to increase, and recent decades have already seen a rise in both the frequency and intensity of heavy-precipitation events. In contrast, southern and Mediterranean regions show clear signs of declining precipitation (IPCC, 2021). For practical impacts, seasonal distribution matters more than annual averages. Precipitation during the growing season (spring and summer) is particularly critical, yet in much of Europe precipitation will decrease over these seasons, especially in summer (see Figure 3). While

increasing winter precipitation can help replenish groundwater reserves, it cannot offset the lack of rainfall during the growing season, when vegetation requires it most. Periods with unusually low precipitation are referred to as *meteorological drought* (Berg & Sheffield, 2018).

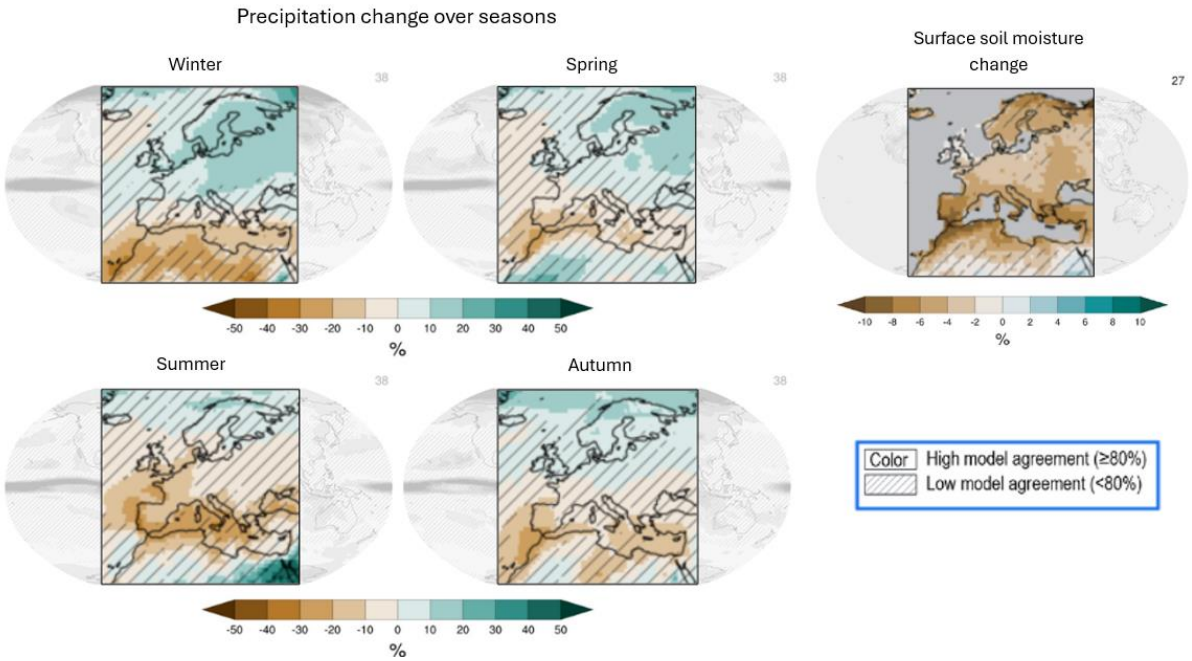


Figure 3: *Long-term precipitation and soil moisture changes for SSP2-4.5 (2081-2100 vs 1995-2014). Adapted from IPCC (2021)*

Precipitation is closely linked to soil moisture, which is ultimately the most relevant water-cycle component for plants. When soil moisture remains unusually low, the condition is termed *agricultural drought* or *ecological drought* (Berg & Sheffield, 2018). Soil moisture depends not only on precipitation and soil properties but also on evapotranspiration, which is projected to rise across most regions (IPCC, 2021). This higher evapotranspiration will further exacerbate declines in surface soil moisture (see Figure 3). Because soils can store water and perennial plants have some drought resistance, drought severity cannot be assessed on a single-year basis alone. The cumulative effects of preceding years must also be considered, giving rise to multi-year droughts. The 2018-2020 period represents a recent multi-year drought that set new benchmarks in terms of both intensity and ecological impacts. Projections indicate that, under ongoing climate change, events of comparable or even greater intensity are likely to occur more frequently and last longer than any droughts experienced by humankind in the past 250 years (Rakovec et al., 2022).

Climate change will also alter storm patterns across Europe, primarily through its influence on temperature gradients, leading to changes in large-scale atmospheric circulation, and through higher moisture availability. A warmer atmosphere can hold more water vapor, enhancing latent heat release and cyclone-associated precipitation while modifying the dynamics of midlatitude cyclones (Catto et al., 2019; Gliksman et al., 2023). Concurrently, rising sea surface temperatures in the North Atlantic are expected to modify the behavior of the North Atlantic Oscillation (NAO)—one of the dominant modes of climate variability in the region. Under global warming, the NAO appears to exhibit greater variability and more extreme positive and

negative phases, amplifying regional weather contrasts (Outten & Davy, 2024). Projections indicate an eastward extension of the North Atlantic storm track into continental Europe, increasing windstorm risk particularly in northwestern and north-central Europe, while southern and northeastern regions may experience reduced storm frequency (Harvey et al., 2020; Pinto et al., 2013; Priestley & Catto, 2022). Climate models further project that while the overall number of windstorms might diminish, the most intense windstorms could become more frequent, with currently rare (e.g., 100-year) events occurring several times per century under high-emission scenarios (Little et al., 2023; Severino et al., 2024). However, these projections are still characterized by considerable uncertainty. Model ensembles differ in their representation of storm track shifts, cyclone dynamics, and NAO responses, leading to variability in both the magnitude and even the sign of projected changes (Mölter et al. 2016). Compared with the relatively robust trends in temperature rise and precipitation patterns, changes in storm frequency and intensity are therefore much less certain. While an intensification of extreme storm events is plausible—driven by increased atmospheric moisture and energy—the precise regional manifestations of these changes across Europe remain difficult to predict with confidence (Catto et al., 2019; Little et al., 2023).

2.2.2 Impacts on forests

Drought

Drought constitutes one of the most acute threats to European forests in the context of climate change, particularly when coinciding with heat waves (Gazol & Camarero, 2022; Senf & Seidle, 2021). Ecological drought—characterized by reduced soil moisture availability—increases the tension of the water column within the water transport cells in the xylem if stomatal conductance is maintained under severe water deficit. This elevated tension heightens the risk of hydraulic failure through the formation of embolisms that disrupt water transport (Choat et al., 2018; Hartmann et al., 2022; Jones & Sutherland, 1991). Conversely, when trees keep their stomata closed for extended periods to reduce water loss and prevent hydraulic failure, photosynthesis is suppressed, which can lead to carbon starvation if carbohydrate reserves are no longer sufficient to maintain vital metabolic functions (Hartmann et al., 2022; McDowell et al., 2008). Although the precise mechanisms underlying drought-induced tree mortality and the relative contributions of hydraulic failure versus carbon starvation remain debated, recent evidence indicates that hydraulic failure is the predominant driver (Adams et al., 2017; Anderegg et al., 2012; McDowell et al., 2008; Sevanto et al., 2014).

Despite these mechanistic uncertainties, the combined physiological consequences of drought are well established. Documented responses include reduced radial growth, premature leaf senescence and browning, progressive crown dieback, and, under prolonged or extreme conditions, tree mortality (Choat et al., 2018; Rukh et al., 2023). Importantly, severe drought may also induce persistent "drought legacy effects," reflecting incomplete recovery of hydraulic function. The extent to which hydraulic function can be restored after drought—either through the refilling of embolized conduits or the formation of new xylem—remains uncertain (Choat et al., 2018; Rukh et al., 2023). Empirical evidence indicates that such impairment often persists over multiple years, leading to reduced foliation, progressive structural damage, and an elevated risk of mortality (Rukh et al., 2023). Furthermore, drought-induced reductions in photosynthetic activity and the associated depletion of carbohydrate reserves limit trees' defensive capacities

against pathogens and herbivores, thereby reducing tree vigor and increasing susceptibility to secondary disturbances such as pest and pathogen outbreaks (Choat et al., 2018; Hartmann et al., 2022; Rukh et al., 2023). These secondary disturbances are often a decisive factor for tree mortality under drought (Anderegg et al., 2012).

Tree species with shallow root systems, such as Norway spruce (Picea abies) or European beech (Fagus sylvatica), are particularly vulnerable to drought, whereas deep-rooted species like sessile oak (Quercus petraea) or European ash (Fraxinus excelsior) show comparatively greater resilience (Kahmen et al., 2022).

Changing Temperatures

Rising temperatures affect European forests through multiple pathways. Elevated mean temperatures can extend the growing season and potentially enhance growth in northern latitudes, where productivity was previously limited by thermal constraints (Ruiz-Pérez & Vico 2020; Yu et al., 2024). In contrast, forests in southern and lowland regions are increasingly exposed to heat stress, which can suppress growth and increase mortality risk. Although direct heat-induced mortality is relatively rare compared to drought-related mortality, the co-occurrence of heat and drought significantly amplifies stress effects and mortality risk (Allen et al., 2010; Hartmann et al., 2022; Teskey et al., 2015).

Heat impacts trees on several levels. Physiologically, elevated temperatures reduce photosynthetic efficiency, as the optimal temperature range for photosynthesis in most tree species lies between 20°C and 30°C (Bernacchi et al., 2023; Teskey et al., 2015). Beyond this range, photosynthetic activity and overall vigor decline (Song et al., 2014). Direct thermal injury to foliage occurs at approximately 44°C, often leading to leaf loss; surviving or regenerated leaves typically exhibit reduced photosynthetic capacity (Teskey et al., 2015).

Heat stress and increased irradiation can also physically damage woody tissues. Trees with smooth bark surfaces, such as beech, are particularly susceptible to sunburn, especially when the protective canopy is suddenly opened due to windthrow, drought-induced dieback, or management interventions. Sunburn can damage the cambium—the layer responsible for xylem formation—thereby potentially exacerbating drought stress (Sheppard et al., 2016). Moreover, damaged bark can facilitate pathogen invasion, including fungal infections (Sheppard et al., 2016).

Phenological shifts associated with warming, such as earlier leaf-out, can further heighten frost damage risk, as tender young leaves may coincide with late frost events, despite the overall decline in frost days (Chamberlain et al., 2021; Ma et al., 2016).

In addition to these direct effects, higher temperatures may facilitate the establishment of new pests or increase the virulence of existing ones (Gullino et al., 2022). For example, the European spruce bark beetle (Ips typographus) can produce additional generations within a single year under elevated temperatures, resulting in exponential population growth and substantial damage during outbreak years (Potterf et al., 2025).

For these reasons, changes in temperature regimes finally affect the climatic suitability of tree species. Cold-adapted species, such as Norway spruce and silver fir (Abies alba), will face

contraction in their range (Bledý et al., 2024; Kolář et al., 2017), whereas thermophilic species, including some oaks and pines, may expand northwards (Kullman et al., 2008). Modeling studies indicate that approximately one-third of European tree species may face climatic conditions outside their optimal range by the end of the 21st century, potentially reducing the species pool available for forestry and threatening biodiversity (Wessely et al., 2024). These changes pose significant challenges for forest management, particularly regarding the selection of species for reforestation, adaptation strategies, and maintaining ecosystem resilience (Wessely et al., 2024).

Storms

Storms are among the most important large-scale natural disturbances in European forests, with profound ecological and economic impacts. They can broadly be distinguished into winter storms, typically associated with strong extratropical cyclones, and summer convective storms, which are often localized but can include violent downbursts or tornado-like winds (Gliksman et al., 2023; Pettit et al., 2021). Winter storms are generally more intense and spatially extensive, capable of affecting millions of hectares of forest within a few hours. Historic examples such as storms Lothar (1999), Kyrill (2007), and Vaia (2018) caused unprecedented windthrow and timber losses across Central and Northern Europe. Summer storms, though more localized, can also inflict severe damage, particularly through intense gusts in combination with heavy precipitation leading to soil saturation and uprooting.

Both storm types primarily damage forests through windthrow via stem damage or uprooting (Gardiner, 2021), which results in canopy loss, mechanical injury, and tree mortality. The likelihood and severity of storm damage depend on multiple biotic and abiotic factors, including stand height, tree species, rooting depth, soil moisture, and topography (Zeppenfeld et al., 2023). Particularly high trees (Díaz-Yáñez et al., 2019) and tree species with shallow root systems, such as Norway spruce (Picea abies) or Scots pine (Pinus sylvestris), are vulnerable (Krisans et al., 2020), especially in wet or poorly drained soils that reduce root anchorage (Štofko & Kodrik, 2008). An important topic with limited empirical evidence is the extent to which forest diversity enhances resilience to storm events. Most studies suggest that greater tree species diversity increases forest resistance to damage and promotes faster recovery following storms (Barrere et al., 2024; Dobor et al., 2020), although some studies report no significant effect (Díaz-Yáñez et al., 2019). With respect to vertical or structural diversity, modeling studies consistently indicate that multi-layered stands exhibit greater resilience to storm damage (Díaz-Yáñez et al., 2019; Hanewinkel et al., 2014; Potterf et al., 2022).

The consequences of storm damage extend far beyond the immediate physical destruction of trees. Ecologically, windthrow creates canopy gaps that drastically alter local microclimates—raising light levels, temperature fluctuations, and soil properties (Camarero et al., 2021; Tong et al., 2024). These changes, together with decaying deadwood on sites without salvage logging, promote the establishment of pioneer and shade-intolerant species, increasing structural heterogeneity and fostering regeneration and biodiversity (Duelli et al., 2002; Piazza et al., 2024). However, extensive storm damage can also destabilize ecosystems, exposing remaining trees to secondary stressors such as bark beetle infestations. By creating large quantities of wind-thrown wood, storms create ideal situations for bark beetles like Ips typographus. Beetle

populations typically surge following major windthrow events, leading to further tree mortality (Kärvemo et al., 2014).

2.2.3 Research gaps

Despite growing understanding of climate change impacts on European forests, significant research gaps remain, which this thesis seeks to address. Previous studies indicate that rising temperatures, altered precipitation patterns, and more frequent droughts and storms are placing considerable stress on forest ecosystems (see previous section). However, comprehensive data on the impacts and damage of recent multi year drought events are fragmented across scientific studies, government reports, and media sources. Moreover, regional differences in vulnerability and damage are poorly quantified, as consistent and comparable information is lacking for many countries. Chapter 4 *(Impacts on and damage to European forests from the 2018–2022 heat and drought events)* responds to these gaps by compiling and harmonizing diverse datasets to provide an integrated overview of forest damage across Europe after recent multi-year droughts, helping to improve understanding of the spatial extent, severity, and drivers of recent climate-induced forest impacts. At the same time, although much is known about the biophysical impacts of climate extremes, empirical research on how forest practitioners themselves perceive these impacts remains limited. Chapter 5 *(A case study on forest practitioners' perspectives on climate extremes: consensus on impacts and conflicts in responses)* seeks to help fill this gap by exploring practitioner viewpoints and analyzing consensus and conflict.

2.3 Adaptation of forests to climate change

This section outlines key conceptual foundations of climate change adaptation and examines its social dimension, highlighting existing research gaps in this area.

2.3.1 Conceptual foundations of adaptation

As outlined in Section 2.2, forests are already exposed to multiple climate-related stressors. Adaptation broadly refers to the processes through which forest ecosystems and the institutions that manage them reduce climate-induced vulnerability. In this context, adaptation should not be conflated with climate change mitigation—even though mitigation is also an important, related topic—which involves managing or modifying forests to enhance carbon sequestration and thereby limit climate change.

While numerous authors have proposed ways to categorize adaptation, there is no universally accepted or consistently applied framework for classifying adaptation types. However, most of the categorizations of adaptation build on the general understanding and categorization of climate change adaptation proposed by the IPCC. According to this understanding, adaptation is defined as adjustments in natural or human systems in response to actual or expected climate stimuli, aimed at moderating harm, exploiting opportunities, or maintaining system functioning (IPCC, 2014). Drawing on this general understanding, many different types of adaptation in forestry have been identified depending on and tailored to the specific focus of the studies, making it useful to categorize adaptation along several conceptual dimensions.

A key distinction can be made between autonomous (or spontaneous) adaptation and planned adaptation (IPCC, 2024), even if definitions are not always clear-cut and mixtures between the two types of adaptation are possible (Maskell et al., 2025). Autonomous adaptation refers to ecological adjustments that occur without deliberate human intervention or everyday adaptation that is not made consciously as adaptation to climate change (Maskell et al., 2025). In forests, these include natural shifts in species composition, altered regeneration patterns, or physiological responses to environmental stressors. Such responses emerge from the ecosystem's inherent adaptive capacity and are largely self-organized. Other sources refer to this type of adaptation in the forestry context as passive adaptation (Bolte et al., 2009; Jandl et al., 2019). Planned adaptation (or active adaptation), in contrast, involves deliberate, intentional actions by forest managers or institutions to reduce vulnerability or enhance resilience (Bolte et al., 2009; Maskell et al., 2025). Examples include revising thinning regimes, diversifying species composition, adjusting rotation lengths, or implementing novel protection measures. Some authors further distinguish reactive adaptation from planned adaptation—the first purely responding to disturbances or other impacts after they occur, whereas the second is anticipatory, based on projections of future climate conditions (Bernier & Schoene, 2009; Keenan, 2015).

Another lens for understanding adaptation focuses on the magnitude and scope of change, typically characterized as incremental versus transformational adaptation (IPCC, 2014). Incremental adaptation involves relatively modest adjustments aimed at maintaining existing (forest) structure, function, and management objectives (Kates et al., 2012). Examples of incremental adaptations include minor modifications to promote existing well-adapted species or assisted migration of tree species (Stanturf, 2015). Transformational adaptation, by contrast,

brings something really new, completely restructures systems on large scales to change pathways of the system, and is often described as superior to incremental adaptation (Fedele et al., 2019; Kates et al., 2012). Applied to the forest sector, such an adaptation entails fundamental changes to forest composition, structure, landscape configuration, or governance arrangements. This may include the use of new non-native species (Stanturf, 2015) or redesigning management objectives to accommodate new disturbance regimes. Incremental measures might be sufficient to cope with moderate climate impacts, while transformational strategies become critical when conventional practices are inadequate for severe or unprecedented stresses (Kates et al., 2012).

Finally, adaptation in forestry is often implemented under considerable uncertainty, arising from unpredictable future climate conditions, disturbance regimes, and ecological responses (Jandl et al., 2019; Radke et al., 2017). Proactive adaptation strategies are particularly challenging in forestry because trees have long life spans and production cycles. From establishment to harvest, trees remain in place for many decades or even centuries, during which they must remain adapted to the climatic conditions that may differ substantially from those prevailing at the time of planting, creating considerable uncertainty regarding future climate, disturbance regimes, and ecosystem responses (Spittlehouse & Stewart, 2024). To address uncertainties no-regret measures such as diversifying species to spread risk are important because they provide benefits regardless of how the climate evolves (Gauthier et al., 2014) but alone they will not be sufficient with regard to the challenges.

Taken together, these conceptual foundations highlight that forest adaptation is a complex process, involving natural ecosystem responses, deliberate management actions, incremental and transformational changes under uncertainty.

2.3.2 The social dimensions of adaptation

Because forests function as coupled social-ecological systems (Bolte et al., 2023; Ekström et al., 2024; Lloret et al., 2024), adaptation encompasses both ecological responses (e.g., species migration, physiological adjustments, epigenetic mechanisms) (García-García et al., 2022) and human interventions that aim to enhance forest adaptive capacity and reduce negative impacts on ecosystem services they provide (e.g., modified silvicultural practices, revised planning frameworks, institutional change) (Keenan et al., 2015; Messier et al., 2019).

While much research on forest adaptation has traditionally focused on ecological, silvicultural, or modeling approaches, a growing body of literature emphasizes that adaptation is also fundamentally a social process (Findlater et al., 2022; Keenan, 2015). Decisions about forest management are not purely scientific decisions; they are shaped by the values, norms, economic constraints, and professional cultures of the practitioners implementing them (Findlater et al., 2022). Consequently, the capacity of forestry institutions to adapt depends on how managers perceive and interpret climate risks, evaluate available options, negotiate trade-offs, and reconcile competing objectives.

Several social dimensions influence adaptation in forestry. Perceptions of climate-related risks vary among forest managers, influencing whether and which types of adaptation measures are implemented (Villamor et al., 2023). In particular, the experience of damaging events tends to

heighten risk perception and stimulate adaptive action (Sousa-Silva et al., 2018). Norms and values also play a central role, as adaptation frequently involves prioritizing among multiple ecosystem services, such as timber production, biodiversity conservation, and recreational use (Paletto et al., 2014). Practitioners' values and priorities influence how these trade-offs are navigated. In addition, the institutional context—including regulations, financial incentives, and ownership structures—can either enable or constrain adaptive responses (Andersson et al., 2017).

Despite its critical role, the social dimension of adaptation remains relatively underdeveloped in the climate-forestry literature (Keenan, 2015). Much research implicitly assumes that if adaptation strategies are available, they will be implemented uniformly across management contexts. In reality, however, adaptation outcomes are shaped by subjective interpretations, professional judgment, and the practical limitations of resources and institutional capacity (Keenan, 2015). Recognizing the social processes that underlie adaptation is therefore essential for understanding how and why forest managers adopt—or fail to adopt—different strategies in response to climate change.

2.3.3 Research gaps

Given the complexities of social-ecological adaptation explained above, a critical gap exists in understanding how practitioners—those directly responsible for managing forests—perceive, prioritize, and respond to climate-induced stresses. While numerous studies document projected ecological impacts or evaluate the technical feasibility of adaptation options, relatively few investigate the social dimensions of the decision-making processes. This creates a disconnect between theoretical adaptation frameworks and real-world implementation.

A central reason for this gap is that climate risks are often examined as biophysical phenomena rather than socially mediated ones. Forest managers may interpret drought impacts, storm damage, or pest threats differently, and these perceptions influence which measures are considered urgent or appropriate. Moreover, adaptation in practice requires navigating trade-offs among ecosystem services—such as timber production, biodiversity conservation, and cultural values—yet research rarely examines how such conflicts are perceived and reconciled in day-to-day management.

These limitations demonstrate that adaptation is not only a matter of developing effective adaptation strategies but also of understanding how practitioners interpret risks, define priorities, and act within institutional constraints. However, empirical evidence on these social dimensions remains scarce.

Chapter 5 (*A case study on forest practitioners' perspectives on climate extremes: consensus on impacts and conflicts in responses*) addresses this gap by examining how forest practitioners perceive climate extremes and how these perceptions translate into management decisions, highlighting areas of consensus and conflict.

2.4 Perception of (forest) landscapes

Landscape perception refers to the processes through which human senses, interpret, and evaluate landscapes, integrating sensory inputs with cognitive and affective responses. Closely related to landscape perception are landscape preferences. Landscape preferences reflect individual or collective judgments about which landscapes are more liked or valued, often based on perceptual cues and aesthetic judgments. These concepts are closely linked because perception forms the basis for preferences. For example, the perception of a forest's openness, species diversity, or structural complexity may guide personal or societal preferences for certain forest types.

This section provides the theoretical background for these concepts. It begins by defining landscape and landscape perception as understood in this work, before reviewing theories on the emergence of landscape preferences and outlining the frameworks used to assess these preferences, thereby situating the thesis within existing theoretical and methodological approaches. The section concludes by highlighting the research gaps in the study of forest perception that are addressed in this thesis.

2.4.1 Landscape perception

How people perceive forests greatly influences the value of ecosystem services that forests can provide. This is especially true for cultural ecosystem services such as aesthetics, recreation, or spiritual services, which are greatly influenced by how people perceive natural environments (Simkin et al., 2021). The extent to which individuals find forests pleasing or unappealing plays a critical role in determining the value of these forests and the services they deliver. Understanding the perception of forest landscapes is therefore essential for assessing the cultural value of forests.

A significant development in the conceptualization of landscape perception came with the adoption of the European Landscape Convention (ELC) by the Council of Europe in 2000. The ELC marked a turning point in landscape research and policy, expanding the scope of landscapes beyond exceptional or scenic areas to include everyday, ordinary, and even degraded environments. It also contributed to the institutionalization of landscape considerations within spatial planning and public policy (Déjeant-Pons, 2006). The ELC defines landscape as "an area, as perceived by people, whose character is the result of the action and interaction of natural and/or human factors" (Council of Europe, 2000a, p. 2). The explanatory report of the ELC further specifies that landscape refers to "a zone or area as perceived by local people or visitors, whose visual features and character are the result of […]" (Council of Europe, 2000b, p. 6). These definitions emphasize the centrality of human perception—particularly visual perception—in shaping landscape meaning and value.

As Daniel (2001) points out, the concept of landscape and landscape perception has been subject to varying interpretations. Some researchers adopt a broad understanding where landscapes encompass not only visible features but also ecological processes and biological functioning, and in which perception includes multisensory experiences such as sound, smell, and touch (Hegetschweiler et al., 2023; Zheng et al., 2024). Others apply a more restricted

definition that focuses solely on the visual characteristics of a territory. In much of the landscape research tradition, for example, the landscape is operationalized as the "visual landscape" and evaluated primarily through visual perception and visual quality indicators (Misthos et al., 2023). Positioned within this tradition, this thesis adopts a visual landscape perspective, emphasizing visual perception as the primary dimension of landscape experience. While broader definitions may more fully reflect the complexity of human-environment interactions, they also pose methodological challenges that make systematic analysis difficult. A visually based approach offers a clearer and more manageable framework for assessment and aligns closely with the conceptualization of landscape advanced by the European Landscape Convention.

2.4.2 Origins of landscape aesthetics and preferences

For classical philosophers like Socrates and Plato, beauty was understood as an inherent property of objects and therefore as an objective value. In contrast, modern philosophers, including Hume and Kant, argued that beauty depends on individual judgment and personal values, making it fundamentally subjective (Mundher, Abu Bakar, Maulan et al., 2022). This philosophical debate has informed two major historical currents in landscape aesthetics (Lothian, 1999). On one side stands the objectivist (or physical) paradigm, which holds that landscape aesthetics are rooted in the intrinsic qualities of the physical environment (Mundher, Abu Bakar, Maulan et al., 2022). On the other side is the subjectivist (or psychological) paradigm, which posits that aesthetic experience arises in the mind of the observer and is therefore profoundly subjective (Karjalainen, 2006; Mundher, Abu Bakar, Maulan et al., 2022).

Today, the subjectivist perspective largely prevails, although the question of how subjective aesthetic preferences are formed remains contested. One influential line of thought—somewhat closer to the objectivist tradition—suggests that there are universal factors determining landscape preferences that can be traced back to our genetic backpack because they have evolutionary origins and reflect prehistoric human needs such as access to shelter, food, and water (Karjalainen, 2006). The most important theories of this current are the Prospect–Refuge Theory of Appleton (1975), stipulating that humans prefer environments offering a balance of clear views (prospect) and protected spaces (refuge); Ulrich's Psycho-Evolutionary Theory (1983), proposing that natural settings promote rapid stress recovery through innate affective responses; the Habitat Selection Theory of Orians and Heerwagen (1992), suggesting that humans favor landscapes resembling ancestral savannah habitats that supported survival; and Kaplan and Kaplan's very influential Knowledge Acquisition Theory (1989), positing that people prefer environments that support efficient information processing through coherence, legibility, complexity, and mystery.

Other perspectives emphasize that landscape preferences are shaped through socialization and therefore depend on cultural norms, prior experiences, and learned expectations. For instance, individuals may be drawn to rare or distinctive vistas, as suggested by the push–pull theory (Dann, 1981), or they may value landscapes that display clear "cues to care" (Nassauer, 1997) reflecting culturally embedded associations between human stewardship and aesthetic quality (Mundher, Abu Bakar, Al-Helli et al., 2022).

This thesis does not rely exclusively on any single one of these landscape preference theories, nor does it assume that any one theory is universally valid to the exclusion of others. Empirical research shows that numerous attributes derived from these theories can predict landscape preferences under certain conditions (e.g., coherence, mystery, openness, prospect/refuge; Dosen & Ostwald, 2016; Franěk, 2023), while other predictions, particularly those tied to universal evolutionary hypotheses such as the savanna preference, receive only weak support (Moura et al., 2018). Accordingly, this thesis assumes that several attributes or factors proposed in these theories are relevant predictors of landscape preference, while additional factors—including non-universal, individually specific influences—also contribute to shaping landscape preferences. In line with this view, landscape quality depends on both the objective physical properties of the environment and the perceiver's cognitive, conceptual, and emotional understanding of the landscape. For example, most people like lakes and big trees (objective, physical; Schirpke et al., 2016; Suchocka et al., 2022), but many people also prefer familiar landscapes (subjective, psychological; Mangone et al., 2021; Svobodova et al., 2011). In addition, the perception of forests and what features are valued depends on the activities that people do in the forests (Eriksson et al., 2012). It is therefore important to include different profiles when valuing forest aesthetics through questionnaires (Paudyal et al., 2018).

2.4.3 Predicting landscape preferences

Landscape assessment studies build on a range of theoretical approaches that reflect different understandings of how humans perceive and evaluate their surroundings. Building on the influential frameworks of Zube et al. (1982) and Daniel & Vining (1983), Karjalainen (2006) refined these into four major paradigms: expert, psychophysical, cognitive, and phenomenological. The expert paradigm corresponds broadly to the objective tradition, whereas the latter three represent distinct forms of the subjective paradigm. These paradigms remain influential as a conceptual foundation, although landscape-perception research has diversified considerably in recent years.

The expert approach assumes landscape quality can be judged based on inherent physical or design principles by trained professionals. It aligns with the objectivist paradigm, seeing beauty as intrinsic to landscape form. However, expert-based evaluations have been criticized for limited consistency and insufficient integration of public perception (Daniel, 2001). With the implementation of the European Landscape Convention, which mandates the inclusion of lay perspectives, the dominance of purely expert-driven assessments has further declined (Chang Cien et al., 2021).

The psychophysical approach treats landscape preferences as measurable responses to physical (usually visible) attributes (e.g., tree density, amount of deadwood…), typically using statistical relationships between these attributes and observer ratings (Daniel & Vining, 1983). This approach remains widely used because it decomposes complex landscapes into clear, measurable attributes and generates statistically robust, interpretable estimates of aesthetic preferences (Mundher, Abu Bakar, Maulan et al., 2022), often with high reliability (Ribe, 2022). Nevertheless, newer research highlights that purely visual models may overlook multisensory, affective, and contextual influences on landscape experience. An increasing body of research shows that visitors' overall attractiveness ratings are shaped not only by visual cues but also by

auditory and olfactory impressions (Edler & Kühne, 2025; Hegetschweiler et al., 2023; Zheng et al., 2024), while personal characteristics and mood further influence perceived quality and satisfaction in natural recreation settings (Chen et al., 2021). These findings suggest that psychophysical models benefit from being embedded within broader, person-centered, and context-sensitive frameworks.

The cognitive approach focuses on how individuals structure and interpret landscape information, linking preferences to constructs such as coherence, mystery, and complexity (Kaplan & Kaplan, 1989; Ruddell et al., 1989). It reveals why people prefer certain landscapes but is less concrete for planning purposes. The phenomenological approach, in contrast, emphasizes lived experience, meaning, and place attachment to explore the subjective significance of landscapes (Herzog, 1985; Ohta, 2001). It often uses qualitative methods that reveal rich but less generalizable insights.

This thesis is primarily grounded in the psychophysical perspective. Although the term *psychophysical approach* appears less frequently in recent literature, the underlying principle—linking measurable visual characteristics to aesthetic judgments—remains central to contemporary visual-preference and scenic-quality research (e.g. Ebenberger & Arnberger, 2019; Giergiczny et al., 2015). The approach underlying this thesis assumes that forest aesthetics arise from the evaluation of observable visual attributes by the public. Although primarily based on observable (objective) attributes, the reliance on public perceptions aligns with the subjective paradigm, recognizing that individual backgrounds influence how these visual attributes are perceived and valued. At the same time, these attributes provide a clear framework for analyzing preferences. The structural characteristics used to assess landscape preferences—or more specifically, forest aesthetics—are therefore central to this approach.

Regarding forests, there is an extensive but not always clear body of literature about the preferences for structural attributes. Stand age and size are often described as one of the most important features increasing forest aesthetics (Edwards et al., 2012; Filyushkina et al., 2017; Giergiczny et al., 2015; Gundersen & Frivold, 2008; Ribe, 1989). Also tree density and spacing play a central role: moderately open forests are often preferred because they allow visibility and create a sense of accessibility, while overly dense stands can feel dark or closed (Edwards et al., 2012; Giergiczny et al., 2015; Gundersen & Frivold, 2008). Vertical structure, thus the variation of tree size, contributes to visual complexity and can enhance visual quality (Arnberger et al., 2018; Ebenberger & Arnberger, 2019; Filyushkina et al., 2017; Giergiczny et al., 2015) if the understory is not too dense (Edwards et al., 2012; Giergiczny et al., 2015; Gundersen & Frivold, 2008). Tree species composition and diversity also shape preferences—mixed-species stands are typically seen as more aesthetically appealing (Ebenberger & Arnberger, 2019; Filyushkina et al., 2017; Giergiczny et al., 2015; Nielsen et al., 2007). Other important features include the presence of large, old trees (Ebenberger & Arnberger, 2019; Ribe, 1989) and the condition of the forest floor, including ground vegetation and absence of excessive debris. Finally, the impact of deadwood on forest aesthetics remains ambiguous. While several studies report that visitors generally dislike its presence (Arnberger et al., 2018; Nielsen et al., 2012), others find a positive effect of deadwood on perceived forest attractiveness (Hauru et al., 2014; Rathmann et al., 2020). Further research indicates that deadwood may be

appreciated when present in moderate or intermediate amounts (Edwards et al., 2012; Ebenberger & Arnberger, 2019; Giergiczny et al., 2015).

2.4.4 Research gaps

Despite substantial progress in understanding how people perceive and evaluate forest landscapes, several important research gaps remain—particularly regarding how people perceive forests undergoing climate-change-induced disturbance and recovery. Existing theories highlight that landscape preferences are shaped by both perceptual processes and structural forest attributes; however, much of the empirical evidence stems from relatively stable forest conditions. In contrast, Central European forests are increasingly characterized by rapid and profound change, including large-scale disturbance, shifts in species composition, and novel silvicultural responses. How these changing conditions affect aesthetic preferences has been insufficiently studied.

Chapter 6 (*Forest management in a changing climate: assessing the impacts of adaptation measures on the visual aesthetics of forests – the example of Germany)* and Chapter 7 (*Aesthetic preferences for forests after climate change-induced disturbance: A discrete choice experiment accounting for temporal evolution of reforestation measures)* address these gaps in two main ways.

First, they respond to the limited empirical understanding of aesthetic preferences for post-disturbance forests. While theories of perception and preference formation emphasize the importance of structural features such as openness, vertical layering, or species diversity, very few studies have examined these attributes in the context of climate change and post-disturbance management of forests. By evaluating preferences for concrete management and reforestation measures, the studies link visual attributes to concrete climate change adaptation strategies.

A second major gap concerns the temporal dimension of forest perception. Most preference studies rely on static representations of forests, thereby neglecting that landscapes are dynamic systems whose aesthetic qualities may change as implemented measures unfold. Chapter 7 (*Aesthetic preferences for forests after climate change-induced disturbance: A discrete choice experiment accounting for temporal evolution of reforestation measures)* responds to this lack of research on the temporal dimension of forest perception by incorporating different time horizons, offering rare insights into how preferences evolve after reforestation.

Together, the two studies contribute to filling key gaps in the literature by examining aesthetic perceptions under conditions of ecological transformation, by integrating temporal dynamics into preference assessment, and by evaluating how specific adaptation practices shape public landscape preferences.

3 Methods

3.1 Methodological approaches and their rationale

This dissertation is based on a range of methods, extending from literature reviews and qualitative analyses of expert interviews to quantitative approaches such as a discrete choice experiment. Across the four studies (Chapters 4–7), the methodological approaches complement one another and form a coherent progression—from the assessment of the physical basis through a literature review to increasingly refined social-science methods. While all studies contribute to understanding different dimensions of forest conditions and human responses, they differ in how data are generated and in the extent to which the methodological design seeks to avoid respondent bias.

A key distinction is that only Chapter 4 relies primarily on physical and quantitative data, drawing on large-scale forest inventory and remote-sensing information from the scientific literature and government reports. This provides a robust biophysical foundation and does not involve human respondents, meaning that issues of opinion-based bias do not arise.

The remaining studies focus on the social aspects of forest change and adaptation, using interview- or choice-based methods. At the simplest level, open-ended interviews, as used in Chapter 5, allow forest practitioners to describe their observations and experiences in their own words. In this context, the aim is not to measure precise preferences or trade-offs but to map the range of perceptions, concerns, and experiential knowledge within the practitioner community. Because the goal is exploratory and interpretive, respondent bias is less problematic; subjective viewpoints are part of the data rather than a distortion of it. These interviews provide depth, context, and nuance—elements that more structured approaches might overlook.

As the research questions shift toward more systematic comparison of views, the methods become more structured. Chapter 6 uses expert assessments with predefined answer options, reducing variability in interpretation while still capturing professional knowledge. Here, limiting bias becomes somewhat more important, since the goal is to evaluate the likely effects of specific management measures on forest attributes. The structured format ensures comparability across experts without fully constraining their judgment.

The highest methodological complexity appears in Chapter 7, which applies a discrete choice experiment. Unlike direct questioning of preferences for certain structural forest attributes, this method infers preferences from respondents' choices among carefully designed forest vistas. This more sophisticated method is required to reduce bias and ensure reliable results, particularly because aesthetic judgments are inherently more subjective than objective assessments, such as climate change impacts. Indeed, they are more prone to respondent bias (Kalivoda et al., 2014) and inconsistent reasoning, reflecting the divergence between judgments based on cognitive interpretation and those based on measurable landscape attributes (Sevenant & Antrop, 2009). The discrete choice experiment used in Chapter 7 provides greater control by eliciting preferences through observed choices rather than stated opinions. By requiring

respondents to trade off multiple attributes, this approach reduces common survey biases such as social desirability and scale inconsistency (Irie et al., 2024).

A detailed description of the methods used is provided in Section 3.3.

3.2 Study area

All four studies (Chapters 4–7) focus on European forests, with a particular emphasis on Central European temperate forest landscapes. Despite this shared focus, the studies differ in their spatial extents and forest contexts. Chapter 4 has a broader, pan-European perspective, whereas Chapters 5–7 primarily address temperate forests in Central Europe, with a main focus on Germany.

Chapter 4 *(Impacts on and damage to European forests from the 2018–2022 heat and drought events)* investigates a pan-European study area, covering forests across 16 countries and multiple biogeographical zones, including the predominantly boreal forests of the northern zone, the Central European temperate zone, the Alpine zone, and the southern zone, largely comprised of Mediterranean forests.

Chapter 5 *(A case study on forest practitioners' perspectives on climate extremes: consensus on impacts and conflicts in responses)* has a geographically narrower focus, concentrating on German forests, with interviewees primarily from two model regions: the northern region (Lower Saxony, Hamburg, Schleswig-Holstein), characterized by lowland mixed forests with a mix of conifers and deciduous species, and the southwestern region (Rhineland-Palatinate, Baden-Württemberg), dominated by temperate forests in low-mountain regions.

Chapter 6 *(Forest management in a changing climate: assessing the impacts of adaptation measures on the visual aesthetics of forests – the example of Germany)* draws on the international literature on Central European temperate forests. The expert assessments involve German practitioners, mainly from the same northern and southwestern regions. Since the experts evaluated biologically driven impacts of specific management practices on forest attributes, their assessments are considered broadly valid for typical Central European temperate forests, allowing the findings to be generalized beyond the narrow regional basis.

Finally, Chapter 7 *(Aesthetic preferences for forests after climate change-induced disturbance: A discrete choice experiment accounting for temporal evolution of reforestation measures)* is based on a representative German sample, though the images used depict disturbed and regenerating temperate forests typical of Central Europe. While the results are broadly relevant for Central European forest types, their generalizability is limited because perceptions of forest aesthetics may vary across cultural contexts (see Section 2.4).

3.3 Methods in detail

This dissertation employs a combination of methods, ranging from literature review and qualitative analysis of expert interviews to quantitative approaches such as discrete choice experiments. The selection of methods primarily depends on the respective research question.

To address Research Question 1—examining how consecutive drought events affect European forests—Chapter 4 synthesizes evidence from the exceptionally hot and dry period between 2018 and 2022. It consolidates data on crown defoliation, insect damage, burned forest areas, and tree cover loss from multiple sources, including scientific literature, government reports, media sources, and datasets such as fire statistics. Impacts are described qualitatively and quantitatively and compared against the reference period 2010–2014. To account for spatial differences, Europe is divided into four climatic zones—northern, central, Alpine, and southern—with national data assigned to zones according to geographic relevance.

Research Questions 2 and 3—concerning forest practitioners' perceptions of climate change impacts and their preferred adaptation measures—are addressed using a co-creative approach that places practitioners at the center. The methodology relies on semi-structured, face-to-face online interviews with 28 forestry professionals. Interviews cover topics such as forest management goals, perceived impacts of various climate extremes, and adaptive silvicultural strategies. Responses are analyzed using qualitative coding in MAXQDA, with over 1,000 statements categorized into thematic groups, including climate impacts, species responses, and socioeconomic concerns. Interviewees are grouped based on management focus—wood production versus protection and recreation—and the results inform a comparative analysis, later complemented by two stakeholder workshops to reflect on and validate emerging findings.

Research Questions 3 to 5 are methodologically linked and follow a three-step methodological process. First, a comprehensive literature review identifies key climate change adaptation measures, complementing the empirical insights from Paper 2 to provide a more comprehensive answer to Research Question 3, which addresses the most important climate change adaptation measures. A preliminary list of 26 measures is refined to nine after pre-tests with forestry experts to eliminate measures that are less relevant or difficult to assess. Second, another literature review identifies forest attributes that influence visual perception, such as tree size, height variation, understory density, and overall stand diversity, noting whether their effect on aesthetics is positive, negative, or bell-shaped. This second step answers Research Question 4 on the influence of structural forest attributes on aesthetics. Third, to address the impacts of climate adaptation measures on forest aesthetics (Research Question 5), the results of the first two steps are combined into a matrix linking adaptation measures to the most relevant forest attributes. This matrix is evaluated through 11 online, face-to-face dialogues with forestry professionals in Germany, following pre-testing and simplification with two experts. Experts categorize the aesthetic impact of each measure as positive, neutral, or negative. Qualitative insights from these sessions are documented, analyzed for consensus and disagreement, and contextualized using background information about the experts' forest districts.

Research Questions 6 and 7, concerning the visual impacts of reforestation, are addressed using a discrete choice experiment that assesses public aesthetic preferences for different reforestation

strategies. To account for temporal forest development, aesthetic preferences are evaluated at three stages: immediately after reforestation, after 15 years, and after 50 years. Each stage features different visual attributes influenced by common reforestation strategies, including deadwood presence, tree spacing, and species composition. Virtual forest images representing all attribute combinations are created using 3D visualization, allowing respondents to select the most visually appealing option in each choice task. The survey is embedded in an online questionnaire and conducted with a quota-based representative sample of German residents, yielding a cleaned dataset of 5,553 participants. Choice data are analyzed using mixed logit models to estimate preference weights while accounting for random variation across respondents. Scenario simulations assess the influence of different time points and illustrate how the aesthetic appraisal of forest scenarios changes over time.

4 Impacts on and damage to European forests from the 2018–2022 heat and drought events

Abstract

Drought and heat events in Europe are becoming increasingly frequent due to human-induced climate change, impacting both human well-being and ecosystem functioning. The intensity and effects of these events vary across the continent, making it crucial for decision-makers to understand spatial variability in drought impacts. Data on drought related damage are currently dispersed across scientific publications, government reports, and media outlets. This study consolidates data on drought and heat damage in European forests from 2018 to 2022, using data related to crown defoliation, insect damage, burnt forest areas, and tree cover loss. The data, covering 16 European countries, were analyzed across four regions, northern, central, Alpine, and southern, and compared with a reference period from 2010 to 2014.

Findings reveal that forests in all zones experienced reduced vitality due to drought and elevated temperatures, with varying severity. Central Europe showed the highest vulnerability, with both coniferous and deciduous trees being impacted. The southern zone, while affected by tree cover loss, demonstrated greater resilience, likely due to historical drought exposure. The northern showed emerging impacts but was overall less effected, possibly due to site-adapted boreal species, while the Alpine zone showed minimal impact, suggesting a protective effect of altitude.

Key trends include (1) significant tree cover loss in the northern, central, and southern zones; (2) high damage levels despite 2021 being an average year, indicating lasting effects from previous years; (3) notable challenges in the central zone and in Sweden due to bark beetle infestations; and (4) no increase in wildfire severity in southern Europe despite ongoing challenges.

Based on this assessment, we conclude that (i) European forests are highly vulnerable to drought and heat, with even resilient ecosystems at risk of severe damage; (ii) tailored strategies are essential to mitigate climate change impacts on European forests, incorporating regional differences in forest damage and resilience; and (iii) effective management requires harmonized data collection and enhanced monitoring to address future challenges comprehensively.

4.1 Introduction

4.1.1 General introduction

The global temperature rise due to the accumulation of anthropogenic greenhouse gases in the atmosphere causes extreme drought and heat events to become more likely and extreme (Seneviratne et al., 2021). Even if we manage to stay below the 2°C global warming threshold by the end of the 21st century (relative to pre-industrial levels), in Europe one out of every two summer months is projected to be as warm as or warmer than the summer of 2010, which was one of the warmest across Europe to date (Suarez-Gutierrez et al., 2018). Furthermore, the likelihood of such extremely warm summers co-occurring with extreme drought conditions over Europe is increasing rapidly (Suarez-Gutierrez et al., 2023). When extreme heat occurs jointly with severe drought conditions, it can lead to devastating ecological and socioeconomic impacts (Bastos et al., 2021; Feller et al., 2017; Zscheischler et al., 2020), such as economic losses (García-León et al., 2021), increased risk of wildfires (Ruffault et al., 2020), crop loss (Bento et al., 2021; Brás et al., 2021), and unprecedented forest mortality events (Schuldt et al., 2020). Extreme drought is often closely linked with extreme heat, which in turn increases heat-related mortality and morbidity (Watts et al., 2021). Vicedo-Cabrera et al. (2021) found that up to 30% of heat-related deaths globally in the last 30 years can be attributed to anthropogenic climate change. Mitchell et al. (2018) found that the risk of heat-related human mortality during the intense 2003 summer heat wave increased in central Paris by ~ 70% and by ~ 20% in London, both attributable to human factors having exacerbated the likelihood for such events. As such, the recent period of drought and heat between 2018 and 2022 is especially concerning, as it could be the beginning of a new climatic era in Europe.

The recent hot and dry extremes are part of a long-term trend being observed in Europe over the last 42 years, making it a kind of hot spot for heatwaves in comparison to other regions of the Northern Hemisphere midlatitudes (Rousi et al., 2022). Central and southern Europe are affected by a longer-term drying trend, in line with expectations from theory and climate model simulations (Ionita et al., 2022). This trend also includes consecutive multiyear meteorological summer droughts, such as those of 2018 to 2022 in central and western Europe, which are characterized by two or more summers of lower-than-normal precipitation and higher-than-normal evaporative demand, resulting in a larger reduction in soil moisture content in the second year of the drought and therefore in potentially more-extreme drought impacts (Van Der Wiel et al., 2022). Worryingly, climate models project a strong increase in dry spells (Rousi et al., 2021) and multiyear droughts in western Europe in response to further global warming (Van Der Wiel et al., 2022; Suarez-Gutierrez et al., 2023).

4.1.2 Scope, aims, and research approach

In this study, we present the impacts documented in European forests during the years 2018–2022, among the warmest and driest on record over Europe (Figure 4). We focus on forest ecosystems to reduce the risk of bias that could arise from variations in irrigation practices, allowing us to better observe the effects of climate extremes. Furthermore, forests are essential to our livelihoods; they provide wood as a renewable raw material and offer a range of vital ecosystem services. For example, forests contribute significantly to maintaining biodiversity,

sequestering carbon, mitigating climate change, preventing land degradation, and offering recreational value (e.g. Jenkins and Schaap, 2018).

We partitioned the forest environment of Europe into four main geographical zones with distinct climatic and environmental conditions: (1) northern Europe, (2) central Europe, (3) the Alpine zone, and (4) southern Europe. The four geographical zones do not overlap in all cases with the international borders. Thus, since some of the information sources (e.g. government reports) used for this study refer to political boundaries (at the country level), we assigned those sources to the most appropriate geographical zone. An exception was made for countries that fall within two zones, as they partly overlap with the Alpine zone (see Table 1). The Alpine zone is defined based on the 28 Nomenclature of territorial Units for Statistics (NUTS) 2 regions outlined in the area covered by the Alpine Convention (Alpconv, 2018).

The evaluation of the extraordinarily intense drought and heat events between 2018 and 2022, along with the impacts, was derived using an interdisciplinary approach integrating different information sources that allow for the assessment of temporal and spatial heterogeneity impacts. We start with the description of the climatic conditions in 2018–2022, with a focus on drought and high temperatures. We describe droughts in the years prior to 2018 to provide a better context for our focal period, 2018–2022. Following this, we focus on the heat and drought impacts on forests and their legacy effects. We collected the damage estimates from research papers, reports, and even media coverage when no other source was available. We focus our assessment on damage caused by drought and heat that induced (i) physiological stress, (ii) insect pest incidents, and (iii) fire events, as these are the three most-well-documented impacts in our sources.

The data sources often posed issues and challenges. Concerning fire events, we focus on forest fires, which are defined as uncontrolled fires occurring in areas that are at least partly forested. However, for some countries, only statistics on all-vegetation and uncontrolled wildfires were available. Additionally, the online data from the European Forest Fire Information System (EFFIS) provide information on the number of wildfires and the total affected vegetation area. To resolve these issues, we used data on forest fires (when available) and clearly indicated when the information pertains to wildfires. Although this study examines forest damage spanning 2018–2022, the exceptional forest fire damage in 2017 in southern Europe was also included to provide context for subsequent damage. Post-2017, significant management measures were implemented in southern Europe to mitigate forest fires, affecting subsequent damage trends (e.g. REA, 2024). Forest damage in other zones is not discussed for 2017 as it was comparatively minimal.

In order to evaluate and provide attribution for the impacts of heat and drought during the years 2018 to 2022, we considered a reference period spanning 5 years from 2010 to 2014. The year 2015 was regarded as an extraordinary drought year in Europe (e.g. Hoy et al., 2017; Laaha et al., 2017), and thus it was not included in our reference period. Compared to other periods in the current millennium, the years between 2010 and 2014 were characterized by fewer climate extremes, large-scale droughts, or severe floods. For example, in Germany, the water balance levels show only small deviations from the climatological mean during that period (see DWD Dokumentation SPEI). The period of 2010–2014 experienced below-average to average annual

mean temperatures across Europe relative to the 1991– 2020 average, particularly in the years 2010, 2012, and 2013 (EC-JRC Drought Reports, 2024; IMKTRO, 2023a; IMKTRO, 2023b). Moreover, damage data availability was sufficient for the period of 2010–2014.

Countries were selected based on their exposure to heat and drought during 2018–2022, as well as on data availability and language barriers (Table 1). Therefore, out of the 44 European countries (UN, 2024), 28 countries could not be included in this study (i.e. Albania, Andorra, Belarus, Bosnia and Herzegovina, Cyprus, Denmark, Estonia, Georgia, Greece, Hungary, Iceland, Latvia, Liechtenstein, Lithuania, Luxembourg, Malta, Moldova, Monaco, Montenegro, North Macedonia, Romania, Russia, San Marino, Serbia, Slovakia, Slovenia, Türkiye, Ukraine, and Vatican City). Data collection was conducted extensively across Europe over several months by a working group from the ClimXtreme project (https://www.climxtreme.net/index.php/en/, last access: 30 October 2024), with additional experts beyond the project contributing their expertise.

Table 1: *The four climate zones and 16 countries associated with the zones in this study. The countries of the Alpine zone were also assigned to other zones.*

Zone	Countries
Northern	Finland (FIN), Sweden (SWE), Norway (NOR), United Kingdom (UK), Ireland (IRL)
Central	Poland (POL), Czech Republic (CZE), Switzerland (CHE), Austria (AUT), Germany (GER), the Netherlands (NLD), Belgium (BEL), France (FRA)
Alpine	Switzerland, Austria, Italy (ITA), France
Southern	Italy, Spain (ESP), Portugal (POR)

Physiological stress indicators, specifically crown defoliation data segregated into conifers and broadleaves, were sourced from ICP Forests Technical Reports (http://icp-forests.net/page/icp-forests-technical-report, last access: 30 October 2024). Insect pest data were gathered by analyzing wood damage from reliable sources, including statistics, government reports, and scientific publications. Forest fire data were derived from the EC-JRC Technical Reports (https://forest-fire.emergency.copernicus.eu/reports-and-publications/annual-fire-reports, last access: 30 October 2024). To broaden our understanding, we incorporated tree cover loss (TCL) data from Global Forest Watch (https://www.globalforestwatch.org, last access: 30 October 2024). Significant differences between the study period (2018–2022) and the reference period (2010–2014) were discerned utilizing a *t*-test conducted with RStudio 2022.12.0. In the following sections, we take a closer look at the climatic situation during the 5 critical years, 2018–2022, in the four European zones (northern, central, Alpine, and southern).

4.2 Meteorological conditions

4.2.1 Occurrence of drought and heat in Europe during 2018–2022

Persistent drought conditions characterized the spring and summer seasons during 2018–2022 across Europe, as shown by the Standardized Precipitation Evapotranspiration Index (SPEI; Beguería et al., 2013; Vicente-Serrano et al., 2012, 2013; Figure 4). These prolonged droughts

co-occurred with hot conditions across large parts of Europe (Xoplaki et al., 2023) and were linked to strong atmospheric blocking conditions over Europe characterized by persistent high-pressure anticyclonic systems. A persistent positive North Atlantic Oscillation (NAO) was found before the heatwave (Drouard et al., 2019; Li et al., 2020). This pattern was further associated with a double jet stream configuration and two highspeed wind currents in the upper atmosphere that influenced the intensity and persistence of atmospheric conditions in the inter-jet region (Rousi et al., 2023).

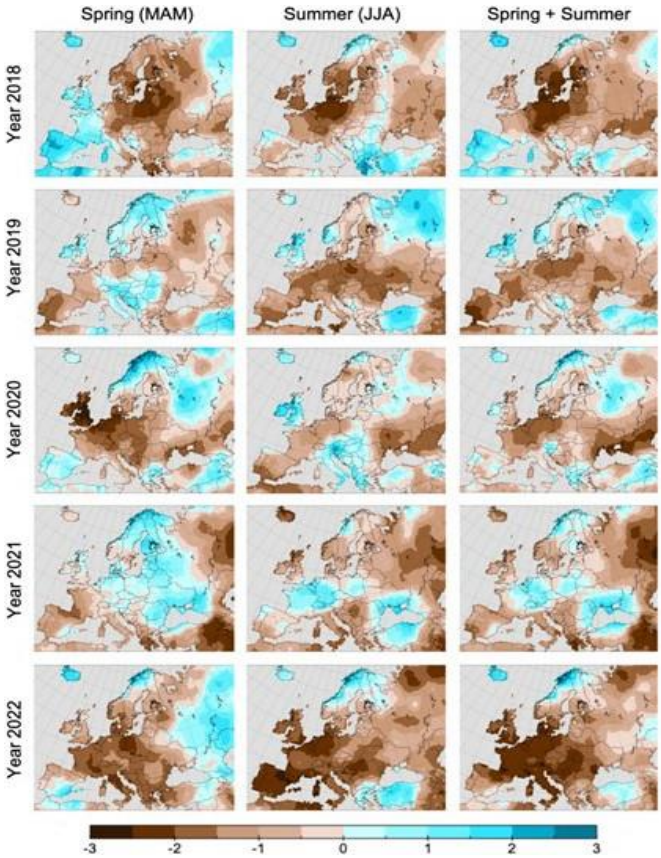


Figure 4: *SPEI (Standardized Precipitation Evapotranspiration Index) for spring (MAM – March to May), summer (JJA – June to August) and the entire growing season (March to August) during the 2018 (top row) to 2022 (bottom row) period. SPEI results are shown in units of standard deviation from the long-term mean of the standardized distribution. The window length for MAM and JJA is 3 months, and it is 6 months for spring and summer.*

Furthermore, sea surface temperature anomalies exhibited a tripolar pattern in the North Atlantic, which has previously been identified as a precursor for European heatwaves (Beobide-Arsuaga et al., 2023) such as the one in 2015 (Duchez et al., 2016), as well as being a precursor for increased drought risk in central Europe via changes in the large-scale atmospheric circulation (Haarsma et al., 2015; Ionita et al., 2022; Rousi et al., 2021).

Hari et al. (2020) used pattern climatology data for Europe and long-term observations to claim that the consecutive droughts in 2018 and 2019 were unprecedented in the last 250 years. Adding the year 2020 to the analysis, Rakovec et al. (2022) found that the 2018–2020 drought was not only unprecedented in intensity, but also what made it truly exceptional was its average near-surface air temperature anomaly of +2.8°C above the pre-industrial period. The authors identified the 2018–2020 drought event as having an unprecedented intensity that persisted for

more than 2 years, exhibiting a mean aerial coverage of 35.6% of Europe. Following the 2018–2020 extreme drought years, 2021 was a rather normal to wet year. However, persistent hot and dry conditions prevailed during spring and summer 2022, which led to depleted soil water levels (similar to 2018) and regionally critical drought conditions (Figure 4). Throughout the summer of 2022, heat waves and exceptionally low rainfall led to very dry conditions in central Europe. Observed runoff anomalies highlighted the 2022 European drought as potentially the worst in 500 years (Henley, 2022; Schumacher et al., 2024). Between May and July 2022, many areas in Europe experienced the strongest 500hPa geopotential height anomalies since 1950 (Toreti et al., 2022a).

4.2.2 Drought and heat in the northern zone, 2018–2022

From 2018 to 2022, Finland experienced a series of unusually warm and dry years. In 2018, prolonged heat and record-low rainfall caused significant groundwater depletion, algal blooms, fish and mussel deaths, and a 20% crop yield reduction (Veijalainen et al., 2019; Winland-project Policy Brief VII, 2019). Groundwater levels remained low in 2019, with central and eastern Finland experiencing the worst dryness since 1955 (Ilmastokatsaus, 2019). The year 2020 saw record-breaking warmth and rainfall, particularly in southern and central Finland (Ilmastokatsaus, 2020). June and July of 2021 were exceptionally hot and dry (Ilmastokatsaus, 2021). In 2022, summer temperatures were nearly 2°C above normal, with varying rainfall patterns across the country (Ilmastokatsaus, 2022).

Sweden experienced dry years in 2016 and 2017, particularly in southern Sweden where streamflow was 28% below normal, prompting local water use restrictions (Geological Survey of Sweden, 2017). This drought persisted and peaked in 2018, leading to the most-severe wildfires in modern Swedish history (Swedish Board of Agriculture, 2019; Teutschbein et al., 2022a, b). Current climate conditions made such fires approximately 10% more likely compared to pre-industrial times (Krikken et al., 2021). Drought conditions eased in subsequent years, with slightly drier conditions returning in 2022 (SMHI, 2023).

Norway experienced significant droughts from 2018 to 2022. In spring and summer 2018, temperatures were up to 4.7°C above normal, and precipitation from May to September was only 18%–46% of the 1991–2020 average (Norwegian Center for Climate Services, 2023). This year had the longest drought period in 5 years of study. The years 2021 and 2022 were also dry, with 83% and 84% of average annual precipitation, respectively, and August 2021 being the driest month (Norwegian Center for Climate Services, 2023). Groundwater (GW) levels below the tree line dropped to 75% of average in southeastern Norway in August 2018 and 2022, impacting agricultural production (NVE, 2023). As for the future, climate models predict more-intense precipitation and less snowmelt. Accordingly, floods induced by rainfall will increase in terms of frequency and magnitude, while floods induced by snowmelt will decrease, potentially leading to drought in late spring and summer (Hanssen-Bauer et al., 2017).

In 2018, the United Kingdom (UK) experienced combined heatwaves and droughts (Holman et al., 2021). This extended into late 2018 and 2019 in some areas (Turner et al., 2021). From June 2019 to February 2020, humid conditions caused harmful floods (Sefton et al., 2021). The year 2020 saw a hot, dry spring followed by a wet summer (Kendon et al., 2021). In 2021, temperatures and rainfall were slightly below the long-term average (Kendon et al., 2022). In

2022, the UK recorded its first annual average temperature exceeding 10°C, while total rainfall remained below average (Kendon et al., 2023). The areas of Coningsby and Lincolnshire recorded temperatures over 40°C for the first time in UK history (Kendon et al., 2023).

4.2.3 Drought and heat in the central zone, 2018–2022

Due to its geographical location and unfavorable hydrological conditions, Poland has relatively few natural water resources compared to the rest of central Europe (Susza, 2023). Almost 40% of Poland's arable and forested land is permanently threatened by drought (Polish Supreme Chamber of Control, 2021). Drought impacts Polish agriculture approximately every 5 years, but recently it has affected large areas nearly annually, including the years 2015, 2016, 2018, 2019, and 2020. In 2018, severe soil drought resulted in over 50d of no plant-available water in regions like Wielkopolska and Kujawy (Wawrzoniak et al., 2019). Soil droughts have also been observed in extensive forested areas in recent years (Lech et al., 2021).

The 2018 severe drought centered over southwest Germany, the Benelux countries, and northeastern France. The 2019 drought shifted east, impacting eastern Germany and neighboring countries. Although the 2019 drought was not exceptionally severe, consecutive drought years exacerbated the water deficits in Germany (soil moisture impacts; Xoplaki et al., 2023) and France. Gravity Recovery and Climate Experiment (GRACE) data indicated severe drought conditions in western Germany in autumn 2018, shifting to eastern Germany and Poland in summer 2019 (Boergens et al., 2020). With the exception of southern Germany, Germany and France experienced continued drought until late summer 2020. Summer 2021 saw heavy precipitation and a severe flooding event in central Europe (Mohr et al., 2023). In 2022, extreme drought conditions affected Germany and France due to low precipitation amounts and the occurrence of early heatwaves in May and June. Drought-affected areas in Germany reached 40% of the country in 2022, followed by 30% in 2019, 19% in 2018, and 16% in 2020.

4.2.4 Drought and heat in the Alpine zone, 2018–2022

In 2018, Switzerland experienced the fourth-warmest spring and third-warmest summer since instrumental measurements began in 1864 (Bader et al., 2019). Summer 2018 received only 70% of the long-term mean precipitation (1981–2010), although above-normal winter rainfall helped mitigate the summer's worst impacts. From 2019 to 2021, frequent summer heat episodes occurred with normal winter precipitation. However, winter 2021–2022 saw anomalously warm and dry conditions, especially in southern Switzerland and northern Italy. Summer 2022 had record-breaking temperatures, with July being one of the hottest months since 1864, and low rainfall led to record-low levels in many lakes in eastern and central Switzerland.

Austria, despite its generally water-rich Alpine areas, faced exceptional heat and drought in 2018 and 2022, raising concerns about water availability (Stelzl et al., 2021). A significant decline in snow depth in the Alpine region that may have balanced the increased summer evaporative demand exacerbated these impacts (Matiu et al., 2021). The summer of 2019 was less dry but broke heat records (Olefs et al., 2021). Summer 2022, the fourth-warmest on record,

followed a dry and mild winter, and while rainfall events occurred, they were too heavy to alleviate drought conditions due to the high runoff (GeoSphere Austria, 2024).

4.2.5 Drought and heat in the southern zone, 2018–2022

Italy experienced less impact from the 2018 drought compared to central and northern Europe, with no significant soil moisture anomalies or forest disturbances reported (Senf and Seidl, 2021a). However, drought conditions persisted into the summers of 2021 and 2022 (Toreti et al., 2022a), exacerbated by a winter rainfall deficit (Bonaldo et al., 2023; Toreti et al., 2022b). The year 2022 was particularly extreme, characterized by 9 consecutive months almost without precipitation, leading to the drying out of the Po River (Montanari et al., 2023). The winter of 2022–2023 remained relatively dry (Toreti et al., 2023).

In Spain, precipitation between 2020 and 2021 was 5% below normal. From October 2021 to early March 2022, accumulated rainfall was 38.2% below average (BOE, 2022). In early March 2022, the peninsular water reserve was 40.5%, markedly below the 5-year average of 52.5% and the 10-year average of 60.8%. The water reservoir system, designed to manage demand during dry periods using reserves from wetter years, has been strained by consecutive years of below-average precipitation since 2012–2013, except during 2017–2018. The 2021–2022 hydrological year was among the three driest on record, with precipitation 25% below average and reservoir levels at 35%, the lowest in 27 years (Greenpeace, 2022).

Over the past 20 years, mainland Portugal has experienced significant drought, with 6 of the 10 driest years occurring post-2000, including 2017–2018, 2019, and 2021–2022. The 2021–2022 hydrological year recorded 488.3mm of precipitation; a deficit of 393.8mm compared to the 1971– 2000 average. It ranks as the third-driest year since 1944– 1945, following 2004–2005 (APA, 2023). From 2018 to 2020, drought in Portugal was less severe, predominantly affecting the southern regions (Figure 4). During 2019–2020, drought conditions were more pronounced, with 5 of 11 hydrographic basins showing negative monthly storage deviations throughout the year. The 2020–2021 year saw four basins with below-average storage levels (APA, 2023).

4.2.6 European droughts from past to future: an attribution challenge

A long-term drying trend has been observed in central and southern Europe in recent years, with climate simulations projecting these trends to continue (Bakke et al., 2023; Stagge et al., 2017; Ukkola et al., 2020). There is high confidence that temperature increases and precipitation decreases have already led to increased aridity in the Mediterranean region (IPCC, 2021a). According to the latest Intergovernmental Panel on Climate Change (IPCC) report (IPCC, 2021b), the combined warming and drying trend is attributable to human causes. This trend is less clear in western and central Europe, but there is high confidence in decreased aridity in response to increased precipitation in northern Europe (IPCC, 2021a). However, Christidis and Stott (2021) found increased drought risk in France and Germany based on summer SPEI trends between 1950 and 2018. Southeastern Europe is also affected, following an analysis based on rainfall and precipitation minus potential evapotranspiration (PPET) reanalysis data (Christidis & Stott, 2021). Longer-term SPEI trends (1902–2020) indicate drying hotspots in Spain, Portugal, southern France, Italy, eastern Germany, the Czech Republic, Poland, Hungary, Slovenia, and Croatia (Ionita et al., 2021a). Changes in large-scale atmospheric circulation in

the North Atlantic region may be linked to these drying conditions (Ionita et al., 2022) and possibly to the slowdown of the Atlantic Meridional Overturning Circulation (AMOC; Caesar et al., 2018). The extent to which these trends are attributable to anthropogenic impact remains a question.

Two approaches have been widely used to address this question: (i) the paleo-climatic perspective based on proxy data and (ii) longer-term climate model projections. Büntgen et al. (2021) found that recent drought extremes (2015–2018) are unprecedented over the past 2000 years in the Czech Republic and neighboring regions, while Ionita et al. (2021b) suggest that mega-droughts during the 15th, the late-18th, and the early-19th centuries were longer and more severe in Europe. Despite differences in the methods and regions studied, these findings highlight the challenge of drawing definitive conclusions about current drought intensity in a historical context.

Climate model projections based on the latest CMIP6 assessment confirm historical trends observed in drought conditions. According to the IPCC (2021b), rainfall deficits are expected to be most pronounced during summers by the end of the 21st century in central and southern Europe. While increased winter and spring precipitation may offset some summer water deficits (i.e. a negative hydrological balance), this is unlikely for France, Germany, and the Mediterranean region. Trends in evapotranspiration, already negative annually, are projected to worsen in summer. Annual mean rainfall changes are not informative for drought attribution, as drought and heavy precipitation events can occur in the same season, creating adverse conditions for agriculture and forestry despite balanced mean rainfall.

Meteorological drought conditions are likely to become more frequent under current climate projections (Moemken et al., 2022). The current series of extreme drought years is likely a precursor to a new normal in Europe. These projections apply to transient warming conditions; if carbon emissions cease, the climate will transition to an equilibrium warming phase, reducing the land–ocean temperature contrast and potentially altering the drying trend (Byrne & O'Gorman, 2013; Dittus et al., 2024).

Attribution studies of individual extreme drought events are complex due to the low signal-to-noise ratio. While heat waves are easily attributed to anthropogenic climate change (Vogel et al., 2019; IPCC, 2021a), drought events remain challenging to attribute robustly. Van der Wiel et al. (2022) found that droughts of a similar magnitude to those from 2018 to 2020 are within the realm of current climate possibilities, with the signal emerging from natural variability over time, impacting biodiversity and human health.

As it is difficult to reconcile the existing lines of evidence, only a few drought attribution studies have tried to quantify the role of humans thus far. A prominent rapid event attribution of the intense 2022 drought in central and western Europe showed that human-induced climate change made the root zone soil moisture drought about 3–4 times more likely and the surface soil moisture drought about 5–6 times more likely (Schumacher et al., 2022). The authors concluded that while the magnitudes of historical trends vary between different observation-based soil moisture products, they all agree that the dry conditions observed in 2022 would have been less likely to occur at the beginning of the 20th century. One study on the 2015 European summer

drought concluded that the attribution results depend on the methodology used (Hauser et al., 2017). Human influence on the increased likelihood of central-European droughts could only be detected when using the largest-possible forcing difference in CMIP5 models. García-Herrera et al. (2019) analyzed the drought that affected France and western Germany from July 2016 to June 2017, stating that recent trends, including those in human-induced higher temperature, have exacerbated the severity of the drought event. Finally, Philipp et al. (2020) investigated the hydrological drought of 2018, stating that the trend is driven by strong trends in temperature and global radiation rather than a trend in precipitation, resulting in an overall trend in potential evapotranspiration. Given that these trends match results from climate model simulations, the authors conclude that the observed trend in agricultural drought can at least in part be attributed to human-induced climate change.

4.3 Damage to forests

Drought events compounded by heat waves can fundamentally transform the composition, structure, and biogeography of forested ecosystems (Allen et al., 2010, 2015). Overall, the consequences for forests can be summarized in three major impact categories: (i) physiological stress, (ii) insect outbreaks, and (iii) forest fires (e.g. Brodribb et al., 2020; Mezei et al., 2022; Salomón et al., 2022; Seidl et al., 2020). From 1950 to 2019, the number of natural disturbances observed in European forests has increased, with wind being the most important factor (46% of total damage), followed by fire (24%) and bark beetles (17%), although the latter's contribution to the total damage has doubled in the last 20 years (Patacca et al., 2023).

One of the primary impacts of heat and drought on forests is increased tree mortality (Allen et al., 2010; Anderegg et al., 2013; George et al., 2022). Trees can be highly sensitive to drought stress and prolonged periods of high temperatures, and together with low precipitation, these conditions can cause trees to experience water deficits, leading to physiological stress and ultimately death. In general, trees under drought and heat stress may experience carbon starvation and face greater risks of embolism, which can cause a failure in the water transport (Allen et al., 2015; Schuldt et al., 2016). Such physiological stress can lead to mortality but also to milder consequences such as crown defoliation, early leaf shedding, or death of branches, which reduce the vitality and growth of the trees (Schuldt et al., 2016). Soil drying may lead to water repellency (soil hydrophobicity), which slows down the infiltration of rainwater following the end of the drought and produces a heterogeneous soil wetting front (Grünzweig et al., 2022). Soil hydrophobicity has been observed in various temperate forests and diverse soil types in Europe, which may increase drought stress and tree die-off (Gazol et al., 2018; Gimbel et al., 2016; Hewelke et al., 2018; Seaton et al., 2019). As a consequence, reduced forest cover can exert a negative (buffering) feedback on climate change impacts by decreasing the aerodynamic resistance of heat transfer from trees to the surrounding air. The reduced resistance increases sensible heat flux, decreases forest temperature, and enhances water savings because of a reduced need for cooling by transpiration (Banerjee et al., 2017; Rotenberg & Yakir, 2010). For example, during the 2003 extreme heatwave in central and western Europe, surface temperatures rose less in forests than in non forested areas, allowing forests to conserve water (Teuling et al., 2010). This "canopy convector effect" is an adaptation mechanism, which can prevent long-term amplification of the consequences of extreme heat and drought (Grünzweig

et al., 2022). A quantitative understanding of regional and local biophysical effects of such land use changes is required to enable effective land-based mitigation and adaptation measures (e.g. Perugini et al., 2017). However, these effects are complex and strongly depend on local conditions, making their quantification challenging.

At the same time, other processes like outbreaks of forest pests can co-occur with and follow droughts. Resin release plays a pivotal role in the resistance of conifers to bark beetles (Morcillo et al., 2019). However, resin production is very costly in terms of available resources and strongly linked to tree vigor and water availability (Zas et al., 2020). But drought-induced host weakening does not determine beetle outbreaks alone. Dry and warm conditions generally also increase the vitality and reproduction of thermophilic insects with consequent shorter generation times, higher fecundity, and survival rates (Jactel et al., 2019; Pettit et al., 2020). It should be noted that heat waves can also negatively affect some insect pest species or pathogens, given their response to the heat stress (Sire et al., 2022).

Heat and drought can create favorable conditions for wildfires to start and spread (Kirchmeier-Young et al., 2019), and drought-stressed trees are more susceptible to ignition and can burn more readily. Although wildfires have decreased on a global scale and across Europe over the last decade (2010–2020), there have also been years with the highest level of fire damage ever recorded in Europe in the past decade (Grünig et al., 2023; Patacca et al., 2023). Several regions (central Europe among others) are likely to face larger and more-frequent wildfires in the future (Feurdean et al., 2020; Milanovic et al., 2021). A study investigating storm and fire disturbances in Europe from 1986 to 2016 identifies storms and fires as the most important abiotic disturbances in the recent past, with wind (i.e. storms) mainly dominating in central and western Europe and fire in the southern part of the continent (Senf & Seidl, 2021b). While in 2018 fire was likely only responsible for about 3% of the area disturbed in northern and central Europe (Senf & Seidl, 2021a), there is strong evidence that wildfires will increase in a warmer and drier environment (Seidl et al., 2017). This increase can facilitate deforestation, loss of habitat, soil erosion, and long-term changes in forest structure and composition that can have severe environmental, economic and social consequences (Leverkus et al., 2019). Wildfires commonly lead to hydrophobic soils (Davies et al., 2013; Mao et al., 2019), thus reducing water infiltration and causing further damage to trees (Grünzweig et al., 2022).

The forest damage caused by drought leads to significant socioeconomic consequences in European forest ecosystems (Lindner et al., 2010) as forest owners, logging companies, and other stakeholders in the forestry sector experience significant losses due to a reduction in volume and quality of timber (e.g. Brecka et al., 2018; Davies et al., 2020; Knoke et al., 2021). Further impacts to local economies and communities can occur, since the forestry sector is an important employer in many rural areas of Europe, employing about 3.6 million people (EU-27; EUROSTAT, 2023). Furthermore, the value of forest areas is likely to decrease if economically valuable tree species decline (Hanewinkel et al., 2013), and the cultural and recreational qualities of forests can suffer (Winkel et al., 2022).

Heat and drought can also disrupt forest ecosystem dynamics and alter community composition (Hicks et al., 2018), as tree species differ in their vulnerability to drought stress, leading to shifts in species abundance and distribution (Morin et al., 2018). These changes can also have

cascading effects on other organisms that depend on forest ecosystems, such as mammals, birds, reptiles, amphibians, or invertebrates (Liebhold et al., 2017), and drought can disrupt these complex ecosystems (Krumm et al., 2020; Vicente-Serrano et al., 2020). Reduced water availability can also strongly affect the carbon cycle by limiting photosynthesis and nutrient uptake and can lead to decreased growth rates and reduced carbon storage in forests. Many recent publications discuss the impact of drought and heat on forest carbon balances, a critical aspect that could not be specifically addressed within this study; relevant information can be found, e.g. in Peters et al. (2020).

The projected increase in frequency and intensity of heat and drought events (Spinoni et al., 2018) will likely increase forest damage. The drought in 2018 alone was probably the largest source of severe forest disturbances in Europe in over 170 years (Senf & Seidl, 2021a). Forest disturbances increased significantly across much of Europe in 2018, particularly in the central and eastern regions, and remained above average in both 2019 and 2020 (Senf & Seidl, 2021a). However, there are opportunities to better understand the damage and to mitigate future harm.

4.3.1 Europe-wide damage to forests, 2018–2022

The central zone exhibited the most significant impacts and damage between 2018 and 2022, showing high or very high significance for crown thinning, pest outbreaks, and TCL compared to the reference period (Figure 5). The southern zone, while still affected, had less pronounced damage extents, although significant differences in crown thinning and TCL were observed. The northern zone experienced highly significant TCL. In the Alpine zone, no statistically significant differences were detected. Additionally, across all zones, there were no significant differences in damage caused by wildfires.

A pairwise *t* test comparing the averages examined whether the observed changes (difference in means) between the two periods (2010–2014 and 2018–2022) are statistically significant. The test results indicate that the difference between the two periods was not statistically significant ($p = 0.06$) for defoliation of both conifers and broadleaves, with a mean difference of 9.4%. The *t*-test results for forest fire occurrence clearly showed no significant difference ($p = 0.34$; mean difference – 3400.9ha). However, for TCL, the mean difference of 0.34% was highly significant ($p = 0.004$). A similar statistical test for wood damaged by insects was not feasible due to insufficient data.

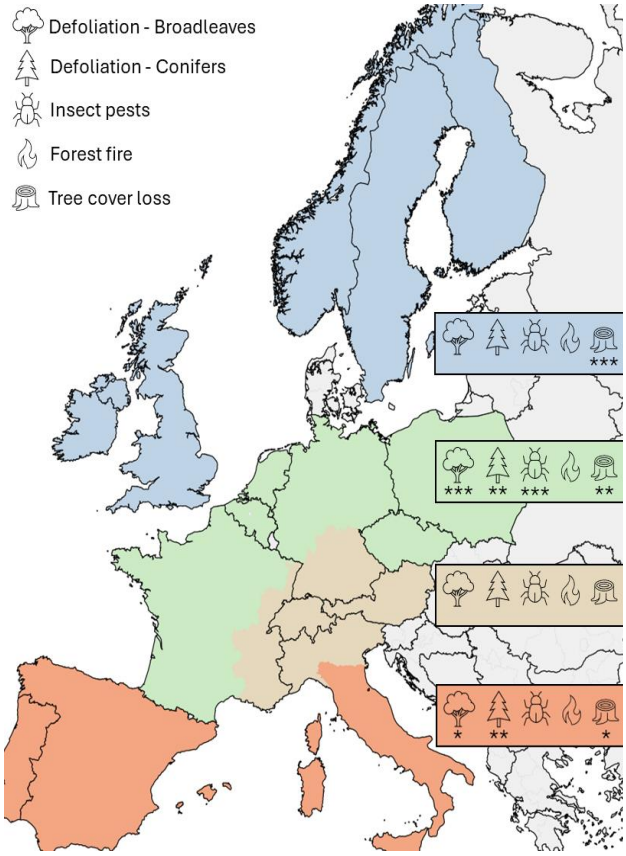


***Figure 6**: Differences in impacts and damages (crown defoliation [%] of broadleaves and conifers; damaged wood by insects [1000m³], burnt forest area [ha], and tree cover loss [%]) between the study period (2018-2022) and the reference period (2010-2014). * significant (p<0.05), ** highly significant (p<0.01), *** very highly significant (p<0.001). Map created with mapchart.net.*

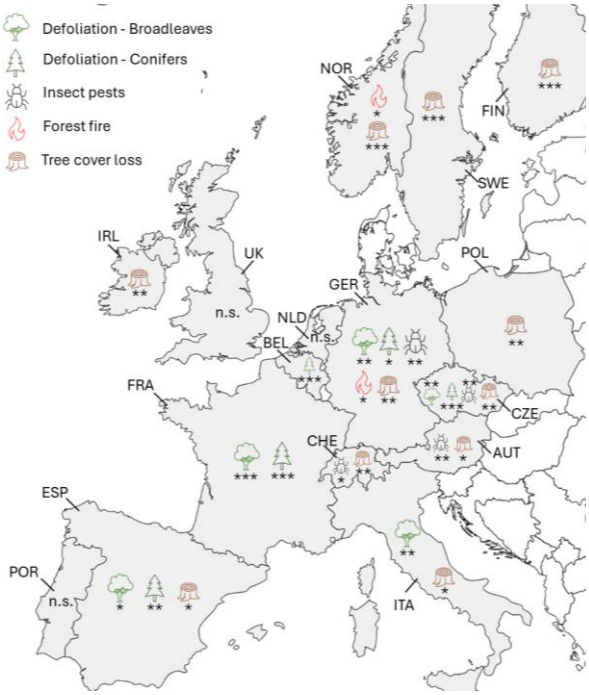


***Figure 5:** Significant differences in the 16 countries regarding impacts and damages (crown defoliation [%] of broadleaves and conifers; damaged wood by insects [1000m³], burnt forest area [ha], and tree cover loss [%]) between the study period 2018-2022 and a reference period (2010-2014); n.s. (not significant), * significant (p<0.05), ** highly significant (p<0.01), *** very highly significant (p<0.001). Map created with mapchart.net.*

Significant differences were observed across the 16 countries (Figure 6). In the Central zone, coniferous trees showed highly significant crown thinning in the Czech Republic, Belgium, and France, while significant effects were observed in Germany (see Figure 7 for more detailed results). For deciduous trees, France exhibited highly significant crown thinning, while Germany and the Czech Republic showed significant effects. In the Southern zone, deciduous trees in Italy were highly significantly affected, and in Spain conifers were highly significantly and broadleaves were significantly affected. In the northern zone, no increased crown thinning was observed during the drought period in individual countries. However, a particularly high incidence of wood damage due to pest infestation was found in the Central zone, which was highly significant in the Czech Republic, Switzerland, Austria, and Germany (see Figure 8 for detailed results). An increase in wildfires during the drought period was only observed in Norway and Germany, where the affected area was significantly higher during 2018-2022 (see Figure 9 for detailed results). TCL was most significant in Finland, Sweden, and Norway, with Ireland also showing highly significant impacts (see Figure 10 for detailed results). In the central zone, Poland, the Czech Republic, Switzerland, and Austria were highly significantly

affected, with Germany showing significant effects. In the Southern zone, Italy and Spain were significantly affected by TCL. No significant differences in impacts were found for the United Kingdom, the Netherlands, and Portugal.

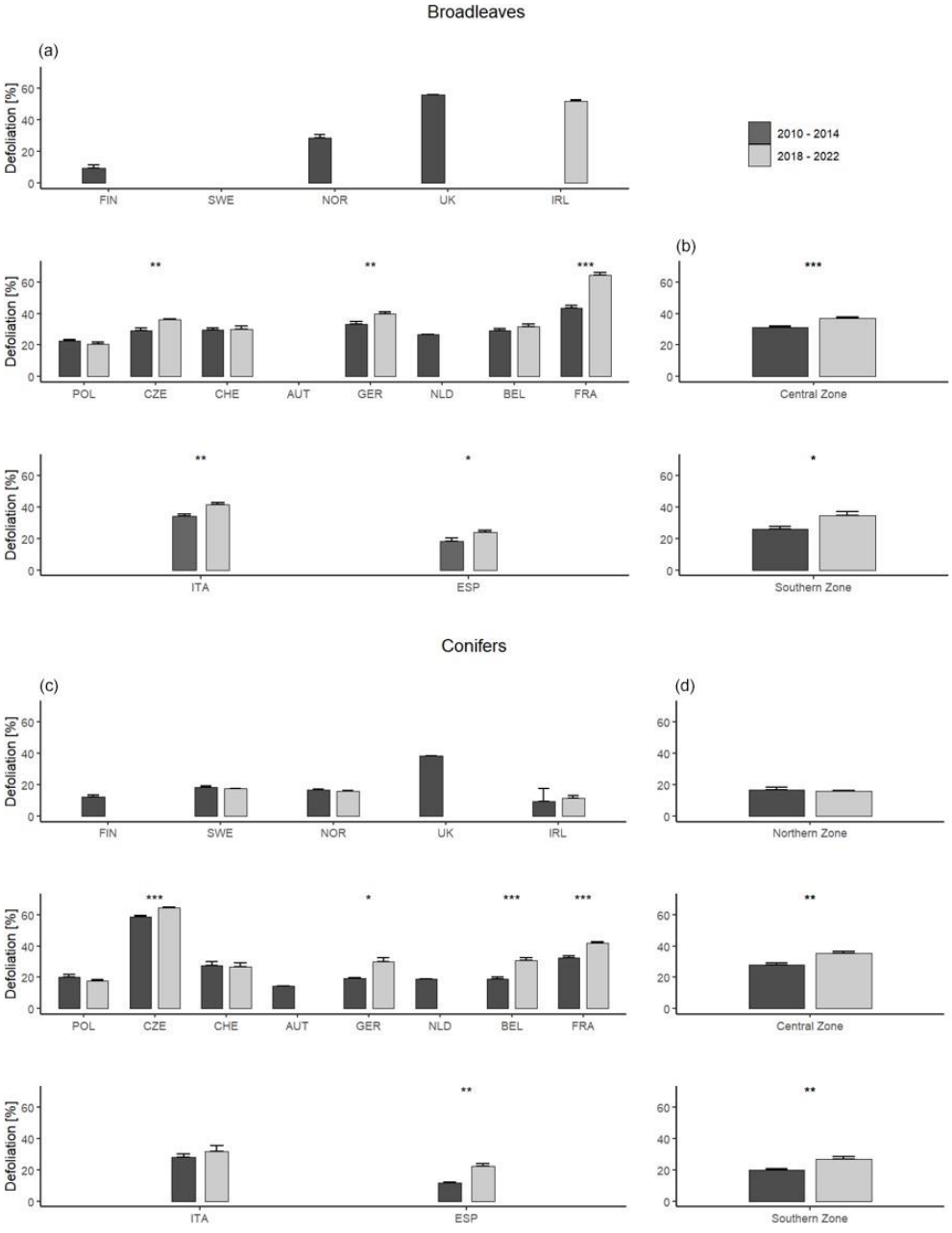


Figure 7: *Relative crown defoliation of broadleaves (A, B) and conifers (C, D) during the dry period 2018-2022 and the reference period 2010-2014 (> 25% needle/leaf loss, i.e. moderate to severe defoliation); data from ICP-forests (2022). For Broadleaves in the Northern zone data was not sufficiently available.*

Wood damage caused by insect infestation was significantly higher across central Europe in the study period of 2018–2022 than in the reference period (Figure 8). Notable is the situation in the Czech Republic, where insect-induced wood damage even surpassed the mean annual roundwood production (2010–2014). Sweden also experienced a degree of roundwood damage attributable to insects during the assessed drought period. While data on roundwood damaged

by insects were accessible for select countries, they were not uniformly available across all regions. Notably, acquiring such data was comparatively easier during the more-recent period, indicative of heightened pressures exerted by insect pests within forest ecosystems and a greater interest in monitoring forest damage.

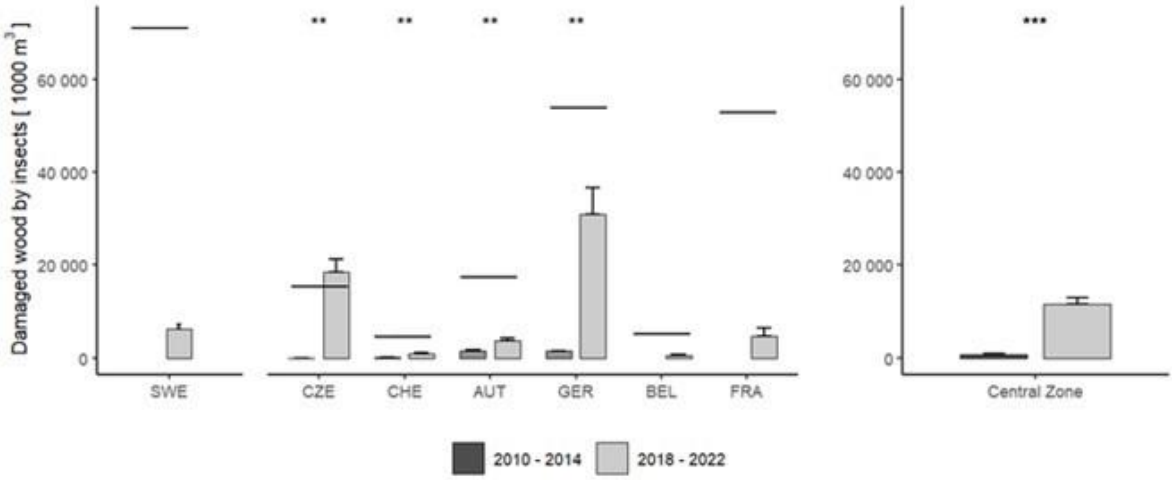


Figure 8: *Roundwood damaged (1000m³) by insect pests in Europe in the period of 2018–2022 partly in comparison with the reference period of 2010–2014. The black lines show the total roundwood production average per year during 2010–2014. Wood data were derived from different sources (EUROSTAT, 2016; Wulff and Roberge, 2020; Öhrn et al., 2021; EUWID, 2022; Michel et al., 2022; DESTATIS, 2020, 2023; Waldschutz, 2023; WSL, 2023b; BFW, 2020, 2023, Czech Statistical Office upon request). For the other countries, no data were available.*

In our analysis of forest fire occurrences, we did not find significant differences between the dry period in 2018–2022 and the reference period of 2010–2014, except for Norway and Germany (Figure 9). This lack of significant differences was consistent across the northern, central, Alpine, and southern zones. Generally, countries in the southern zone experienced severe impacts from forest fires. For example, the damage in Sweden and France, which had the highest amounts of burned area in their climatic zones (5 000 and 10 000ha, respectively) during the period of 2018–2022, was only a fraction of that observed in Portugal during 2017.

The loss of tree cover can stem from various human and natural factors, such as forestry activities (e.g. logging or deforestation), natural occurrences (e.g. diseases or storms), and fire incidents. Notably, very highly significant disparities between the dry period (2018–2022) and the reference period (2010–2014) were observed in the northern zone (Figure 10).

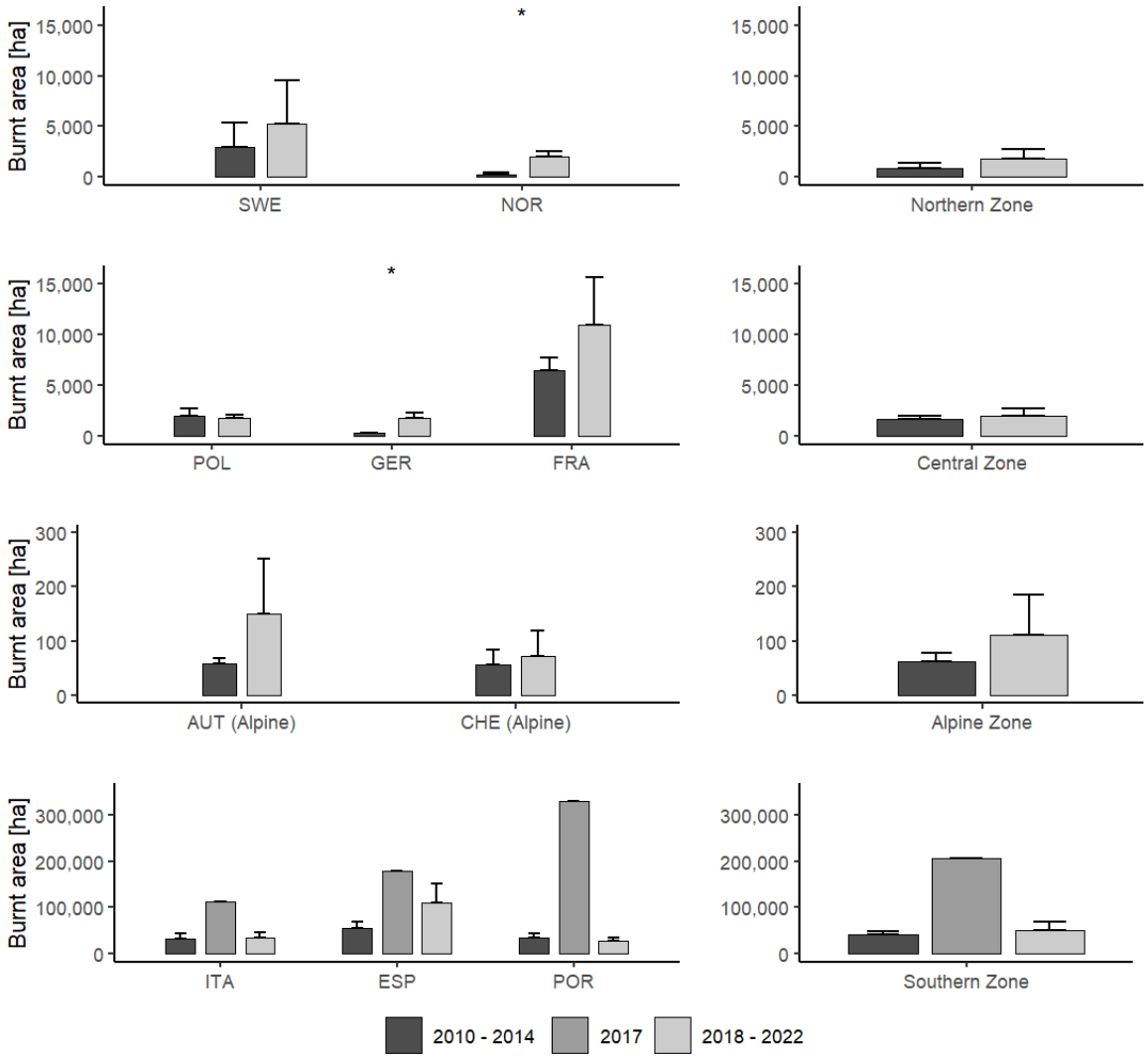


Figure 9: *Burnt forested area (mean for the two periods under consideration) in selected European countries. Italy and Portugal had large fires in 2017 (accordingly, value for 2017 is given for the Southern zone). All data from JRC Technical Reports of the years Forest Fires in Europe, Middle East and North Africa of the years 2010 to 2022 (https://forest-fire.emergency.copernicus.eu/reports-and-publications/annual-fire-reports). The data utilized here stem from the EC-JRC national reports of the years 2010 until 2022, where areas are designated as forested regions. Absolute values were employed instead of relative values due to inconsistent forest area data across all countries within the dataset. Please note the different scales.*

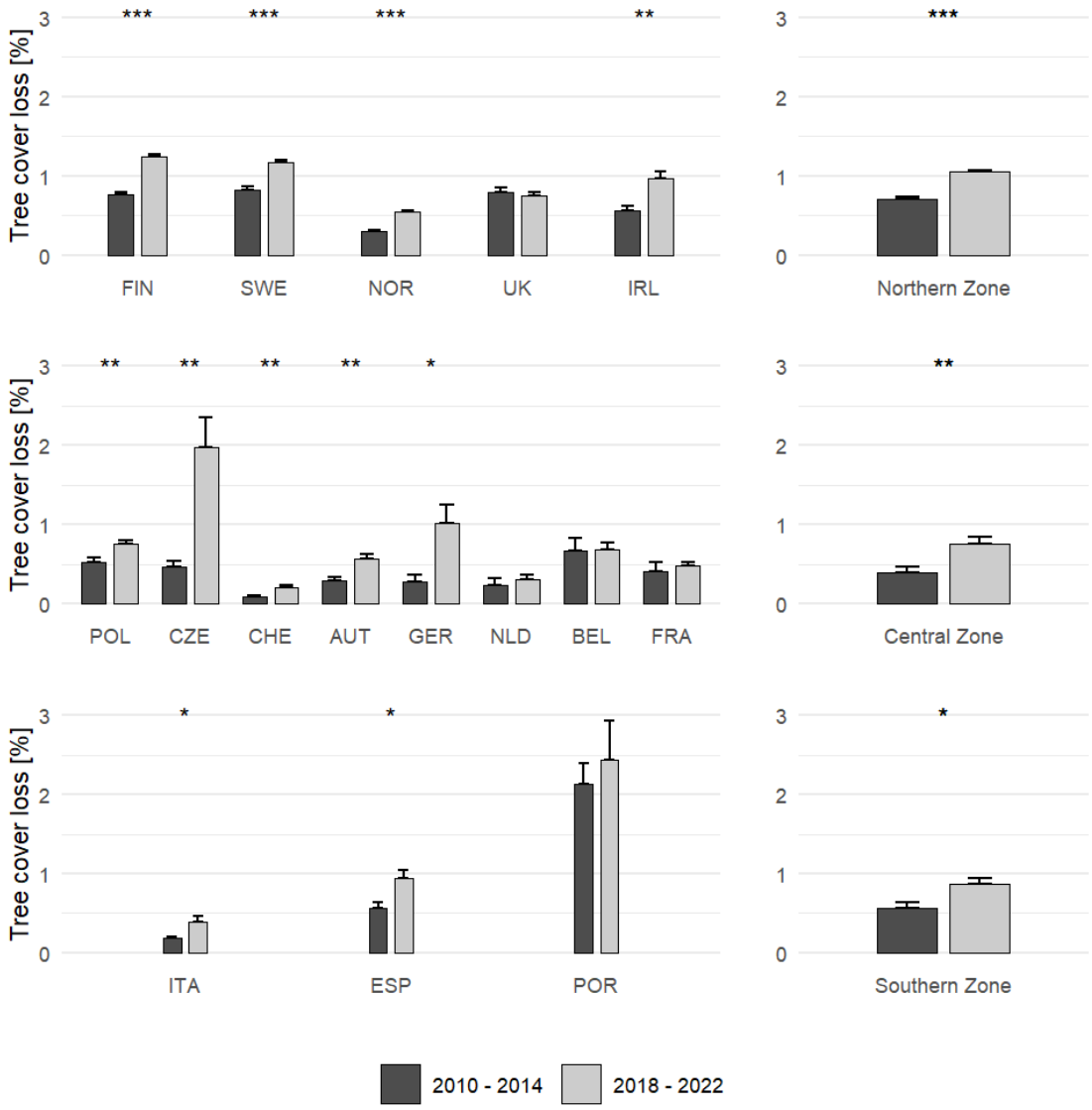


Figure 10: *Relative tree cover loss (mean for the two periods under consideration) Data from GlobalForestWatch.*

4.3.2 Damage to forests in the northern zone, 2018–2022

The total forested area in Finland is 26×10^6 ha (EFFIS: 24.1×10^6 ha), of which 20×10^6 ha is suitable for forest production. Forest damage in Finland was highest in 2018 (21 700ha) and has been decreasing since then, followed by an increase in 2022 (damage levels in 2019 – 15 800 ha; 2020 – 14 000 ha; 2021 – 12 000 ha; and 2022 – 19 100 ha; Melin et al., 2022; Nuorteva, 2019; Nuorteva et al., 2022; Terhonen et al., 2023). These numbers are high for Finland given that the accumulated forest drought damage in the years 2009–2015 was 8 700 ha (Nevalainen & Pouttu, 2017).

The areas influenced by drought and bark beetles were localized and, on an annual scale, quite small when compared, for example, to snow and moose-based damage (Melin et al., 2022; Nuorteva, 2019; Nuorteva et al., 2022; Terhonen et al., 2023). In Finland, the bark beetle population grew slightly between 2018 and 2020, and the damage increased from 12 600 to 21 400 ha but declined slightly to 20 800 ha and 18 000 ha in 2021 and 2022, respectively. In 2021, the bark beetle damage was slightly lower than in 2020, but in 2022 the Finnish Forest

Centre received reports of more damage than usual from more-northern areas (South Karelia and North Savo). The reported salvage logging due to insect outbreaks was 3 400ha by November 2022, which is 3 times higher than in 2021 (Metsäkeskus, 2022). Overall, beetle damage in Finland has been increasing during the last decade, and in the future, the risk of more intense damages is rising (Neuvonen, 2020). It should be mentioned that the storm damages to forest in Finland have also increased from 2018 to 2022: from 249 000 ha to 276 300 ha (being highest in 2021: 307 100 ha). Forest damage could be influenced by the overall well-being of the trees. Additionally, the efficiency of collecting the fallen trees influences the bark beetle spread and outbreaks, since they provide prime habitat for the beetle population to grow (Hroššo et al., 2020).

The number of forest fires in Finland in 2018 was the second highest recorded, but approximately only 1 200 ha of forest was damaged (Lehtonen & Venäläinen, 2020). In 2019 the area damaged by forest fires was roughly 500 ha, in 2020/2021 slightly over 1 000 ha and in 2022 only slightly over 265 ha (Aalto & Venäläinen, 2021; Melin et al., 2022; Terhonen et al., 2023). Kosenius et al. (2014) estimated the financial losses of forest fires in Northern Karelia and the Republic of Karelia for the years 2009 to 2012. They considered the direct and indirect costs when preparing estimates for the total costs. Venäläinen et al. (2016) used the estimates made by Kosenius et al. (2014) to derive a median estimate for forest fire costs in Finland: 6660 €/ha (estimate ranged from 5381 €/ha in 2009 to 8810 €/ha in 2012). Using the Swedish forest fire costs estimates of Venäläinen et al. (2016) for Finland, between 2018-2021 these caused roughly 25 million € of total damages.

In Sweden, about 90×10^6 m^3 of trees is felled every year (UNECE, 2022), and the total forested area is 27.9×10^6 ha (SCB, 2020). Physiological damage, expressed as crown defoliation, ranged between 17.1% and 17.8% for conifers during 2018–2021 (data for 2022 and for broadleaved trees were unavailable; Michel et al., 2022). In Sweden, bark beetles damaged 3×10^6–4×10^6 m^3 of spruce in 2018, 7×10^6 m^3 in 2019, and 8×10^6 m^3 in 2020 and 2021, more than 20 times the average of the previous years (Öhrn et al., 2021; UNECE, 2022; Wulff & Roberge, 2020). This increase in mortality and damage was caused by the heat and drought in 2018, which allowed for rapid beetle population growth (Öhrn et al., 2021). In Sweden, the dry and warm period of summer 2018 led to the most-severe outbreak of forest fires, estimated at around 25000ha and with 3×10^6 m^3 of wood damaged (NordicWoodJournal, 2018). Using the estimate of Venäläinen et al. (2016), the costs for the year 2018 are more than EUR 166 million. This is a similar estimate as though the forest fires in Sweden in 2014 (14 000 ha; costs – SEK 1 billion) were upscaled to 2018 – EUR 160–200 million.

Norway has a total forested area of more than 12×10^6 ha, of which 8.6×10^6 ha is suitable for forest production (SSB, 2022). On a national level, the drought did not have a serious impact on Norwegian forestry. In 2017, there was a total of 96.5×10^6 m^3 of standing forest, which increased to 987×10^6 m^3 in 2020 (SSB, 2022). Physiological damage, expressed as moderate-to-severe crown defoliation, ranged from 14.9% to 17.2% for conifers in 2018 to 2021 (data for 2022 and for broadleaved trees were not available; Michel et al., 2022).

Norway's annual roundwood production is about 11× 10^6 m^3 (ICP, 2022). Numbers from NIBIO's forest portal Kilden (NIBIO, 2023) show an increase in bark beetles in the region, from 8540 per trap in 2017 to 20 600 in 2021, and although concerning, these levels remain below outbreak levels.

The forest area affected by fires in Norway was more than 3000 ha in 2018 and 2019 and decreased to less than 400 ha in 2019 and 2020 (NIBIO, 2023). A record number of 1906 forest fires occurred between January and August 2018. Wells and drinking water resources were almost empty, low water levels in rivers led to fish dying, and electricity production was at times 20% below normal production levels (−23 TWh), leading to higher electricity costs (MET Norway, 2019). Favorable wind conditions meant that the total area affected was relatively small (2000 ha affected by forest fires), so the consequences were more related to costs and social uncertainty. The Norwegian Directorate for Civil Protection – DSB (2019) estimates that about EUR 8.4 billion (NOK 100 million) was spent on fighting the forest fires; while indirect costs are unknown, they are expected to be high (loss of infrastructure, houses, and cabins). Reports from the county governor of Vestfold and Telemark (Statsforvalteren, 2020, 2021) show some of the consequences for the forests in the region. Vestfold and Telemark county has 6.5×10^6 ha of productive forest and annual growth of 2.75×10^6 m^3 in timber volume. Damage from forest fires has led to an increase in tree felling: 1.1×10^6 m^3 in 2018, 1.23×10^6 m^3 in 2019, and 1.1×10^6 m^3 in 2020, despite low timber prices, especially in 2020. In comparison, the average felling in the 2010–2014 reference period was 896 000 m^3 yr^{-1}. To mitigate the consequences of the 2018 fires, 296 599 saplings were planted in 2019, and another 250 000 in 2020 compared to an average planting of 131 000 in the reference period. While there have been some short term effects, the drought in Norway has not yet had a lasting negative impact. However, there are indications of increased beetle attacks and more deadwood because of periods with heavy snow in winter, and forest authorities are concerned about the future (e.g. Gunther, 2019; Wataha, 2021).

In the UK, woodlands cover approximately 3.24×10^6 ha, with an almost equal distribution between conifers (1.65× 10^6 ha) and broadleaves (1.59×10^6 ha) (Forest Research, 2022a, b). Drought events have significantly impacted these woodlands in recent years. In 2018, early leaf senescence was observed in southern regions due to drought (Michel et al., 2019). Although 2019 was wetter and milder, thus mitigating severe drought impacts (Michel et al., 2020), challenges persisted in subsequent years. The 2020 weather extremes exacerbated ash dieback (caused by *Hymenoscyphus fraxineus*), with widespread future mortality expected (Michel et al., 2021). By 2021, *Phytophthora pluvialis* was affecting mature trees, and 2022's severe drought led to widespread defoliation (Forest Research, 2022c; Michel et al., 2022).

Wildfire activity has varied, with significant events in 2018 (17 689 ha burned), 2019 (28 754 ha), 2020 (13 793 ha), and 2022 (20 362 ha). The average annual burned area from 2011 to 2022 was around 10000ha (EFFIS Annual Statistics for UK, 2023). In England, woodlands span 1.32× 10^6 ha, of which 26% constitutes conifers and 74% constitutes broadleaves (Forest Research, 2022a, b). Notably, 2018 saw severe wildfires in Greater Manchester, which burned 3600 ha and predominantly affected broadleaved woodlands (BBC, 2018; Telegraph, 2018). In 2022, the English fire services managed nearly 25 000 wildfires

(BBC, 2022). Wales, with 310 000 ha of woodland equally divided between conifers and broadleaves, faces frequent fires, especially in the south. In the spring of 2020, fires in the Afan Valley and Seven Sisters forests caused over EUR 115 000 in damage and destroyed nearly 140 ha (NRW, 2020).

Scotland has 1.49×10^6 ha of forest, 74% of which constitutes conifers and 26% broadleaves. The region's forests, including Sitka spruce plantations, are particularly vulnerable to drought (Kirkpatrick et al., 2021). Although no insect damage data were available, the great spruce bark beetle (*Dendroctonus micans*) is now established in southern Scotland (Scottish Forestry, 2023a) and has expanded northwards from 2018 to 2022 (Scottish Forestry, 2023b). Sitka spruce is Scotland's most important commercial tree species, and it is the primary host of this pest. The 2018 drought hindered forest regeneration, while wildfires in April 2018 and 2019 affected significant areas (Copernicus, 2023; The Herald, 2021). In March and April 2022, 95 wildfires were recorded (Highland Council, 2023). Key industries such as whisky production and forestry are heavily reliant on a stable water supply (Kirkpatrick et al., 2021).

Northern Ireland, with 118 000 ha of woodland (54% conifers, 46% broadleaves), experienced wildfires in spring 2022, damaging approximately 720 ha (DAERA, 2022). Ireland's forest area ranges from 551 110 ha (EFFIS, 2023) to 770 020 ha (Forest Statistics Ireland, 2020), with a predominance of conifers (three-quarters, including 51% Sitka spruce) and broadleaves (one-quarter). Forest health remains generally good, with high defoliation rates reported only in 2020 and 2021 (Michel et al., 2022). Ireland's strict pest regulations and island status protect against many forest pests (O'Hanlon et al., 2021). Approximately 3000 ha of forest burned annually from 2018 to 2022, which is moderate compared to record years (EFFIS Annual Statistics for Ireland, 2023).

4.3.3 Damage to forests in the central zone, 2018–2022

Poland has a forest area of 9 242 000 ha (Central Statistical Office, 2017). In 2018, the drought significantly weakened the condition of the forests over an area of 43 500 ha. In the same year, forest damage was observed on 29 400 ha (Jabłonski et al., 2019a, b). In 2019, the order of species from healthiest to most damaged was determined based on the analysis of three parameters: average defoliation, the proportion of healthy trees (up to 10% defoliation), and the proportion of damaged trees (more than 25% defoliation). The order is as follows: *Fagus sylvatica, Alnus* spp. < *Abies* < other deciduous, other coniferous < *Pinus sylvestris* < *Betula* spp. < *Picea abies* < *Quercus* spp. (Wawrzoniak, 2019). In 2020, symptoms of weakened or damaged forest stands caused by disruption of water relations mainly due to drought were reported in 253 out of 430 (i.e. 59%) forest districts (Lech, 2021).

Pests, which until a few years ago were considered of little concern in Polish forests, today cause the death of many hectares (Sierota et al., 2019). As a result of the drought in the years 2015–2019, secondary factors leading to the death of pine stands (which represent 58.2% of the Polish forests), have become more active (Sierota et al., 2019). The key role was played by the following pests: the bark beetle (*Ips acuminatus*), mistletoe (*Viscum spec.*), Sphaeropsis blight (*Sphaeropsis sapinea*), the steelblue jewel beetle (*Phaenops cyanea*), Heterobasidion root disease, and *Armillaria* spp. (Sierota & Grodzki, 2020). Observations in Poland indicate a

significant correlation between drought and engraver beetle (*Ips acumintus*) outbreaks (Jabłonski et al., 2019a, b; Plewa & Mokrzycki, 2017), a species that until not long ago was not considered a significant forest pest (Głowacka, 2013). The occurrence of mistletoe was also underestimated (*Viscum* sp.). After prolonged drought periods, the area of the coniferous (mostly pine) forests heavily infested by mistletoe has drastically increased, from 1400 ha in 2017 to almost 23 000 ha in 2018 (Jabłonski et al., 2019a). Mistletoe was found on 14 forest tree species: the most severely infested were fir and pine trees and to a lesser extent birch, as well as a mixture of deciduous species and spruce (Lech et al., 2019). In addition, well-known forest pests such as the European spruce bark beetle (*Ips typographus*) continue to pose a major threat to Polish forests. The dieback of Norway spruce stands was already increasing in central and eastern Europe in the 1970s and 1980s (Sierota et al., 2019). After the drought in 2015, the Norway spruce decline continues, with new bark beetle outbreaks affecting stands in the Western Carpathian and Sudeten mountains. The ongoing climatic conditions, combined with high bark beetle populations, make the risk of a further outbreak extremely high (Grodzki, 2010).

Recent years have seen significant surface losses on Poland's state forest land due to drought and high temperatures. Drought-related losses were 40 852 ha (2018), 60 356 ha (2019), 58 056 ha (2020), 34 673 ha (2021), and 20 258 ha (2022). High temperature losses (burns, wilt, dieback) were reported affecting 80 ha (2018), 340 ha (2019), 2574 ha (2020), 197 ha (2021), and 244 ha (2022). Long-lasting drought in Poland has also led to a lowering of the surface and GW table, as well as to a decrease in tree growth, stand vitality, and resistance to pathogens and pests (Kwiatkowski et al., 2020). Among the species affected by this process are oaks, where the impact of declining GW has been observed since the late 1980s (Przybył, 1989). Current GW fluctuations further weaken oak trees and accelerate their decline (Skrzecz et al., 2022), e.g. on the Krotoszyn Plateau (Danielewicz, 2016).

Furthermore, the prolonged drought has increased the risk of forest fires. Despite the high number of fires, the situation in Poland is relatively good. The average forest fire in the state forests is only 0.25 ha, which indicates a high efficiency of fire protection systems. According to official statistics, between 2011 and 2020, almost 25 000 fires with a total area of 6049 ha occurred in the areas managed by the state forests, causing losses of approximately PLN39 million. However, the year 2020 was marked by a large fire (6000 ha) in the Biebrza National Park in northeastern Poland.

In the Czech Republic, forest disturbances, mainly by pests, were triggered by drought and high temperature. Near Kostelec and Cernými Lesy, studies found that bark beetle outbreaks were related to the duration of April solar radiation in the previous year and the mean in annual air temperature in the current year (Pirtskhalava-Karpova et al., 2024). In the Bohemian Forest, researchers observed that the surface temperature in stands subsequently attacked was higher in the year preceding pest colonization when compared to intact stands (Kozhoridze et al., 2023). At the beginning of the massive bark beetle attacks, spruce accounted for 50.5% of stands and pine for 16.4% (Zahradník & Zahradníková, 2019). This abundance of bark-beetle-sensitive trees led to the suggestion that the Czech Republic may have been the epicenter of bark beetle outbreaks in Europe (Hlásny et al., 2021) since more than 50% of Czech forests were seriously

threatened by this pest, resulting in high ecological and economic losses (Fernandez-Carrillo et al., 2020). The commonly harvested volume of wood per year is about 15×10^6 m^3, of which around 1×10^6 m^3 is designated wood infected by insects (WII). In 2018, 25.6×10^6 m^3 was harvested and 13×10^6 m^3 was WII; in 2019, 32.5×10^6 m^3 was harvested with 22.8×10^6 m^3 of WII; and in 2020, the estimate ranges between 40×10^6 and 60×10^6 m^3 of WII (Fernandez-Carrillo et al., 2020). The timber damage was almost exclusively caused by European spruce bark beetle infestations (*Ips typographus* L.). The largest forest fire in Czech history broke out in the Bohemian Switzerland area in the northern Czech Republic and spread to Germany. The fire affected an area of about 1060 ha; over 1000 firefighters, 5 helicopters, and 2 firefighting aircraft were needed to get the fire under control (Worlds Aid, 2022). On the German side of the border, an area of about 150 ha in the Saxon Switzerland National Park was affected (DAV, 2022). During the decade of 2010–2020 in the Czech Republic, almost 100×10^6 m^3 of solid timber was harvested and linked to bark beetle attacks, which led to financial losses in the Czech forestry sector of ca. EUR 1.12 billion (Toth et al., 2020). More than half of this volume has been extracted since 2017, and this amount of unplanned salvage logging represents an increase of about 3-fold from 2017 to 2018 (Moravec et al., 2021). There were also clear signs of loss of vitality during the dry period (2015–2019), with growth reductions in five major species due to drought conditions that were observed when compared to the reference period of 2005–2009 (Jiang et al., 2024).

In the German forestry sector, 2018–2020 and 2022 are considered dry years (e.g. DFWR, 2021; NW-FVA, 2022). Monthly data from the Earth observation satellites Sentinel2 and Landsat-8 show dramatic canopy losses in Germany, with coniferous forests in the central part of the country particularly affected – from Saxon Switzerland in the east, through Thuringia, to the Harz Mountains, into the Sauerland region, and finally to the Eifel region in the west (Thonfeld et al., 2022). From January 2018 up to and including April 2021, tree losses were recorded on around 501 000 ha in Germany, which corresponds to 5% of the total forest area. The results of the German forest condition survey show that in 2018, 29% of the trees investigated showed moderate to severe crown defoliation (≥25%), which is the highest value since records began in 1984, when it was 23% (BMEL, 2023a). This value increased to about 26%–37% during the years 2019 through 2022. On a regional scale results are the same, e.g. the forest condition survey in the German federal state of Lower Saxony shows that defoliation values are at their highest level in the time series since 1984 (NWFVA, 2022). High water availability enabled trees to maintain growth in the Leipzig floodplain forest during summer 2018, but the subsequent drought in 2019 caused a significant reduction in tree growth, even in a forest ecosystem with a comparably high water supply, demonstrating the cumulative effect of consecutive drought years (Schnabel et al., 2021).

Even if in Germany deciduous forests are not dying off to the same extent as coniferous stands, they are also strongly affected by climate change. In the forest condition survey (BMEL) of 2020, a record-high number of dead trees was documented across all tree species examined. The survey revealed that only 20% of trees exhibited no crown thinning, with European beech showing an even-more-pronounced decline – only 11% of these trees were unaffected. Specifically, older trees (exceeding 60 years of age) and those growing in drier sites experienced

notably reduced growth rates and increased mortality. These findings were corroborated by additional studies (e.g. Leuschner, 2020; Weigel et al., 2023), which highlight the ongoing stress and vulnerability faced by European beech. Even tree species that are considered relatively drought-resistant, such as Scots pine (*Pinus sylvestris*), have experienced massive mortality since 2018 (e.g. Kunert, 2019, 2020). In this case, in addition to the hot and dry summers, the fungus *Spaeropsis sapinea* (or *Diplodia pinea*) causes pine dieback (Mette & Kölling, 2020).

In Germany, outbreaks of the European spruce bark beetle (*Ips typographus*) have caused widespread damage to forests, particularly during periods of heat and drought. In many cases, there was a need for emergency felling and even deforestation to prevent the pest from spreading (e.g. Bork et al., 2024; Thonfeld et al., 2022). In Thuringia, almost 21×10^6 m^3 of deciduous (mainly beech) and coniferous (mainly spruce) deadwood occurred between 2018 and the end of September 2022, of which around 65% was due to insect infestation and 35% due to drought and storms (TMIL, 2022). In 2022, around 344 000 m^3 of damaged wood (202 000 m^3 of hardwood and 142 000 m^3 of coniferous wood) was registered due to drought alone, without the primary pests being involved. In the period of 2018–2022, 4.9×10^6 m^3 of damaged wood resulted from heat and drought (TMIL, 2022). It is estimated that around 500 000 ha, or 4.4% of Germany's forest area, has been damaged by climate impacts, fires, and bark beetles. These areas will need reforestation to mitigate the impacts of the drought from 2018 to 2022 (BMEL, 2023c). For the approximately 13.3×10^6 m^3 of wood damaged by bark beetles, 95.6% is due to activities of the European spruce bark beetle and 2.8% to the spruce wood engraver (*Pityogenes chalcographus*). Although the latter still plays a subordinate role, it could gain increasing importance given that it specializes in younger spruce stands. This is a large-scale threat in the future in terms of reforestation or rejuvenation with conifers (TMIL, 2022).

The years 2018, 2019, and 2022 were also above average for forest fires in Germany (DWD, 2022; UBA, 2023a). The burnt area in 2022 was more than 5 times the annual average of almost 776 ha (since 1991), and damage was estimated at EUR 30 to 40 million (Feuerwehrverband, 2022). In Germany during 2018–2019, damage due to natural disturbances was estimated at EUR 2.5 billion (DW, 2019). It is difficult to disentangle the exact costs of a big disturbance in the German forestry sector, which generates about EUR 170 billion annually and employs directly and indirectly more than 1.1 million people (Popkin, 2021). Möhring et al. (2021) estimated the economic damage caused by the extreme weather events of 2018 to 2020 in the forestry sector at more than EUR 12.7 billion, which is 10 times the annual net profit of the entire German forest industry.

In the Netherlands, there are clear signs that trees suffered from the drought and heat of 2018, with deciduous species in particular experiencing stunted or no growth (Salomón et al., 2022). On a national level, the average volume of living wood and deadwood increased during 2017–2021, although at a slower rate due to the dry summers in 2018–2020 (NBI-7, 2022). There are several indications of tree mortality: the volume of standing deadwood compared to the NBI-6 (2012–2013) shows an increase from 6.1 to 10.0 m^3 ha^{-1} from 2012–2013 (NBI-6) to 2017–2021 (NBI7), respectively, and lying deadwood increased from 6.6 to 9.2 m^3 ha^{-1} for the same

periods. However, there is no information on crown defoliation. The next systematic monitoring of forests in the Netherlands started in 2022 and will be completed in 2026.

In the northern part of Belgium (Flanders), new forest plantations have suffered from the droughts, especially on sandy soils: several have died in 2018 without further quantification available (CIW, 2019). In 2019, besides young trees, widespread mortality of mature deciduous trees, as well as Norway spruce and larch, was observed. Oak and beech trees exhibited dead tops or crowns, and dying juvenile trees of chestnut, sycamore, and silver birch were observed (CIW, 2020). Additionally, in 2020 it was reported that several trees exhibited needle and leaf loss and that Norway spruce trees in particular had died (CIW, 2021). The annual forest vitality inventory for Flanders (Sioen et al., 2022) provides information on the state of the forests for each year by monitoring trees at approximately 70 locations, each with a radius of about 18m. The annual inventories (Sioen et al., 2019, 2020, 2021, 2022, 2023) provide an indication of trends in vitality (e.g. loss of leaves and needles) but do not provide an overall estimate of the total damage to the complete stock of forests and wood in Flanders. Despite the effects of drought in the years 2019–2020, the year 2021 demonstrated some recovery, with a significant reduction in the loss of leaves and needles (as of the time this text was written, data for 2022 had not yet been published). The inventories also show that the number of damaged trees in the samples increased since 2008 (Fig. 16 in Sioen et al., 2022), with a recent peak in 2020 (30% of broadleaved trees damaged; 20% of deciduous trees damaged) and a decline in 2021.

In Wallonia, the southern part of Belgium, nearly one-third of the 550 000 ha forest is covered with spruce. Accordingly, mortality has been high throughout Wallonia since the beginning of the drought years in 2018. In 2018, 500 000 m^3 of spruce were infested by bark beetles compared to 5000–10 000 m^3 in normal years. This number increased to approximately 1×10^6 m^3 in the years 2019 and 2020 (Saintonge et al., 2021). During the colder and wetter year 2021, the newly infested timber volume dropped again to about 500 000 m^3 (Saintonge et al., 2021). Wildfires occur in Belgium but not excessively, and they were highest in 2021, causing 659 ha of area to be burned (EFFIS, 2023).

In France, from 2018 to 2020, 300 000 ha were affected by forest dieback in public forests alone (ONF, 2020). The northeast is particularly affected by bark beetles. In the two most-affected regions, Grand-Est and Bourgogne-Franche-Comté, 170 000 ha of forest, equivalent to 58×10^6 m^3 of wood, was covered with spruce at elevations below 800m before the 2018–2022 drought event (Saintonge et al., 2021). The 2018–2019 drought and associated bark beetle damage was the main reason for the dieback (ONF, 2020). Salvage logging of the damaged public forests led to the harvest of 6.5×10^6 m^3 of low-value wood in the period of 2019–2020 compared to less than 1×10^6 m^3 on average in a normal year, which represents 26% of the total harvest in public forest (ONF, 2021). If the share of affected spruce stands is extrapolated to private forests, 19×10^6 m^3 of spruce can be considered to have been killed by bark beetles in the two most affected regions in the period 2018–2021 (Saintonge et al., 2021). Interestingly, the damage increases from year to year, reaching a temporary peak of 9×10^6 m^3 in 2021 (Saintonge et al., 2021), although this year was the only one in the period of 2018–2022 that was not particularly hot and dry. The French government has allocated EUR 150 million between 2021 and 2022 to regenerate and adapt the impacted areas (Gouvernement Français, 2020).

The share of harvested wood of all tree species declared as accidental (often related to storm damage) and sanitary (often related to drought damage or insect pests) products in metropolitan France increased from 0.8% in 2017 to 1.5% in 2018 (MAA, 2019a), to 5.5% in 2019 (MAA, 2021a), to 10.6% or 3.8×10^6 m^3 in 2020 (MAA, 2022a) and 4.1×10^6 m^3 in 2021 (MAA, 2023). Spruce is particularly impacted, with more than 2×10^6 m^3 in 2020 (MAA, 2022a).

In addition, higher defoliation rates have been observed since 2015, which is probably largely due to the droughts and heat waves and the resulting increase in pests. While in 1997 only 2.2% of the deciduous trees and 1.8% of the conifers were affected, in 2019 the figures were 9.6% and 4.3%, respectively. In addition to Scots pine (*Pinus sylvestris*) and Norway spruce (*Picea abies*), European beech (*Fagus sylvatica*) is particularly affected (Piton et al., 2021).

In terms of wildfires, the situation in France in the period of 2018–2022 is also exceptional. During this period, researchers observed the 3 years (namely 2019, 2021 and 2022) with the largest cumulative wildfire-burnt area since the start of systematic Copernicus observations in 2006. In 2022, the largest cumulative wildfire-burnt area to date was measured; at 66 393 ha, which was more than 13 times higher than the 2006–2017 average (EFFIS, 2023).

4.3.4 Damage to forests in the Alpine zone, 2018–2022

In Austria, the regions most affected by drought and heat are primarily in the lowlands, particularly in the east (Vienna, Lower Austria, Burgenland), as well as in the southeast (Styria) and the northern foothills of the Alps (Upper Austria, Northern Salzburg). The country experienced severe bark beetle infestations between 2018 and 2022, resulting in significant timber losses, especially in 2018 (5 210 000 m^3), 2019 (4 690 000 m^3), and 2022 (3 750 000 m^3; see Figure 6). In 2022, forest damage in Austria, primarily attributed to climate change, was estimated at approximately EUR 28 million (Bundesforste, 2023). Around 940 000 m^3 of wood was damaged, representing about 59% of the total wood harvested in 2021. The primary cause of this damage was a significant increase in bark beetle infestations, with these pests now spreading up to the tree line at approximately 2000 m above sea level due to climate change (Bundesforste, 2023). Additionally, in March 2022, a massive wildfire in Allentsteig, Lower Austria, burned approximately 800 ha, including 400 ha of forest, making it one of the largest forest fires in Austria's history (Müller, 2022).

Due to rainfall in the summer months, the Alps are usually less hot and dry than it is in lower areas (climate monitoring of GeoSphere Austria, 2024). A study based on normalized difference vegetation index (NDVI) data confirms that drought impacts decrease with elevation, especially above 1500m (Rita et al., 2020).

Damage caused by forest insects in Austria was only sporadically detected, such as in East Tyrol during 2022 (CIPRA, 2022). In March 2022, a significant wildfire occurred in Tyrol, near the German border, where around 35 ha of mountain forest was destroyed in Pinswang (SZ, 2022; Merkur, 2024). The total direct costs for firefighting and necessary measures for burnt areas in the Alpine region, excluding preventive actions, are estimated to be around EUR 75 million per year (Müller et al., 2020).

In Switzerland, in 2018 and 2022, the canopy of numerous beech trees had already changed color by the end of July, with extensive areas of the forest in the Mendrisiotto region appearing brown by August (WSL, 2022). The volume of spruce wood damaged by bark beetle calamities amounts to approximately 800 000 m^3 in 2018, twice as high as in 2017. In 2019, the volume increased further to 1.5×10^6 m^3 before decreasing in 2020 (Dubach et al., 2021) and 2021 to 1.2×10^6 m^3 and 600 000 m^3, respectively, given the colder and wetter spring and summer (Saintonge et al., 2021). A study based on Swiss National Forest Inventory (NFI) data (5092 NFI plots) up to 2017 showed that only 14% of the Swiss forests were classified as naturally disturbed, most of them (59%) by wind, 16% by insects (predominantly bark beetle), 1.2% by fire, and 1.6% by drought (Scherrer et al., 2022). The interim results of the fifth state forest inventory (NFI5) over the survey years 2018 to 2022 clearly show that there is an increase in dead and damaged trees (WSL, 2023b). Spruce has declined in the Jura, the Mittelland, and the foothills of the Alps, while the sweet chestnut has declined on the southern side of the Alps. The decline in ash trees, attributed to ash dieback caused by the fungus *Hymenoscyphus fraxineus,* spread rapidly and reached the inner Alpine valleys within a few years, with East Tyrol being affected by 2010 at the latest (Heinze, 2017). In addition, fewer young trees are growing in a quarter of all forests throughout Switzerland. The Alps, and especially the southern side of the Alps, are particularly affected. Besides the interim results of NFI5, only a few reports were found for high altitudes in Switzerland, as, for example, on a regional increase in bark beetles in the Alps in 2020 (e.g. Schreiner Zeitung, 2020; SRF, 2020).

In Italy, following the Vaia windstorm in 2018, pest activity was initially moderate. However, a significant heat wave in early June 2021 triggered a massive swarming of the spruce bark beetle (Agrar- & Forstbericht Südtirol, 2021). By 2022, around 5000 ha of the 350 000 ha of forest in South Tyrol was infested with the bark beetle (Tagesschau, 2022). The pest then rapidly spread in Tyrol from mid-May 2022 (CIPRA, 2022), with approximately 105 000 m^3 of wood affected in 2021 and around 1×10^6 m^3 in 2022. The total amount of damaged wood from 2018 to 2022 is roughly equivalent to 15 times the normal annual harvest (Dolomitenstadt, 2023).

Additionally, a prolonged drought during the 2017 growing season led to the most-extensive outbreak of simultaneous fires in the Alpine region in the past 30 years. In the Piemonte region, 11 large fires occurred in the autumn of 2017, burning nearly 10 000 ha of mostly broadleaved forests within a week (Müller et al., 2020). Furthermore, in October 2018, one of Italy's largest forest fires occurred in Monte San Lucano, Veneto, burning 632 ha (Müller et al., 2020).

4.3.5 Damage to forests in the southern zone, 2018–2022

Italy was not under extreme drought conditions in spring and summer 2018 (Senf & Seidl, 2021b; Rousi et al., 2023), but it suffered from extended forest damage caused by the extratropical windstorm Vaia over northeastern Italy in autumn 2018 (Motta et al., 2018). Vaia damage accounted for more than 70% of the total roundwood removed in Italy in the year 2018 (Pilli et al., 2021). Although there was no extreme drought in northern Italy in 2018, the precipitation was below normal for the months April, June, and September (Desiato et al., 2018), which might have contributed to the forests being drier than normal and thus more vulnerable to Storm Vaia in October 2018. Italy did suffer from an extreme heatwave and drought in 2017, which contributed to significant wildfire activity and a subsequent burned-

forest total of 16 1987 ha, the highest annual total since 2007 (European Commission, 2018; RAF Italia 2017–2018, 2019).

In general during 1998–2021, there was an increase in defoliation, forest mortality, and leaf discoloration in Italian forests, especially in montane conifer forests, with peaks reached in 2021 (Bussotti et al., 2022) and leaf discoloration mainly observed in deciduous and evergreen oak forests. These high damage levels in 2021 are a result of a combination of increased summer drought and the lagging effect of Storm Vaia of 2018 that compromised the stability of the trees and increased the probability of insect attacks due to high accumulation of deadwood in the forests (Bussotti et al., 2022).

The summer of 2022 was affected by a severe-to-extreme meteorological drought (Toreti et al., 2022a). Northern Italy was strongly affected, facing the warmest and driest winter on record in the last 30 years (Toreti et al., 2022b). It resulted in strong hydrological drought and unusually low streamflow of the Po River, which was also related to the lack of snow in the Italian Alps that winter (Koehler et al., 2022). A study looking at the impacts of the 2017–2022 drought and heatwaves in forest areas in Tuscany found that the most-severe impacts, including defoliation and mortality, were observed in the tall evergreen Mediterranean woodlands and in the aged coppices (holm oaks; Bussotti et al., 2023). The study suggests that the impact of the 2022 prolonged drought on forests could have been larger, but trees might be responding to current climate change via rapid acclimation based on epigenetic modifications (Rico et al., 2014).

Due to an increase in precipitation during 2018–2019 in Spain, there was some recovery or stabilization in terms of forest defoliation and discoloration following the drought of 2017 (AIEF, 2019). However, more-recent reports over areas in northeastern Spain reveal an increase in defoliation during 2019–2021 due to more-severe heat and drought conditions and, in particular, due to extreme events occurring during critical vegetation growth periods (GAN-NIK, 2019). In the period of 2018–2020, physical damage such as drought and wind were the main drivers of forest defoliation, followed by insects. Both drivers cause forest damage 3 to 5 times larger than every other driver (fungi, fires, etc.), and their impacts have increased dramatically since 2014 (AIEF, 2020). In this period, physical damage, insects, and forest fires are the three main drivers of tree mortality in Spain (AIEF, 2020). In 2022, the country experienced almost 270 000 ha of burned area, a drastic increase from previous years amounting to up to 3 to 6 times more surface area compared to 2018–2021. In the 2018–2021 period, around 300 fires per year were recorded versus 400 fires in 2022, indicating not only more fires and a larger burned area but also a larger burned area per fire on average (see Figure 9).

Although Portugal has recently shown increasing frequency of drought conditions coupled with heatwave events (Bezak & Mikoš, 2020; Ribeiro et al., 2020; Vogel et al., 2021), leading to the exacerbation of limiting climatic conditions for plant growth, the situation of Maritime pine (*Pinus pinaster*, one of the most-common species) is, according to Kurz-Besson et al. (2016), not completely discouraging. Detailed information regarding defoliation and wood damaged by insects in Portugal is unavailable since 2006 (ICP Forests, 2007).

Since 1980, the mean annual burnt area has been around 115 000 ha, with a large interannual variability and with particularly severe years, such as 2003 (~425 000 ha), 2005 (~350 000 ha),

or the record value in 2017 (~540 000 ha; EFFIS, 2023). The interannual variability in burned areas in Portugal is attributable to high temperatures and drought, which are influenced by the amount of precipitation during and before the fire season (from May to September). In addition, atmospheric circulation patterns in the summer induce extremely hot and dry spells over western Iberia (Pereira et al., 2005; Russo et al., 2017). Dry conditions contributed extensively to the massive wildfires that took place in Portugal during 2017 (San-Miguel-Ayanz et al., 2020; Turco et al., 2019). The total burned area in Portugal in 2017 corresponds to nearly 60% of the total burned area in Europe in 2017. The economic losses due to the 2017 wildfires totaled around EUR 1 billion, and the local insurance sector declared it to be the costliest natural disaster in the country's history, with pay-outs exceedingly around EUR 270 million (AON, 2018; Global Fire Monitoring Center, 2018).

According to Global Forest Watch, Portugal experienced significant TCL from 2001 to 2021, totaling approximately 1.13×10^6 ha. A notable portion of this loss occurred in 2017 alone, with 226 000 ha lost primarily due to wildfires. In comparison, the cumulative tree cover loss from 2018 to 2022 amounted to 188 000 ha. The loss during this period was predominantly driven by deforestation, with permanent deforestation mainly attributed to urbanization and shifting agriculture.

4.4 Drought legacy

4.4.1 Drought legacy effects

Drought and heat impact vegetation not only immediately but can also have long-term effects that persist for years. Short-term damage assessments often underestimate the overall impact on forest ecosystems. Recovery times vary; for instance, carbon cycle recovery and compositional changes may span several years (Müller & Bahn, 2022). Severe droughts in temperate forests have led to growth reductions lasting up to 6 years, depending on tree species (Orwig & Abrams, 1997). Furthermore, long-term damage assessment is complicated by vegetation adaptation to persistent conditions. For example, pre-existing structural changes in tree hydraulic traits can either mitigate or exacerbate damage, influenced by shifts in plasticity (López et al., 2016). Trees in drier environments often show greater drought resistance (Orwig & Abrams, 1997).

Assessing the impact of consecutive drought years involves disentangling the effects of specific events from ongoing conditions that may influence hazard levels. This task includes evaluating long-term changes in water availability due to extreme droughts and understanding the legacy damage to forest ecosystems from the 2018–2022 drought events. While this section focuses on damage, it is important to recognize that long-term positive effects can also arise following extreme climate events (Müller & Bahn, 2022).

4.4.2 Linking vegetation drought legacy with groundwater drought legacy

GW is a key component of the terrestrial water cycle, contributing dynamics and feedback to vegetation processes on timescales far beyond the weather and seasonal timescales (Aeschbach-Hertig & Gleeson, 2012), which are especially important for the development and persistence of droughts.

The vegetation water supply under meteorological and hydrological drought is determined by the redistribution of moisture in the shallow subsurface (soil) and its hydraulic connection with GW (Yu et al., 2017). Thus, the impact and legacy of drought strongly depends on the local and regional distribution of soil moisture, infiltration, and GW recharge (e.g. capillary rise and baseflow along the rivers). These fluxes and their spatiotemporal dynamics are a function of the subsurface heterogeneity, land surface processes, and climatology. The feedback of GW on vegetation is strongly non-linear and occurs via the capillary rise of water from the free water table or direct extraction of water from GW due to root water uptake. Both processes can be especially pronounced under drought conditions and depend on the vegetation type and associated root depth distribution (Fan et al., 2017). In turn, if the free GW table is at the critical depth along, e.g. a hillslope, even small changes on the order of 10^{-1} m may result in significant feedback on root water uptake and changes in evapotranspiration (Kollet et al., 2008). For example, Rabbel et al. (2018) showed sap flow density data for a Norway spruce stand in the Eifel Mountains, Germany, from observations in a riparian zone and nearby hillslope exhibiting shallow and deeper water table depth. In the riparian zone, the shallow-rooting spruce exhibited generally large evapotranspiration compared to the hillslope. Thus, GW drought legacy that is manifested in increased GW table depths will impact drought legacy effects in forests in all types of vegetation and land surface processes. Because water use by vegetation is consumptive, vegetation constitutes a sink for GW under these conditions. Thus, a positive feedback loop may arise in which GW drought legacy influences vegetation drought, and in turn, vegetation influences GW drought legacy. Since the timescale of GW drought legacy acts far beyond the weather and seasonal timescale (Hellwig et al., 2020; Van Loon, 2015), one can expect a strong connection to shallow-moisture redistribution and drought legacy over very large timescales in regions of critical GW depths.

To assess the connection of drought legacy with GW drought legacy from observations, the state of GW (including soil water) must be known in space and time. The state of GW is usually observed in boreholes via in situ GW table or piezometric head measurements. These measurements provide information at the point scale in space and commonly at low frequency in time because they are usually performed manually and thus not logged continuously. This leads to discontinuous images of the GW state in space–time, which is commonly interpolated with the help of models, inversion, and data assimilation. Note, however, that no collated GW observational database exists over Europe or for specific countries. Thus, the data remain fragmented and dispersed across many political and private institutions, and they are not publicly available. This renders a formal analysis of the connection infeasible within the scope of this study, and only the general principles can be discussed here.

In northern and central Europe, dispersed borehole observations of GW levels revealed that the 2018 drought was indeed one of the most severe in decades and comparable to the drought in 1976 (Bakke et al., 2020; Hellwig et al., 2020). In 2018 in many observation wells, GW levels were at or close to the lowest levels ever observed by in situ measurements (Bakke et al., 2020), resulting in the cessation of capillary rise, a reduction in root water uptake, and severe drought stress, even beyond the year 2018 (Schuldt et al., 2020). For example, Süßel and Brü (2021) studied tree–water relations in 2018 in mature oak stands in southwest Germany. They found that sites with continuous capillary rise toward the root zone maintained a canopy conductance

at 50% of the maximum, while sites with hydraulic disconnection from the water table showed a collapse of conductance and significant leaf shedding. In these settings, the long-term effect of droughts may be especially pronounced because GW recovery after drought is a slow process leading to strong memory effects and an increased probability of drought at the interannual timescale, which was indeed observed in the ensuing years (2019 and 2020) in addition to precipitation deficits (Hartick et al., 2021). It is important to note that vegetation stress under the 2018 to 2022 drought conditions showed distinct spatial patterns, with limited stress along river corridors and extreme stress in the upper parts of hillslopes along ridges (Cartwright et al., 2020). These patterns are directly related to GW processes, specifically GW discharge and recharge, respectively. Under drought conditions, along river corridors, GW discharges as baseflow toward the stream, constituting essentially an outcrop of the GW table, thus leading to shallow GW tables connected to the land surface via capillary rise and root water uptake. In contrast, along hillslopes and ridges, capillary rise for root water uptake is mainly sustained by shallow soil water without a connection to the GW compartment, leading to tight coupling of root water uptake and plant stress with quite-limited soil moisture storage. In the case of GW, these patterns are well-known and are shown by in situ GW measurements. However, the lack of remote sensing information for the subsurface, data scarcity, and fragmentation lead to much-more incomplete spatial coverage of information. Preliminary inspection of leaf area index (LAI) products from remote sensing does not show a systematic pattern at the large scale dependent on topography or the potential GW convergence zone. In the future, a merger of in situ, remotely sensed, and model data with ensuing in-depth analyses will be required to identify potential tree and forest legacy effects induced by GW drought legacy. In this context, data from hyperspectral remote sensing regarding photosynthetic activity may be useful.

4.4.3 Drought legacy effects in forests – the accumulation of long-term damage due to soil moisture deficit

Drought events can leave longer-lasting impacts on forests, depending on which tree demographic processes are most affected (Müller and Bahn, 2022; Rukh et al., 2023). Adult tree mortality can create gaps in forests, altering carbon and water cycles, species composition, and long-term profitability. These gaps also increase understory solar radiation, temperature, and soil dryness, which can lead to further damage through soil hydrophobicity and nutrient loss (Grünzweig et al., 2022). Similarly, the death or weakened vitality of saplings can hinder forest recovery, leaving trees vulnerable to future droughts, storms, fires, and pests (Gliksman et al., 2023). A study from Matías Resina et al. (2020) showed that the impact of drought on tree level resilience was not strongly dependent on its latitudinal location but rather on the type of sites the trees were growing on and their growth performance (i.e. magnitude and variability in growth) during the pre-drought period. Examples of drought damage during 2018–2022 in European forests highlight these impacts. The most-pronounced legacy effects involved saplings and young trees, with long-term seedling establishment varying by location and species (Salomón et al., 2022). In central eastern Germany, the 2018 drought caused 65% defoliation in saplings across multiple species, with some species suffering over 85% defoliation. Despite some recovery, 25%–32% of saplings still showed damage in 2020 (Beloiu et al., 2022). In Scotland, the droughts in 2018 and 2020 caused significant losses, including 50 000 seedlings at a Sitka spruce farm in Galloway and notable mortality rates in privately managed young

forests (Locatelli et al., 2021). In Poland's Brodnica forest district, 20% of trees planted died, leading to replanting costs of approximately EUR 33 000 (LASY, 2023). Similar damage was observed in young spruce and beech trees across Germany (BMEL, 2020). Growth reductions occurred in northern Germany following the 2018 drought, exacerbated by insufficient winter water recharge, with similar reductions in 2019 and 2020 (Beloiu et al., 2022). In Switzerland, forest gross primary productivity recovered in about 50% of forested area by 2019, while 49% remained at 2018 damage levels, indicating a strong legacy effect (Sturm, 2022).

4.5 Discussion

Overall, the findings of this study emphasize that the central zone of Europe is the most vulnerable to drought years, such as those between 2018 and 2022, due to its specific forest composition, climate conditions, and susceptibility to secondary effects like pest infestations. The southern zone, although significantly affected by TCL, exhibited less-severe impacts compared to the central zone. The relatively smaller impact in the southern zone could be attributed to the region's long-term exposure to drought, which may have fostered adaptive mechanisms and built resilience over time. At the same time, the varying occurrence of drought conditions along the southern zone may also have contributed to the moderate impact. In the northern zone, the first impacts of drought and heat start to emerge, although the severity is not yet pronounced. The presence of site-adapted boreal forest tree species is likely to contribute to the region's overall resistance. The Alpine zone displayed the least impact, which may highlight the potential protective role of altitude in mitigating the effects of climate extremes.

4.5.1 Central zone

The central European forests experienced severe impacts during the drought years, 2018–2022, with both coniferous and deciduous species suffering significant damage. Notable crown thinning, particularly among broadleaved species, was observed in France, with similar trends observed in the Czech Republic and Germany. These observations indicate that broadleaved trees across central Europe are increasingly vulnerable to climate-change-related stressors. Conifer defoliation was especially pronounced in the Czech Republic, Belgium, France, and Germany. The region also witnessed high levels of forest damage from pest infestation, underscoring the susceptibility of central European forests to secondary drought effects, such as increased pest activity. The significant rise in TCL and bark-beetle-infested wood highlights the profound impact of prolonged water deficits on these ecosystems, suggesting that the resilience of central Europe's forests is being severely tested by climatic stressors.

The intense drought in 2018, characterized by an exceptionally hot summer, led to early wilting in about 11% of central European forests, with central and east Germany and the Czech Republic being the most affected (Brun et al., 2020; Buras et al., 2021). These drought conditions, combined with above-average water vapor pressure deficits in subsequent years, were the primary drivers of forest disturbances affecting around 4.74×10^6 ha between 2018 and 2020, particularly in Germany, the Czech Republic, and Austria (Senf et al., 2021). The physiological damage from 2018, marked by reduced greenness in Austria, Germany, and Switzerland, significantly contributed to forest mortality, and the reduced greenness persisted into 2019 (Brun et al., 2020; Schuldt et al., 2020). The record-hot summer of 2022 further

exacerbated this trend, with forest greenness decreasing more sharply than in any other summer since 2002, surpassing even the 2018 drought record (Buras et al., 2023; Hermann et al., 2023).

The prevalence of spruce bark beetles in central Europe has increased over recent decades (Fernandez-Carrillo et al., 2020). From 2018 to 2022, drought and heat triggered an unprecedented outbreak, severely affecting standing timber, particularly in the Czech Republic, Germany, and Austria (Hlásny et al., 2019, 2021; Kautz et al., 2023; Nardi et al., 2023). In 2019, over 50% of timber harvests in Austria and Germany, and over 90% in the Czech Republic, were associated with salvage logging due to bark beetle damage (Senf & Seidl, 2021a). The vulnerability of Norwegian spruce monocultures significantly contributed to this damage. Projections suggest a potential 7-fold increase in bark beetle disturbances by 2030 compared to 1971–1980 (Seidl et al., 2014), with a possible 2-fold increase throughout the 21st century depending on climate conditions and forest management practices (Dobor et al., 2020a, b). The cumulative growing stock affected by bark beetles is expected to rise significantly under moderate climate change scenarios, with even greater impacts under more-extreme conditions (Sommerfeld et al., 2021).

In addition to drought, storm impacts must also be considered. While there is no definitive evidence of a significant increase in storm frequency in Germany, windthrow damage notably increased during 2018–2022 (BMEL, 2023a). The trend towards milder winters and increased precipitation outside the growing season in parts of central Europe may contribute to greater windthrow susceptibility, as heavy rainfall can weaken root systems, and drought-stressed stands are more prone to wind damage (Stredová et al., 2020; UBA 2023b).

Economic losses in central Europe's forestry sector during 2018–2022 were substantial, although precise estimates are challenging due to an incomplete understanding of the full economic impacts (Knoke et al., 2021). While direct damage such as the loss of immature trees can be quantified, more complex factors like stand destabilization, market price fluctuations, and impacts on forest workers and machinery are difficult to assess.

4.5.2 Southern zone

In the southern zone, crown thinning in deciduous trees was particularly pronounced in Italy and Spain. This indicates that even regions well-adapted to dry conditions, which have fostered the development of various adaptive mechanisms in both plant species and forest ecosystems, experienced unprecedented stress during these years. Mediterranean vegetation in the southern zone seems to cope better with seasonal droughts through physiological and structural adaptations, such as deep rooting systems and reduced leaf area. Access of roots to deep water reserves enables hydraulic redistribution, whereby plants transport water from moist, deep to dry, shallow soil layers through their root systems along a water potential gradient (Prieto et al., 2012). This mechanism, occurring frequently in the southern zone (Kurz-Besson et al., 2006; Peñuelas & Filella, 2003), improves plant nutrition, extends root lifespan, and preserves hydraulic conductance in the xylem during dry periods.

Observed damage attributed to increasing temperatures and drought conditions in the southern zone shows that forests are encountering significant repercussions. Data on damage caused by wood-boring insects are unavailable, suggesting that insect pests may not have posed a major

threat between 2018 to 2022. Nevertheless, a significant increase in TCL compared to the reference period was observed. Assessing the incidence of wildfires during the period of 2018–2022 was not possible. However, the exceptionally severe wildfires in 2017 with staggering losses, particularly in Portugal, necessitated their inclusion in this study. The devastation caused by wildfires presents a continuously growing challenge for southern Europe, despite wildfires generally being a part of the southwestern European ecosystems. Italy was strongly affected by the windstorm Vaia in 2018. We found no increase in insect infestation during the period from 2018 to 2022 nor in the years prior. Up to 2018, 3×10^6 ha of forest has been reported as having been converted into shrublands or grasslands in the European Union Mediterranean countries. Fire and drought are the main drivers underlying this deforestation (Karavani et al., 2018). In Spain, forest health showed some recovery between 2018 and 2019, contrasting with greater damage in central Europe (AIEF, 2019; Blunden & Arndt, 2019).

The situation for Maritime pine (*Pinus pinaster*, one of the most-common species) in Iberia is not completely discouraging. According to Kurz-Besson et al. (2016), wood radial growth and density highly benefit from the strong decrease in cold days and the increase in minimum temperature. Yet, the benefits are hindered by long-term water deficit, which results in different levels of impact on wood radial growth and density. Despite the intensification of long-term water deficit, tree ring width appears to benefit from the minimum temperature increase, whereas the effects of long-term droughts significantly affect tree ring density. Since the particularly extreme year 2017, stringent prevention and rapid response measures have been implemented in the area. When comparing the periods 2007–2017 and 2018–2022, the total number of fires has decreased by half, particularly on days of high fire danger. Larger fires have occurred less frequently since 2017. The average number of fires burning more than 1000 ha decreased from 19 events to just 8 in recent years. Although forest losses are decreasing in the latest period, Portugal experienced an increasing trend in forest area loss due to fires between 2001 and 2019 (Tyukavina et al., 2022). Without the unique events in 2017, the decline in fire incidents might not have been as apparent. This highlights the challenges of interpreting long-term fire trends, as exceptional circumstances can significantly impact annual statistics. Furthermore, the effective implementation of prevention strategies and rapid response efforts in the Iberian Peninsula have played a substantial role in mitigating fire damage (e.g. REA, 2024).

4.5.3 Northern zone

The relatively low impact observed in the northern zone suggests that it has not yet experienced the full extent of climate extremes or that its forests are more resilient. Nonetheless, the data indicate potential vulnerability to future drought impacts, highlighting the need for ongoing monitoring and conservation efforts. It is important to note that the lack of data on crown defoliation for broadleaves limits a comprehensive assessment of the situation.

The northern zone's forests might benefit from a reduced severity of climate extremes i.e. more consistent precipitation patterns and cooler temperatures, which reduce evapotranspiration rates and alleviate drought stress. Several indices based on Europe-wide data support this assumption, showing that the northern zone was still affected during the 2018–2022 drought period. Specifically, evidence from Sweden reveals significant insect damage to coniferous

wood, with high levels recorded in 2018 and even higher levels in subsequent years (2019–2021). Additionally, TCL increased markedly, from 0.7% to over 1%.

Overall, in Fennoscandia, forest management during the last decades has favored conifer monocultures, causing Norway spruce and Scots pine to be the dominant species (Huuskonen et al., 2021). This means that the large forest ecosystems may be more vulnerable to climate extremes. For conifers, however, no significant differences in defoliation were observed in the northern zone or within individual countries within this zone. This suggests a relative stability of conifer health in this region despite variations in environmental conditions. Overall, our findings suggest that conifers in the northern zone exhibit a greater resilience to drought and heat stress compared to those in other regions.

The example of Norway may make it clear that Fennoscandia is probably the area where climate change has had fewer consequences thus far for forest ecosystems. In Norway, larger seasonal differences in precipitation/drought and temperature are expected. Periods of drought are replaced by periods of heavy rains and flooding. The consequences are moderate for forests but can be severe for agriculture in particular during dry seasons. So far, the effects seem to cancel each other out (Bardalen et al., 2022; Miljødirektoratet, 2023). For example, while winter, spring, and summer in 2021 were dry, Norway experienced an autumn and winter with more rain than usual, with GW levels that went above normal. Insect attacks after the 2018 drought could have become severe, but cold and wet preceding years probably mitigated the impact. Overall, the major concern in Norway is periods of drought followed by periods of heavy rainfall leading to passing floods.

In the British Isles, the damage during the study period was not exceptional. Indirect signs of previous drought impacts were noted, with 77% of UK respondents agreeing on the need for protective measures against pests and diseases (Forest Research, 2021). An earlier spatial-modelling study (Forest Research, 2008) even predicted an improvement in tree growth due to a warmer climate in Scotland in the future, particularly in southern and eastern Scotland for high-quality broadleaved trees, on suitable deep fertile soils, and for conifers on sites where water and nutrients are not limiting. However, a breeding population of the European spruce bark beetle (*Ips typographus*) has now become established in southeast England, likely arriving by flight across the English Channel following a large-scale dispersal from continental Europe due to extreme weather in 2021–2022 (Inward et al., 2024). This poses a future threat to the spruce in the UK, which is the dominant timber species. It should also be noted that when it comes to drought damage recorded in England and Scotland in 2018, wildfires only ranked third, while impacts on freshwater ecosystems and water quality ranked higher (Turner et al., 2021).

4.5.4 Alpine zone

The Alpine zone exhibited minimal impact, with no statistically significant differences observed in any forest health or damage indicator used in this study. This limited impact may be attributed to the region's higher altitudes, which might provide mitigating effects such as cooler temperatures or reduced evapotranspiration, potentially buffering the area from extreme drought conditions. But it should be noted that mountain forests are particularly under pressure

from climate change impacts due to their temperature limitation and high exposure to warming (Albrich et al., 2020). Such impacts can vary greatly with elevation and topography (e.g. Lindner et al., 2010; Thrippleton et al., 2020) and require a careful study addressing the target species and the abiotic conditions. The main tree species in central European mountain forests are Norway spruce, European beech, and silver fir. All of them are late successional, shade tolerant (Dyderski et al., 2023), and sensitive to drought stress. Additionally, drought can also destabilize mountain forests and result in soil erosion, landslides, and rockfalls. Warmer temperatures, reduced precipitation, and shorter cold periods can lead to reduced snow cover and trigger the distribution of harmful organisms or alien and invasive species that have an impact on biodiversity (Eriksen & Hauri, 2021). Since the length of the growing season decreases with altitude, a warmer climate could also lead to more growth as long as there is sufficient access to water, as confirmed by previous studies (e.g. Dyderski et al., 2023; Thom & Seidl, 2022). Tree lines will shift upwards over a longer period, and tree species from the lowlands will establish at higher altitudes. A simulation of forest dynamics in the northern Alps predicts, for the first half of the current century, the probability of increasing gains in stem density, structural complexity, and tree species diversity (Thom et al., 2022). An inventory of Alpine drought impact reports conducted by Stephan et al. (2021) reveals that pre-Alpine areas experience more-significant effects compared to higher elevations. The majority of reported impacts are related to agriculture and public water supply, with less focus on forestry and terrestrial ecosystems. Drought impacts are found to be most severe during summer and early autumn, likely due to the mitigating effect of spring snowmelt on water shortages. The analysis also highlights spatial variability across the Alps, with notably greater impacts observed in the northern Alpine regions. Eriksen and Hauri (2021) mentioned that forest fires have traditionally been more common on the southern side of the Alps, and the countries have introduced better forest fire management strategies.

4.5.5 Forest fire and tree cover loss

Contrary to our expectations, no significant differences in forest fire outbreaks were observed between the dry period (2018–2022) and the reference period (2010–2014). This trend was consistent across the northern, central, Alpine, and southern zones. Additionally, consultations with local offices, such as those in Austria, confirmed that there were neither more fires nor larger burnt areas during 2018–2022 compared to the reference period. The absence of significant differences in wildfire damage across all zones suggests that the fire prevention measures implemented, such as enhanced forest and fire management, monitoring, and rapid detection and response, as well as international collaboration, might play a more substantial role than drought conditions alone (e.g. REA, 2024). In Nordic countries, for example, differences in early detection, forest road density, and the number of local fire brigades contribute to variations in forest fire incidence and damage (Lehtonen & Venäläinen, 2020). Wildfires in the Alps are influenced by a range of factors, including the high level of human activity driven by recreational activities (Garbarino et al., 2020; Müller et al., 2020). Consequently, there is a complex interplay of elements affecting fire activity, including climatic conditions, forest management practices, preventive measures, public awareness, and the effectiveness of firefighting efforts. The countries in the southern zone experienced severe impacts from forest fires and not just during the 2018–2022 period. Our decision to include data

from 2017, despite not being originally part of the study design, provided insights into the significant impact of fires during that year, especially in Portugal where a vast area of forest land was affected. This emphasizes the importance of considering extreme events and their implications for forest management and conservation efforts. Further research is needed to explore the underlying drivers of fire activity and to develop effective strategies to mitigate the impacts of forest fires in vulnerable regions. For Alpine forests, data availability was limited to Austria and Switzerland for both periods, showing no significant differences in fire damage. Identifying trends in fire risk in the Alps is challenging due to differences in forest fire documentation systems between Alpine countries (Müller et al., 2020). Based on the available data for 2018–2022, the occurrence of forest fires in the Alps appears consistent with the long-term average. Although our study found no increase in forest fires in Europe during the hot and dry period of 2018–2020, research in the USA has clearly linked the rising frequency and severity of forest fires to climate change. For instance, northern and central California experienced a 5-fold increase in summer burned-forest area during 1996–2021 compared to 1971–1995 (Turco et al., 2023). In the western United States, climate change and other factors have doubled the cumulative forest fire area since 1984 (Abatzoglou & Williams, 2016). Global projections for the 21st century suggest that climate change will worsen fire weather conditions, affecting a significant portion of the burnable land worldwide (Abatzoglou et al., 2019). The significant disparities in TCL observed across European regions between the dry period of 2018–2022 and the reference period of 2010–2014 highlight the complex interactions between human activities, natural phenomena, and climate change, emphasizing the importance of comprehensive forest management strategies to mitigate the impacts of environmental changes on forest ecosystems. The escalating frequency and intensity of extreme weather events such as storms, droughts, and wildfires pose significant threats to forest health and resilience. However, forests are under increasing pressure, not only from climate extremes but also from human activities such as logging, deforestation, and urbanization, underscoring the urgent need for proactive measures to address these challenges. Further research is needed to better understand the specific drivers behind the disparities in reporting and to develop targeted interventions for sustainable forest conservation and management.

4.5.6 Future trends, biophysical feedback, and impacts on forests

Future global warming is expected to lead to more-frequent and intense periods of hot and dry conditions in European regions (e.g. Seneviratne et al., 2021), which will further enhance climate-related risks to European forests. Furthermore, extreme levels of compound heat and drought stress are projected to occur successively year after year, with a much higher likelihood in the coming decades than in recent years (Suarez-Gutierrez et al., 2023). For example, Hari et al. (2020) found a 7-fold increase in the occurrence of consecutive drought events as of 2018–2019 in Europe under SSP5-8.5 (Shared Socioeconomic Pathway). Gazol and Camarero (2022) expect an increase in forest drought mortality over the next decades due to the more-frequent compounding of extreme drought and heat waves. Martinez del Castillo et al. (2022) project severe future growth declines in European beech forests, ranging from 20% to more than 50% by 2090 depending on the region and climate change scenario (i.e. CMIP6 SSP1-2.6 and SSP5-8.5). This is in line with CMIP6 (SSP2-4.5) multi-model mean simulations, which support the notion that mean annual precipitation decreases with increasing proximity to the Mediterranean,

linked to roughly similar spatial changes in surface runoff (IPCC, 2021a, b). At the same time, evapotranspiration increases the further east in Europe one gets (IPCC, 2021a, b). Combined, those two meteorological aspects lead to a pronounced surface-soil moisture deficit, which increases the (hydrological) drought risk substantially (IPCC, 2021a, b). Accordingly, forest disturbance regimes are expected to intensify with continuing global warming, leading to increasing forest biomass losses due to windthrow, fires, and insect outbreaks (Forzieri et al., 2021; Patacca et al., 2023).

Biophysical feedback from land use changes on near-surface temperature can be locally or regionally on the same order of magnitude as those associated with the effect of global greenhouse gas forcing (e.g. de Noblet-Ducoudré et al., 2012). The first regional climate model (RCM) ensemble experiments in the framework of the CORDEX Flagship Pilot Study (FPS LUCAS) investigated the effects of extreme forest cover changes on local and regional climate in Europe (Rechid et al., 2017). Davin et al. (2020) found significant biophysical effects of reforestation and afforestation on regional and local climates seasonally, with RCMs showing consistent winter warming due to albedo changes but differing summer temperature responses due to varying evaporative fractions. Summer temperature changes are mainly driven by land processes, while atmospheric processes dominate winter responses. Breil et al. (2020) found opposing effects of reforestation and afforestation on the diurnal temperature cycle at the surface and in the overlying atmospheric layer. Most RCMs simulate cooler daytime and warmer nighttime summer surface temperatures, aligning with other observational studies. In contrast, the diurnal temperature cycle in the overlying atmospheric surface layer is increased due to higher surface roughness, which increases turbulent heat fluxes. Sofiadis et al. (2022) investigated the impact of reforestation and afforestation on the seasonal soil temperature cycle using the LUCAS RCM ensemble, finding a general reduction in the annual amplitude across Europe, although not all models showed this trend. Observations at paired FLUXNET sites confirmed summer ground cooling in forested areas compared to open areas. While most models align with this trend, variability in change magnitude exists. Daloz et al. (2022) explored the snow–albedo effect of FPS LUCAS RCMs in Sub-polar and Alpine climates, and Mooney et al. (2022) examined extreme forest cover changes within FPS LUCAS simulations. Their findings suggest that reforestation and afforestation reduces the snow-albedo sensitivity index, enhancing snowmelt with robust direction but uncertain magnitude of change. The FPS LUCAS phase 1 simulations highlight the significance of biophysical feedback from forest cover changes in Europe, with potential for intensification under further climate change through regional and local processes.

4.6 Conclusions

Our main conclusions from this study are as follows.

1. European forests are highly vulnerable to heat and drought, with even currently resilient ecosystems at significant risk of severe damage in the decades to come.
2. The geographical variability in the distribution of forest damage needs to be integrated into Europe-wide strategies to effectively mitigate future impacts.

3. The study underscores the challenges in data collection and highlights the necessity for harmonized data and enhanced monitoring to address future environmental challenges effectively.

European forests are critically vulnerable to the combined effects of increasing heat and drought, which threaten even those ecosystems currently deemed resilient. This vulnerability is likely to escalate, leading to severe consequences such as heightened tree mortality, shifts in species composition, increased risk of insect pests and wildfires, and diminished forest productivity and carbon sequestration. These potential impacts are far-reaching, undermining the goals of reforestation and climate-smart management efforts (Albrich et al., 2023; Verkerk et al., 2022) and potentially exacerbating local and regional climate extremes (Lejeune et al., 2018).

As extreme heat and drought are projected to intensify, persist longer each year (Hundhausen et al., 2023), and become more frequent (Suarez-Gutierrez et al., 2023), the impacts on forest ecosystems are likely to increase. Central Europe is already facing considerable stress from these conditions, and other regions are expected to experience heightened impacts as well. Global warming is forecasted to prolong thermal summers and shorten winters in northern Europe (Ruosteenoja et al., 2020). The European Alps are predicted to undergo substantial warming throughout the 21st century, accompanied by a marked decrease in snow cover at lower elevations (Kotlarski et al., 2023). Additionally, regions such as the Iberian Peninsula may see persistent drought conditions by the late 21st century (Moemken et al., 2022). These projected changes highlight the urgent need for comprehensive adaptation and mitigation strategies to address the increasing frequency and severity of extreme climate events.

While the extent of damage might have been anticipated, the surprising element is the pronounced heterogeneity in its distribution across different regions. This variability underscores the necessity for Europe-wide strategies that accommodate regional differences. Effective mitigation and adaptation efforts must integrate these diverse regional impacts to comprehensively address and reduce future damage. Overcoming language barriers and improving information accessibility are essential for not only mitigating climate impacts but also raising public awareness of the severe effects of drought and heat. Forest managers must be better equipped to tackle these challenges through adaptive-management techniques and the selection of climate-resilient tree species, mixtures, or provenances. Tailored climate information, such as that demonstrated by Bülow et al. (2024) for the Karlsruhe municipal forest, is crucial for this purpose. Thus, a comprehensive, transdisciplinary approach to managing forest vulnerability should include robust forest management practices – such as species choice, thinning, or prescribed burning – alongside climate adaptation measures, early warning systems, and wildfire risk reduction strategies. Enhancing forest resilience through these measures on a regional scale will be pivotal in addressing future environmental challenges effectively.

The assessment and management of forest damage are significantly complicated by substantial challenges in data collection and reporting. This study highlights notable inconsistencies in impact reporting across sectors and countries, characterized by delays and gaps in data availability. For example, Spain’s national forest damage inventories were outdated at the time

of this study (AIEF, 2020), and comprehensive data for the Alpine zone were particularly scarce. To illustrate another example, the Swiss stone pine (*Pinus cembra*), which is crucial to Alpine forests, grows in small, fragmented populations across Switzerland, Germany, Austria, and Italy (EUFORGEN, 2024). Many natural systems extend across national borders, and understanding the impact of climate change on the Alps, as well as other regions, necessitates a broader, cross-national perspective. Additionally, while a description of heat and drought damage to grasslands was planned, limited data availability restricted this assessment despite the critical ecosystem services provided by grasslands. These inconsistencies in data availability impede the ability to rapidly assess multi-country drought impacts and develop effective responses. Addressing these challenges requires the establishment of harmonized data collection and enhanced forest monitoring. A unified, accessible platform for drought damage data and improved cross-linguistic and cross-sectoral communication are essential for effective impact assessment and response formulation.

To effectively address the complex challenges posed by recurrent heat waves and droughts, a comprehensive and collaborative approach is essential. The impacts of these extreme climate events extend beyond forests, affecting water resources, air quality, recreation, wood supply, and overall human wellbeing, and can also heighten risks such as political instability through forest fires and climate feedback. Recent extreme weather has highlighted deficiencies in current preparedness and the critical need for enhanced information accessibility for forest managers. Developing adaptive management techniques and climate-resilient forest strategies requires the joint efforts of researchers, policymakers, and forest managers. Integrating forest management, climate change adaptation, and global greenhouse gas reduction strategies is crucial for mitigating future environmental impacts and ensuring broader ecological and societal stability.

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5 A case study on forest practitioners' perspectives on climate extremes: consensus on impacts and conflicts in responses

Abstract

Climate extremes present significant challenges to the German forestry sector, impacting forest ecosystems, biodiversity, and overall forest health. This study examines the perspectives of forest practitioners regarding the impacts of climate extremes, such as drought, heat waves, storms, and heavy rainfall, as well as their proposed responses and potential conflicts. Utilizing a transdisciplinary approach, semi-structured interviews were conducted with 28 forest practitioners. The findings reveal that over 89% of practitioners acknowledge drought as the most significant climate extreme affecting forests, highlighting its detrimental impacts on tree health and forest ecosystems. Drought-related damage since 2018 has also resulted in significant economic losses and necessitates large-scale reforestation. Notably, two divergent management approaches were identified: those prioritizing wood production (FWP) tend to focus on economic viability and timber management strategies, while those emphasizing protection and recreation (FPR) concentrate on ecological sustainability and biodiversity conservation. There is a broad consensus on the impacts of climate change, but responses remain contested. Both groups agree on the importance of promoting mixed, multi-layered forest stands to enhance resilience to climate extremes. However, important differences remain: the FWP group advocates active interventions and favors conifer species such as spruce for economic reasons, while the FPR group emphasizes natural processes and prefers native species like beech. Although climate adaptation serves as a shared rationale, their underlying priorities differ considerably. These insights underscore the need for integrating diverse perspectives in forest management to effectively address the complexities of climate change, facilitating collaborative approaches that address both economic aspects and environmental co-benefits through integrated forest management.

5.1 Introduction

Climate extremes pose significant challenges to German forestry, affecting ecosystems, biodiversity, and overall forest health (Bastos et al., 2021, Knutzen et al., 2025). Extreme weather events such as droughts, heat waves, storms, and heavy rainfall are expected to occur more frequently and/or with greater intensity (Cardell et al., 2020). Many of these events have already become more likely due to human-induced climate change (IPCC 2021), including droughts (Bevacqua et al., 2024). Extended droughts increase tree stress and susceptibility to pests and diseases (Frank, 2021), while heat waves reduce growth and increase mortality (Haberstroh et al., 2022). Storms between 1950 and 2000 accounted for over half of the total wood damage caused by weather extremes (Schelhaas et al., 2003), with Kyrill in 2007 alone causing around 49 million m^3 of timber loss in Germany (Gardiner, 2021). Drought between 2018 and 2020 led to an estimated 180 million m^3 in wood loss, triggering reforestation efforts over 285,000 hectares and economic damages in the range of €13 billion (BMEL, 2020; BMEL,

2022). Heavy precipitation is also known to affect forest soil and infrastructure (Schauwecker et al., 2019). Mixed and structurally diverse forests help buffer these impacts by enhancing biodiversity (Jactel et al., 2017), improving microclimates and water retention (Floriancic et al., 2022), and providing stable carbon storage (Luyssaert et al., 2008). Rising temperatures may further disadvantage native species and favor invasive ones (Martinez del Castillo et al., 2022), while promoting pest outbreaks such as bark beetles (Hlásny et al., 2021). While forest fires are currently rare in Germany, climate change may increase wildfire risks, adding challenges for management and firefighting (Fekete & Nehren 2023, Grünig et al., 2023).

These changes threaten wood production and occupational safety, increasing the need for effective adaptation strategies (FAO, ILO, UN, 2023; Keenan, 2015; Rosenkranz et al., 2023). To address these pressures, the forestry sector is adopting measures such as promoting climate-resilient species, sustainable management practices, and early warning systems (Hanewinkel et al., 2022; Madruga de Brito et al., 2020; WBW, 2021). Public awareness and cooperation are being strengthened to support these efforts (Bülow et al., 2024; UBA, 2022), aiming to balance economic, protective, and recreational functions.

Our study investigates these challenges using a transdisciplinary approach linking practice and science (Mauser et al., 2013; Renn, 2021). We investigate how forest practitioners perceive climate extremes and what strategies they consider effective in response. Given the multifunctionality of forests - anchored in German forest law since 1975 (FFA, 1975) and reinforced by European forest policy (BMEL, 2022; COM, 2006; NBS, 2021) - it is essential to consider the diverse perspectives of different forest users. Practical, context-specific knowledge is key to sustainable forest management under climate change. Understanding practitioners' views can thus help develop strategies that are both realistic and broadly supported.

In this study we aim to assess and quantify practitioners' perceptions employing a transdisciplinary research approach. What are the users' needs, and how can our research strategy reflect them in an objective, transparent, and mutually beneficial way? Considering the challenges of interdisciplinary work, which includes cross-institutional collaboration and cooperation, we follow established recommendations for bridging science and practice (Bammer et al., 2020; Jahn et al., 2012; Scholz 2011), often referred to as "integrative research" (Brinkmann et al., 2015; Schuck-Zöller et al., 2023). Against this backdrop, this study addresses the following questions:

1) How do forest practitioners perceive the impacts of current climate extremes on forest ecosystems and their work managing the forests?

2) Is there general agreement among forest practitioners on the impacts of climate change and optimal management responses, or do perspectives diverge?

3) What adaptation strategies and management responses are forest practitioners implementing to address the challenges posed by climate extremes?

To answer these questions, we proceed as follows: first we introduce our interview methodology as well as the underlying concepts of transdisciplinarity and co-creation. We then present our

results, notably concerning species selection, forest management practices, and climate change mitigation, highlighting differences among forest practitioners. In the subsequent discussion we compare our results with the existing literature before drawing conclusions in the last chapter.

5.2 Methods

5.2.1 Applying transdisciplinary concepts and co-creation to forestry contexts

This study draws on two core concepts of "integrative research": *transdisciplinarity*, rooted in environmental and sustainability sciences, and *co-creation*, developed in economics (Schuck-Zöller et al., 2024). Mauser et al. (2013) bring both terms together and describe - rather implicitly - the *ideational* approach as transdisciplinary and the *joint research activities* as co-creation.

Transdisciplinary research goes beyond disciplinary and interdisciplinary research by involving stakeholders directly in the research process. It aims at practical challenges (Hirsch-Hadorn et al., 2008) and their management (Biggs et al., 2021; Hoffmann-Riem et al., 2008; Lang et al., 2012; Renn, 2021; Von Wehrden, 2019). Transdisciplinary discourse and research have developed since the 1990s, especially in the environmental and sustainability sciences (Vilsmaier & Lang, 2014). The potential of this form of research is seen in capturing complex problems by considering different – scientific as well as real world perspectives – and enabling a linkage of practical and scientific knowledge (Biggs et al., 2021; Krohn, 2008; Lam et al., 2021; Pohl & Hadorn, 2006; Renn, 2021; Von Wehrden, 2019). Transdisciplinary research processes can be structured by a phase model, distinguishing different problem approaches especially in the following three phases (Jahn et al., 2012): i) problem formulation and transdisciplinary team building, ii) knowledge integration, and iii) re-integration of results into science and practice.

Problem framing integrates diverse perspectives to capture an issue's full scope and identify knowledge and action needs. It requires involving those directly affected, turning research into a process of mutual learning and negotiation between science and society (Lam et al., 2021).

The diversity of complex societal problems has led to a broad range of transdisciplinary formats and methods, particularly in sustainability science and social sciences (Biggs et al., 2021; Defila & Di Giulio, 2019). Examples of methods are actor and context analysis, interviews, questionnaires or visioning workshops as well as methods for successful interaction between practitioners and scientists (Bergmann et al., 2012; Defila & Di Guilio, 2019; Lam et al., 2021).

In our case-study we focused on interviews with forest practitioners as a rather established method of transdisciplinary work with stakeholders (Kujala et al., 2022; OECD, 2020; Steger et al., 2021), which is true from the perspective of academics as well as practitioners in the forest sector (Jakobsson et al., 2021). The COVID-19 pandemic made on-site events and in-person meetings unfeasible from spring 2020 onward. As a result, semi-structured online interviews proved to be the most effective method for timely stakeholder engagement. Similar experiences are reported in the literature (Hall et al., 2021; Köpsel et al., 2021).

Following Renn (2021) and Schuck-Zöller et al. (2024), the transdisciplinarity or ideational and the co-creational or joint research activity approach are our conceptual methods. They can be

seen as a modular but coherent framework to integrate transdisciplinary knowledge into societal discourse (Renn, 2021). Transdisciplinarity serves as a bridge between science and action (Bergmann et al., 2005, 2012; Lang et al., 2012; Renn, 2021). In addition to classical features of interdisciplinary cooperation, the linking of research to relevant contexts and a focus on complex and socially controversial problems promotes a deliberative methodology to combine scientific knowledge with the experience and contextual knowledge of affected people (Jahn et al., 2012; Renn, 2021). Co-creation emphasizes dialogue between scientists and stakeholders as equal partners, combining scientific and experiential knowledge in a shared learning process (Renn, 2021).

Our dialogue-based approach acts as a merger of scientific and practical knowledge, which has proven effective in a forest management context (Ciccarino et al., 2023). The relevance of stakeholder participation is growing as also demonstrated by Jakobsson et al. (2020) for southern Sweden, where growing pressure on forests bears the risk of conflicts between stakeholder groups.

5.2.2 Knowledge transfer through interviews with forest practitioners and analysis

Interviews, averaging 90 minutes each, were conducted online with 28 forest practitioners. In some cases, follow-up interviews were arranged to explore key insights in greater depth. One interviewer moderated the semi-structured interviews, while two others took notes and ensured all topics were covered as planned. Each interview began with a brief self-introduction by the practitioner, covering their role and a short inventory of the forest they manage (Figure 11). Subsequently, participants were asked about their main management goal, which was categorized as: (i) wood production (WP), (ii) forest and biodiversity protection (P), or (iii) recreation (R). We then asked experts to rank which climate extremes—such as heatwaves, droughts, heavy rainfall, and storms—are most relevant to forestry, inviting participants to mention other significant extremes if applicable and to identify the key impacts of each. The final part of the interview was a less formal discussion where practitioners elaborated on the major impacts of climate extremes and discussed silvicultural responses to these challenges.

The practitioners interviewed brought extensive experience in forest management (Table 2). The primary stakeholders of interest are forest managers and district foresters—those directly confronted with and responding to the impacts of climate extremes. Another important set of actors includes senior forest officials, such as forest office heads, who translate field-knowledge into strategies and guidelines to address the challenges posed by climate change. To ensure a broader representation of perspectives, interviews were also conducted with forest owners and independent consultants. Interviewees were selected through our networks, recommendations from colleagues, targeted internet research, and personal outreach to motivated experts, all based in one of two model regions: the northern region (Lower Saxony, Hamburg, Schleswig-Holstein) and the southwestern region (Rhineland-Palatinate, Baden-Württemberg).

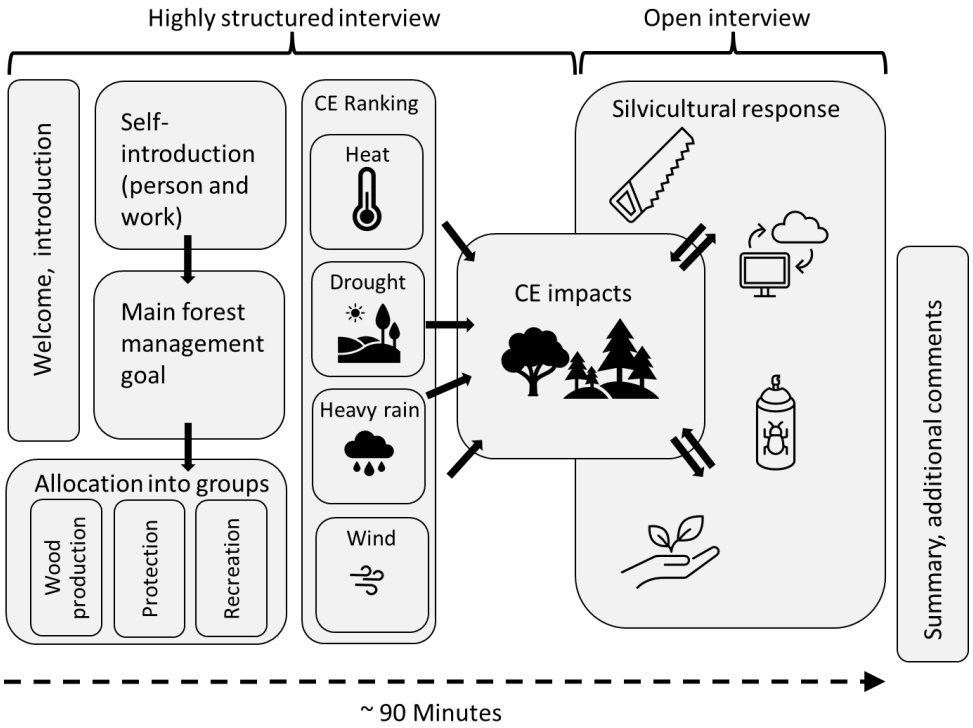


Figure 11: *Structure of the interviews conducted with forest practitioners*
CE = Climate extremes

To streamline analysis, we merged the three original categories—wood production, protection, and recreation (Figure 11) into two groups: 1. practitioners focused on wood production (Nr. 1–14) 2. practitioners focused on protection and recreation (Nr. 15–28). This grouping—based on the self-assessment of their primary management goals—highlights a fundamental distinction in practitioner objectives: FWP practitioners prioritize wood production and operational efficiency, while FPR practitioners focus on conservation and public use. These underlying goals shape contrasting perspectives on climate adaptation and management intensity. This simplification greatly facilitates our analysis, given the substantial overlap in the views of practitioners focused on protection and those emphasizing recreational—both of which are strongly oriented towards public health and wellbeing.

Table 2: *Interviewed forest practitioners and assignment of position (for - work in forest; sup - at superior level), main forest goals: wood production (WP), Protection (P), and recreation (R); Region: N=Northern Germany, S=Southwestern Germany, Ger=Germany.*

Nr.	Organization	Position	Main goal	Region
1	consulting	for	WP	N
2	forester	for	WP	N
3	forester	for	WP	N
4	forester	for	WP, R	N
5	forester	for	WP	S
6	forester	for	WP	S
7	politics	sup	WP	Ger
8	forest owner	sup	WP	Ger
9	expert	sup	WP	N
10	forest owner	sup/for	WP	N
11	forester	sup/for	WP	S
12	forester	for	WP	S
13	forester	sup/for	WP, (P)	N
14	forester	for	WP, R	N
15	forester	for	P	N
16	public authority	for	P	N
17	expert	for	P	Ger
18	forester	for	R, P	S
19	public authority	sup	P, R	N
20	consulting	sup	P	N
21	public authority	sup	P, R	N
22	consulting	sup	P	S
23	forester	sup/for	P	N
24	expert	sup/for	P (WP)	S
25	expert	sup/for	P, R	Ger
26	forester	for	P	N
27	forester	for	P, R, WP	N
28	politics	sup	P, R	N

Interview protocols were analyzed using MAXQDA Plus 2020 (Verbi GmbH, Berlin). The coding process was independently performed by two researchers. Interviewee statements from the minutes were categorized with a coding system comprising 35 individual codes, grouped into the following categories: Climate Extremes, Tree Species, Silvicultural Response, Impacts, Socioeconomics, Ecology, and Climate Change. The initial coding structure was based on the interview guide and prior research but was further developed during the coding process to reflect recurring themes raised by practitioners. This flexible approach allowed us to incorporate both predefined categories and new, empirically grounded insights. From the total of over 1,000 mentions assigned to the 28 practitioners, the 6 most frequently mentioned topics per person were identified, resulting in a total of 168 topics (i.e., 28 practitioners x 6 topics each). These were then separated for the two groups (i.e., 84 topics from the FWP group and 84 from the FPR group, see Figure 13). To illustrate our findings, we include selected quotes that reflect views commonly shared across the groups. Furthermore, we conducted two workshops with forest practitioners, reflecting on our science-practice dialogue as part of the

tdAcademy initiative (Schäfer et al., 2024). These workshops revealed points of conflict between the involved forest practitioners, confirming some of the disagreement found in the interview analysis. However, the workshop format proved less effective for addressing our three main research questions, as meaningful discussions about climate extremes, their impacts, and adaptation measures were limited. In contrast, one-on-one interviews turned out to be much more effective for this purpose. To strengthen the link between empirical data and practical recommendations, the interviews were designed not only to document perceptions but also to capture practitioner experiences with implementing adaptation strategies. Practitioners were asked to describe specific barriers and enablers in their forest work, as well as to reflect on which silvicultural approaches had proven effective or problematic. These insights directly informed the practice-oriented recommendations in the discussion.

5.3 Results

5.3.1 Perception of forest practitioners

5.3.1.1 Major climate extremes

All interviewed forest practitioners acknowledged climate change and cited associated extremes and their effects from personal experience. There is consensus that harmful events affecting all tree species have increased since 2005 - 2010, with the years from 2018 onwards described as particularly severe. Respondents acknowledged the complex interaction among climate extremes, making it challenging to delineate their individual impacts, further complicated by regional, soil, and tree species variations.

Drought was identified as the most significant climate extreme (89.3%, Figure 12). Specifically, 53.6% mentioned that drought in the growing season is harmful in general while 28.6% and 7.1% respectively mentioned drought in spring and summer as particularly harmful. Especially consecutive dry years (60.7%) between 2018 and 2020 led to forest dieback on an unprecedented scale (“2018 until 2020 have nevertheless reached completely new dimensions.”; “For many foresters it was devastating, also emotionally.”). Practitioners estimated the impact of drought based on the relative abundance of plant-available water, highlighting thresholds of 40% and 30% of usable field capacity (nFK) as significant points of concern. While summer droughts were also mentioned, the overall emphasis was on drought duration and the potential compound effects with heat rather than seasonal timing. However, no clear threshold for problematic drought duration emerged, instead it was generally reiterated that the longer the drought persists, the more severe the impacts tend to be. Despite the general agreement on the severity of droughts, some locations and stands reported minimal or no effects. This was attributed to local precipitation regimes (“We have a friendly climate regime, precipitation every now and then.”), soil properties (“We have a great locational advantage with our beautiful silt loam clay slate soils.”), but also management techniques (“In our deciduous forests with rich reserves of wood, drought damage has not yet been measured.”).

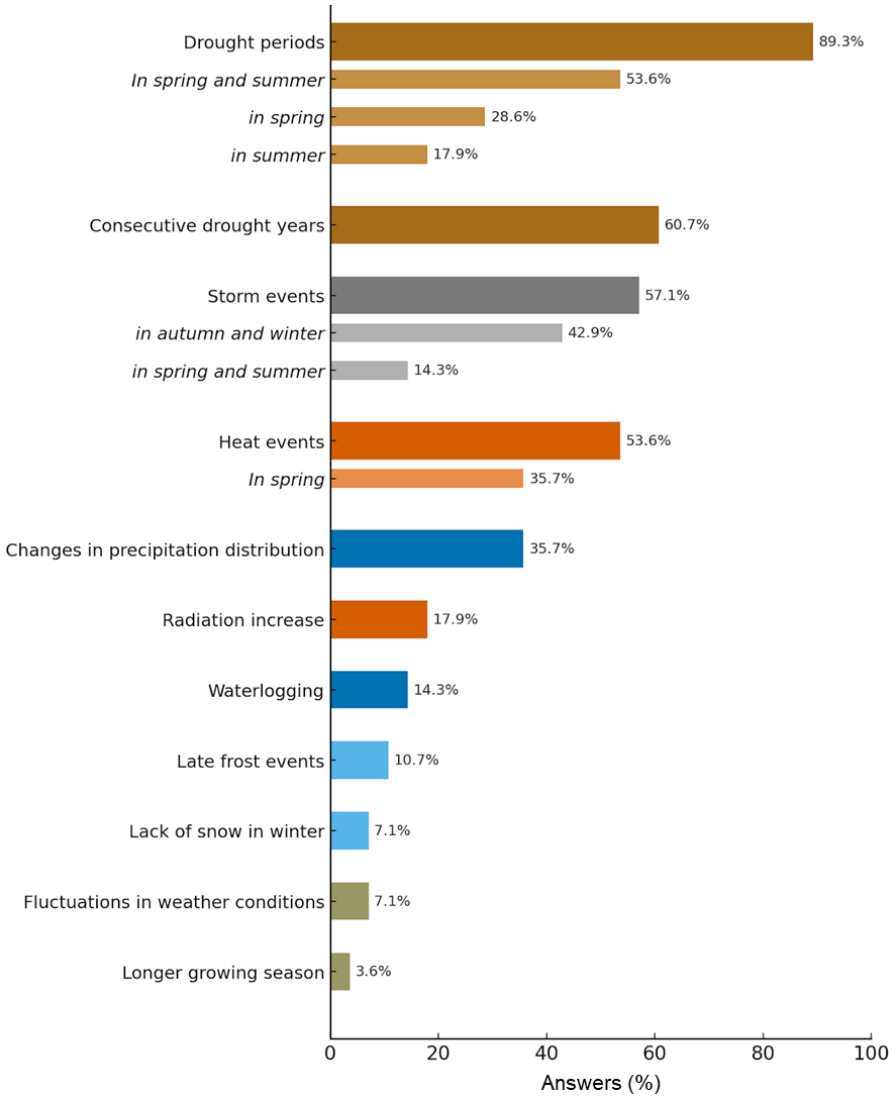


Figure 12: *Responses from 28 forest practitioners to the question: "In your opinion, which climate extremes have the greatest impact on forests?"*
Multiple answers were allowed. A total of 100 responses were recorded and categorized by climate extremes , with percentages indicating the share of practitioners identifying each category as impactful.

Storm events were identified as one of the most impactful climate extremes by 57.1% of stakeholders, especially in autumn and winter (42.9%), compared to spring and summer (14.3%). There was consensus that winter storms typically cause larger-scale damage and higher economic losses. Forest practitioners particularly emphasized storms that did not originate from the prevailing wind direction ("Storm from West is OK, but the bad one came from East."; "... the storm came from the North, not from the weather side."). Opinions on storm frequency and intensity do not show a coherent picture: some perceive an increase ("There have also been storms in the past, but the frequency seems to be increasing."), while others disagree ("We experienced no more devastating storms since 1992.").

Heat events were another concern, cited by 53.6% of respondents, particularly during spring (35.7%) and to a lesser extent in summer (17.9%). Duration and amplitude of heatwaves seem to be inextricably linked in terms of their importance ("Long periods above 30°C are critical."; "...a week with 35°C is a burden.").

Other climate-related concerns identified by the surveyed forest practitioners were changes in precipitation distribution (35.7%), followed by waterlogging (14.3%), increased solar radiation (17.9%), late frost events (10.7%), reduced snowfall (7.1%), fluctuations in weather conditions (7.1%), and longer growing seasons leading to increased water consumption (3.6%). While heavy rainfall is not generally considered a significant threat to forests, it was noted to have adverse effects on infrastructure, such as forest paths. Some practitioners also pointed out that heavy rain often results in rapid runoff, limiting soil absorption and reducing its overall benefit to the forest ecosystem.

5.3.1.2 Major impacts of climate extremes

Of the 28 forest practitioners surveyed, 89.3% identified increasing Norway spruce mortality and bark beetle infestations as the most significant impact (Table 3). More than half (53.6%) reported damage to European beech ("Currently, we are losing our classic beech forests."). 39.3% pointed to the rising risk of forest fires, with higher hazard levels occurring more frequently ("Risk of forest fires is relevant, but mostly we have only small fires."; "Forest fire hazard levels 4 and 5 (high and very high risk) show a clear upward trend, while levels 1 and 2 (low to medium risk) are decreasing."). Early spring droughts were repeatedly mentioned as an important fire trigger.

***Table 3**: Distribution of answers (in percent) from 28 forest practitioners to the question: "In your opinion, what are the main impacts of climate extremes on the forestry sector?"*
A total of 100 responses were collected, categorized by the impacts listed below. The percentages indicate the proportion of forest practitioners identifying each impact as significant, multiple answers were possible.

Answers (%)	Impact from climate extreme
89.3	Mortality of Norway spruce / Bark beetle
53.6	Damage to European beech
39.3	Increase in forest fire risk
39.3	Appearance of other biotic pests
39.3	Groundwater lowering
25.0	Lower working safety
17.9	Increase of windthrow
17.9	Damage to rejuvenation
14.3	Damage to Oak
10.7	More masting events
7.1	Lower general vitality of forest stands
3.6	Increase of neobiota

Besides bark beetles, other biotic stressors were frequently mentioned (39.3%), including Ash dieback (*Hymenoscyphus fraxineus*), an increase in ticks (*Ixodes spp.*), and the oak processionary moth (*Thaumetopoea processionea*), particularly in urban areas. Scots pine (*Pinus sylvestris*) was noted for its sensitivity to temperature extremes, which also facilitates pest outbreaks. Similarly, Norway spruce reacts to heat with needle shedding or yellowing, and European beech showed crown thinning even under good water supply—likely due to solar radiation, as 17.9% reported sunburn at forest edges. 39.3% observed lowered groundwater

levels, a critical concern for forest health as well as sectors like agriculture and domestic water use.

Reduced working safety (25%) is mainly linked to climate-induced tree mortality and falling dead wood (“One of our workers died in an accident with deadwood. It shook me.”). Consequently, some called for restricted access to risky areas ("Leaving deadwood only makes sense if I then no longer go in."). Additionally, heat impairs working conditions: “Once we were on the open southern slope, our thermometer showed more than 45 °C—unbearable for dogs and humans.”

Less frequent effects included windthrow. Regarding the impacts from storms i.e. increased windthrow (17,9%), single-layer and pure stands are reported to be more vulnerable, particularly Norway spruce and Scots pine. Tree height (rather than height-to-diameter ratio) is reported to be crucial, with shorter trees preferred. Conifers, especially Norway spruce, Silver and Douglas fir, are more vulnerable to winter storms due to their leaf retention, whereas Scots pine and European larch are considered safer.

Damage to regeneration was mentioned by 17.9%, particularly from spring droughts. Oaks (14.3%) were reported as vulnerable to late frosts, dry soils, and abrupt changes between drought and flooding. Increased masting (10.7%), especially in beech, was seen as a drought response, while 7.1% noted reduced stand vitality and 3.6% an increase in neobiota. Overall, climate extremes are intensifying forest management demands through increased monitoring and control.

To summarize, forest practitioners widely acknowledge the growing impact of climate change, with drought identified as the most damaging climate extreme—especially the drought between 2018 and 2020 was frequently cited as having led to unprecedented forest dieback. Storms and heatwaves are also major concerns, particularly due to their compounding effects with drought. Norway spruce mortality and bark beetle outbreaks are seen as the most severe impacts, followed by damage to European beech and increased forest fire risk. Local soil conditions, precipitation patterns, and forest management practices clearly influence how climate extremes affect different regions. Overall, climate change is intensifying forest management challenges, increasing the need for adaptation and risk mitigation.

5.3.2 Identification of differences and groups

The workshops and interviews revealed clear divisions among participants, often resulting in two contrasting groups. While there was broad consensus on the challenges facing German forestry, perspectives on how to respond diverged considerably. These differences were primarily driven by distinct forest management goals: those focused on recreation and conservation frequently held different priorities than those emphasizing wood production and economic outcomes. This fundamental divide influenced attitudes toward forest adaptation and management strategies under climate change.

To better understand these differences, participants were grouped based on their primary forest management objectives and categorized in two groups:

- **Forest practitioners focused on wood production (FWP)**, who aim to ensure a sustainable wood supply while acknowledging ecological and recreational functions.
- **Forest practitioners focused on protection and recreation (FPR),** who emphasize nature protection and public use, with wood production as a secondary objective.

Each group included 14 practitioners. To highlight similarities and differences between them, we now present the analysis of the 6 most frequently mentioned topics per person in each group (Figure 13). To avoid repeating the findings already presented in Section 5.3.1, we omit climate extremes and their associated impacts here and focus instead on the response strategies. It is important to note, however, that both methods (direct question and analysis of most frequently mentioned topics) yielded identical rankings regarding the most significant climate extremes and impacts.

The FWP group places strong emphasis on the economic role of forests, particularly the production of softwood, which is seen as essential for societal needs and industrial use. Practitioners in this group prefer fast-growing conifer species such as spruce (57.1%), pine (14.3%), and Douglas fir (14,3%). They also support the introduction of non-native species to safeguard wood supply and productivity in the face of climate change. Their management strategy includes practices such as thinning to optimize yield and reduce risk. Minimizing economic losses from natural disturbances—such as storms or pests—is a key concern. In their view, forest management must also account for historical use patterns and ownership structures.

Illustrative statements include:

- "We need softwood. 10 commercial trees per hectare or similar ideas are therefore no option."
- "If we import wood from other countries, the question is whether they are so sustainable."
- "If you only see nature conservation, it would be best not to do anything at all, but only from this extreme point of view."
- "We have to be careful that we don't just get on an eco track."

In contrast, the FPR group emphasizes ecological conservation and social functions over wood production. Their management approach is grounded in native broadleaf species such as beech (42.9%) and oak (14.3%), while spruce (14.3%) is seen as suitable only in limited cases. Species like pine and Douglas fir were not frequently mentioned by this group. Ecological considerations take precedence, with the expectation that the forest sector will adapt to changes in wood supply—such as through increased use of hardwood or sourcing softwood from other regions. They advocate for minimal intervention, long-term ecosystem resilience, and biodiversity. This orientation is reflected in topics that appear exclusively in this group, such as “close-to-nature forestry” (21.4%), forest set-asides (7.1%), neobiota (14.3%), epigenetic adaptation (7.1%), and deadwood (7.1%).

- "We are relying on significantly more deciduous trees to create ecological sustainability."
- "Economic profit can only be made with ecologically healthy forests."
- "In the forestry context, the disruption of the system is still given far too little attention."
- "Take the forest away from the foresters!" [regarding their preference for softwood]

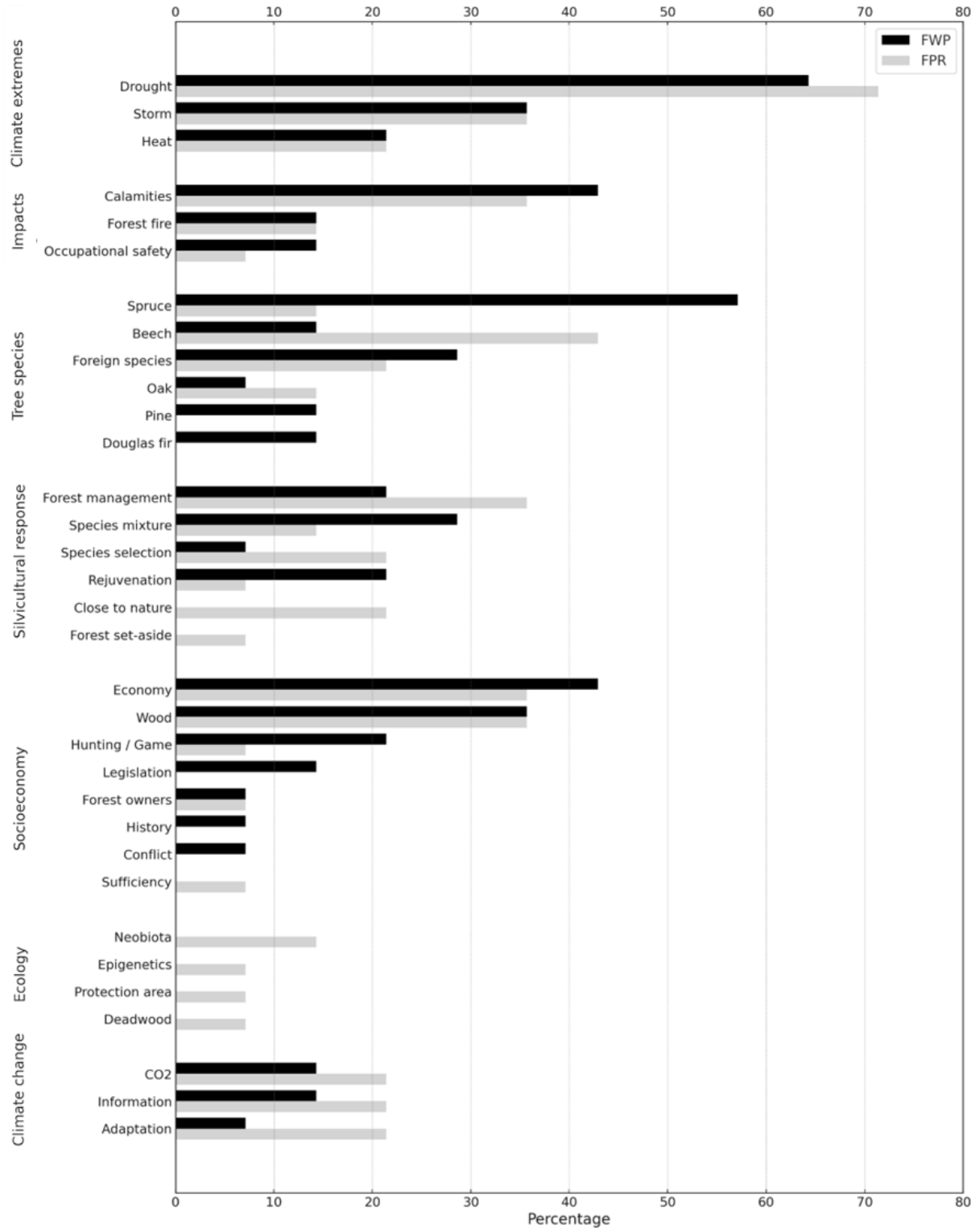


Figure 13: *A comparative analysis of the most frequently mentioned topics by individual forest practitioners*
grouped into FWP (black) and FPR (grey), each comprising fourteen persons. The chart shows the proportion of practitioners in each group who raised a given topic as one of their main concerns. From over 1,000 total mentions, the six most frequently cited topics per practitioner were selected, resulting in 168 total topics (84 per group). Many of these topics were raised by multiple practitioners; less frequently mentioned topics that appeared equally in both groups are not displayed.

While both groups recognize the pressure climate change places on forests, differences emerge in how the groups frame tree species and management approaches. The FWP group highlighted the economic importance of spruce and discussed species mixtures (28.6%) as a means to balance climate resilience and the economically motivated use of conifers. This strategy prevails over species selection (7.1%) where specific species are used to fulfill both functions. In contrast the FPR group emphasized species selection (21.4%) —primarily in relation to ecological suitability and climate resilience— over mixture (14.3%) and focused on beech and oak. Forest management itself was mentioned more frequently by the FWP group (35.7%) than by the FPR group (21.4%). Topics like CO_2 (21.4% in FPR; 14.3% in FWP) and climate information (21.4% in FPR; 14.3% in FWP) appeared occasionally in both groups, though they were not central. Overall, the findings illustrate two contrasting yet overlapping perspectives on forest adaptation —one economically driven, the other ecologically oriented— each responding to climate challenges in different ways.

In brief: Workshops and interviews revealed two distinct forest practitioner groups: those focused on wood production (FWP) and those prioritizing protection and recreation (FPR). While both share a commitment to sustainable, multifunctional forest management and recognize similar climate threats, their perception of associated risks and especially the required responses to climate change differ. These differences will be explored in detail in the next section.

5.3.3 Forest use between climate adaptation and wood demand

On the one hand, a shared understanding exists that climate change is driving a paradigm shift in forestry, with increasing emphasis on conservation and a reduced role for pure economic interests. The FPR Group expresses this more strongly. On the other hand, both groups highlight the global nature of the wood market and anticipate rising demand, driven by trends like increased construction, packaging needs due to online commerce and high international consumption (“China buys everything they can get, sawn timber as well as raw timber”).

The FWP group supports continued reliance on softwood, emphasizing its economic importance ("Norway spruce is the bread tree of Germany", "added value of deciduous wood has been low so far, the actual added value happens with the softwood") and the difficulty of replacing it with hardwood for many social needs, such as construction ("Hardwood glulam is not really a sustainable alternative because more energy is required compared to KVH (Konstruktionsvollholz - construction solid wood)". Thus, this group sees it as their responsibility to support the German economy by ensuring a steady supply of softwood ("Construction wood is necessary, which is why the forests should be managed accordingly"). They argue that reducing softwood production could lead to an increase in unsustainable imports (“Other countries farm wood without ecological standards”).

The FPR group agrees that softwood has advantages but stresses that long-term economic viability depends on ecologically healthy forests ("... coniferous wood has some benefits, what good is that to me if the conifers don't survive?"). While not opposed to imports, they prefer a shift toward native hardwoods and criticize the forest sector’s close alignment with the timber industry ("Foresters often listen very carefully to what sawmills and the timber industry tells

them, many foresters are pure raw material suppliers for the timber industry."). They argue that the economy must adapt to forests, not the forests to the economy ("Nature cannot adapt to humans, but humans can adapt to nature"). Some practitioners noted that Germany's softwood supply over the next 50–80 years is largely set by the current forest composition, providing a sufficient transition period to develop hardwood processing and gradually reduce dependence on softwood. Lastly, the FPR group occasionally calls for more sustainable wood use, stressing its limits as a resource.

5.3.4 Responses of forest practitioners to climate extremes

5.3.4.1 Forest management

Both groups agree that mixed and multi-layered stands are more resilient to climate extremes. This is attributed to species complementarity, improved humus formation, and better water retention. Additionally, species-rich, near-natural forests offer recreational benefits and greater species diversity supports risk distribution. Adaptation efforts are often integrated into broader forest management initiatives, such as those that prioritize transitioning forests to near-natural conditions.

FWP practitioners adopt a more interventionist approach, viewing shortening production cycles as a key strategy ("... shortened spruce from 100 to 80 years, beech from 160 to 120 years, and oak potentially from 220 to 180 years."). In this regard, softwood is considered advantageous in terms of adaptability ("The adaptability of softwood is better because the rotation period is shorter, providing more opportunities to adapt the stock"). Overall, this group views climate change as a call for more intensive forest management ("In the course of climate change, you have to take care of the forest more intensively"), emphasizing cultivation methods, species choice and mix, and pest control as critical for adaptation.

FPR practitioners, by contrast, prefer minimal intervention ("Our guideline is: We manage nature, and it hasn't noticed!"). The focus (also in an economic sense) is on minimizing human input rather than maximizing timber output ("No more foresters, just let the forest do its thing."). The underlying belief is that a natural forest possesses a greater capacity to cope with climate extremes. In addition, positive effects on species conservation are emphasized ("Protecting biodiversity is one of the social goals, which is just as relevant to the future as climate change."). While there were divergent views on whether thinning contributes to beech damage, the group largely agreed that open stands are less resilient to drought conditions, leading to move away from large-scale shelterwood cuts.

Natural regeneration is preferred when conditions allow and seedlings are abundant. FWP group practitioners often cite cost-effectiveness and a lack of available saplings as reasons for this preference ("Planting or natural regeneration? The former in particular is very expensive"), while FPR practitioners primarily emphasize the vulnerability of planted saplings. For 17.9% of all foresters, damage to regeneration efforts ranked among the top six concerns (Table 3). Growing awareness of sapling vulnerability—particularly to drought—has led to adjustments in planting schedules, with a shift from traditional spring planting to autumn. However, some foresters from the FWP group question whether natural regeneration alone is sufficient in all areas, warning that without intervention, some forests could face degradation or even

desertification (“If nothing is done, some areas could head toward desertification”). Overall, FWP foresters tend to rely more on planting compared to those in the FPR group (Figure 13).

To prepare forests for storms, the most common silvicultural measure is to stagger tree heights from the edge inward (“... we therefore like to plant cherries on the edge.”). As long-term adaptation, foresters try to convert sensible single layer stands into multi-layer stands, to create a rough canopy and to reduce the general height of stands (“Spruce only up to 28 m …”).

The FWP group supports interventions that enhance individual tree stability and growth, emphasizing timely thinning as crucial. Delayed thinning, they argue, leads to weak trees, which is "...a homemade problem, because you have to create enough space for target trees so that they develop a strong crown and roots." Thinning is seen as key to developing storm-resilient trees, especially in calamity-prone spruce areas, following the principle: “1m³ of thick wood is better than more thin wood”.

On the contrary, the FPR group, advocated for minimal intervention to reduce stress on the ecosystem. They favor maintaining closed canopies, believing they offer greater storm resistance (“... thinning of stands is therefore a great risk with 1-2 guaranteed storms in the tree lifetime.”). In their view, consistent thinning increases vulnerability, leading to more damage in managed forests ("Damage to forests increases with management."). Thus, both perspectives aim to reduce storm impacts, though the methods they endorse are diametrically opposed.

5.3.4.2 Tree species choice and mixture

Choosing suitable tree species to adapt forests to climate extremes is a major challenge due to uncertain future conditions. There is broad agreement on the need for mixed-species forests to increase resilience ("Mixing is the optimal strategy as it is currently not known which species will cope best with the changing conditions."). In practice, they mainly strive to integrate a wide variety of species ("when we remediate, we try to bring in at least 5 species."). There is also a strong acknowledgment of the need for experimentation to find which species perform best under changing conditions ("We have tried out, coastal fir and small-leaved lime on very small areas …”; “... you have to observe what works and what doesn’t and draw conclusions from that."). The FWP group places greater emphasis on tree species mixture (14.3% vs. 7.1%, Figure 13), whereas the FPR group more frequently discusses individual species, especially native deciduous trees like European beech and oak.

Norway Spruce

All interviewed foresters unanimously identified the sharp decline of Norway spruce ("Spruce hardly has a future"), due to drought and bark beetle attacks ("...bark beetles become active as soon as it gets warm and spruces cannot defend themselves when it is dry."), as the most urgent challenge currently facing the German forest sector (Table 3). Some foresters observed that spruces in boggy areas are among the most severely affected by drought, while "... spruce in consistently drier areas are often less susceptible in dry phases.".

The FWP group takes a nuanced approach on managing spruce. While they critically assess its future—particularly in pure stands—they still see it as viable under certain conditions. Spruce is considered acceptable where it currently performs well or can be reintroduced, such as in

windfall areas or higher altitudes. Some respondents noted that "relatively few problems with spruce" have occurred so far. Economic considerations also play a role: where natural regeneration succeeds, spruce is often accepted and harvested after 50–60 years, aligning with current market demands for smaller-diameter coniferous wood. Overall, it seems that these foresters are happy to use spruce wherever possible ("At the moment we still see a high proportion of spruce as an advantage from an economic point of view."; "We've been converting our forest for decades, but we are glad we still have some spruce trees").

In the FPR group, spruce has largely been abandoned, except in certain specialized locations ("... in areas where spruce is now dying, one knows that it no longer has a future."). These foresters foresee significant challenges for spruce, as it is frequently found in locations that are not suitable for the species ("Spruces are of course severely affected by climate change, because in many places they are outside their natural range."). Consequently, there is a tendency to not maintain spruce stands or actively reduce the presence of spruce ("If the natural regeneration of the spruce is too dominant, … we also push it back"; "... in the case of spruce stands over 60 years old, we carry out advance cultivation for the next forest generation, mostly beech, sometimes silver fir").

European beech

Practitioners from both groups report that European beech is under considerable stress, primarily due to drought during the growing season, often in combination with pests and fungal infections. Older trees are particularly vulnerable: “Up to 100 or 120 years is OK, after that it gets bad—by 140 years it’s almost over.” Many respondents foresee serious long-term problems: “Beech will be the next loser after spruce.” Damage is often multifactorial. Key stressors include the beech leaf-miner beetle (*Orchestes fagi*), the oak splendour beetle (*Agrilus biguttatus*), slime flux fungi, and sunburn from excessive solar radiation—especially at stand edges or in former mixed stands where spruce has died off. One practitioner noted: “Beech is mainly affected at the edge of the stand—the radiation leads to sunburn!”.

The FWP group is critical of beech’s long-term viability ("I see beech in particular really critical …"). They also note beech’s potential to dominate other species. A connection between thinning practices and drought damage is not acknowledged ("Beeches become dry at the top, whether they were previously protected or not"). Instead, thinning is viewed as a beneficial management strategy for forests ("I started thinning out old beech stands a long time ago, and natural regeneration has been great in recent years.").

The FPR group holds a more favorable view of the future of beech ("No problem with beech so far, they stand on sand, so maybe they are more adapted to dry episodes?"). While acknowledging current stress factors, some see potential for adaptation and resilience under changing conditions. FPR practitioners emphasize site-specific suitability and the ecological value of beech, suggesting that—with proper management—it may still play a key role in future forests.

Oak, Douglas fir and Scots pine

Oak, particularly sessile oak, remains important but surprisingly received relatively little attention from forest practitioners. The FWP group often cites oaks' need for light and resulting low competitiveness with beech to justify intensive interventions, particularly in beech-dominated forests ("In Beech Oak mixed forest beech would dominate and kill oaks without beech felling.").

Douglas fir and Scots pine were primarily mentioned by the FWP group. Douglas fir is widely valued as an established and economically viable substitute for Norway spruce, especially in mixed stands. Many practitioners emphasized that it has a long history in German forestry: "Douglas fir has been here for 150 years and is therefore hardly a real foreign tree anymore.". It is often underplanted to improve forest microclimate and soil conditions, thereby enhancing long-term resilience and enabling the introduction of more demanding deciduous species. However, concerns about pest pressure are increasing: "We no longer plant Douglas fir because it is under too much pressure from the weevil, which then causes damage to the roots." In contrast, FPR practitioners tend to be more cautious, viewing Douglas fir as a non-native species that should not be overused.

Scots pine is regarded by the FWP group as an important component of future mixed forests, valued for its low site demands and adaptability. Despite increasing concerns about drought stress and pest pressure, it is still considered viable where site conditions permit. Temperature plays a crucial role, and where precipitation is sufficient, its prospects are viewed positively. As a result, Scots pine is expected to remain relevant in future forestry—either in mixed stands or as a stabilizing element within pine-dominated forests.

Alternative tree species

Both groups recognize the precarious future of many native species under climate change ("If we cannot quickly limit climate change, many native species will have a hard future"). As a result, identifying alternative, climate-resilient species has become a key focus in forest management. However, many of these alternatives present challenges. Sitka spruce (*Picea sitchensis*), for example, has often been removed due to poor performance and ecological disruption. Efforts to establish species such as downy oak (*Quercus pubescens*), Turkey oak (*Quercus cerris*), northern red oak (*Quercus rubra*), and sweet chestnut (*Castanea sativa*) have frequently failed due to late frosts. Despite this, downy oak is valued for its drought tolerance, although seed availability remains limited. Other species commonly planted on damaged sites include sycamore (*Acer pseudoplatanus*), Norway maple (*Acer platanoides*), and sweet chestnut, though seed sourcing remains difficult.

The FWP group is more open to introducing non-native species, arguing that the selection of viable native species is too limited to meet future needs ("The tree species that are still possible are limited and one cannot avoid foreign tree species"). Their approach emphasizes pragmatic adaptation focused on resilience and economic viability. As such, they are often critical of legal and funding restrictions that limit the planting of established non-native species like Douglas fir, coastal fir, red oak, and Japanese larch ("The district does not allow red oak and fir trees to be cultivated there, only for political reasons"; "There is no rational reason not to allow certain foreign tree species"). Some are currently exploring alternatives to Norway spruce, including

Douglas fir, Great silver fir (Abies grandis), and Japanese larch (*Larix kaempferi*), though concerns about wood quality persist. Other species under consideration include Turkish hazel (*Corylus colurna*), black pine (*Pinus nigra*), black walnut *(Juglans nigra*), and Atlas cedar (*Cedrus atlantica*). Regulatory frameworks such as the Forest Reproductive Material Act (FoVG) are seen as obstacles, and the group calls for more flexible and locally appropriate rules, particularly within protected areas.

In contrast, the FPR group adopts a more cautious approach. While they recognize the vulnerability of native species, they place greater trust in natural adaptation processes ("Epigenetic adaptation will help in some cases, but some species will go extinct") and prefer species from Europe and Asia that could theoretically migrate naturally. North American species are generally avoided due to limited natural dispersal. Their use of non-native species is minimal ("We only use very few foreign tree species, at most we sprinkle in red oak or sweet chestnuts; we are FSC-certified and are allowed to include a maximum of 20% foreign trees"). This group emphasizes the importance of reliable data to assess ecological risks, particularly related to invasiveness and biodiversity. Species such as Lebanon cedar and black locust (*Robinia pseudoacacia*) are viewed with caution due to their potential ecological impact. Overall, the FPR group prioritizes ecological integrity and risk minimization, while the FWP group favors a more flexible, adaptive strategy to meet the demands of a changing climate.

5.3.4.3 Management of calamity areas

FWP foresters prioritize prompt removal of infested trees to prevent pest spread. This immediate extraction also mitigates economic losses due to timber degradation and addresses safety concerns. Protected areas where intervention is restricted are often seen as hindering effective management ("An area under nature protection is now completely dead because intervention was not allowed there."). In some cases, FWP foresters prefer clearing entire areas after partial damage for economic reasons ("In large forestry operations, decisions have to be made to optimize processes, although it might make sense from a silvicultural point of view to leave remaining trees."). In disturbance-affected areas, decisions regarding management strategies—such as promoting natural regeneration versus introducing targeted planting of alternative tree species—are often made on a case-by-case basis. Some foresters advocate for non-native but better adapted species, while others favor natural regeneration, even when it may not be well adapted ("... where spruce grows again, let's just hope that it won't go down again for 50 years."). Although pesticides are considered a last resort, strict regulations frustrate some foresters ("Fighting harmful insects with plant protection products is difficult because permits for forest protection are seldom authorized."; "Many chemicals are no longer permitted, which means that protective measures almost become impossible.").

FPR foresters see the collapse of pure spruce stands as a catalyst for forest conversion, which is considered inevitable anyway. There is a stronger tendency to leave deadwood ("... important habitat; shades and cools the area."), to allow natural succession, and to rely on pioneer species ("Seeds from many pioneer trees fly very far, other species can also be brought in by birds, for example."). In calamity areas, they advocate allowing more space and time for these natural processes ("In case of a forest damage initially 10 years without any management and then see what emerges from pioneer trees.").

Both groups acknowledge rising forest fire risk and stress prevention. Deciduous and mixed stands are seen as less flammable, and technical tools are valued (“fire watch cameras,” “automated drones”). Green undergrowth is noted as a protective factor. District foresters maintain access routes and coordinate recovery, which requires significant resources.

5.3.4.4 Climate mitigation

Both groups agree on the critical role of using sustainably sourced wood as a carbon sink and in reducing CO_2 emissions, as it requires minimal fossil energy for processing. They recommend practices such as cascading use and substitution of carbon-intensive materials with wood products. Even so, the potential of forests to mitigate climate change is recognized as limited, all practice partners support the idea that the climate mitigation benefits of forests should be rewarded. The main differences among them involve the specifics of how these benefits should be measured and recognized, such as whether to use performance-based or area-based criteria.

The FWP group highlights the critical importance of faster-growing species in absorbing CO_2 ("Binding CO_2 depends heavily on growth. Douglas fir grows 16-18 m^3 per hectare per year, but beech only 4-5 m^3"). This significant difference in growth rates makes softwood species particularly valuable for effective carbon capture. While the shift towards more deciduous trees has environmental benefits, FWP members emphasize that the impact on carbon sequestration is relatively small ("That is why there is no optimal climate balance here, which is why mixed forest would be optimal”; “Fast-growing trees are still necessary, not only for economic reasons!"). Mixed forests, combining both fast-growing softwoods and slower-growing hardwoods, are seen as a more balanced approach for both environmental and economic sustainability. Foresters also stress the importance of looking beyond system boundaries when evaluating forest management practices. As one expert stated, "... with good and long-term use of wood, it is ultimately the growth that counts, not the carbon stored in the forest." This perspective emphasizes the importance of sustainable wood use over the lifespan of a forest. Some even view recent policy initiatives like the European Green Deal as obstacles to maximizing carbon storage pointing to the potential impact of regulations on the wood supply ("This means that there is simply less wood available").

In contrast, most forest practitioners of the FPR group highlight the climate value of hardwood species, arguing that their denser wood sequesters more carbon per cubic meter than softwoods ("CO_2 storage in hardwoods is similar to that in spruce, because wood is much harder and thus stores more carbon per cubic meter."). Additionally, they consider hardwood better suited as a long-term carbon sink because it is frequently used in high-quality products like furniture, whereas softwood is often used for packaging and paper products with a short lifespan. They promote mixed deciduous forests as long-term carbon sinks (“Natural forests eventually reach a steady state/storage optimum because at some point (max. 1000 fm/ha) biomass degradation and new formation are in balance"), pointing out the role of mature forests in storing carbon not only in trees but also in deadwood and soils. Lower harvesting levels enhance this effect.

To summarize the responses to climate extremes, both forest practitioner groups agree on the importance of species-rich, climate-resilient mixed forests and sustainable wood use for climate mitigation. However, their approaches differ significantly. FWP practitioners prioritize active

management to enhance tree vigor, reduce damage risk through shorter rotation cycles, and maintain a stable softwood supply for economic purposes. They support thinning, rapid intervention in calamity areas, and are open to introducing non-native species to secure productivity. In contrast, FPR practitioners emphasize ecological resilience, favoring native species, natural regeneration, and minimal intervention, with a focus on long-term adaptation and ecosystem integrity. They advocate for adapting the economy to the forest, not the other way around, and prioritize carbon storage in mature hardwood stands. While both groups manage forest edges to mitigate storm damage, their stand-level strategies reflect broader differences in values and objectives.

5.4 Discussion

5.4.1 Perception of the forest practitioners of climate extremes and their impacts on forests

5.4.1.1 Consensus on drought as the major climate extreme

Drought emerged as the dominant concern among forest practitioners (Figure 12), reflecting both global patterns of drought-induced forest dieback (Allen et al., 2015) and recent large-scale tree mortality events in Central Europe between 2018 and 2020 (Knutzen et al., 2025). Their responses also highlight the broader complexity of climate change impacts, particularly regarding the effects of consecutive drought years. Emphasis on plant-available water and seasonal drought sensitivity reflects scientific concepts of critical water thresholds (McDowell et al., 2022) and vulnerability through early-season water deficits (Bréda et al., 2006; Weemstra et al., 2013). Local variability in drought impacts, attributed to soil and precipitation differences, corresponds with findings on the complex interplay between climatic, edaphic, and biotic factors (Tijdemann et al., 2022).

Respondents often conflated **heat** and drought, indicating that practitioners struggle to grasp the isolated effects of heat. Concerns focused on spring and summer events, consistent with findings on seasonal heat stress in forests (Teskey et al., 2024). Duration of heat events was seen as critical, echoing evidence of cumulative effects of prolonged high temperatures on tree physiology (Allen et al., 2015). The noted sensitivity of Scots pine to temperature extremes is corroborated by research demonstrating heat-induced mortality and pest outbreaks (Diers et al., 2024; Gette et al., 2020). Observations of sunburn on European beech at forest edges and crown thinning in old beech trees match research on edge effects and age-related heat sensitivity (Reinmann et al., 2016). Observed reduced dew formation during heat periods reflects changes in forest microclimates, potentially affecting ecosystem water relations (Grünzweig et al., 2015).

While drought was the most emphasized stressor, the long-term effects of **storms** on German forests from 1850 to 2000 have been the most severe in Europe (Schelhaas et al., 2003). Storms like Kyrill (2007) and Lothar (1999), caused unprecedented damage, both in timber volume and carbon balance (Gardiner, 2021; Hanewinkel et al., 2011). Practitioners' varied views on storm trends reflect scientific uncertainty: While some studies report an increase in extreme wind events (e.g. Gregow et al., 2017), others find no clear trend (Feser et al., 2015; Priestley et al.,

2024). Furthermore, the impact of storm direction on forest damage aligns with findings that non-prevailing wind directions can cause localized damage (Gliksman et al., 2023).

Less frequently mentioned extremes—such as increased solar radiation, late frost events, lack of winter snow, and weather fluctuations—align with research on climate-induced alterations in forest environments (Lindner et al., 2014). The recognition of longer growing seasons and related challenges, like heightened water consumption, corresponds with findings on phenological shifts (Grossiord et al., 2022). Concerns about changes in precipitation distribution resonate with studies emphasizing the significance of rainfall patterns for forest health and productivity (Allen et al., 2015). While a study by Yousefpour and Hanewinkel (2015) found that the majority (83%) of forestry professionals viewed climate change as a reality, human-caused, and a significant risk, the present study, conducted approximately 10 years later, found no remaining doubt among forest practitioners regarding the impacts of human-induced climate changes.

5.4.1.2 Shared understanding of impacts from climate extremes on forestry

Practitioners' observations of forest impacts align with current research, particularly regarding drought and heat waves, which can drastically alter forest composition, structure, and biogeography (Allen et al., 2015). The three main consequences identified in the interviews - physiological stress, insect outbreaks, and forest fires- also reflect findings in the literature (Anderegg et al., 2022; Forzieri et al., 2021; Harvey et al., 2023). Reports of increased Norway spruce mortality reflect the growing impacts of bark beetle outbreaks in European forests, driven by drought-weakened tree defenses (Hlásny et al., 2021; Netherer et al., 2015). Damage to European beech reflects growing concerns about its drought vulnerability (Leuschner, 2020). The emergence of other biotic pests, such as ash dieback and the oak processionary moth, is consistent with the documented expansion of forest pests under changing climatic conditions (Jactel et al., 2019).

The increasing risk of forest fires noted by practitioners is supported by research showing a trend towards more frequent fire-conducive conditions (Jones et al., 2022). Preventive strategies include both technological solutions (surveillance systems, drones) and ecological measures (promoting deciduous and mixed forests), an approach supported by research on vegetation’s role in fire dynamics (Moreira et al., 2011). Observations about increased windthrow, particularly regarding pure single-layer stands of Norway spruce, align with research showing that such stands are more wind-sensitive than mixed and structurally diverse forests (Jactel et al., 2017). Concerns about occupational safety, such as increased risks from deadwood, are echoed in findings by FAO, ILO, UN (2023). Reports from practitioners regarding operational disruptions—like heat-related schedule changes and equipment failures—also correspond to this study’s conclusions on rising physical stressors in forest work. The FWP group’s focus on legal obligations and worker protection reflects awareness of these issues and supports the emphasis placed by ILO (2019) on safe and regulated working conditions as a foundation for sustainable forestry.

5.4.2 Different opinions on forest use between climate adaptation and wood demand

The FWP group prioritizes softwood species and proactive silvicultural transitions to more diverse and resilient forests which is in line with BMEL (2020) and Hanewinkel et al. (2022). In contrast, the FPR group prefers hardwood species, natural adaptation, "close to nature" practices and forest set-asides, which aligns with the growing public interest in more natural forests (Logmani-Aßmann et al., 2021; Nikolaides & Innes, 2020). This divergence underscores differing philosophies in responding to climate change impacts. The contrasting views on tree species like Norway spruce and European beech, are telling: the FWP group still relies on spruce for economic reasons despite its climate change vulnerabilities, while the FPR group values beech as a native species, even if there are doubts about its future viability (Langer & Bußkamp, 2023). These contradictions suggest that the underlying values may shape adaptation strategies more than considerations solely based on climate data.

The FWP group's greater focus on softwood species is likely driven by economic factors and traditional forestry practices. The continued reliance on spruce in certain regions, despite its vulnerability to climate extremes, underscores its economic importance in German forestry (Spiecker & Kahle, 2023). Indeed, in 2022, Germany produced approximately 24% of EU sawn softwood (EC, 2023), and European net exports of sawn softwood increased by 26.5% (Taylor & Koskine, 2023), indicating strong global demand. However, climate-resilient mixed forests could impact softwood supply, with experts predicting reduced availability post-2040 (Knauf, 2024). This potential shortage poses a challenge for industries reliant on softwood, such as construction. From this point of view, ecological approaches to forest management, prioritizing hardwoods and diverse forest compositions, may not meet economic demand. As Knoke et al. (2008) point out, there is a trade-off between biodiversity conservation and wood production. A shift toward more natural forest management practices can reduce softwood yields, potentially affecting the ability to meet market demands. Additionally, recent bark beetle infestations and drought-related damage have led to a temporary oversupply of softwood due to salvage logging (Toth et al., 2020), highlighting both the vulnerability of softwood monocultures and the need for a reliable long-term softwood supply.

All this explains the FWP group's preference for coniferous species like Norway spruce and Scots pine; Rather than complete species changes, they favor species mixtures to enhance stand stability while maintaining productivity. Research supports this, indicating that mixed stands offer both ecological and economic benefits (Pretzsch et al., 2017). The group’s consideration of socioeconomic factors underscores the complex interplay of economic, ecological, and social dimensions in German forest management, as highlighted in recent policy documents (BMEL, 2020). This reasoning also informs the group's practices, such as thinning and rapid rejuvenation, designed for economic optimization. Eggers et al. (2020) showed that intensive management can significantly increase the net present value (NPV) of forest stands. The group's efforts to mitigate disaster risks is likewise economically justified, given the substantial climate-related losses in German forestry (Spiecker & Kahle, 2023).

In contrast, the FPR group's preference for minimal intervention aligns with a "close-to-nature" forestry approach, which promotes long-term ecological sustainability over short-term

economic gains (Brang et al., 2014). The group's advocacy for native species like beech and oak, is supported by research indicating that mixed broadleaved forests enhance biodiversity and resilience to climate change compared to monoculture coniferous stands (Ammer et al., 2018). Their skepticism towards Norway spruce reflects its climate change vulnerability (Hlásny et al., 2019) and suggests openness to adaptive forest management strategies which aligns with the principles of Climate-Smart Forestry (Yousefpour et al., 2017). Their preference for native species and "close-to-nature" practices reflects their focus on ecological resilience and biodiversity conservation. This approach balances multiple ecosystem services, including carbon sequestration and recreation (Ammer et al., 2018), with deadwood preservation and non-intervention areas further supporting biodiversity (Parajuli & Markwith, 2023; Yang et al., 2021). All these considerations seem to form the basis for their view that industry should adapt to changing wood supply rather than forcing forests to meet market demands. This idea marks a significant shift towards a circular bioeconomy focused on sustainable resource use and innovative product development (Hetemäki et al., 2016).

Even in the FPR group, the interviewees mainly talked about protection; on average, recreation is of secondary importance. However, individual practitioners from this group - the majority of whom operate near cities - attach great importance to forests' recreational function. This is in line with literature recognizing recreation as a key ecosystem service provided by forests, especially in the vicinity of cities (Dudek, 2016; Lupp et al., 2016). Its importance stems from the localized nature of everyday forest recreation, unlike services such as wood production, which are not tied to specific locations (Meyer et al., 2019).

In conclusion, while ecological approaches to forest management provide vital benefits for biodiversity and forest health, they struggle to meet Europe's demand for softwood. This tension presents a significant challenge for policymakers balancing ecological concerns with economic needs. Without changes in wood consumption — Germany's per capita wood use is more than double the global average and exceeds its domestic supply capacity (Beck-O'Brien et al., 2022) — or improvements in hardwood processing, purely ecological approaches may not be economically viable in the long term.

5.4.3 Responses of forest practitioners to climate extremes

5.4.3.1 Contrasting levels of management intensity

The FWP group advocates for adaptive forest management strategies like shortening of production times, which seems to be suited to enhance forest adaptability (Vacek et al., 2023). However, this strategy raises concerns regarding carbon sequestration and biodiversity (Zimová et al., 2020). Additionally, measures like selecting drought-tolerant species or controlling pest outbreaks illustrate "active adaptation" (Keenan, 2015): a strategy to shape forest structure and species composition in ways that anticipate and buffer against expected climate stressors.

The FWP group advocates for adaptive forest management strategies like shortening of production times, which seems to be suited to enhance forest adaptability (Vacek et al., 2023). However, this strategy raises concerns regarding carbon sequestration and biodiversity (Zimová et al., 2020). Additionally, measures such as selecting drought-tolerant species or managing pest outbreaks exemplify "active adaptation" (Keenan, 2015): an approach that proactively shapes

forest composition and structure to increase resilience against anticipated climate-related disturbances.

In contrast, the FPR group's preference for minimal intervention aligns more closely with the concept of "close-to-nature" forestry, as described by Brang et al. (2014). This approach assumes that natural processes are essential for fostering resilient forests, as they allow ecosystems to adapt and thrive in the face of environmental changes. Studies confirm that biodiversity strengthens forests' ability to withstand and recover from disturbance (Falk et al., 2022; Rybar & Bosela 2024). However, as Bolte et al. (2009) point out, passive adaptation strategies may not be sufficient in the face of rapid climate change. Furthermore, the differing opinions within the FPR group regarding thinning practices, especially in beech dominated forests, reflects ongoing scientific discussions about the effects of thinning on forest resilience (Schmied et al., 2022).

Natural regeneration dominates reforestation in Germany, covering 91% of young forest areas (BWI 4), favored for its ecological benefits and cost-effectiveness (Forest Europe, 2020; Knoke et al., 2008). Given that drought impacts the shallow root systems of young trees (Brunner et al., 2015), it is unsurprising that 17.9% of foresters report damage to regeneration efforts due to water stress (Table 3). In response foresters are shifting to autumn planting and improving techniques to enhance success rates (Brang et al., 2014). While natural regeneration can support forest resilience (Kramer et al., 2014), we found no scientific evidence supporting concerns from some FWP practitioners that certain areas may face desertification without human intervention. However, ecological degradation is documented in cases where high browsing pressure hinders forest regeneration (Mason et al., 2022). Long-term strategies, such as pre-cultivating beech under spruce, are conducted especially among the FPR group, aligning with more natural approaches to forest adaptation and resilience (Ammer et al., 2018; Brang et al., 2014).

Regarding storms, tree height was frequently mentioned as a factor, supported by biomechanical studies demonstrating higher vulnerability of tall trees (James et al., 2014). Differing views on thinning between FWP and FPR foresters reflect existing debates in forest management literature: while thinning may enhance wind resistance (Bourke et al., 2023), it may also increase vulnerability in the short term due to altered structural integrity (Gardiner et al., 2021; Gliksman et al., 2023; Peltola et al., 2013).

5.4.3.2 Consensus on tree species diversity, with diverging views on softwoods and beech

Practitioners unanimously recognize the value of mixed forests with diverse tree species in enhancing resilience and spread risk. This strategy is supported by e.g. Jactel et al. (2017), who demonstrated that mixed-species forests are more resistant and resilient to disturbances than monocultures. The emphasis on experimentation and learning through trial and error reflects an adaptive management approach, which is increasingly recognized as essential in the face of climate uncertainty (Bolte et al., 2009).

The FWP group prioritizes productive species such as Norway spruce, Scots pine and Douglas fir (see Section 5.4.2), despite ongoing debates about their vulnerability to climate change (Hlásny et al., 2019). This preference reflects their economic importance (Spiecker, 2000),

while the strong support of this group for mixed stands reflects the ability to balance ecological stability with economic benefits (Pretzsch et al., 2017). In contrast, the FPR group's greater emphasis on European beech and oak, along with other native deciduous and marginalized tree species, reflects a more ecologically oriented approach. This aligns with research suggesting that mixed broadleaved forests offer higher levels of biodiversity and are more resilient to climate extremes compared to coniferous monocultures (Seliger et al., 2023).

The debate over **Norway spruce** highlights the differing priorities of the FWP and FPR groups, reflecting the broader challenge of balancing economic, ecological, and climate adaptation goals in forestry. Despite general reservations, even the FPR group sees potential for Norway spruce in specific contexts, such as mixed stands. This partial convergence could guide future forest management by promoting flexible, site-specific strategies that balance economic and ecological goals —an approach both necessary and increasingly urgent as climate change continues to challenge forest resilience.

Both the FWP and parts of the FPR groups express concerns about the vulnerability of **European beech** to drought. Recent studies support these concerns, indicating that beech is increasingly vulnerable to drought stress (Leuschner, 2020), with older individuals especially affected (Hammond et al., 2022). Leuschner (2020) emphasizes that beech is more drought-sensitive than many other temperate broadleaf species—a finding underscored by the extensive damage observed during the extreme droughts of 2003 and 2018–2019 (Rukh et al., 2023). Long-term studies also show that beech growth has slowed since the 1980s (Knutzen et al., 2017). Further dendrochronological analyses link this decline to low precipitation and high temperatures, particularly in older trees (Scharnweber et al., 2011; Zimmermann et al., 2015). Looking ahead, climate models project further declines of 20-50% in beech growth by 2090, especially in southern regions facing increased drought (Martinez del Castillo et al., 2021). These predictions raise serious concerns about the long-term viability of beech in a warming climate.

Despite the well-documented drought vulnerability of beech, parts of the FPR group take a more optimistic view of its future, highlighting its adaptability and potential resilience through epigenetic mechanisms. Indeed, recent studies suggest considerable adaptive potential, with evidence of local adaptation (Gárate-Escamilla et al., 2019), drought-tolerant traits along precipitation gradients (Cuervo-Alarcon et al., 2018), and stronger resistance and recovery of trees from drier sites (Kijowska-Oberc et al., 2020). Further studies have highlighted beech's physiological resilience to drought and recovery (Stojnić et al., 2018). Ongoing research uses provenance trials and genetics to identify traits that may improve its future drought resilience (Bogunović et al., 2020; Petkova et al., 2022).

While **oaks** are considered more drought-tolerant than beech, they are not without their own set of challenges, as both practitioners and scientific studies suggest. These include crown defoliation after dry periods, susceptibility to late frosts, vulnerability to pest infestations (Vanoni et al., 2016), and poor performance in sides with rapid shifts between drought and flooding (Leuschner & Ellenberg, 2017). Oaks' high light demands are often cited by the Forest Wood Production (FWP) group to justify intensive interventions, especially in beech-dominated

areas, where competition threatens oak survival, despite beech being more vulnerable to drought (Jacobs et al., 2022).

Introducing **alternative tree species** is controversial due to risks of poor site adaptation, invasiveness, and ecological impacts (Bindewald et al., 2021). Still, selected non-native species like **Douglas fir** are gaining acceptance. The FWP group favors Douglas fir in mixtures due to its drought tolerance (Spangenberg et al., 2024), fast growth, and high-quality wood, which sells at prices around 25% higher than Norway spruce in Western Europe (Pulkrab et al., 2014). Integrating non-native species like Douglas fir into mixed plantings represents a form of assisted migration, which is gaining traction as a promising adaptation strategy.

5.4.3.3 Calamity areas: active intervention versus natural regeneration

Regarding calamity areas the FWP group emphasizes the immediate removal of infested trees, which is a common pest control strategy (Stadelmann et al., 2013; Trubin et al., 2023), but one that may conflict with biodiversity goals, as dead and dying trees are vital for habitat diversity (Thorn et al., 2020). The group's advocacy for pesticides contrasts with the growing trend to reduce chemical use (Jactel et al., 2019). Furthermore, the FWP group's characterization of protected areas as obstacles illustrates the tension between conservation objectives and active forest management. Elsen et al. (2020) note that strict protections can impede adaptive responses to climate change.

Conversely, the FPR group sees calamities —at least the spruce dieback— as an opportunity for natural forest conversion. This perspective aligns with research indicating that disturbances can facilitate the development of more diverse ecosystems (Seidl & Turner, 2022). Their preference for natural succession and reliance on pioneer species is supported by studies showing that natural regeneration enhances forest resilience (Kohler et al., 2020; Tripathi & Khan, 2007). Furthermore, the FPR group's emphasis on deadwood retention is also scientifically grounded, with research highlighting its importance for biodiversity (Chivulescu et al., 2022; Thorn et al., 2020), microclimate regulation, and water retention (Błońska et al., 2019; Floriancic et al., 2022).

The FPR group sees significant potential in epigenetic mechanisms to enhance tree resilience, particularly in European beech. They consider these heritable stress responses a key factor in enabling forests to adapt naturally without intensive human intervention. This perspective supports their preference for non-invasive strategies, such as promoting natural regeneration and allowing trees to build stress tolerance over time—approaches that could reduce the need for large-scale species replacement (García-García et al., 2022; Miryeganeh & Armitage 2025).

5.4.3.4 Shared practitioner views on forests mitigation role, diverging strategies for carbon storage

Both groups acknowledge forests' role in carbon mitigation, though they differ in strategy. The FWP group prioritizes carbon storage in harvested wood products like construction wood. Therefore, they argue for intensive forest use and faster-growing species like Douglas fir, which can sequester carbon more rapidly, a view supported by recent studies (Liang et al., 2016; Paquette & Messier 2011). Conversely, the FPR group emphasizes the importance of the carbon sequestered in the living forests, arguing for lower wood extraction and higher stocks. This

argument holds until natural old-growth forests achieve a steady state in carbon storage and release (Luyssaert et al., 2008). They further argue for a greater use of hardwood species and mixed deciduous forests because hardwood store more carbon per cubic meter due to their higher density, a claim backed by research on wood density and carbon storage (Chave et al., 2009). They see the increasing use of wood as problematic, pointing to the huge amount of wood that is used for products having a short lifespan like packaging and low-quality furniture.

Both groups stress the importance of considering the full lifecycle of wood products in carbon accounting, consistent with life cycle assessment (LCA) methodologies (Klein et al., 2015). Cascading wood use and substitution of carbon-intensive materials are recognized as key mitigation strategies (Leskinen et al., 2018). Building on this, both groups support climate-related rewards in the form of payments for ecosystem services (PES), but differ in how these should be structured: while the FWP group favors area-based PES to incentivize continuous forest use, the FPR group argues for performance-based schemes tied to actual carbon storage. This reflects an ongoing debate in forest policy about how best to align incentives with climate goals (Nabuurs et al., 2017).

Empirical research suggests that performance-based PES can lead to more measurable ecological outcomes, especially in carbon-focused schemes (Salzman et al., 2018). However, our findings suggest that combining area- and performance-based criteria may gain stronger support from practitioners and improve effectiveness by rewarding both carbon sequestration pathways. In this context, market-based tools such as results-based contracting may offer promising ways forward (Schomers & Matzdorf, 2013).

5.5 Conclusion

Our findings highlight the urgent need to foster constructive dialogue and collaboration among diverse forest practitioners to better inform policy makers in addressing the growing challenges that climate change poses for forests. Shared concerns—such as the need for adaptation and economic viability—provide a basis for cooperation. Climate adaptation policies should build on these shared values to bridge differences and prevent further polarization. This is essential in a science-based dialogue, even when scientific findings challenge long-standing traditions and livelihoods in forest management.

Moving forward, efforts must focus on overcoming existing conflicts within the forestry sector, as the severity of climate change demands a joint effort from all parties involved. To navigate this polarized landscape, conflict-sensitive, participatory platforms are needed to bring together actors with divergent goals (Fraser et al., 2006). Such forums can enable shared learning, build trust, and support adaptive co-management tailored to regional conditions (Keenan, 2015). Policymakers must develop frameworks that accommodate diverse perspectives and reduce conflict, while forest practitioners must actively work toward mutual understanding. Inclusive governance models that reflect both ecological and economic forest functions will be essential to secure long-term societal support and sustainability (Gritten et al., 2009).

Equally important is strengthening communication between researchers and practitioners—particularly in translating climate science into practical, accessible tools. Deepened collaboration will be key to developing robust forest adaptation strategies. Future research,

especially in partnership with social scientists, can help illuminate the social dimensions of forest management and support greater understanding across conflicting perspectives.

Based on our findings, we recommend advancing forest adaptation policy frameworks. Financial incentives may help promote structurally diverse, mixed-species forests that enhance resilience and biodiversity. Reward schemes should, where feasible, be tied to ecological performance—such as carbon storage or biodiversity outcomes—and developed with input from both science and practice. Native species should remain central to forest management, though the regulated use of well-assessed non-native species is likely to grow in importance.

By integrating diverse viewpoints and offering practical, flexible tools and incentives, forest policy can better address the complex challenges of climate change—uniting actors across sectors and supporting the multifunctionality of forests in the long term.

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6 Forest management in a changing climate: assessing the impacts of adaptation measures on the visual aesthetics of forests – the example of Germany

Abstract

Climate change presents major challenges to forest ecosystems, requiring adaptive management to sustain their ecological, economic, and recreational functions. This study explores the impact of climate change adaptation measures (CCAMs) on the visual aesthetics of forests, an important yet underexplored area of forest management influencing recreation and well-being. Through a combination of literature review and expert interviews, we evaluate how common CCAMs affect key forest attributes—such as tree size, species diversity, and understory density—and their influence on aesthetic perceptions. The CCAMs are grouped into three strategies: (1) diversification of tree species, (2) strengthening ecological functions, and (3) reducing biotic and abiotic stressors. Our findings indicate that diversification of tree species generally enhances the visual aesthetics of forests by increasing tree height variation and species diversity while reducing clear-cuts. Conversely, measures aimed at strengthening ecological functions, such as rapid reforestation and leaving more residues, often negatively affect visual aesthetics due to visible residues and reduced structural complexity. Measures that reduce stressors yield mixed results, depending on the specific intervention. Intensive forestry activities, like early intensive thinning and shortened production cycles, tend to have negative impacts, at least in the short term, while measures that promote structural diversity and tree growth through the conversion of forests into multi-layered stands or reducing game populations generally improve the visual aesthetics of forests. This study underscores the importance of integrating aesthetic considerations into CCAMs, particularly in urban forests, where public perception is crucial. Incorporating these considerations can enhance public acceptance of climate adaptation strategies, ensuring that forests remain resilient and visually appealing in a changing climate.

6.1 Introduction

Climate change has manifold effects on forests. Changes in average temperature and precipitation regimes, coupled with the increasing frequency and intensity of climatic extremes such as droughts and storms, are expected to significantly alter the suitability of tree species and the management practices employed in forestry (Vacek et al., 2023). Moreover, climate-related stressors can intensify biotic disturbances, including large-scale bark beetle outbreaks, resulting in extensive damage and raising questions about appropriate afforestation strategies (Das et al., 2025). The primary objective of forest management in most European countries is to ensure that forests can simultaneously provide a range of different functions. As climate change progresses, forests must adapt to future climatic conditions in order to continue fulfilling their diverse functions. Given the wide variety of forest types, specific adaptation measures must necessarily be tailored to individual cases (Joyce et al., 2009; Kolström et al., 2011).

However, there is also an ongoing debate regarding general adaptation strategies and which forest functions should be prioritized in the adaptation process.

Climate change adaptation frequently prioritizes maintaining wood production (Kölling et al., 2010). In addition to the production function, attention is often given to nature conservation and biodiversity (Augustynczik et al., 2020; Felton et al., 2016a). However, the state of knowledge regarding other functions of forests is less developed (Lindner et al., 2010). To date, there has been limited research on the effects of adaptation measures on forest aesthetics, despite their critical importance for the recreational function of forests (Edwards et al., 2012; Simkin et al., 2021). While forest aesthetics is influenced by various factors such as olfactory, acoustic, and other sensory impressions, the visual dimension is generally considered the most important (Brady, 2003). Therefore, in line with classical studies such as Ribe (1989) and more recent work like Mu et al. (2022), we focus exclusively on visual factors, referring to this as visual aesthetics. Only a few studies have examined visual aesthetics in specific contexts related to climate change. For example, Arnberger et al. (2018) and Averbeck et al. (2025) explore visual preferences for forests damaged by bark beetles, while Ebenberger and Arnberger (2019) investigate preferences in the context of heat relief. Jenkins et al. (2020) examine public preferences for several adaptation scenarios, inter alia forest landscapes in the US. However, their study combines aesthetic preferences with other preferences, limiting the ability to draw broad conclusions about preferences beyond the specific scenarios analyzed. To our knowledge, no studies have specifically investigated the impacts of general adaptation measures on forest aesthetics or their recreational value. Yet, the recreational function significantly contributes to the overall value of forests, often exceeding that of timber harvesting (Giergiczny et al., 2021), particularly in areas close to urban centers (Lupp et al., 2016). Specifically in (sub-)urban forests, aesthetics should be carefully considered when planning climate change adaptation measures. Following Gobster et al. (2007), we argue that aesthetics is not a superficial add-on to ostensibly more important landscape functions, such as ecological integrity or resource provision, but a key driver of landscape management that carries direct ecological implications. In particular, interactions with forest visitors—who may prefer neatly maintained stands or criticize certain interventions—illustrate how aesthetic expectations can strongly influence, and at times constrain, management decisions. Therefore, creating aesthetically pleasing forests can enhance public acceptance for forestry in general and of climate change adaptation measures in particular. The goal of this article is to address this research gap by analyzing how common adaptation measures influence the visual aesthetics of forests. Forests adapted to climate change are, of course, a prerequisite for the provision of most forest functions. Our objective is not to question the necessity of forest adaptation to climate change but rather to establish a foundation for incorporating the impacts on the visual aesthetics of forests into the selection and implementation of adaptation measures.

Our research questions are the following:

1.) What are the most commonly recommended climate change adaptation measures (CCAMs) in forestry according to recent scientific literature?

2.) Which specific structural forest attributes are most influential in shaping the aesthetic perception of forests?

3.) How do the most common climate adaptation measures influence the visual aesthetics of forests, and what can be done to counter negative impacts on forest aesthetics?

To address our research questions, the remainder of this paper is structured as follows. We first outline the methodological approach applied in this study. The subsequent section presents the results. It begins with a review of the most common climate change adaptation measures (CCAMs) and the forest attributes that influence aesthetic perceptions. This is followed by the findings from expert interviews, which assess how various adaptation measures affect these attributes. This combination of expert assessments and insights from the literature review enables us to infer how different adaptation strategies influence the visual aesthetics of forests. Finally, we discuss the main practical implications for forest adaptation and the methodological limitations of the study before providing concluding answers to the research questions.

6.2 Materials and Methods

To answer our research questions, we conducted a three-step process:

1. **Selection of climate change adaptation measures**: Based on scientific literature and practical guidelines, we review general adaptation strategies and identify the most important CCAMs based on these strategies.
2. **Selection of forest attributes and assessment of their relevance to visual aesthetics**: Drawing from relevant literature, we determine the key structural forest attributes that influence the visual aesthetics of forests and assess their respective impacts on visual appeal.
3. **Assessment of the impacts of climate change adaptation measures on forest attributes**: We combine the findings from the first two steps by consulting forestry experts to evaluate how the identified adaptation measures affect the most relevant forest attributes. This allows us to estimate the overall impacts of these adaptation measures on the visual aesthetics of forests.

We will now outline the key methodological considerations for each of these steps.

6.2.1 Selection of climate change adaptation measures

To identify the key adaptation strategies and the associated adaptation measures, we relied on both existing adaptation guides and related scientific literature—particularly the comprehensive catalog of measures by Swanston et al. (2016)—and interviews conducted with 28 forest experts as part of the ClimXtreme project. The semi-structured interviews, each lasting approximately 90 minutes, were conducted online. The interviewees were primarily forest managers, consultants, and other experts, and the discussions focused on climate extremes, their impacts, and adaptation strategies (see Knutzen et al., 2025, for details). Our analysis does not aim to encompass all possible CCAMs. Instead, we focus on a selection of CCAMs that are frequently discussed in the literature and considered relevant by forestry practitioners. Based on these criteria, we compiled a preliminary list of 26 CCAMs, each paired with a reference scenario that represents the conditions in the absence of adaptation efforts. This reference scenario serves as a baseline, enabling a comparative evaluation of each CCAM's influence on the visual aesthetics of forests relative to the situation without adaptation. Some of these measures serve

not only to address climate change adaptation but also to achieve other objectives, such as enhancing biodiversity. In such cases, the reference situation still depicts the situation where the measure is not applied, in order to account for the impacts of the measure, even if these impacts can only partially be attributed to climate change adaptation.

During the two pre-tests of the final stage of our investigation (see Section 6.2.3), we refined the list to 9 CCAMs (see Section 6.3.1) by consolidating similar measures or eliminating those that the interviewed foresters deemed less important, with minimal consequences on forest attributes, or too difficult to assess in terms of their consequences on forest attributes.

6.2.2 Selection of forest attributes and assessment of their relevance for visual aesthetics

In the literature on forest aesthetics, various approaches exist regarding the object of consideration. Some studies examine the consequences of specific practices (e.g., harvesting methods) (Deng et al., 2013; Ribe, 2005; Shelby et al., 2003; Silvennoinen et al., 2002), while others look at the structural attributes of forests (e.g., size of trees) (Nielsen et al., 2007; Edwards et al., 2012; Ebenberger & Arnberger, 2019). In some cases, both aspects are combined within a single study (Ribe, 1989; Gundersen & Frivold, 2008). Management practices influence the structural attributes that, in turn, determine aesthetics. Thus, these studies look at the same issue, but they look at different parts of the impact chain. At first glance, it may seem more useful for addressing our research question to look at the specific practices rather than the attributes, as that is ultimately the subject of interest. However, by skipping the structural attributes, we miss the valuable insights provided by the numerous studies that focus on the structural level. Therefore, the attribute-based approach is ultimately more suitable.

Our selection of structural forest attributes is based on previous research on forest preference (e.g. Ribe, 1989; Edwards et al., 2012; Heyman, 2012; Giergiczny et al., 2015). To identify relevant literature, we conducted a narrative (non-systematic) review, searching key databases and reference lists for studies addressing forest structure and human preferences. We limited our selection to attributes that are visible at the stand level and are influenced by forest management. For example, terrain slopes can have a significant impact on the aesthetic value of a forest (Dudek, 2018), but forest management does not have any influence on this attribute. For all selected attributes we reviewed existing literature to assess how they influence the visual aesthetics of forests.

6.2.3 Assessment of the impacts of climate change adaptation measures on forest attributes

We compiled the selected CCAMs alongside the forest attributes in a table, which served as the basis for consultations with forestry experts (see headings of Table 7). The experts were asked to evaluate, drawing on their experience and knowledge, how each CCAM influences each forest attribute. To enhance the comparability of responses across experts, we provided a reference situation for each measure depicting the situation without adaptation efforts (see Table 4) against which the respective measure was to be assessed. The response options provided were 'positive', 'neutral', and 'negative'. It is important to note that the experts evaluated only the effects of each CCAM on the forest attributes, not the aesthetic outcome. Prior to conducting

the formal survey, we conducted a pretest with two forestry experts to evaluate the clarity and practical relevance of the adaptation measures. Based on the pre-test, we streamlined the table to reduce the completion time to 60–90 minutes. During both the pre-test and the actual survey, the table was filled out through a face-to-face online dialogue with each forestry expert. This approach allowed us to clarify ambiguities, ensure consistent and accurate understanding of the adaptation measures, and thereby minimize errors in the evaluation process. Additionally, it enabled us to capture brief explanations of the impacts directly, providing insights into the reasons behind differing assessments. All discussions were recorded or documented for further analysis. Before evaluating the table with the experts, we asked general questions about the forest district they oversee, the tree species present, and their management practices. This contextual information helped us interpret their responses.

We conducted interviews with 11 forestry experts, all in 2021. The selection of these experts was based on the network of the authors and the research project ClimXtreme (Knutzen et al., 2025). We designated as experts only those contacts who hold leadership positions (e.g., forest office managers or district managers) and have direct practical experience. Additionally, these experts were required to have the ability to observe the long-term consequences of these measures in their respective regions. All experts were based in Germany, with a focus on regions in the north, particularly around Hamburg, and in the southwest.

In the subsequent phase of analysis, we examined the results by analyzing in which sections of the table the forestry experts mainly agreed regarding the impacts of the implemented measures and where not. Where divergent assessments arose, we carefully reviewed the interview transcripts to ascertain whether the differences were due to genuine variations in perceived outcomes or resulted from differing interpretations of the measures by the respondents. These insights are integrated into the discussion of the findings. In a last step, we combined the insights from the literature review on forest attributes with the expert assessment of how different CCAMs influence these attributes, in order to evaluate the overall impact of each adaptation measure on the visual aesthetics of forests.

6.3 Results

6.3.1 Climate change adaptation strategies and measures

Adaptation strategies can be derived from two primary options: ‘forestall change’ and ‘accept change’ (see Figure 14). The ‘forestall change’ option can be further divided into two approaches: 1) resistance strategies and 2) resilience strategies (Millar et al., 2007). Resistance strategies aim to maintain forests in their current state, such as through the use of pesticides to combat new pests or the removal of invasive species. Resilience strategies, on the other hand, focus on enabling forests to recover quickly after disturbance events, such as designing multilayer tree stands that can regrow swiftly following storms.

The ‘accept change’ option can be subdivided into three strategies: 1) strategies that aim to enhance the natural adaptive capacity of forests (passive adaptation). This should not be confused with a "business as usual" approach under the assumption that natural adaptation will resolve the problem unaided. For natural adaptation to be effective, forests must be managed in a way that allows these processes to occur (Bolte et al., 2009). 2) Strategies that seek to

anticipate natural adaptation (active adaptation) by transforming forests to make them more suited to future climatic conditions (Bolte et al., 2009; Jandl et al., 2019), such as by introducing new species. 3) Strategies that attempt to reduce the negative impacts of climate change and subsequent forest changes on humans (Brang et al., 2008). A prominent example of this is risk diversification, for example by spreading the risk across various tree species (Kölling et al., 2010).

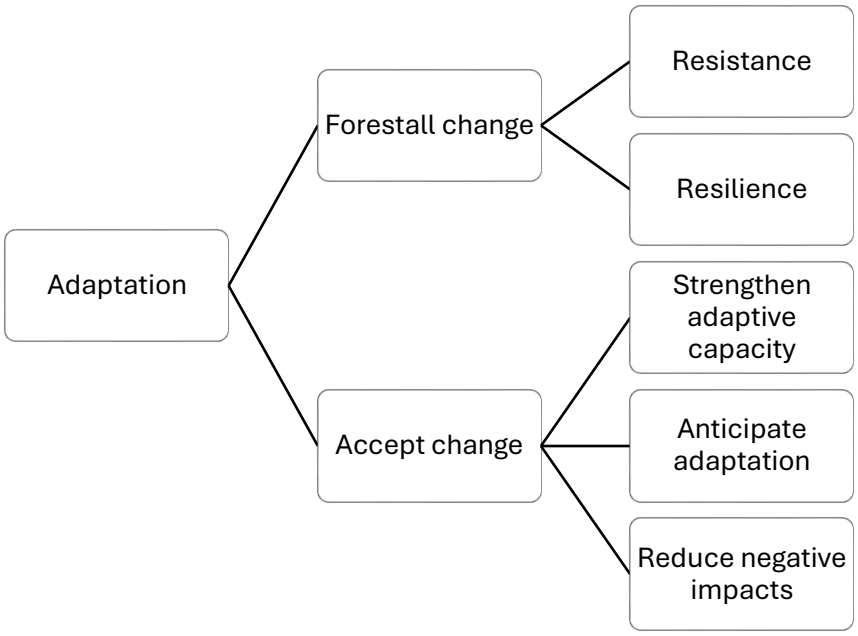


Figure 14: *Adaptation pathways in forest management illustrating primary adaptation strategies.*

Various concrete strategies and climate change adaptation measures can be derived from these general response strategies (see Table 4). However, clearly assigning the specific adaptation measures to a general response strategy is often not possible, as adaptation measures can serve multiple purposes. For instance, underplanting beech in a young pine stand can enhance the stand's stability against storms in the medium term (resistance). At the same time, this intervention creates a fundamentally new, two-layered stand consisting of multiple tree species (adaptation). Additionally, the increased species diversity reduces the risk of total loss, as the entire stand is less likely to be affected by a calamity (risk diversification).

This study identifies three primary adaptation strategies: (1) diversification of species composition, (2) strengthening of ecological functions, and (3) reduction of biotic and abiotic stressors. In the following, we briefly present some of the most important CCAMs discussed in the literature, which fall under these three strategies. In this study, we focus on the measures themselves – visible and tangible interventions within the forest stand – since they affect the visual aesthetics of forests and consequently their recreational function. The strategies listed here primarily serve the general understanding of the measures (Table 4).

***Table 4**: Overview of adaptation strategies and measures to enhance resilience to climate change, comparing traditional forestry practices (Reference situation) with corresponding adaptation measures and their expected effects.*

Strategy	Reference situation	Adaptation measure	Expected climate adaptation effect
Diversifying the tree species composition	Focus on and promotion of a few traditional main tree species	Diversifying the tree species mix by promoting marginalized tree species or introducing non-indigenous tree species	Risk diversification through increased species diversity and improvement of resilience to future climate conditions
	Natural regeneration occurs but is not the focus; planting is common	Increased use of natural regeneration	Utilization of genetic diversity for risk reduction
Strengthening of basic ecological functions	Full use of trees wherever possible/economically viable	Leaving wood residues	Maintenance of nutrient cycles, water retention, and humus levels
	Harvesting occurs even when soils are wet	Implementing soil-friendly harvesting techniques and seasonal timing	Soil protection, including erosion prevention and preservation of soil organisms
	Reforestation is left to natural processes, even if it takes several years	Accelerating reforestation after extreme events	Soil stability improvement, reducing degradation and erosion
Reduction of biotic and abiotic stressors	High game populations	Regulating game populations	Promotion of regeneration and forest growth by reducing browsing pressure
	Stem density is reduced slowly, partly by natural processes	Early, intensive thinning	Vitality improvement of trees by reducing competition
	Current rotation periods and target diameters remain unchanged	Shortening rotation periods / reducing target diameter	Lowered exposure (probability) to extreme weather events
	Preservation or renewal of single-layer stands	Transitioning to multi-layer stands	Resilience enhancement through structural diversity

Within the strategy of tree species diversification we distinguish between the measures diversification by promoting marginalized tree species or introducing non-indigenous tree species and an increased use of natural regeneration. The idea behind the first measure is that mixed stands are less vulnerable to external disturbances, such as extreme weather events, and tend to recover more quickly than monocultures (Jactel et al., 2017; Knoke et al., 2008; Lebourgeois et al., 2013; Neuner et al., 2015; Schütz et al., 2006). A diverse species mix also provides greater flexibility for adaptation, allowing species composition in young stands to be adjusted over time (Brang et al., 2016). This flexibility allows forest managers to delay decisions on species selection, providing more time to assess climate change impacts and the suitability of various species. Moreover, increasing species diversity helps to select species that

are better adapted to future climate conditions, thereby enhancing the long-term resilience of forests.

The idea of natural regeneration is to rely on natural selection processes to shape future species compositions and genotypes, drawing on the high genetic diversity generated by the large number of seeds involved (Lindner et al., 2008). However, species and genotypes highly competitive under current conditions may be poorly adapted to future climates (Young et al., 2020). Additionally, seed availability can limit this approach, as dominant but poorly adapted species may face insufficient competition from seeds of other species in species-poor forests. To address this limitation, assisted migration—the deliberate introduction of climate-adapted tree species—can complement natural regeneration by ensuring a broader range of species with traits suited to anticipated climatic changes (Kijowska-Oberc et al., 2020).

The second strategy focuses on strengthening the basic ecological functions of forests to enhance their resistance, resilience, and adaptation to climate change (Swanston et al., 2016). A key aspect of this strategy is the forest soil, which plays a critical role in determining water retention and nutrient cycling, and is therefore essential for ensuring the long-term stability of forest ecosystems (Bilyera et al., 2025). Key adaptation measures include leaving wood residues to maintain soil fertility, employing soil-friendly harvesting techniques, and accelerating reforestation efforts after disturbances.

Leaving more wood residues in the forest, enhances nutrient cycling by contributing to humus formation and improving soil structure (Swanston et al., 2016). This, in turn, increases the soil's ability to retain moisture, making forests more resistant to drought conditions (Teshome et al., 2020). Similarly, minimizing soil compaction through low-impact harvesting techniques preserves microbial activity and root penetration capacity, ensuring long-term ecosystem productivity (Cambi et al., 2015; Picchio et al., 2020). Another measure is fast reforestation after extreme events, addressing the widespread forest diebacks in central Europe. Climate change is expected to increase such calamities (Kautz et al., 2017; Millar & Stephenson, 2015; Paritsis & Veblen, 2011), and rapid reforestation, particularly on sensitive sites, is seen as an effective way to preserve soil (Ontl et al., 2020).

The next set of adaptation measures falls under the strategy of reducing biotic and abiotic stressors. Regulating game populations seeks to prevent deer damage to young trees. A high density of game can indeed prevent climate-adapted regeneration species through selective browsing, which alters species composition by reducing or eliminating browsing-sensitive species (Klopčič et al., 2017; Löf et al., 2019). Therefore, adapted game populations are seen as an essential prerequisite for establishing climate-adapted forests (DVFFA, 2019).

Early intensive thinning reduces competition among trees. By focusing limited resources on fewer trees, early thinning enhances the vigor and resilience of individual trees, making them better equipped to withstand stressors such as drought, pests, and extreme weather events (Brang et al., 2016). At the same time this approach increases the number of valuable, thick trees (Lindner et al., 2008).

Shortening the rotation periods – or reducing target diameters in continuous cover forestry – aims to minimize the risk of economic losses due to climate-related disturbances (Bréda &

Brunette, 2019). With the increasing frequency and intensity of disturbances such as storms, droughts, and pest outbreaks, forests face greater risks of abrupt dieback (Choat et al., 2012; Hartmann et al., 2022). By shortening rotation periods, forest managers can reduce the likelihood of trees being damaged or lost before harvest.

The last measure, transitioning to multi-layer stands, sometimes also referred to as continuous cover forestry, enhances resistance to biotic and abiotic stressors and faster recovery after disturbances (O'Hara & Ramage, 2013; Ming et al., 2020; Štěrbová et al., 2024). For example, after a storm, younger trees in a multi-layered stand can maintain ecosystem functions (resistance) and quickly close canopy gaps (resilience).

6.3.2 Forest attributes and visual aesthetics

The structural attributes of forests that influence visual aesthetics are well-researched, with comprehensive literature reviews by Ribe (1989) and Edwards et al. (2012). In view of the maximum feasible scope of the expert evaluation, we have limited ourselves to the attributes listed in Table 5. Below, we summarize the current understanding of the relationship between these attributes and forest visitors' aesthetic perceptions. Of particular importance is identifying the optimal level of each attribute, whether its impact is positive (i.e., more is better), negative (i.e., less is better), or bell-shaped (i.e., a moderate amount is preferred, with extremes being undesirable). Additionally, the relative importance of each attribute—how strongly it influences aesthetic appraisal—is also considered.

Table 5: *Impact of the most important attributes on visual aesthetics as described in the literature. Some studies reported attribute importance; high importance: numbers in bold, low importance: numbers in parentheses.*

Attribute	Impact on visual aesthetics described as			
	Positive	Negative	Bell shaped	Other
Size of trees	3,**4**,(5),6,**8**, 9,14,18			
Variation in tree size	1,(4),(5),6,7,(8), 9,12			
Understory		(9),17	**4**,(8),11	14, unclear positive and negative
Tree species	1,(4),(5),6,7,**8**, 11,12,14, 18	2,17		9, unclear
Size of clear-cuts		**4**,**8**,9,14, 15,16		
Residues		2,**4**,**8**,14		
Traces of intervention		2,9,10,13		

1=(Alvarez et al., 2021), 2=(Averbeck et al., 2025), 3=(Blasco et al., 2009), 4=(Edwards et al., 2012), 5=(Ebenberger & Arnberger, 2019), 6=(Filyushkina et al., 2017), 7=(Füger et al., 2021), 8=(Giergiczny et al., 2015), 9=(Gundersen & Frivold, 2008) 10=(Heyman, 2012), 11=(Meo et al., 2020), 12=(Nielsen et al., 2007), 13=(Nielsen et al., 2012), 14=(Ribe, 1989), 15=(Ribe, 2006), 16=(Silvennoinen et al., 2002), 17=(Tyrväinen et al., 2003), 18=(Dudek, 2018)

Tree size plays a significant role in the visual aesthetics of forests, with large, thick trees being consistently assessed as having a positive impact (Edwards et al., 2012; Filyushkina et al., 2017; Gundersen & Frivold 2008; Giergiczny et al., 2015; Ribe, 1989). This applies not only to the overall height of the stand but also to individual dominant trees (Ebenberger & Arnberger, 2019; Ribe, 1989). Edwards et al. (2012) identify tree size as one of the most important attributes influencing aesthetic value.

Variation in tree size is also clearly positive, as people generally prefer stands with mixed-age trees over uniform, age-class forests (Arnberger et al., 2018; Ebenberger & Arnberger, 2019; Edwards et al., 2012; Filyushkina et al., 2017; Giergiczny et al., 2015; Ribe, 1989). However, this preference holds as long as young trees do not dominate and obstruct views (Gundersen & Frivold, 2008). This characteristic is critical from a silvicultural perspective, as altering the age structure requires changes to the management regime (e.g., clearcutting vs. single-tree removal).

The preference curve for understory density is bell-shaped, meaning the optimal level is moderate—some understory is present but does not fully obstruct views into the forest (Edwards et al., 2012; Giergiczny et al., 2015; Gundersen and Frivold 2008). Several studies suggest that visual penetration into forest stands, largely determined by the understory, is a key factor in enhancing perceived scenic beauty (e.g. Edwards et al., 2012; Meo et al., 2020).

Regarding tree species diversity, greater diversity is generally viewed positively (Edwards et al., 2012; Ribe, 1989). However many studies demonstrating this relationship simply compare pure deciduous or coniferous forests with mixed forests (Ebenberger & Arnberger, 2019; Filyushkina et al., 2017; Giergiczny et al., 2015; Nielsen et al., 2007). Overall, tree species diversity seems to have relatively minor importance in aesthetic evaluations (Ebenberger & Arnberger, 2019; Edwards et al., 2012;).

The presence and size of clear-cuts is a very relevant attribute, with a clearly negative impact on visual aesthetics compared to other harvesting methods, such as umbrella cutting (Edwards et al., 2012; Giergiczny et al., 2015; Gundersen & Frivold, 2008; Ribe, 1989). However, a long-term study by Shelby et al. (2003) found that while clear-cuts are rated much lower than alternative harvesting methods immediately after intervention, these ratings tend to converge over time. In Germany, large-scale clear-cutting is typically not authorized unless it follows exceptional events like storm damage or insect infestations (Panek, 2020). Therefore, in the context of climate change adaptation, we assume that certain measures may increase clear-cut areas if they raise the likelihood of large-scale disturbances.

Harvest residues, such as fallen branches and logging debris, also have a significantly negative effect on aesthetic perceptions (Giergiczny et al., 2015; Gundersen & Frivold, 2008; Edwards et al., 2012). The final attribute considered is "traces of intervention," which includes signs of human activity such as wheel tracks, fences, and other infrastructure related to tree protection and hunting. Although there is limited research on the aesthetic impact of these components, Heyman (2012) found, using the visitor-employed photography method, that forest visitors are highly sensitive to man-made objects and wheel tracks, generally disliking them. Interestingly, man-made objects made from natural materials tend to be viewed more positively (Nielsen et

al., 2012). The results of the previous literature analysis are presented in Table 6 and will be used for the next step of the analysis.

***Table 6**: Forest attributes and their aesthetic impact from a visitor's perspective. Overview of key forest attributes influencing visual aesthetics. The impact on aesthetics is categorized as linear positive, linear negative, or bell-shaped, with visitor preferences indicated by descriptive quotes.*

Possible point of view of a forest visitor	Attribute	Impact on visual aesthetics
	**Tree size** Tree height and stem diameter	Linear positive  "The bigger, the better"
	**Variation of tree height** Determining the number of canopy layers	Linear positive  "The more layers the better"
	**Density of understory** A dense understory and shrub layer results in a low visual penetration	Bell shaped  "Presence of understory without obscuring the view"
	**Tree species variability** Number of different tree species within a stand	Linear positive  "The more species the better"
	**Probability and size of clear-cut areas** Determined by the probability of calamities	Linear negative  "The lesser clear cuts the better"
	**Volume of woody residues** Resulting from harvesting and thinning e.g. tree stumps, branches etc.	Linear negative  "The lesser residues the better"
	**Traces of intervention** E.g. lanes, fences, high seats	Linear negative  "The lesser traces the better"

6.3.3 Impacts of climate change adaptation measures on forest attributes and visual aesthetics

This section presents the results of the expert survey and describes the effects of different CCAMs on the visual aesthetics of forests, with detailed results provided in Table 7. The first CCAM is explained in detail to guide readers on how to read the table, while the description of the remaining measures focuses on overall effects.

Regarding the effects of increasing tree species diversity on tree size, the expert opinions are divided, showing no trend (NT). Some experts foresee no impact, while others predict changes, depending on the species introduced. Forestry practitioners largely agreed (thick borders) that the introduction of new species is likely to increase variation in tree height, which in turn positively affects the visual aesthetics of forests (green arrow). Regarding the understory, the majority expects an increase, but the aesthetic impact depends on the initial density: if dense, further densification reduces visual aesthetics, but if sparse, it enhances them (two-colored arrow). The number of tree species will increase, while the size of clear-cuts is expected to decrease, which positively impacts visual aesthetics (green arrow). Most experts predict an increase in harvesting residues, as marginalized tree species often produce less stem wood. Regarding other signs of intervention, most experts do not foresee any changes, as no traces of intervention would occur if marginalized species are simply taken from natural regeneration (grey circle). However, a notable minority foresee planting or increased hunting activity, increasing noticeable signs of human impact (small arrow in circle). Overall, diversifying the tree species mix probably enhances visual aesthetics, especially long-term, though short-term effects may be less favorable if diversification involves planting. Increased use of natural regeneration, mainly impacts visual aesthetics through greater tree height variation and understory density. While tree height variation contributes positively to visual aesthetics, the understory can have a negative effect when the natural regeneration is very dense. Most experts do not foresee the same impacts on the other attributes, with differing opinions mainly due to assumptions about planting diversity and seed potential. Overall, increased natural regeneration tends to improve visual aesthetics, mainly through tree height diversification and reduced clear-cuts. Further benefits emerge if species-diverse regeneration and moderate understory levels can be ensured.

Table 7: *Expert assessment of climate change adaptation measures (CCAMs) and their impacts on forest attributes and outcomes for visual aesthetics. Arrows indicate whether a measure increases (upward), decreases (downward) , or has no effect on the attribute (circle). The consistency of expert responses is represented by the borders of the icons: a strong majority (thick border), means at least 9 of 11 experts agree; an absolute majority (no border), indicates at least 6 of 11 experts agree; no clear trend (NT) if less than 6 experts agree. A small arrow within a circle reflects a majority with no expected effect but a strong minority opinion on its potential impact. The color of the symbols indicates whether the resulting impact on aesthetics is positive (green), negative (red), situation-dependent (two-colored), or neutral (grey).*

Attribute:		**Tree size**	**Variation of tree height**	**Density of understory**	**Tree species variability**	**Clear cuts**	**Residues**	**Traces of intervention**	**Overall impact on visual aesthetics**
Influence on visual aesthetics:		Linear positive	Linear positive	Bell shaped	Linear positive	Linear negative	Linear negative	Linear negative	
Adaptation strategy	**Adaptation measures**	**Impacts on forest attributes, consistency of responses & impact on visual aesthetics**							
Adaptation of the tree species mixture	Diversifying tree species mix	NT							positive
	Increased use of natural regeneration				NT		NT		positive
Strengthening basic ecological functions	Leave more harvest residues								negative
	Soil-friendly harvesting								positive
	Fast reforestation after calamities								negative
Reduction of biotic and abiotic stressors	Early, intensive thinning								short term negative, long term positive
	Effective regulation of game populations							NT	positive
	Reducing production time/ target diameter			NT	NT		NT		negative
	Conversion into multi-layered stands								positive

Leaving more harvest residues mainly impacts the forest attributes through improved nutrient conditions and by promoting small-scale mosaic structures. However, foresters expect the resulting increase in tree size, height variation and understory density to be relatively small. While these changes have positive visual effects, the residues themselves lead to negative visual effects. Overall, the positive effects are likely to be outweighed by the strong negative impact of the residues, resulting in a somewhat negative effect on visual aesthetics. Soil-friendly harvesting has little impact on most attributes but reduces intervention traces, namely wheel tracks, which contributes positively to forest aesthetics. It also improves growth conditions, resulting in a slight increase in tree size and height variation, although foresters consider these effects marginal. Since there are no negative effects, the measure is overall clearly positive aesthetically, mainly due to the reduction of wheel tracks. Fast reforestation after calamities increases tree size but reduces tree height variation and species diversity, while also increasing traces of intervention. Thus, the overall visual impact is negative, primarily due to intensive planting interventions and the establishment of initially dense forests, which later develop into uniform, single-layered stands.

Early, intensive thinning likely has a negative visual impact in the short term and medium term due to the large amounts of residues, intervention traces and because it results in a temporarily open canopy that promotes dense undergrowth, likely exceeding the ideal moderate range. However, in the long term, it is expected to have a positive effect, particularly due to the larger tree sizes, improved structural layering, and reduced calamity risks, which minimize the need for clear-cuts. More effective game regulation promotes taller, more diverse stands with denser understory by reducing browsing pressure, probably resulting in an overall positive visual effect—at least where the initial understory is sparse and provided it does not become overly dense. The primary drawback may be the presence of hunting infrastructure. However, experts differ in their views on whether this measure increases intervention traces—due to the need for additional hunting infrastructure—or reduces them by decreasing the necessity for protective measures such as fencing. The effects of shortening production time are uncertain due to differing expert opinions on understory, tree species diversity, residues, and to a lesser extent also traces of intervention. However, foresters largely agree that it reduces tree size and height variation. Overall, the impact is generally negative, as it leads to smaller trees, less structural layering, and often more traces of intervention. A positive aspect is the reduced likelihood of calamities resulting in fewer clear-cut areas. The forest experts largely agree on the effects of transforming forests into multi-layered stands. Overall, nearly all effects positively contribute to the visual aesthetics of forests, with the only potential drawback being overly dense understory, which may reduce visibility.

6.4 Discussion

6.4.1 Common approaches of CCAMs in forest management

In this study, we focus on nine CCAMs that are frequently mentioned by our practice partners (Knutzen et al., 2025), supported by literature, or included in funding programs (BMUV, 2024). Climate-adaptive forest management, as outlined in the latter, includes key criteria to enhance forest resilience. These measures focus on promoting natural regeneration, increasing genetic diversity, and reducing monocultures by diversifying tree species. Avoiding clear-cutting and

accelerating reforestation after extreme events help restore ecosystem functions and prevent soil erosion. Retaining deadwood and fostering multilayer stands enhance biodiversity and forest stability. Other measures, such as soil-friendly harvesting, regulating game populations, and thinning, support regeneration, improve timber quality, and promote forest adaptability. These measures largely reflect the common approaches to forest adaptation to climate change in Germany and beyond. However, it is important to note that many of these methods, such as rapid reforestation after extreme events or thinning, are also subject to critical evaluation, particularly from those in the forestry community who advocate for close-to-nature forest management. For instance, thinning is considered a CCAM because it reduces competition, enhances tree growth, and lowers wildfire risk (Ganatsas et al., 2024; Ogaya et al., 2020). However, it also alters microclimatic conditions, potentially increasing drought vulnerability and windthrow risk (Lohmander & Helles, 1987; Menge et al., 2023; del Río et al., 2017). Thus, its effectiveness as a CCAM remains debated and requires site-specific application (Moreau et al., 2022).

6.4.2 The effects of CCAMs on the visual aesthetics of forests

This study examines how various adaptation measures affect forest structure and, in turn, the visual aesthetics of forests, ensuring that forest aesthetics are not overlooked in climate change adaptation. To put it in a nutshell, measures that adjust the tree species mix generally enhance the visual aesthetics of forests by increasing tree height diversity and reducing the likelihood of clear-cutting. Additionally, soil-friendly harvesting, more effective game regulation, and the conversion to multi-layered stands contribute positively and can therefore be considered 'no-regret' adaptations from the aesthetic viewpoint. However, early intensive thinning, shortened rotation periods, rapid reforestation, and increased harvest residues may negatively impact the visual aesthetics of forests. The following detailed analysis highlights both the negative and positive visual effects, offering strategies to enhance the visual appeal of adaptation measures. These insights should help foresters balance silvicultural goals for climate change adaptation with public perception, guiding visually appealing forest management practices.

Drawing conclusions about the overall visual impact based on individual attributes can be challenging, especially when both positive and negative aesthetic effects are present. The overall impact depends not only on the relative importance of the attributes but also on the extent to which they are influenced by the measures. For instance, while most foresters expect that leaving more harvest residues will positively affect tree size, the expected increase is generally small, resulting in minimal impact on visual aesthetics. The time frame in which these effects occur is also a critical factor. For example, the impact of harvest residues or other traces of intervention may be quite pronounced in the short term, but often diminishes significantly over a few years. Consequently, the assessments in this study are contingent on specific circumstances and the relative importance assigned to different time periods. The fact that the overall effects of adaptation measures on visual aesthetics vary depending on context does not diminish our analysis. Rather, our detailed examination helps forestry practitioners to identify key aspects to emphasize, maximizing positive visual effects while minimizing negative impacts. In the case of tree species diversification, for example, combining large, fast-growing trees with slow-growing ones can enhance positive effects on tree size and height variation. Furthermore, minimizing the visual impact of interventions and logging residues

during planting and harvesting is crucial. Nielsen et al. (2012) suggest that using natural materials for plant protection measures and fencing can effectively minimize their visual impacts.

From an aesthetic standpoint, increased use of natural regeneration is generally recommended. However, ensuring sufficient seed potential is crucial to support a visually appealing diverse natural regeneration, which is also beneficial from a silvicultural perspective (Piqueray et al., 2013). At the same time, excessive density of natural regeneration across the entire area should be avoided, as it can obstruct views into the stands. In areas with dense natural regeneration, selective, mosaic-like removal of the understory can result in stands with varying understory heights. This approach not only enhances aesthetic appeal (Wang et al., 2017) but also promotes long-term structural diversity within the stand (Fahey et al., 2018).

Most experts agree that leaving more harvest residues has only marginal effects on tree size and height variation. However, since full tree exploitation depletes nutrients (Achat et al., 2015), long-term effects might be more severe, especially on poor soils. In these areas, the positive visual effects of increased tree size and height variation likely outweigh the negative visual effects of residues. To reduce visual disturbances, residues can be placed at some distance from the trails. Studies also show that as deadwood decomposes, its visual impact diminishes and can even become positive over time (Rathmann et al., 2020). In addition, it should be noted that aesthetic perception in general, and particularly the perception of deadwood, is strongly influenced by an individual's background and knowledge (e.g., awareness of the ecological importance of deadwood). Consequently, the overall appraisal of forest vistas containing large amounts of deadwood can be enhanced by providing information about its ecological role (Gundersen et al., 2017). If large quantities of harvest residues are removed, at least the leaves should remain to prevent severe nutrient depletion (Achat et al., 2015).

In Central Europe and Scandinavia, harvesting traditionally occurs in winter, with operations ideally carried out on frozen soils to prevent soil damage. However, climate change is shrinking this time window in many regions (Labelle et al., 2022). Consequently, damage caused by machinery is likely to become more common without increased soil protection efforts. Our discussions with forestry practitioners revealed a conflict: forest visitors often criticize wheel tracks, while practitioners often regard them as unavoidable. This underscores the importance of adaptation measures, even if most forest attributes are minimally affected. Beyond wheel tracks and harvest residues, little research exists on other traces of interventions, though experts identify hunting infrastructure and tree protection measures as important for climate change adaptation.

To mitigate the negative effects of rapid reforestation after calamities, we recommend planting a variety of tree species with different sizes and harvesting ages to promote a multi-layered structure. In the short-term, maintaining visual corridors with sparse natural regeneration can help to prevent uniform, dense young growth.

Early intensive thinning with its visual short-term drawbacks and long-term benefits, illustrates the challenge of evaluating measures with effects spanning over different time horizons. On the one hand, it can be debated whether and to what extent the impacts in the near future should be

given more weight than those in the distant future (Newell & Pizer, 2003). Additionally, it is unclear to what extent aesthetic preferences will remain consistent over decades. While the attributes studied by Ribe (1989) and, more than 20 years later, by Edwards et al. (2012) are essentially the same, research suggests that knowledge and cultural background can influence aesthetic judgments (Lim et al., 2015). This implies that as forests, our demands on them, and our understanding of their functions evolve, aesthetic preferences are also likely to change. Recognizing that preferences are not stable is important when considering tensions between ecological management goals and public visual preferences like discussed in the "ecological–aesthetic conflict" (Gobster et al., 2007; Nassauer, 1995). Similar aesthetic challenges are likely to emerge with climate change adaptation measures, such as leaving harvesting residues or maintaining deadwood, which may initially be viewed negatively but become appreciated as public awareness of ecological processes grows. This underscores the importance of communication and participatory approaches to help forest visitors understand the rationale behind such measures.

A key drawback of regulating game populations is the necessity of hunting infrastructure, which should be carefully placed to remain out of sight from the trails in order to avoid negatively impacting visual aesthetics. Our analysis focuses on the visual aesthetics of forests and does not address the likelihood of wildlife sightings. Nevertheless, since wildlife sightings can significantly enhance the forest experience, many visitors are willing to accept less aesthetically pleasing forests for the chance to observe wildlife (Skov-Petersen et al., 2021). Therefore, it is conceivable that incorporating the likelihood of wildlife sightings could result in a negative overall assessment of this measure.

Our finding that shorter rotation periods negatively affect the visual aesthetics of forests is supported by existing literature, at least for even-aged forests (Roberge et al., 2016). However, in forests at high risk of extreme events that may result in clear-cuts, this approach could be aesthetically advantageous if it helps mitigate large-scale damage. Outside of such scenarios, we recommend against this measure in forests where recreation and aesthetics are prioritized, given its substantial negative impact on key attributes such as tree size and height variation.

Overall, a conversion into multi-layered stands enhances the visual aesthetics of forests, aligning with existing recommendations (Dudek, 2018). Therefore, we recommend this measure for forests where aesthetics and recreation are prioritized, particularly if certain sightlines with sparse understory are maintained.

6.4.3 Evaluating methodological limitations and literature alignment

Given the limited number of expert interviews, the reliability of the experts' assessments could be questioned. However, the limited existing literature on the topic largely supports their conclusions. For instance, Juchheim et al. (2019) confirm that a higher tree species diversity leads to greater variation of tree height. Similarly, Guyot et al. (2016) and Felton et al. (2016b) confirm that higher tree species diversity reduces vulnerability to pests and diseases, lowering the risk of clear-cutting. Furthermore, studies support the link between rapid reforestation and tree size (Schwitter et al., 2015; Wohlgemuth et al., 2017), as well as the role of multi-layered stands in enhancing tree species diversity (Hakkenberg et al., 2016; Mason et al., 2022). Overall, existing research aligns with our expert assessment.

Our analysis confirms that all forest attributes identified in the scientific literature are crucial for evaluating adaptation measures. None of the attributes are merely marginally affected- each plays an important role in shaping the visual aesthetics of forests. While some, such as tree size, may be only slightly influenced by certain measures, they remain crucial for other measures. This underscores the importance of considering these attributes when assessing adaptation strategies. Foresters prioritizing aesthetics can use these findings as a solid framework for evaluating the visual effects of adaptation measures.

While our study provides valuable insight into the visual aesthetics of forests linked to climate adaptation, its scope is necessarily limited. By focusing on individual stands, we excluded broader attributes such as diversity between stands, despite its importance for forest aesthetics (Edwards et al., 2012). Further own research suggests that forest visitors have diverse preferences regarding many attributes (Averbeck et al., 2025). Therefore, overall appreciation may be enhanced when forests are managed using various concepts rather than an average aesthetic standard (Alvarez et al., 2021). Additionally, this strategy can help mitigate trade-offs among different forest functions at larger geographic scales by establishing a mosaic of areas managed with different functional emphases (Lucash et al., 2023). Beyond diversity between stands, several structural forest attributes -such as forest edge naturalness, deadwood quantity, and tree spacing - could not be included. Although pretest evaluation by two foresters suggested these factors likely have minimal relevance for climate change adaptation, their unaccounted influence could alter our results. Moreover, non-silvicultural elements like parking lots, tourist infrastructure, or water bodies can influence the recreational value of forests (Giergiczny et al., 2015). These features present opportunities to enhance visitor experience without altering forestry practices, potentially offsetting the negative visual impacts of adaptation measures.

Research highlights polarized debates in many countries over forest management, often opposing ecologically oriented actors who advocate for natural forests against those prioritizing economic outcomes and intensive management (e.g., Knutzen et al., 2025). These contrasting value frameworks also shape aesthetic perceptions, leading to divergent views of what is considered an appealing forest. This may help explain why previous studies have found considerable heterogeneity in aesthetic preferences for forests (Averbeck et al., 2025). Our approach, which focuses on average perceptions, cannot fully reflect this diversity of views. Nevertheless, since the main goal of our work is to inform forest management and enhance the aesthetic outcomes of management measures, concentrating on the average visitor’s perception is appropriate for this purpose.

Looking critically at the methodology of this paper, we acknowledge that the visual aesthetics of forests cannot be conclusively evaluated by simply adding up individual, predetermined forest attributes. The interplay of the different factors, such as local characteristics, observation conditions and many others, always influences aesthetic evaluation. Ultimately, it is the forester’s task to consider these diverse factors and manage the forest in a way that either maintains or improves its overall aesthetic quality. Nevertheless, we believe it is crucial to provide an approximate assessment of the aesthetic impacts of common adaptation measures from the perspective of the average visitor, as we have done here. This is important because the observer's perspective significantly influences their evaluation. Research shows that foresters

tend to view the visual consequences of forestry interventions less negatively than the average forest visitor (Gundersen & Frivold, 2008; Petucco et al., 2013). Thus, it would be short-sighted to base aesthetic evaluations solely on foresters' perceptions without also taking into account general visitor preferences for the most important interventions.

6.5 Conclusion

In conclusion, our research revealed the following concerning our research questions:

1. While many climate change adaptation measures (CCAMs) exist, those affecting forests at the stand level can be grouped into strategies that diversify tree species, strengthen ecological functions, and reduce biotic and abiotic stressors.
2. The main attributes influencing the visual aesthetics of forests are tree size, height variation, and understory density, with larger trees, diverse stand structures, moderate undergrowth being preferred. Additionally, forests with a mix of tree species and minimal signs of human intervention, such as clear-cuts, visible residues, wheel tracks or fencing, enhance visual appeal. While our focus was on individual stands, broader landscape diversity and non-silvicultural elements, like tourist infrastructure, also influence forest aesthetics and recreational quality and warrant further study.
3. Overall, the CCAMs we examined tend to have predominantly positive effects on the visual aesthetics of forests. However, the impacts vary depending on the specific measure, with some resulting in mainly negative outcomes. Measures that enhance diversity and structural complexity mainly improve visual aesthetics, while intensive interventions, visible residues, and shortened production cycles tend to have negative aesthetic consequences. To enhance both ecological resilience and public appreciation, foresters should prioritize diverse stand structures, natural regeneration with varied species while maintaining sightlines, and careful planning of interventions and infrastructure placement to minimize visual disruption.

6.6 References

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7 Aesthetic preferences for forests after climate change-induced disturbance: A discrete choice experiment accounting for temporal evolution of reforestation measures

Abstract

In recent years, extensive forest areas across Central Europe have experienced significant dieback due to climate change-induced disturbances such as drought and insect outbreaks, prompting the need for large-scale reforestation efforts. Given the importance of forests as recreational spaces, it is essential to understand how different reforestation strategies impact forest aesthetics. This study employs a discrete choice experiment to examine how deadwood management, species composition, tree protection, tree spacing, and forest floor conditions influence aesthetic preferences. Using visual prompts specifically developed to capture temporal evolution, we assess preferences for these factors at three time points: immediately, 15 years, and 50 years after the implementation of measures. Results suggest that most respondents perceive substantial amounts of deadwood and many mixed forest compositions as aesthetically unappealing. Additionally, the aesthetic evaluation of the same policies varies significantly over time. This underscores the importance of incorporating multiple time points into the assessment of forest management practices to fully understand their long-term effects on forest aesthetics.

7.1 Introduction

Forest calamities in Europe have resulted in an average of 43.8 million cubic meters of disturbed timber annually (Patacca et al., 2023). Since 2018, these disturbances, especially in Central and Eastern Europe, have exceeded historical levels (Senf & Seidl, 2021). Wind disturbances have been a major contributing factor (Forzieri et al., 2020), as also illustrated by the extensive impacts of the VAIA storm in Northern Italy (Tempesta et al., 2024; Vecchiato et al., 2023). In addition, consecutive droughts have triggered insect infestations and caused physical tree damage across large parts of Central Europe (Knutzen et al., 2025). In Germany, heatwaves and droughts since 2018 have caused significant canopy cover loss, further exacerbated by bark beetles (Kacic et al., 2023). Approximately 500,000 hectares of German forest have been severely affected, with large portions urgently requiring reforestation (BMEL, 2024). These visible forest changes affect public perception, as visitors tend to prefer intact, healthy forest stands with minimal signs of beetle damage (Arnberger et al., 2018). Climate change projections indicate that disturbances will intensify in the future (Rousi et al., 2023). Accordingly, a key challenge for forestry will be ensuring climate-resilient reforestation in disturbed areas. This includes the dual challenge of reforestation and adapting management practices to enhance forest resilience against changing climatic conditions. However, various strategies and different perspectives exist on how this reforestation should take place and which tree species are most suitable (Hlásny et al., 2021; Lindenmayer et al., 2017; Müller et al., 2020;

Riccioli et al., 2019; Tempesta et al., 2024; Vecchiato & Tempesta, 2013). In this context, the question arises as to what effects different reforestation approaches have on various ecosystem services. In this study, we analyse the impact of reforestation on forest aesthetics, given its importance for the recreational function of forests. Understanding the role of aesthetics in forest restoration is essential for engaging the public and fostering positive perceptions of reforestation efforts. Our understanding of forest aesthetics aligns closely with the conceptualization of landscapes as defined by the European Landscape Convention, which defines landscapes as "an area, as perceived by people, whose character is the result of the action and interaction of natural and/or human factors" (Council of Europe, 2000). This definition emphasizes the multidimensional nature of landscapes, combining physical elements, aesthetic values, and subjective perception (Jones, 2007), while simultaneously challenging the traditional notion that landscapes are limited to picturesque rural environments (Antrop, 2018). Accordingly, this research is not confined to exceptional forests specifically designed for high recreational value but rather encompasses all forests in which recreation—among other functions—plays a significant role. In simplified terms, forest aesthetics can be interpreted as a function of structural forest attributes (Edwards et al., 2011), and prior research has examined how various forest attributes influence aesthetic perceptions. For example, tree species diversity is generally found to have a positive influence on forest aesthetics (Edwards et al., 2012; Filyushkina et al., 2017; Füger et al., 2021; Giergiczny et al., 2015; Nielsen et al., 2007; Ribe, 1989), although one study reports contradictory results (Tyrväinen et al., 2003). However, most of these studies compare only pure coniferous or deciduous forests with mixed forests, without accounting for differences between specific tree species (Ebenberger & Arnberger, 2019; Filyushkina et al., 2017; Giergiczny et al., 2015; Nielsen et al., 2007). Thus, detailed knowledge of forest visitors' aesthetic preferences regarding individual species is lacking.

The perception of deadwood is another well-researched forest attribute, yet the literature remains inconclusive regarding its role in forest aesthetics. While many studies report that forest visitors dislike deadwood (Arnberger et al., 2018; Nielsen et al., 2012; Tyrväinen et al., 2003), others find a positive influence of deadwood on perceived forest attractiveness (Hauru et al., 2014; Pastorella et al., 2014; Rathmann et al., 2020). Still, other studies suggest that intermediate amounts of deadwood are attractive to visitors (Ebenberger & Arnberger, 2019; Edwards et al., 2012; Giergiczny et al., 2015) or find no significant impact (Garms, 2020; Sacher et al., 2022). The perception of deadwood plays a prominent role in the assessment of damaged areas due to the large number of dead trees. While it is known that recreationists generally dislike large amounts of deadwood resulting from insect outbreaks (Sheppard & Picard, 2006), clear-cut areas are also rated very poorly from an aesthetic perspective (Ribe, 2005; Silvennoinen et al., 2002). It therefore remains unclear whether forest visitors prefer maintaining extensive stands of dead trees or favour clearcutting. Although Arnberger et al. (2018) indicate a preference for clear-cutting, it is not clear whether this is the optimal aesthetic choice or if more balanced alternatives exist that combine the removal and retention of dead trees. In addition to tree species and the treatment of deadwood, other factors such as soil preparation, tree protection, and tree spacing are important variables in afforestation that can affect forest aesthetics. To our knowledge, little research has been conducted on the aesthetic impacts of these factors.

The present study contributes to this literature by examining how different reforestation strategies in the context of climate adaptation affect the aesthetic attractiveness of forests for recreational visitors. A key challenge in addressing this issue is the long timeframe required for forestry measures to take effect. Management decisions made today will shape the appearance of the forest for many decades to come. As a result, certain decisions may negatively affect forest aesthetics in the short term but yield positive effects in the long term, or vice versa. To analyse the effects of silvicultural measures on forest aesthetics, it is essential to consider forest's temporal evolution following the implementation of these measures. Some initial studies have explored changes over time. For example, Shelby et al. (2003) and Silvennoinen et al. (2002) found that while clear-cutting is initially rated much lower than alternative harvesting methods, visitors' ratings tend to converge over time. The survey study by Arnberger et al. (2018) includes forest images taken several years after a calamity. Yet, these images are compared to those depicting the situation immediately after the calamity, which does not provide a consistent timeframe for comparison. While these studies offer valuable insights, they do not fully address the issue of temporal evolution. Overall, the literature on forest aesthetics remains dominated by static assessments at individual points in time, largely ignoring developments over time (Ebenberger & Arnberger, 2019; Füger et al., 2021; Meo et al., 2020; Petucco et al., 2013). To address this gap in the literature, we aim to answer the following research questions:

1. Which components of reforestation measures are appreciated by people, and to what extent? Specifically, the present study examines the aesthetic effect of tree species, soil treatment, browsing protection, tree spacing, and the presence of deadwood.

2. What are the preferences for the aesthetic outcomes of reforestation measures at different points in time, and how do these temporal differences affect the choice of an optimal reforestation strategy?

To address these research questions, we employ a discrete choice experiment, a survey-based approach widely used in environmental economics and management to elicit preferences for non-market goods and ecosystem services (Hoyos, 2010; Mariel et al., 2021). DCEs have been extensively applied to assess preferences among the general population or of forest visitors for aesthetic elements of landscapes (e.g. Schaak & Musshoff, 2018; Schüpbach et al., 2021; Zanten et al., 2016), including forest landscapes (e.g. Arnberger et al., 2018; Filyushkina et al., 2017; Meo et al., 2020). Our study is based on a German sample gathered via an online panel.

The remainder of the paper is structured as follows. Section 7.2 outlines the applied research methodology. Section 7.3 presents the results, which are analysed and interpreted in Section 7.4. Section 7.5 concludes by addressing the research questions and discussing practical implications.

7.2 Materials and Methods

7.2.1 Structure of the DCE survey study

In DCEs respondents are presented with a series of choice questions consisting of alternative policy options, each characterized by a set of attributes. Respondents are then asked to state their most preferred alternative in each series. These discrete choice responses can be used to assess the effect of the attributes on choice probabilities (Train, 2009) and hence, quantify the preference weights in the utility function of a representative respondent. To address the research questions outlined above, the present study conducts three parallel DCE surveys, each assessing preferences for visual forest characteristics at a different stage of growth: right after reforestation, after 15 years, and after 50 years of growth. In the following, we refer to these different time points as Treatment 1, 2 and 3. In each treatment, choice attributes (see Table 8) were selected corresponding to the characteristics that are substantially influenced by the most important strategies for dealing with calamity areas and those factors that are known to play an important role in forest aesthetics. This setup serves to answer Research Question 1. With respect to Research Question 2, comparisons across treatments are necessary. While the choice attributes in each treatment differ to some extent, there are clear links between a number of attributes across treatments. Figure 15 shows the attribute levels and their links across the three treatments, which will be introduced in detail in the following.

Table 8: *Choice attributes and levels*

Choice Attributes	Levels in Treatment 1	Levels in Treatment 2	Levels in Treatment 3
Standing deadwood	None High stumps Groups Everywhere	None High stumps Groups Everywhere	Not included
Forest Flor	Mulched Natural Dead branches	Not included	Not included
Tree protection	Tree guards everywhere Groups of tree guards Wooden fences Fence	Not included	Not included
Tree spacing	Not included	Regular Irregular	Regular Irregular
Tree species	Not included	Spruce Oak Oak dominated mix Oak cluster mix Succession	Spruce Small oak Big oak Small oak mix Small oak mix with rowan Big oak mix with rowan Succession 1 Succession 2

7.2.2 DCE design

The first attribute captures the presence of *standing deadwood* (Figure 15, blue boxes). This attribute is featured in Treatments 1 and 2 but is absent in Treatment 3, where all deadwood is assumed to have naturally decomposed. The reference level is *None*, indicating that all standing deadwood has been completely removed. Alternative levels are *High stumps*, where dead tree stumps of two meters in height remain; *Groups*, where clusters of approximately 30 entire dead trees are retained while trees between the groups are removed; and *Everywhere*, where all dead trees are left standing. In Treatment 2, the same attribute levels are present, but dead trees are partly downed, broken, and hidden by regenerating vegetation.

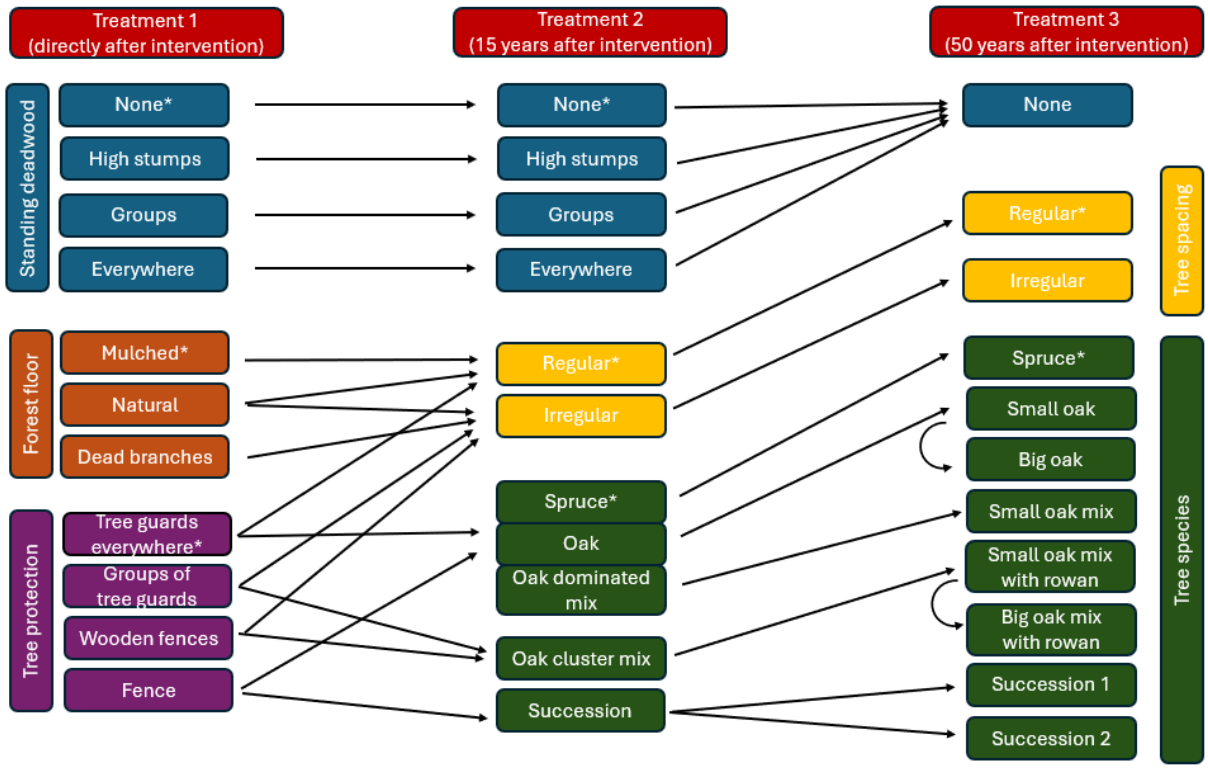


Figure 15: *Attributes (vertical boxes) and attribute levels (horizontal boxes) and their links between treatments.*
*The first level of each attribute (marked with a *) is the reference value.*

The second attribute refers to the *forest floor* (brown boxes) and it features only in Treatment 1. Three levels are distinguished. The reference level is *Mulched*, where the forest floor is mechanically processed to prepare for reforestation. In contrast, the level *Natural* describes a condition in which branches are removed but the soil remains otherwise undisturbed. The Dead *branches* level describes a situation where dead branches remain scattered on the ground after tree removal. We assume that all these initial soil conditions are not visible anymore in Treatments 2 and 3, i.e. after 15 and 50 years, respectively.

The third attribute addresses *tree protection* (purple boxes) and appears exclusively in Treatment 1. This attribute illustrates how seedlings are protected from animal browsing—an important factor given the low survival rates of saplings of certain tree species in areas with high game populations. Four protection levels are distinguished. The reference level is *Tree guards everywhere*, where plastic tree guards are regularly placed throughout the entire area.

The level *Groups of tree guards* refers to tree guards placed only in groups of about 20 saplings. In the next level, *Wooden fences* are used in the same location as the groups of tree guards. Lastly, the *Fence* level refers to a continuous wildlife protection fence made of knotted mesh that encloses the entire area. We assume that all tree protections are correctly dismantled and no longer visible in Treatments 2 and 3. However, *Tree guards everywhere* and in a lesser extent also the *Fence* only make sense for systematic area-wide planting which leads to regular stands and one of the regular tree mixes (see last attribute) in Treatments 2 and 3. In contrast, *Groups of tree guards* and *Wooden fences* lead to irregular tree spacing and tree mixtures.

The fourth attribute, *Tree spacing* (yellow boxes), appears only in Treatments 2 and 3 and describes the spatial arrangement of trees. The reference level is *Regular,* where all trees are planted in rows with uniform spacing. The alternative level is *Irregular*, where the trees are distributed in a more random and naturalistic manner. The tree spacing in Treatments 2 and 3 indirectly results from the *forest floor* in Treatment 1. Specifically, mulching only makes sense if trees are systematically replanted, leading to *regular forest stands*. Conversely, leaving dead branches obstructs regular planting and is, therefore, linked with *Irregular tree spacing* in later stages.

The fifth and final attribute is *Tree species* (green boxes). It appears in Treatments 2 and 3 and reflects the tree species mix used for reforestation. In Treatment 2, five species compositions are included. The reference level is *Spruce*, which also serves as a visual proxy for Douglas fir assuming that lay people cannot visually distinguish between the two species. In times of climate change, a spruce plantation, contrary to a Douglas fir plantation, is not realistic, but regarding natural regeneration it is still important. For technical reasons, we used one level for both species. Other levels are *Oak*, a mono-species oak stand; *Oak-dominated mix*, which is primarily oak with some spruce and birch; *Oak cluster mix*, where oaks are planted in groups of about 20 saplings and natural regeneration (spruce, birch and rowan) fills the space in between; and *Succession*, composed primarily of naturally regenerated spruce along with birch and rowan.

In Treatment 3, we distinguish eight tree species compositions, which are naturally derived from those in Treatment 2. However, as management decisions can still influence species composition between Treatments 2 and 3, some species mixtures in Treatment 2 can result in multiple mixtures in Treatment 3. The first level remains *Spruce*. We then differentiate *Small oaks* and *Big oaks* to assess whether the visual impact of oaks is driven by their slower growth and smaller size or by their species-specific appearance. Similarly, *Small oak mix with rowan* and *Big oak mix with rowan* are both derived from the *Oak cluster mix* in Treatment 2 and differ in the visual maturity of the oaks. The level *Small oak mix* maintains the same species composition as the *oak dominated mix* in Treatment 2 (oak, spruce, birch), but with a relatively greater importance of oak; here we do not differentiate the oak size. Finally, two levels represent naturally regenerated mixtures: *Succession 1*, dominated by spruce with some birch and rowan, and *Succession 2*, consisting of roughly equal parts of spruce and birch with some rowan.

In collaboration with the company Lenné 3D, we created virtual forest images that depict forests from the eye-level perspective of a visitor walking along a trail. For each treatment, we generated images representing all possible combinations of the selected attribute levels, except

for the unrealistic combinations that included both *standing deadwood everywhere* and *dead branches* on the *forest floor,* the latter being a logical consequence of felling the dead trees. In total, 44, 36 and 39 different images were used in Treatments 1, 2 and 3 respectively. Using virtual images makes it possible to vary the attribute levels exactly according to the underlying experimental design to identify marginal effects while minimising unforeseen effects. Examples of choice cards in Treatments 1 to 3 are displayed in Figure 16.

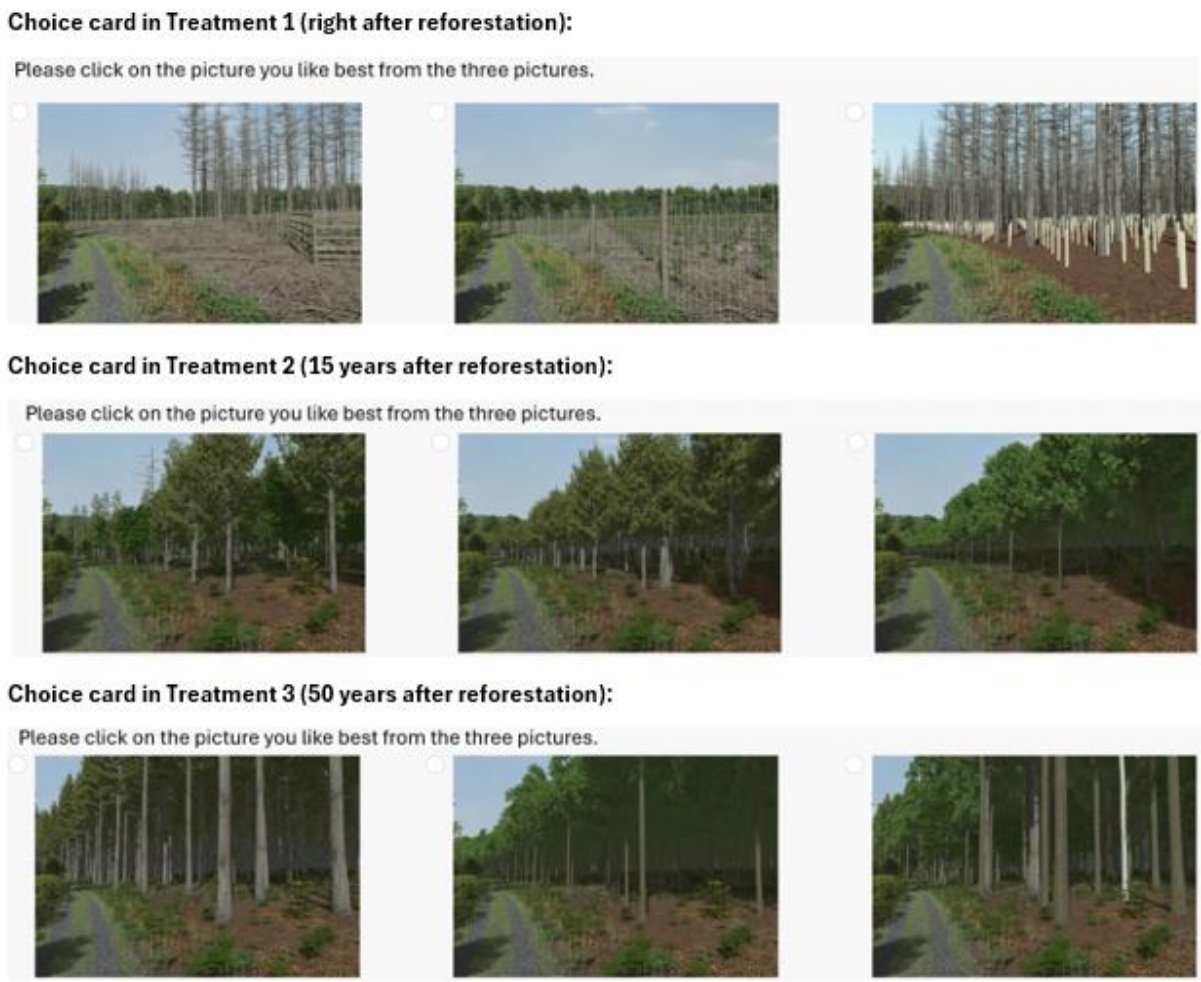


Figure 16: *Examples of choice sets for all treatments*

The attribute levels presented on the choice cards are based on a D-efficient design, which was generated in NGENE (Version 1.3; Choicemetrics) with restrictions to prevent unrealistic combinations. Priors were based on knowledge from previous literature (see introduction) and expert opinion. The final designs included 48 image combinations for Treatments 1 and 2, and 24 for Treatment 3. These were blocked into four survey versions for Treatments 1 and 2, and two versions for Treatment 3. Respondents in each treatment were randomly allocated to one of the blocked versions. Each version was composed of 12 choice tasks, each consisting of three images (i.e. alternatives) without any labels. The order of choice tasks was randomised. All respondents were asked to select the picture they find most beautiful when they imagine spending time in that particular forest.

In line with the methodology of Schüpbach et al. (2021) and Arnberger et al. (2018) we did not provide any information about attributes. Neither did we include a monetary attribute or a status quo in the DCE. We exclusively presented the unlabelled images, first each of the three images individually in full-screen mode, followed by a display of all three options side by side, as shown in Figure 16. As a result, respondents' stated choices were to be based solely on their aesthetic preferences.

7.2.3 Survey structure and data collection

The actual DCE was embedded in an online questionnaire composed of four parts. First, we asked questions about respondents' use of and proximity to forests. In the second part we asked some general questions about the respondents' assessment of the importance of various forest features. This part intended to draw respondents' attention to relevant forest attributes without influencing them in any particular direction. This section was directly followed by the DCE as described above. Finally, we asked some questions to collect typical sociodemographic data.

The survey was conducted in July 2023 using an online panel comprising respondents from all over Germany. For each treatment, respondents were randomly selected with quotas for age, gender and region to approximate the distribution of these demographic characteristics in Germany. In this way, we obtained a total of 7,315 completed surveys. From this original dataset, we removed 732 respondents for speeding using a speed index based methodologically on Steinbrecher et al. (2009). We further removed 1,030 respondents who failed to correctly answer an attention test question or had other logical errors in their answers. This yielded a final dataset with a total of 5,553 surveys. As displayed in Table 9, this dataset comprises three treatment datasets for each of the three points in time (with N=2,213, N=2,225 and N=1,115, respectively). The dataset for Treatment 3 is smaller than the others because we have fewer attributes and, therefore, need fewer respondents to obtain reliable results.

7.2.4 Data analysis

The choice responses were analysed separately in each treatment employing the mixed logit model (Mariel et al., 2021; Train, 2009) grounded in random utility theory (McFadden, 1974). The model assumes that respondents evaluate the utility of each alternative offered and choose the alternative with the highest utility. Utility of alternative *i* as seen by respondent *n* in choice task *t* is modelled as a linear combination of the choice attributes *X* as follows:

$$U_{nti} = \beta_n{}' X_{nti} + \varepsilon_{nti} \quad (1)$$

A vector of preference weights β_i is obtained by estimation. Assuming that respondent n chooses the alternative yielding the highest utility and that the error term ε_{nti} follows a Type I Extreme Value distribution, the probability of alternative *i* being chosen is

$$P_{nt}(i) = \frac{\exp\left(\beta_n{}' X_{nti}\right)}{\sum_{j=1}^{J} \exp\left(\beta_n{}' X_{ntj}\right)} \quad (2)$$

All attributes in *X* are dummy coded, this means that the estimated coefficients must always be interpreted relative to the respective reference level. The mixed logit model assumes that preference parameters vary randomly across respondents (which is why the elements of β_n are

indexed by n), and it is up to the analyst to assume a distributional form. In this study, all parameters in β_i are assumed to follow a normal distribution, hence the mean and standard deviation of each random parameter are reported. Since this model does not have a closed-form solution, we use 1,000 Modified Latin Hypercube Sampling draws (Hess et al., 2006) to find the maximum likelihood. Models are run in R (Version 4.3.2) using the package "Apollo" (Hess & Palma, 2019, 2021).

To analyse the temporal evolution of attributes following afforestation measures, we use simulated scenarios for which we calculate choice probabilities according to eq. (2). The three scenarios represent typical procedures for dealing with damaged areas (Figure 17). In Scenario 1, 'Intensive intervention', the aim is to utilise the dead trees and quickly establish an economically interesting new stand. Therefore, *standing deadwood* is *none* in Treatment 1 and the *forest floor* is *mulched* in order to plant new trees over the whole area, which are protected with *tree guards* everywhere. This results in a pure stand of Douglas fir (*spruce*) with *regular tree spacing* and without *standing deadwood* (*none*) in Treatment 2 and 3.

The second scenario 'Natural development' –somewhat the opposite of the first– aims to minimise intervention and allow the forest to develop naturally. Therefore, in Treatment 1 there is *standing deadwood everywhere* and the *forest floor* remains *natural*. For the *tree protection* of emerging natural regeneration a *fence* is used. This initial situation results in *irregular succession* with *standing deadwood everywhere*. In Treatment 3, this becomes an *irregular* succession stand with a balanced proportion of birch and spruce (*succession 2*).

The third scenario, 'Active forest conversion', takes a middle path between the other two scenarios and has the main objective of creating stands that are better adapted to climate change and at the same time economically interesting in the long term. In Treatment 1, *groups* of *standing deadwood* are left in place and seedlings are protected with *wooden fences* while *dead branches* are left on the *forest floor*. In Treatment 2, this results in an *irregular* stand of oak clusters with succession in the intermediate fields (*oak cluster mix*) and *groups* of *standing deadwood*. In Treatment 3, the oak groups are no longer recognisable as such, and the stand has developed into an *irregular small oak mix with rowan*. These scenarios are visualised in Figure 17.

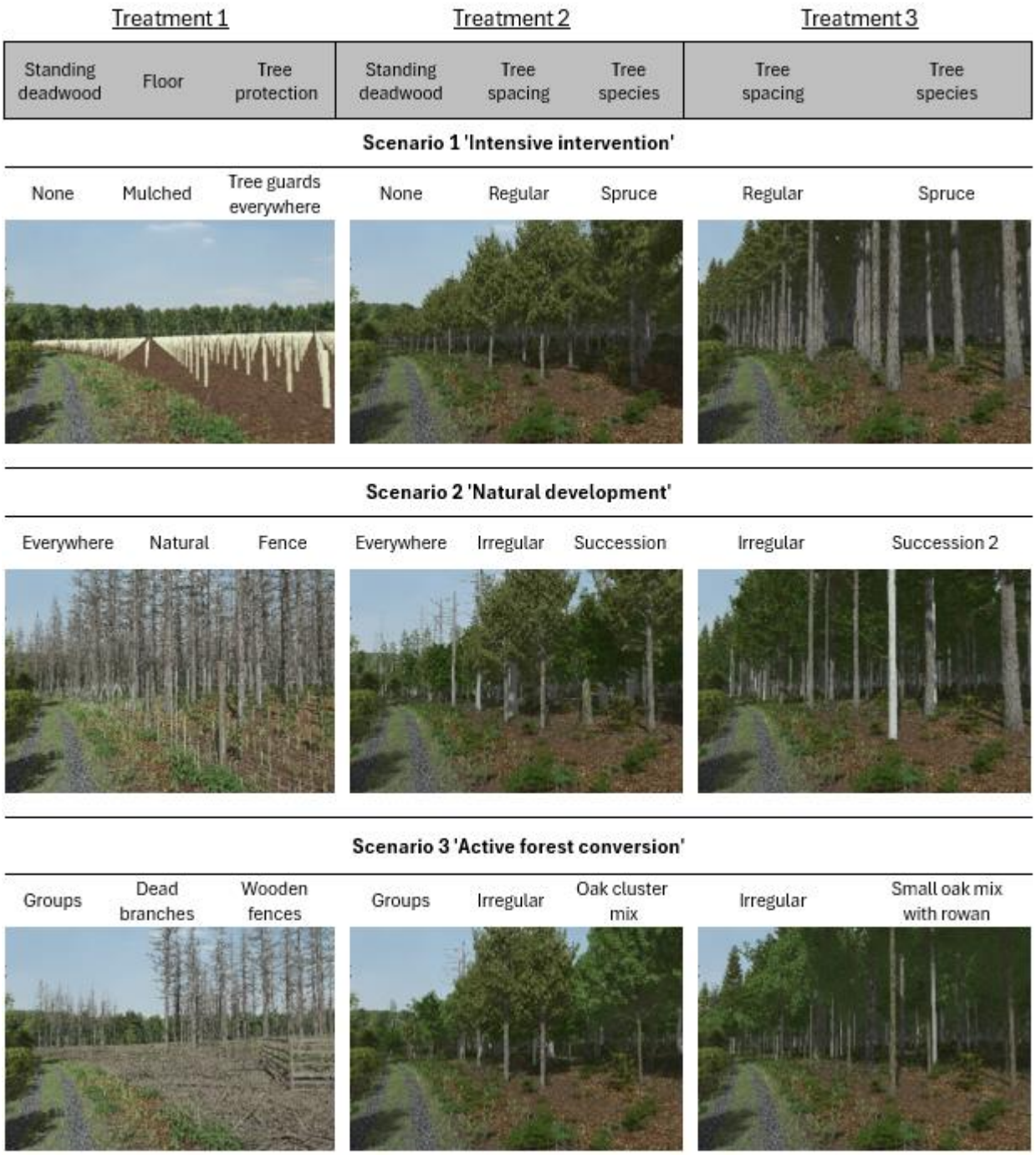


Figure 17: *Attributes (grey background) and attribute levels (white background) of the scenarios over time*

7.3 Results

7.3.1 Sample characteristics

As shown in Table 9 the characteristics of the three treatment samples are comparable. The proportion of females roughly corresponds to the average of the total German population. Regarding age however, the over 70-age group is heavily underrepresented in our sample due to a limited number of panel members of this age group. Most respondents visit forests at least once a month and only 7% have not been to a forest in the last year. The majority of visits to

forests last from 20 to 120 minutes, with shorter and longer visits being rather the exception. Approximately half of the respondents had also been to a forest with extensive calamities at least once in the last year. It can therefore be assumed that the majority of respondents can visualise the images of reforested areas and most of the attributes in a realistic setting. By far the most important activity when visiting the forest is going for a walk, followed by observing nature, cycling, walking the dog, jogging and collecting mushrooms.

***Table 9**: Descriptive statistics of treatment samples*

Variable name	Treatment 1	Treatment 2	Treatment 3	German average
	N=2,213	N=2,225	N=1,115	
Sex				
Female	53%	52%	51%	51%[1]
Age Class				
18-29	16%	17%	16%	16%[2]
30-39	17%	17%	18%	16%[2]
40-49	19%	18%	18%	15%[2]
50-59	25%	25%	26%	18%[2]
60-69	23%	23%	22%	16%[2]
Above 70	0.1%	0.5%	0.3%	19%[2]
Frequency of forest visits the last year				
At least 1x week	31%	30%	31%	
At least 1x month	34%	35%	34%	
Less than 1x month	27%	29%	28%	
Never	7%	7%	7%	
Frequency of visits of highly damaged forests the last year				
More than 12 times	7%	6%	6%	
5-12 times	11%	12%	11%	
1-4 times	39%	34%	35%	
Never/haven't noticed	43%	42%	41%	
Typical duration of forest visits				
Longer than 2h	9%	9%	9%	
1-2h	32%	30%	29%	
20min-1h	53%	47%	47%	
Less than 20min	7%	7%	7%	
Main activities during forest visit *(multiple answers possible)*				
Walking	84%	85%	85%	
Nature observation	29%	30%	29%	
Cycling	23%	22%	24%	
Walk the dog	22%	22%	23%	
Jogging	20%	21%	21%	
Pick mushrooms/berries	19%	20%	20%	
Working	2%	3%	2%	
Horse riding	2%	2%	2%	
Other activities	2%	3%	2%	

[1] Statistisches Bundesamt, 2024b, [2] Statistisches Bundesamt, 2024a

7.3.2 Preferences for structural forest attributes

This section presents the results of the three mixed logit models (Table 10). In our case, the ASC terms indicate preferences for certain positions of the unlabelled pictures; however, these preferences are not consistent across treatments. Regarding *standing deadwood,* in Treatment 1 on average respondents prefer dead trees to be completely removed (*none*) the other extreme of *deadwood everywhere* is considered second best. Both options involving the partial preservation of deadwood are less favoured, with a preference for *high stumps* over the retention of *groups* of *standing deadwood* which are particularly disliked. In Treatment 2, where dead trees are somewhat hidden and less dominant, the *standing deadwood* level *'high stumps'* is favoured on average followed by *'none'* and then *'groups'* with *'everywhere'* being particularly disliked. Thus, except of the level *'high stumps'* in Treatment 2, the more dead wood is visible, the worse the aesthetics are rated. However, the estimated random parameter coefficients have a large significant standard deviation, indicating that there is a large random heterogeneity in preferences regarding the treatment of *standing deadwood*, i.e. many respondents have preferences that are far from the average preferences.

When the *standing deadwood* is cut down the branches usually remain in the forest. However, the results of Treatment 1 show that, on average, respondents strongly dislike a thick layer of *dead branches* on the *forest floor*. Respondents prefer a *natural forest floor*, with the reference level '*mulched'* falling between these two preferences.

Concerning *tree protection*, most respondents prefer *wooden fences* followed by a *fence* made of knotted mesh. Individual plastic tree guards are less favoured, particularly when used across the entire area (*everywhere).* However, large standard deviations indicate a high degree of preference heterogeneity for *tree protection*.

Table 10: *Results of the mixed logit models for Treatments 1-3*

	Treatment 1		Treatment 2		Treatment 3	
Attributes and Attribute levels	**Coef.**	**Rob.s.e.**	**Coef.**	**Rob.s.e.**	**Coef.**	**Rob.s.e.**
Mean of random parameters						
ASC1	-0.280 ***	0.026	0.074 **	0.025	0.017	0.031
ASC2	-0.049 *	0.024	0.085 ***	0.024	-0.120 ***	0.032
Standing deadwood (ref. none)						
High stumps	-0.238 ***	0.032	0.406 ***	0.025		
Groups	-0.455 ***	0.049	-1.870 ***	0.054		
Everywhere	-0.204 **	0.073	-3.683 ***	0.109		
Forest floor (ref. mulched)						
Natural	0.290 ***	0.032				
Dead branches	-0.904 ***	0.057				
Tree protection (ref. everywhere)						
Wooden fences	1.517 ***	0.058				
Groups	0.278 ***	0.037				
Fence	1.229 ***	0.063				
Tree spacing (ref. regular)						
Irregular			-0.083 ***	0.020	0.424 ***	0.032
Tree species (ref. spruce)						
Oak			0.543 ***	0.038		
Small oak					-0.289 ***	0.077
Big oak					1.021 ***	0.067
Oak dominated mix			0.878 ***	0.037		

Small oak mix						0.354	***	0.063
Oak cluster mix			0.476	***	0.039			
Small oak mix with rowan						-0.019		0.070
Big oak mix with rowan						0.085		0.072
Succession			0.001		0.044			
Succession 1						-0.216	***	0.065
Succession 2						-1.005	***	0.109
Standard deviation of random parameters								
ASC1	0.047	0.107	0.404	***	0.047	0.229	**	0.080
ASC2	0.119	0.099	0.222	***	0.067	0.267	***	0.071
Standing deadwood								
High stumps	0.722 ***	0.049	0.558	***	0.039			
Groups	1.502 ***	0.058	1.564	***	0.051			
Everywhere	2.461 ***	0.078	2.692	***	0.099			
Forest floor								
Natural	1.568 ***	0.064						
Dead branches	0.884 ***	0.040						
Tree protection								
Wooden fences	1.825 ***	0.055						
Groups	0.590 ***	0.065						
Fence	1.993 ***	0.063						
Tree spacing								
Irregular			0.262	***	0.047	0.657	***	0.043
Tree species								
Oak			1.299	***	0.046			
Small oak						1.923	***	0.094
Big oak						1.949	***	0.095
Oak dominated mix			0.531	***	0.059			
Small oak mix						0.894	***	0.075
Oak cluster mix			0.532	***	0.060			
Small oak mix with rowan						0.841	***	0.078
Big oak mix with rowan						1.040	***	0.081
Succession			0.918	***	0.050			
Succession 1						1.016	***	0.084
Succession 2						1.551	***	0.124
Number of individuals	2,213		2,225			1,115		
Log-likelihood	-22,728		-20,117			-12,946		
Adj. Rho-square	0.221		0.3142			0.1193		
Bayesian information criterion (*BIC*)	45,660		40,437			26,082		

Note: *, **, *** indicate the significance at 5%, 1% and 0.1% levels. The coefficients (Coef.) express the utility weights that obtain information about aesthetic preferences for the different attribute levels relative to the reference level (ref.). The Robust standard error (Rob.s.e.) provides the standard error consistent for heteroscedasticity. The alternative specific constants (ASC) control whether there is a tendency of respondents to choose the picture on the left (ASC1) or the picture in the centre (ASC2) disproportionately often compared to the picture on the right (reference) and independent of the attribute levels in each alternative.

As far as *tree spacing* is concerned, respondents prefer *regular* stands in Treatment 2, i.e. when the trees are 15 years old, and an *irregular tree spacing* in Treatment 3, i.e. when the trees are 50 years old. Regarding *tree species* in Treatment 2, the average respondent prefers the *oak dominated mix* followed by pure *oak* stands and then the *oak cluster mix.* Spruce is disliked, and there is no clear difference in preference weights for '*succession*' compared to '*spruce*'. In Treatment 3, the preferred *tree species* are *big oak*, followed by *small oak mix* which are both preferred over *spruce*. *Small oak* as well as *succession 1 and 2* on the contrary are disliked compared to *spruce*. It thus appears that at the same height *oak* is preferred over *spruce*, but with a realistic height after the same growth time respondents prefer *spruce*. Regarding the *small and big oak mix with rowan* the means of random parameters are not significant, but the standard deviation is. This means that roughly equal proportions of respondents respectively

liked and disliked this attribute. Overall, the standard deviations of many random parameters in Treatments 2 and 3 are quite high compared to their respective mean estimates, meaning that there is a high degree of variation in respondents' visual preferences for these attributes.

7.3.3 Evolution of scenarios over time

To compare the scenarios presented in Section 7.2.4, for each point in time we computed the choice probability of each scenario in relation to the two other scenarios in that respective treatment (Figure 18). The choice probabilities are calculated according to eq. (2) using the mean preference weights as estimated in the MXL model (Table 10). The analysis of these choice probabilities reveals that the aesthetic appreciation of the scenarios undergoes significant changes over time. The linear development between the time points is purely an assumption; when interpreting Figure 18, only the three defined time points should be considered. Specifically, immediately after the implementation of the measures (Treatment 1), the average respondents in the sample would have chosen Scenario 2 'Natural development' rather than one of the two alternative scenarios. Yet the equivalents of this scenario after 15 and 50 years (in Treatment 2 and 3) have the lowest average choice probabilities compared to their respective alternatives. In Treatment 2, 15 years post-implementation, Scenario 1 'Intensive intervention' emerges as the clearly preferred option. After a period of 50 years, Scenario 3 'Active forest conversion' turns out to be the preferred option, with the performance disparities between scenarios being relatively small. The implications of these findings will be discussed in Section 7.4.2.

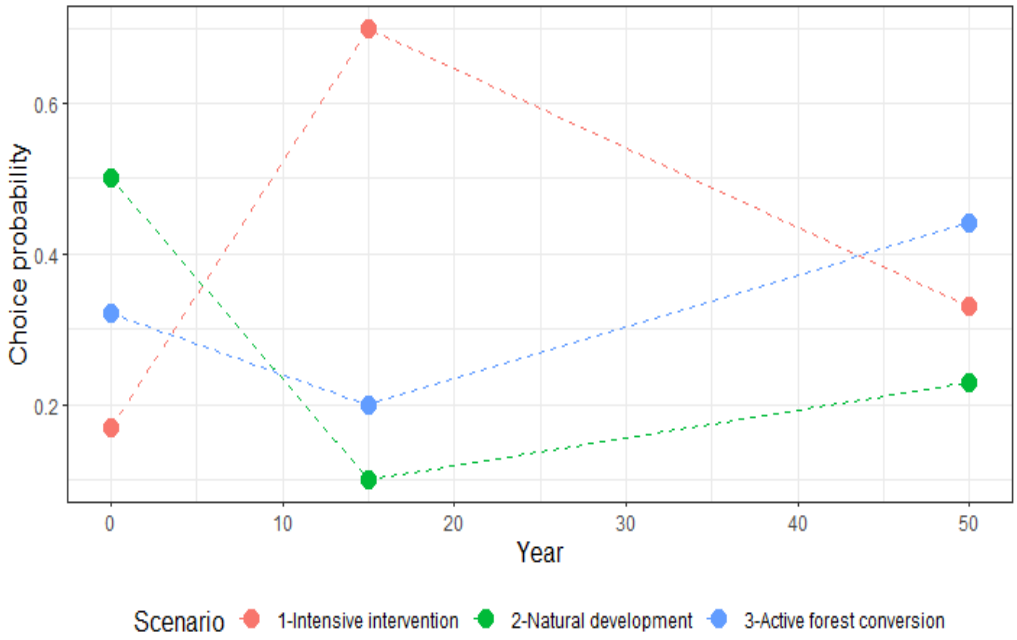


***Figure 18**: Choice probabilities of the scenarios at three time points*

7.4 Discussion

7.4.1 Preferences for structural forest attributes

In this section, we discuss some implications of the results concerning preferences for forest attributes, before addressing the time factor in the following section. Regarding the question of

how to deal with *standing deadwood*, our analysis shows that, on average, respondents prefer deadwood removal. This is in line with findings from Arnberger et al. (2018) and Tempesta et al. (2024). However, the complete removal (*none*) of *standing deadwood* is not desirable from a nature conservation perspective (Thorn et al., 2018). Therefore, if some of the deadwood is to be left, our results and the marginal substitution rate of 0,523, show that leaving *high stumps* is preferable to leaving *groups* of dead trees from an aesthetic point of view. The fact that respondents dislike *groups* of *standing deadwood* is consistent with similar findings on the retention of green trees (Ribe, 2005). In some cases, however, the preference for deadwood removal in Treatment 1 may be the result of an unwanted context effect caused by the intact forest in the background of our images. Indeed, the fewer dead trees remain, the better the intact forest is visible. In contrast, in a landscape where large parts of the forest are dead, the cutting of dead trees might be perceived less favourably, as it does not lead to the sight of intact forests but rather to extensive clear-cut areas.

A comparison of the relative importance of the attributes within the treatments shows that in Treatment 1 *tree protection* is much more important for aesthetics than *standing deadwood*. This is interesting because the choice of tree protection is generally considered less important from a forestry point of view, yet it can outweigh the visual impact of the deadwood. This opens up interesting opportunities for forestry practice to reduce the negative visual impact of management decisions. Our results concerning the *forest floor*, especially with regard to the strong aversion to *dead branches*, confirm the results of previous literature on harvesting residues (Edwards et al., 2012; Giergiczny et al., 2015; Gundersen & Frivold, 2008).

The results on *tree spacing* are somewhat surprising. Our models show that in Treatment 2, i.e. when the trees are 15 years old, respondents prefer a *regular tree spacing.* Conversely, in Treatment 3, i.e. when the trees are around 50 years old, an *irregular tree spacing* is favoured by the average respondent. The latter is consistent with the results of Giergiczny et al. (2015) and Meo et al. (2014). The discrepancy between Treatments 2 and 3 may be attributed to the fact that in Treatment 3 there are naturally fewer trees and, consequently, fewer rows in total than in Treatment 2, making the rows more easily recognisable in our images. This suggests that the majority of respondents dislike clear lines but appreciate some order and thus prefer an intermediate regularity of *tree spacing*.

Regarding *tree species* in Treatment 2, there is a preference for broadleaf (*oak)* and mixed forests compared to coniferous (*spruce)* forests. Our results also show a significant preference for the *oak dominated mix* over the rather similar *oak cluster mix*. Apart from the subtle difference in the arrangement of the oaks (randomly or in groups), the main difference between these mixtures is the presence of rowan in the *oak cluster mix*. Our results, therefore, lead to the somewhat surprising conclusion that the presence of rowan trees is rated negatively. Also, in Treatment 3 the bad performance of all tree species mixes with rowan clearly indicates that rowan is disliked. This is surprising because one might have expected that the increased variety provided by the red berries and the more shrubby growth form of rowan would have been rated positively. The most likely explanation for the fact that rowan nevertheless has a negative effect on the visual assessment is that the low growth form reduces the visual depth into the stand, which according to Edwards et al. (2012) is known to be an important criterion for the beauty

of forests. Additionally, it is surprising that in Treatment 3, unlike in Treatment 2, most species mixtures perform worse than pure stands. This contradicts most other research findings (Edwards et al., 2012; Filyushkina et al., 2017; Giergiczny et al., 2015; Nielsen et al., 2007; Ribe, 1989). The aversion to rowan trees likely contributes to the poor reception of mixed species compositions in Treatment 3. However, it remains uncertain whether this is the sole factor accounting for the dislike of mixtures in Treatment 3. The fact that *succession 2* performs worse than *succession 1* suggests that birch, at least in high proportions, is also disliked and contributes to respondents' rejection of the succession mixtures. Given that research at the landscape level has demonstrated a prevalent preference for familiar vistas (Mangone et al., 2021), it is plausible that a high concentration of the distinctive white birch trunks is perceived as unfamiliar and consequently visually disruptive rather than enriching.

It is noteworthy that *small oak* is rated more negatively in Treatment 3 than *spruce*. This is not very surprising, as existing literature shows that large and thick trees are favoured by most forest visitors over smaller trees (Arnberger et al., 2018; Edwards et al., 2012; Filyushkina et al., 2017; Giergiczny et al., 2015). The slow-growing oaks are consequently at a comparative disadvantage relative to faster-growing tree species. This interpretation is substantiated by the observation that *big oak* clearly outperforms *small oak* and is, indeed, the most highly rated *tree species* composition. Specifically, this implies that while oaks are visually less appealing than faster-growing species in the medium term, they ultimately compensate for this initial disadvantage over an extended time horizon.

When comparing the mean coefficients of the different attributes, it is striking that the relative importance of *standing deadwood* in Treatment 2 is quite high compared to Treatment 1. Since it seems obvious from the pictures that the deadwood is not visually more conspicuous in Treatment 2 than in Treatment 1, this indicates that the attributes *tree spacing* and *tree species* are less important compared to the attributes *tree protection* and *forest floor*. To the best of our knowledge, there are no other studies that evaluate the visual impacts of tree protection. However, some studies show that artificial items (Heyman, 2012; Lupp et al., 2022; Tempesta et al., 2015) or traces of forest management in general (Gundersen & Frivold, 2008) are often disliked which further supports the relative importance of tree protection.

We note that the estimates of the standard deviation parameters of the random coefficients are significant in most cases. This indicates a substantial degree of preference heterogeneity between respondents in the three treatment samples. For many preference weights, the estimated standard deviation of the random coefficient even exceeds its respective mean, which implies that there is some share of respondents whose preferences have another sign than the estimated mean. In fact, we are aware of the capabilities of alternative choice models, such as latent class or discrete mixture models, to explore this heterogeneity further, as recommended by Barona et al. (2022). However, we note that this goes beyond the scope of the present paper and leave it for future research. Since the focus here is on the comparison of sample-average preferences across treatments, the MXL model and the assumption of normally distributed random preference coefficients seem most appropriate.

7.4.2 Development of the scenarios over time

When interpreting the scenarios, it is important to keep in mind that the results are only valid for the displayed attribute level combinations. It would also be possible to slightly change the scenarios and, thereby, their visual evaluation without changing the idea behind the scenarios fundamentally. For example, Scenario 3 almost reaches the preference level of the most preferred scenario in Treatment 1 if the *dead branches* are replaced by a *natural forest floor (resulting in choice probability of 13%, 44% and 43% for scenario 1, 2, 3, respectively)*. With regard to its aesthetics, the main strength of Scenario 1 is the absence of *standing deadwood,* while the choice of *tree protection* and *tree species* are its main weaknesses. Scenario 2, on the other hand, is negatively influenced primarily by the *standing deadwood everywhere*, but also because the succession mixtures are not popular. Scenario 3 is penalised by the *dead branches* on the *forest floor* and, particularly in Treatment 1, by the *groups* of *standing deadwood*.

All three scenarios are visually superior to the other two scenarios in one of the treatments (see Figure 18). It is therefore not possible to clearly identify a scenario that is most preferred throughout the different points in time. Ultimately, it is a question of weighting how much the individual treatments and thus the different points in time are valued, i.e. whether, for example, the time immediately after the intervention or after 50 years seems more important. Even if this is ultimately a normative question, it must be taken into consideration that forest states represented by Treatment 1 only last for a very short time, while the appearance of the forests changes increasingly slowly in Treatments 2 and 3. We therefore tend not to give too much weight to Treatment 1. On the other hand, the appearance of the forests is associated with greater uncertainties and is less predictable the further into the future it lies. In any case, our results underscore the importance of evaluating long-term effects, rather than focusing solely on the immediate aesthetic impacts observed shortly after the implementation of measures. This is in line with the limited literature that exists on this topic (Shelby et al., 2003).

7.4.3 Limitations and potential improvements

Although the images for the DCE were designed with meticulous care, it is essential to acknowledge that they depict artificial representations of forests rather than authentic forest views. This approach was necessary to eliminate unwanted variations and ensure optimal comparability among the images. However, it may result in judgments that differ from those made in a genuine forest setting. Prior research has shown that visual assessments are shaped not only by individual elements but also by their spatial arrangement and contextual integration (van den Berg et al., 2003; Sevenant & Antrop, 2009). Moreover, other sensory modalities—such as olfactory and auditory impressions—play a significant role in landscape perception (Xu et al., 2022), yet are omitted in our assessment. This limitation could be at last partly addressed in future research through the application of emerging technologies, such as virtual reality headsets, which could provide a more immersive and realistic forest experience for participants.

In addition, the scope of our study is confined to respondents residing in Germany. As Schüpbach et al. (2021) have shown for agricultural land, there are cultural differences in visual preferences for landscapes. Consequently, our findings may not be directly transferable to other countries. Additionally, the forest scenes were depicted in a flat landscape without mountains, which results in a typical eye-level, ground-based perspective. This setting limits the

generalizability of our findings to other contexts—such as landscapes where visitors experience elevated viewpoints and a more panoramic view of the forest.

Methodologically, our analysis of tree species encounters limitations due to the aggregation of various species into mixtures. This approach constrains our ability to precisely discern which individual tree species contribute positively or negatively to the overall value of the mixture. To draw more definitive conclusions, it would be necessary to conduct comparative analyses of a wider range of distinct mixtures. Such an expanded study would provide a more comprehensive basis for making precise determinations regarding the impact of specific tree species within mixed forest compositions.

Another potential methodological concern is the relatively high number of choice tasks per respondent, which may raise concerns about fatigue effects (Bradley & Daly, 1994). However, recent studies suggest such effects are likely overstated (Hess et al., 2012; Mariel et al., 2021). Moreover, our tasks are simpler—focused solely on aesthetic judgments—making them more natural and cognitively less demanding, which likely reduces fatigue despite the high number of tasks.

7.5 Conclusion

The adaptation of forests to climate change is crucial, both due to changing climate conditions and to the need to rebuild forests affected by extreme events. The manner in which forests adapt significantly influences numerous ecosystem services. Given the long-term impact of forest management decisions, we analysed the aesthetic implications of climate change adaptation measures across three different time points. Regarding the first research question—the appreciation of reforestation measures—our results indicate that substantial amounts of standing deadwood are generally disliked, even when compared to clear cuts. Furthermore, tree protection methods substantially influence forest aesthetics, with individual tree guards being particularly unpopular compared to fences. Unexpectedly, many mixed forest compositions are viewed less favourably than monospecific deciduous or coniferous forests. These findings provide valuable insights into how forest management, even through subtle changes, can enhance forest aesthetics in reforestation and climate change adaptation efforts.

The analysis of preferences for forest aesthetics at various time points—prompted by our second research question—underscores the critical importance of considering effects over time. Indeed, management measures that create visually appealing forests in the short term may lead to forests that are less preferred by the public further in the future. In contrast, initially less attractive approaches can result in enhanced visual qualities over time. This potential temporal variability emphasises the risk of drawing misleading conclusions when preference assessments are limited to a single time point of a forest's growth cycle. By examining forest aesthetics across multiple temporal stages, we can develop more nuanced and comprehensive management strategies that account for both immediate and long-term visual considerations.

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8 Synthesis and discussion of the results

This chapter summarizes the answers to the research questions by detailing how each paper individually contributes, with emphasis on the respective key findings. This is followed by a cross-paper synthesis, examining the overarching methodological, theoretical, and practical implications.

8.1 Answers to the research questions

Research Question 1: How do consecutive drought events impact European forests?

This research question is primarily addressed by Paper 1, which examines the impacts of consecutive drought events on crown defoliation, insect damage, burnt areas, and tree cover loss across 16 European countries spanning four climatic zones, compared with a reference period.

European forests show clear vulnerability to repeated heat and drought, with impacts varying by region. Central Europe experienced the strongest effects, including crown defoliation, widespread bark beetle outbreaks, and notable tree cover loss, particularly during the severe 2018 drought. Southern Europe displayed relative resilience, likely due to historical drought exposure, though crown defoliation and tree cover loss were still evident. Northern forests show emerging impacts, including increased fire activity and pest damage, alongside rising tree cover loss, while Alpine forests remain largely unaffected.

Importantly, damage persisted even in average climatic years, indicating legacy effects of consecutive droughts. Overall, the findings highlight the high susceptibility of European forests to recurring heat and drought, stressing the need for improved monitoring, management strategies, and harmonized data collection to mitigate escalating risks under climate change.

Research Question 2: How do forest practitioners perceive the impacts of climate change and climate extremes on forest ecosystems and their work?

This question is addressed by Paper 2, which draws on semi-structured interviews with 28 forest practitioners in Germany. The findings indicate that practitioners perceive drought as the most pressing threat, affecting tree health, growth, and regeneration while also increasing vulnerability to pests and diseases, particularly in species like spruce and European beech. Storms are also considered risky, whereas heavy rainfall is less concerning. Climate extremes are driving shifts in forest dynamics, including changes in species composition, regeneration difficulties, and increased vulnerability to biotic threats, which together affect ecosystem services—mainly biodiversity and timber supply.

Research Question 3: What are the most important climate change adaptation measures in forestry?

This question is addressed by Papers 2 and 3. Paper 2 provides empirical insights from interviews with 28 forest practitioners in Germany, highlighting measures such as increasing species diversity by promoting mixed-species stands, use of drought-resilient native species, early thinning and flexible harvesting. The interviews also reveal tensions between production-

oriented and protection-oriented practitioners: while the former favor fast-growing conifers to secure timber supply, the latter prioritize native species, biodiversity, and long-term ecosystem stability. These differing priorities, reinforced by policy incentives that often favor short-term economic returns, can hinder broader adoption of some adaptation measures.

Paper 3 complements this with a literature-based analysis, identifying three broad adaptation strategies—diversifying tree species composition, strengthening ecological functions, and reducing vulnerability to disturbances—and nine key practices widely recommended or implemented in Central European forestry: diversifying the tree species mix, increasing use of natural regeneration, retaining deadwood and residues, soil-friendly harvesting, rapid post-disturbance reforestation, regulating game populations, increasing thinning intensity, shortening production cycles, and multi-layer continuous-cover forestry.

Research Question 4: Which structural attributes of forests most strongly influence aesthetic perception, and what is the nature and strength of these relationships?

Paper 3 addresses this question through a systematic literature review identifying forest attributes that influence visual perception. Only attributes observable at the stand level and influenced by management were considered, linking aesthetics directly to potential management interventions. Key attributes shaping forest aesthetic preferences include tree size, with large and mature trees consistently rated as visually attractive; variation in tree size and vertical layering, which is appreciated for enhancing structural diversity; species diversity, which has a generally positive but comparatively smaller effect; and understory density, where moderate understory increases visual interest, whereas dense undergrowth obstructs the view and is perceived as unattractive. Finally, visible signs of management, such as large clear-cuts, residues, or tree protection tubes, generally reduce scenic quality, though negative effects often decrease over time as vegetation recovers.

Research Question 5: How do the most common climate adaptation measures influence forest aesthetics, and what can be done to counter negative impacts on forest aesthetics?

Paper 3 combines insights from literature reviews with expert assessment to evaluate how the most common adaptation measures affect forest structure and aesthetics. Measures that enhance structural and species diversity—such as promoting mixed stands, regulating game populations, and transitioning toward multi-layer continuous-cover forestry—tend to improve visual appeal. Conversely, measures aimed at strengthening ecological functions or reducing disturbances—such as leaving harvest residues, shortening rotation periods, or rapid reforestation after disturbances—may, at least temporarily, reduce visual appeal. These effects can be mitigated through spatial and temporal planning (e.g., locating interventions away from recreation areas or scheduling outside peak visitor times), thoughtful design of interventions and infrastructure, and clear communication of ecological objectives. Overall, the study demonstrates that climate adaptation can coexist with, and even enhance, forest aesthetics when carefully planned, highlighting the importance of integrating aesthetic considerations into adaptive forest management.

Research Question 6: Which components of reforestation measures most strongly influence people's aesthetic appraisal?

This question is addressed in Paper 4, which employs a discrete choice experiment to assess public aesthetic preferences for forest reforestation strategies. Respondents evaluated visual simulations of forest scenes that varied systematically in deadwood levels, tree protection methods, soil treatment, tree spacing, and tree species composition.

Key findings indicate that forest vistas without dead trees are generally preferred, pointing to a predominantly negative perception of large amounts of deadwood. This preference is evident even in comparison with clear-cut areas, as respondents often rated complete removal of dead trees more favorably than scenarios in which deadwood was left partially or entirely in place. Tree protection methods also significantly influenced visual appeal: wooden or knotted mesh fences were preferred over plastic guards, reflecting a strong aversion to highly visible artificial elements. Similarly, respondents tended to favor natural-looking forest floors without visible traces of interventions such as harvesting residues or mulching. With regard to tree species composition, average respondents unexpectedly preferred monospecific plantings over certain mixed-species combinations (e.g., those including rowan). Preferences for tree spacing were age-dependent, with regular spacing favored in young stands and more irregular, natural spacing preferred in older forests. Overall, the findings reveal substantial heterogeneity in aesthetic preferences, underscoring considerable individual variation in how forest regeneration measures are perceived.

Research Question 7: How do aesthetic preferences for reforestation measures change over time, and what are the long-term implications for forest management?

Paper 4 further examines aesthetic outcomes at three temporal stages: immediately after implementation, after 15 years, and after 50 years. Results show that aesthetic preferences are highly time-dependent. Forest scenes perceived as attractive shortly after reforestation may lose appeal as the forest develops, while some initially less appealing scenarios improve over time. This highlights the importance of considering multiple temporal stages and the projected forest appearance when evaluating reforestation aesthetics. Accordingly, assessments that integrate these developmental stages are essential for sustainable forest management, enabling planners to select strategies that balance ecological objectives with public aesthetic preferences over time.

8.2 Cross-Paper synthesis and discussion

8.2.1 Methodological implications

Understanding how climate-induced stress, management decisions, and human values intersect in European forests is a multidimensional challenge. Across the four papers presented in Chapters 4 to 7, this thesis applies a sequence of complementary methods, ranging from large-scale environmental monitoring to qualitative stakeholder interviews, structured expert assessments, and stated-preference modelling. Together, these approaches address different but interconnected facets of forests under climate change and illustrate how methodological diversity is essential for studying forests as coupled socio-ecological systems.

The first paper, *Impacts on and damage to European forests from the 2018–2022 heat and drought events* (Chapter 4), adopts a broad-scale observational approach. By collating and harmonizing diverse datasets across 16 European countries, including crown defoliation, insect damage, burnt area, and tree cover loss, the paper provides a continental assessment of drought- and heat-related damage. The harmonization of heterogeneous data sources enables the identification of broad spatial patterns in forest stress across Europe, but it also entails important methodological trade-offs. Aggregating data across countries with differing monitoring protocols inevitably smooths local variation in species sensitivity, microclimatic conditions, management practices, and adaptive capacity. As a result, the analysis cannot resolve fine-scale drivers of vulnerability or directly capture management responses. Nevertheless, by providing robust, comparable evidence of the extent and severity of recent climate impacts, the study establishes a crucial empirical reference point that frames subsequent, more context-specific and socially informed analyses of forest adaptation.

To link these biophysical stress patterns to human actors, the second paper, *A case study on forest practitioners' perspectives on climate extremes: consensus on impacts and conflicts in responses* (Chapter 5), employs semi-structured interviews with forest practitioners in Germany. This qualitative approach captures situated knowledge, operational constraints, and value-based reasoning that are not visible in large-scale ecological datasets. However, being rooted in a particular geographic and institutional context, the findings cannot easily be generalized—what holds for these German practitioners might not apply elsewhere in Europe, under different governance systems or forest types. In addition, the sample of 28 practitioners, while diverse enough to reveal conflicts and consensus, remains relatively small and potentially biased (Creswell & Poth, 2016; Guest et al., 2006). Moreover, although the semi-structured questions allowed respondents considerable freedom, they nevertheless framed the discussion and may have emphasized particular adaptation options or extremes while implicitly de-prioritizing others, thereby constraining the range of responses—a well-recognized limitation of semi-structured interview methods (Kvale & Brinkmann, 2015). At the same time, these limitations are intrinsic to the method's strength: the study provides depth rather than breadth, generating rich insights into how adaptation decisions are shaped by values, management goals, and institutional contexts, thereby complementing the large-scale perspective of Paper 1.

The third paper, *Forest management in a changing climate: assessing the impacts of adaptation measures on the visual aesthetics of forests–the example of Germany* (Chapter 6), combines

literature reviews with structured expert interviews to systematically assess how common CCAMs influence forest attributes and visual aesthetics. Compared with the open-ended interviews used in Chapter 5, this approach introduces a more formalized framework that translates management interventions into changes in specific aesthetic-relevant attributes. However, the approach also introduces potential bias through expert selection (e.g. location and background of the expert; Von Soest, 2023), the framing of adaptation measures (Kvale & Brinkmann, 2015), and the aggregation and interpretation of individual assessments into overall aesthetic impacts. Moreover, the accuracy of the overall aesthetic evaluation is limited by the quality of the underlying studies used to translate attribute changes into visual preferences. Despite these constraints, the approach provides a transparent and replicable way to connect climate adaptation strategies with anticipated aesthetic outcomes, offering a structured bridge between ecological management decisions and social perception.

A further methodological evolution appears in *Aesthetic preferences for forests after climate change-induced disturbance: A discrete choice experiment accounting for temporal evolution of reforestation measures* (Chapter 7), which applies a discrete choice experiment to elicit public aesthetic preferences for reforestation scenarios. This quantitative, survey-based method allows the estimation of preference weights for different forest attributes and explicitly incorporates temporal development by assessing multiple post-reforestation stages. Stated preference methods are also subject to a range of potential biases (Frör, 2007). However, compared with open-ended interviews or expert assessments, discrete choice experiments tend to yield more robust and generalizable preference estimates (Hensher et al., 2015; Louviere et al., 2000). Nevertheless, methodological constraints persist. The design of the discrete choice experiment—including the selection of attributes, time horizons, and the arrangement and visualization of these attributes—may influence the elicited preferences (Hensher et al., 2015; Louviere et al., 2000). Moreover, the survey may not fully capture participants' real-world preferences, as the artificial representations of forest vistas necessarily simplify the multidimensional experience of actual forest visits (Daniel, 2001). Nonetheless, this approach allows a systematic estimation of public visual aesthetic preferences for different forest attributes and alternative reforestation pathways, thereby complementing expert-based and qualitative assessments with population-level preference data.

Taken together, the four papers form a coherent methodological progression that addresses the multidimensional challenge of understanding forests under climate change. Paper 1 provides essential baseline evidence of forest vulnerability at a continental scale, though its broad scope smooths out local variation and excludes social and management dimensions. Paper 2 addresses these limitations by eliciting forest practitioners' situated knowledge, values, and decision-making processes, yet remains context-specific and limited in scale. Paper 3 combines literature and expert assessments to link adaptation measures to visual forest attributes, thereby translating management interventions into potential aesthetic outcomes, but is constrained by the reliance on expert judgments and the quality and breadth of the underlying literature. Finally, Paper 4 quantitatively captures public preferences for reforestation scenarios across multiple time points, overcoming the expert reliance of the previous paper by providing generalizable, population-level insights. Nevertheless, it remains limited by its attribute design, chosen time horizons, and the simplified visual representations. Together, these studies

demonstrate how complementary methods—each offering distinct strengths and perspectives—can be combined to investigate forest–climate interactions. Their diversity is a strength: no single method can capture all dimensions—ecological, social, and perceptual—of forests as socio-ecological systems, yet together they provide a solid foundation for integrative climate adaptation planning.

8.2.2 Theoretical and practical implications

The four papers collectively advance both the theoretical understanding and the practical governance of forests as complex socio-ecological systems under climate change. The results demonstrate how biophysical stressors, human decision-making, and societal values interact to shape forest management and public evaluations of forest landscapes. By bringing these dimensions together, the thesis contributes to an integrated perspective on climate adaptation in forestry and provides practical insights for managers and policymakers.

A first theoretical contribution lies in bridging ecological impacts with human perception and valuation. Paper 1 establishes a robust empirical basis for understanding how heat and multi-year droughts affect forest condition, emphasizing the importance of capturing climate extremes and legacy effects. Papers 2–4 situate these ecological disturbances within human systems by showing how practitioners as well as the public interpret and assess visible forest change—and how practitioners respond to it. Paper 2 shows that practitioner responses are shaped not only by ecological criteria but also by management objectives, institutional constraints, and values, highlighting the socially constructed nature of risk assessment. Paper 3 extends this perspective by linking adaptation measures to aesthetic outcomes, thereby underscoring the importance of the recreational function of forests and the need to consider visual quality in adaptation planning. Paper 4 incorporates public aesthetic preferences at multiple points in time, demonstrating that social valuation is dynamic and contingent on the forest's recovery trajectory. These findings reinforce the theoretical perspective that forests under climate change should be viewed as socio-ecological systems in which human perceptions, management interventions, and ecological processes co-evolve, underscoring the need for mechanisms that reconcile conflicting priorities and incorporate diverse stakeholder perspectives. This aligns with existing literature emphasizing that adaptation in forestry requires multiple forms of knowledge, integrating researchers, managers, and local actors to build shared understanding and support decision-making (Keenan, 2015), and with work conceptualizing forest landscapes as socio-ecological systems that demand integrated, multi-actor governance (Brietzke et al., 2025; Fischer et al., 2018).

This theoretical perspective has direct practical relevance. Because perceptions strongly influence acceptance of management interventions, forest managers cannot treat adaptation measures as purely technical or ecological decisions. Instead, adaptation planning should explicitly integrate aesthetic and recreational dimensions and target win-win situations wherever possible. For instance, species-diverse and structurally complex stands can enhance both ecological resilience and public acceptance, whereas residue-heavy logging or visually disruptive early thinning—though potentially efficient from an operational standpoint—may undermine societal support. The temporal evolution of aesthetic preferences shown in Paper 4 further implies that communication about long-term benefits is essential when short-term visual

impacts are negative. Forest management guidelines should therefore include aesthetic criteria alongside ecological and economic ones (even if they will be of lower importance in most cases) to ensure that adaptation measures are both effective and socially legitimate.

A second combined theoretical-practical contribution, building on the first—which conceptualizes forests as socio-ecological systems—concerns the value-laden and pluralistic nature of adaptation decision-making. Traditional literature often emphasizes silvicultural and structural measures as the core of adaptation (e.g. diversification, thinning, assisted migration) (e.g. Kolström et al., 2011). This thesis extends that perspective by demonstrating that these measures are never purely technical choices but are embedded in different management philosophies. Paper 2 demonstrates that practitioners interpret and prioritize adaptation measures differently depending on whether they are primarily oriented toward production or protection and recreation, leading at times to conflicting opinions about measures such as integrating new species or post-disturbance regeneration. Recognizing these value-based tensions is essential both for theory and praxis.

Theoretically, it reframes adaptation as a negotiation of worldviews and trade-offs, rather than a technical optimization problem, complementing prior work that emphasizes structural determinants of adaptation (Andersson et al., 2017). Practically, it shows that planners and adaptation strategies must reconcile differing priorities—for instance, through participatory processes or by spatially or organizationally segregating management approaches to accommodate multiple objectives. Managers and policymakers cannot assume a one-size-fits-all approach. Consequently, multi-criteria decision-making frameworks that jointly integrate ecological performance, social acceptability, and perceived forest quality are necessary to address real-world complexity.

A third theoretical implication concerns the integration of temporal dynamics in impact assessment and adaptation planning. Classic reviews (Keenan, 2015) have noted that many adaptation studies rely on long-term average climate scenarios, paying limited attention to extreme events. This thesis addresses these gaps by analyzing multi-year drought impacts to capture disturbance extremes rather than gradual change (Paper 1) and by tracking aesthetic preferences throughout forest recovery (Paper 4). In doing so, it demonstrates that both ecological vulnerability and social valuation are strongly contingent on temporal framing. Specifically, ecological vulnerability is more accurately revealed by focusing on extreme and compounding events rather than on average conditions, while social valuation requires the integration of long-term perspectives that capture perceptions over different time horizons. Practically, this implies that adaptation strategies must consider not only immediate outcomes but also medium- and long-term trajectories. With respect to climate extremes, managers need to account for multi-year, compounding climate events that exceed what annual averages suggest, while also planning forest conversion and regeneration in ways that anticipate how people's perceptions evolve as stands develop.

Taken together, the four papers advance the current state of knowledge by integrating three domains that are often examined separately: biophysical impacts, managerial perceptions, and societal valuations. They show that climate adaptation in forestry is not merely a technical task of choosing the "best" silvicultural measures but a complex socio-ecological process shaped by

disturbance regimes, management priorities, aesthetic considerations, and temporal dynamics. This highlights the co-constitutive relationship between forest systems and the people who manage and value them.

Building on this integrative perspective, the thesis demonstrates the importance of temporally dynamic and multi-dimensional analyses for understanding climate adaptation while also emphasizing the normative and perceptual dimensions of forest decision-making. In doing so, it complements and extends existing calls to integrate social perspectives—such as stakeholder engagement, socio-economic knowledge, and multidisciplinary approaches—into adaptation frameworks (e.g., Keenan, 2015; Kolström, 2011). At the same time, it fills specific research gaps related to public valuation, temporal dynamics, and the interplay between ecological and aesthetic outcomes (see Section 8.1), thereby contributing a more comprehensive understanding of adaptation as a socio-ecological process.

9 Conclusion and outlook

This dissertation demonstrates that European forests are entering a period of accelerated transformation in which climate-induced disturbances, human decision-making, and societal expectations interact closely and will jointly shape the forests of the future. By combining ecological evidence on climate impacts with practitioner perspectives, expert assessments, and public aesthetic preferences, the thesis provides a multidimensional understanding of forest climate adaptation—and shows why it is inherently both a scientific and a social challenge.

The findings confirm that repeated heat and drought events have already pushed many forest ecosystems beyond critical thresholds. Declining vitality, pest outbreaks, and large-scale dieback are no longer isolated phenomena but widespread and persistent patterns that challenge established tree species, management practices, and the quantity and quality of ecosystem services provided by forests. At the same time, the research reveals that forest practitioners possess substantial knowledge of these changes, yet their views on appropriate responses diverge markedly due to differing management goals, traditions, and institutional constraints. This underscores that effective adaptation cannot be reduced to the technical selection of species or silvicultural measures; rather, it requires navigating competing value systems and governance contexts.

A central contribution of the thesis lies in integrating visual forest aesthetics into the climate adaptation discussion—an ecosystem service that is often overlooked despite being highly valued by the public and crucial for social acceptance. The results show that practices enhancing structural complexity and species diversity (e.g. mixed stands, controlled ungulate densities, and uneven-aged management) generally improve scenic quality. In contrast, interventions primarily aimed at maintaining basic ecological functions or controlling disturbances (e.g., extensive logging residues or standing deadwood, shortened rotations, rapid replanting, or early-successional species dominance) tend to reduce visual attractiveness. Importantly, aesthetic responses are strongly time-dependent: forest scenarios preferred at one point in time may be rated least attractive at later stages of development. This highlights the need to explicitly consider forest recovery trajectories in planning and communication.

The integrative perspective of this dissertation revealed several research gaps for future work. First, there is a need for more harmonized, fine-grained monitoring of climate impacts across Europe to better quantify regional vulnerabilities. As vulnerabilities are shaped not only by climate but also by adaptation measures themselves, such monitoring should include ongoing adaptation efforts to assess their effectiveness. Second, further research on conflict resolution and participatory governance in forestry could help identify institutional and economic barriers to adaptation while fostering dialogue between practitioner groups and more collaborative management cultures. Finally, aesthetic evaluations should be expanded to encompass cultural, recreational, and psychological dimensions, as well as the perspectives of diverse user groups such as children, elderly people, and forest-dependent communities. Such insights could support more targeted communication strategies that help explain the ecological rationale behind visually disruptive yet ecologically necessary measures, such as deadwood retention or sapling protection.

In sum, this thesis demonstrates that successful forest adaptation requires both ecological foresight and social sensitivity. By bridging scientific, professional, and societal perspectives, it provides a foundation for designing future forests that are resilient, multifunctional, and widely valued. Continued interdisciplinary research will be essential to guide Europe's forests through the uncertainties of climate change while preserving their ecological integrity and cultural significance.

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Declaration of Authorship

I hereby declare that I conducted the work presented in this thesis, entitled *"Climate Change and European Forests: Impacts, Adaptation, and Consequences for Aesthetics"*, independently. All forms of assistance have been fully disclosed, and all contributors are listed as co-authors of the respective publications. This thesis has not been submitted, in whole or in part, for examination, as a thesis, or for evaluation in any similar context to any department of this university or to any other academic or scientific institution. I am aware that any violation of these conditions may lead to the withdrawal of the doctoral degree.

Landau, 09.01.2026

Paul Averbeck

Declaration of generative AI support

During the writing of this thesis, I used DeepL and ChatGPT-4 to enhance grammar, spelling, and phrasing in English. All content produced with the assistance of these tools was carefully reviewed and edited by me, and I take full responsibility for the final version of the text.

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Publications

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