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

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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.

Key results: 1. Drought is identified as the most significant climate extreme by 89.3% of forest practitioners, with 60.7% observing consecutive drought years as a major concern for forest health and management.
2. There is a broad consensus on the importance of climate adaptation, especially through mixed and multi-layered stands, species diversity, and flexible, site-specific management approaches.
3. Clear differences exist between groups: the FWP group prioritizes wood production and supports conifers and active interventions, while the FPR group focuses on ecological sustainability and favors native broadleaf species and natural processes.

Keywords: forest management, resilience, stakeholder engagement, adaptive strategies, climate extremes, drought, storms, transdisciplinarity, sustainable forestry.

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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 m³ of timber loss in Germany (Gardiner, 2021). Drought between 2018 and 2020 led to an estimated 180 million m³ 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 (Keenan 2015, Rosenkranz et al. 2023, FAO, ILO, UN, 2023).

To address these pressures, the forestry sector is adopting measures such as promoting climate-resilient species, sustainable management practices, and early warning systems (Madruga de Brito et al. 2020. WBW 2021, Hanewinkel et al. 2022).

Public awareness and cooperation are being strengthened to support these efforts (UBA 2022, Bülow et al. 2024), 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 (COM 2006, NBS 2021, BMEL 2022) - 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 (Scholz 2011, Jahn et al. 2012, Bammer et al. 2020), 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?

2) 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.

Methods

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 (Hadorn et al. 2008) and their management (Hoffmann-Riem et al. 2008, Lang et al. 2012, Von Wehrden 2019, Biggs et al. 2021, Renn 2021). 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 (Pohl and Hadorn 2006, Krohn 2008, Von Wehrden 2019, Biggs et al. 2021, Lam et al. 2021, Renn 2021).

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 (Defila & Di Giulio 2019, Biggs et al. 2021). 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 (OECD 2020, Steger et al. 2021, Kujala et al., 2022), 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.

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 1). 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

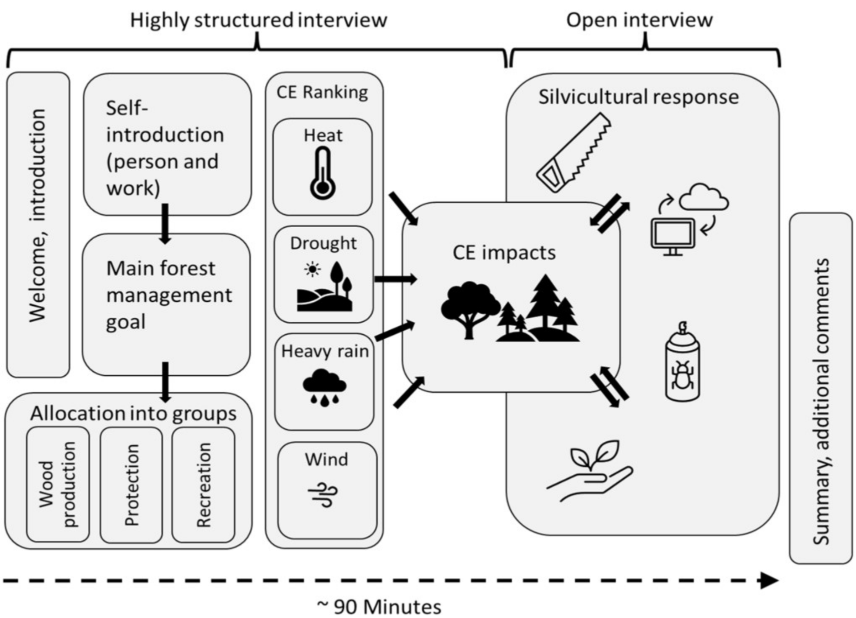

Figure 1 Structure of the interviews conducted with forest practitioners; CE = Climate extremes.

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 1). 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).

Table 1 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

To streamline analysis, we merged the three original categories—wood production, protection, and recreation (Figure 1) 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.

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 (see Table S1).

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 3).

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.

Results

Perception of forest practitioners

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 2). 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").

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

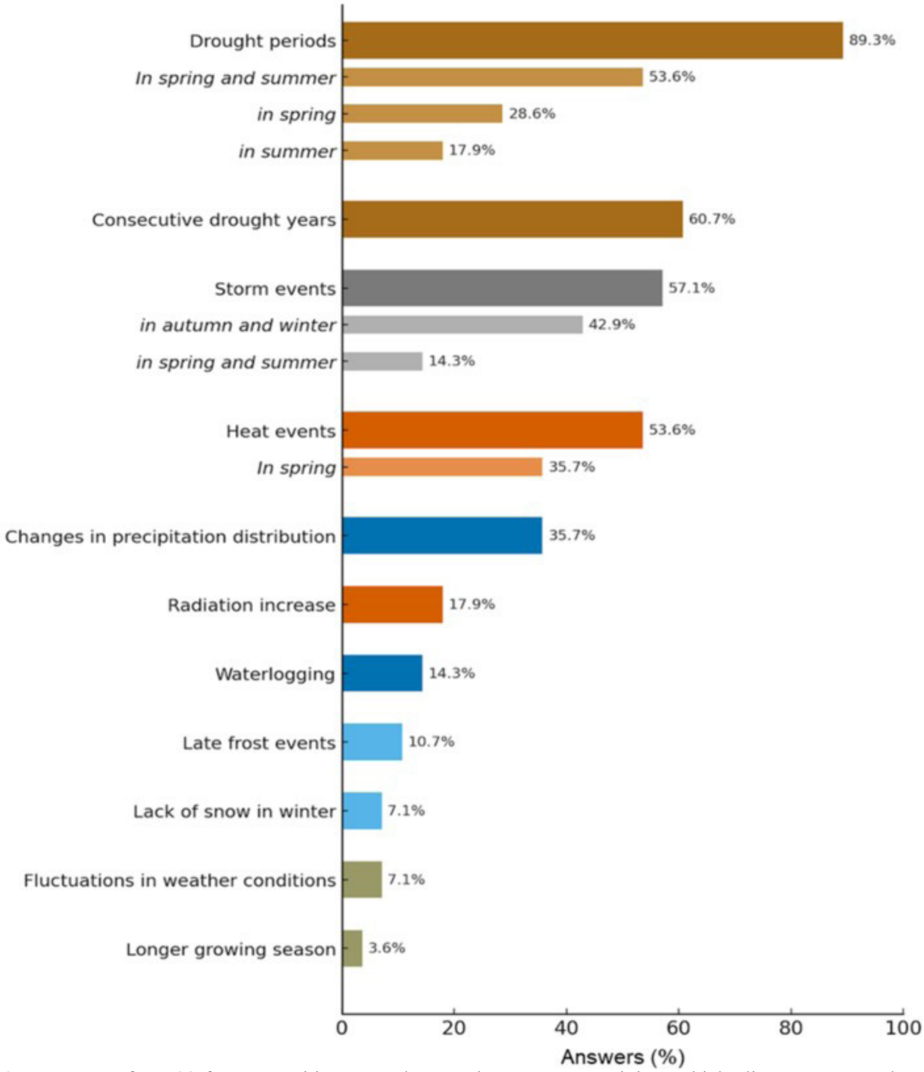

Figure 2 Responses from 28 forest practitioners to the question: "In your opinion, which climate extremes have the greatest impact on forests?" Multiple answers were allowed. A total of 100 responses were recorded and categorized by climate extremes, with percentages indicating the share of practitioners identifying each category as impactful.

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.

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 2). 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 2 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.

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 3). To avoid repeating the findings already presented in section 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—

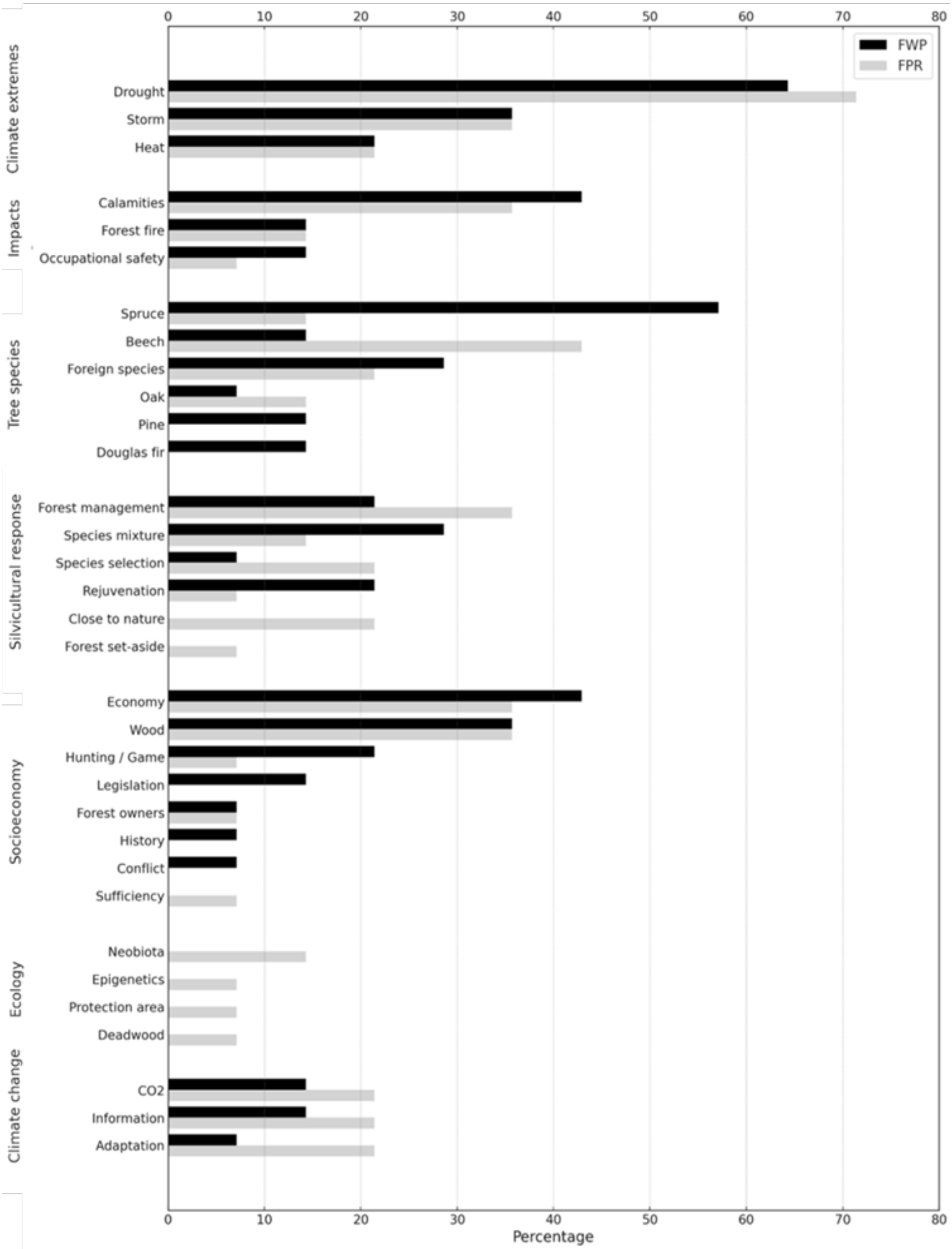

Figure 3 A comparative analysis of the most frequently mentioned topics by individual forest practitioners, grouped into FPR (black) and FWP (grey), each comprising fourteen persons. The chart shows the proportion of practitioners in each group who raised a given topic as one of their main concerns. 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. For comprehensive results, see Table S1 in the supplement.

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]

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 FPR group (35.7%) than by the FWP group (21.4%), indicating their attention to systemic approaches. 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.

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.

Responses of forest practitioners to climate extremes

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 2). 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 3).

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.

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 3), 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 2). 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.

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.

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.

WP 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.

Discussion

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

Consensus on drought as the major climate extreme

Drought emerged as the dominant concern among forest practitioners (Figure 2), 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 (Gette et al. 2020, Diers et al. 2024). 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 (Hanewinkel et al. 2011; Gardiner 2021). 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.

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 (Forzieri et al. 2021, Anderegg et al. 2022, 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 (Netherer et al. 2015, Hlásny et al. 2021).

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.

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 (NIkolaides & Innes, 2020, Logmani-Aßmann et al. 2021). 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 (Yang et al. 2021, Parajuli & Markwith, 2023).

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.

Responses of forest practitioners to climate extremes

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 (Knoke et al. 2008, Forest Europe 2020). 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 2). 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 (Brang et al. 2014, Ammer et al. 2018).

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 (Peltola et al. 2013, Gardiner et al. 2021, Gliksman et al. 2023).

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 Chapter 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). 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.

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 (Tripathi & Khan, 2007; Kohler et al. 2020). Furthermore, the FPR group's emphasis on deadwood retention is also scientifically grounded, with research highlighting its importance for biodiversity (Thorn et al. 2020, Chivulescu et al. 2022), 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. 2021, Miryeganeh & Armitage 2025).

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 (Paquette & Messier 2011, Liang et al. 2016).

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).

Conclusions

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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