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Information access, governance support and operational flexibility are needed to drive adaptation of European forests to global change

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ABSTRACT

Many forest owners and professionals recognize global change and increasing forest disturbances as pressing challenges but have yet to implement adaptation options to counteract the impacts on their forests. The ecological effectiveness of these options is context-dependent, influenced by site conditions and the quality of implementation. In addition, the socio-economic context can support or impede the implementation of adaptation options. To assess the relevance of implementation barriers and how they are perceived, we surveyed over 800 forest owners and professionals across Europe.

Adaptation options that were perceived as effective were also more likely to be applied. Owing to its low evidence of effectiveness and conflicts with other management objectives, non-management was largely regarded as a non-viable adaptation option. Overall, respondents rated the importance of most implementation barriers as low to moderate. However, for certain adaptation options, specific barriers were perceived as particularly relevant. Forest owners and professionals with experience in practicing forest adaptation regarded potential barriers as less constraining than other groups of participants. More timber production-oriented owners and professionals identified economic issues as particularly constraining. To facilitate implementation of adaptation, participants suggested improved communication, more education, more flexible legislation and simpler access to financial support.

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Different specific site and management contexts complicate the development of general recommendations. Therefore, local science-practice collaborations and platforms to share experiences regarding adaptation options could promote the adaptive capacity of forest owners and professionals.

1. Introduction

1.1. Study background – novel disturbances and adaptation options

Novel disturbance regimes driven by global change have major impacts on European forests (Allen et al., 2015; Gardiner, 2021; Hlásny et al., 2021; Patacca et al., 2023; Seidl et al., 2017). Drivers of disturbance include climate change, through rising temperatures and altered precipitation patterns, as well as other factors like introduced pests and diseases. The direct and indirect impacts of these factors in emerging novel disturbance regimes can lead to a decline in ecosystem service provision, affecting the livelihoods and well-being of people who rely on forests, for example, through the loss of climate and water regulation or their income from forest products (Cantarello et al., 2017). Hence, there is a need to adapt forests and forest management to these new conditions to ensure the future provision of ecosystem services (Roshani et al., 2022).

Adaptive capacity is the ability of a system to adjust incrementally to changing conditions through reconfiguration and interaction among its elements (Béné et al., 2012; Folke et al., 2010). Higher adaptive capacity enables a system to follow multiple potential development pathways depending on external conditions. In the context of this study, ecological adaptive capacity of existing forest stands was attributed to the suitability of the current tree species to thrive under future climatic conditions and the tree species' regeneration potential (Temperli et al., 2023). Social adaptive capacity is expressed as the flexibility of forest professionals and owners to adjust management practices or invest into new options (Folke et al., 2010; Nikinmaa et al., 2020; Puettmann and Messier, 2020).

In this study, we distinguished between active and passive adaptation options. Increasing resilience of forests through active management is seen as one solution to cope with the impacts of more intense and more frequent disturbances (Himes et al., 2023; Lindner et al., 2020). In recent decades, evidence for the effectiveness of different forest management options to adapt forests to global change has been accumulated, for example on thinning and planting tree species mixtures. Yet, the effectiveness of such options was often found to be dependent on site conditions and certain aspects of implementation, such as the intensity of thinning or type of tree mixture (for thinning see Castagneri et al., 2021; Sohn et al., 2016; for mixing tree species see Grossiord et al., 2014).

Passive adaptation through the cessation of management has also been discussed as a strategy to increase forest resistance and resilience to global change (Jandl et al., 2019), though it has thus far been explored only in a few studies and the results are contradictory. For example, a comparison between European beech forests in strict reserves and neighbouring forests with regular thinning and single tree selection harvest showed that during droughts, tree mortality was higher in passively managed areas, whereas in actively managed forests, mortality shifted towards dominant canopy trees (Meyer et al., 2022). A remote sensing based study showed that natural disturbance impacts from windthrow and bark beetles were not higher in set-aside areas than in managed forests under comparable conditions in Germany (Krüger et al., 2025). In contrast, active management approaches such as "adaptation thinning" proposed by Vacek et al. (2020) have been found to enhance species and structural diversity, forest health, and climate change resilience more effectively than non-intervention practices in Central European Forests. Similarly, a study analysing mortality over the last 80 years at five different research sites in North-Eastern USA found that actively managed forests showed lower mortality losses than those passively managed (Kern et al., 2021).

In recent decades, the interest in forest adaptation options and the motivations behind their application have received some attention through research in Europe. Several examples of survey and interview studies have shown that an increased awareness of climate change impacts results in a greater willingness to adapt (e.g. Blennow et al., 2012; Brunette et al., 2020; Hoeben et al., 2025; Roitsch et al., 2023; Sousa-Silva et al., 2018). However, the results of a European-wide survey of forest owners and managers revealed that approximately half of the participants, who confirmed that they were aware of climate change impacts, stated that they had not yet adapted their forests (Sousa-Silva et al., 2018). Similarly, in a study of perceptions of climate change adaptation feasibility and effectiveness in Europe's wood value chain, although the importance of adaptation was recognized, many respondents viewed it as more feasible and effective in the future rather than at present (Hoeben et al., 2025). This gap between the recognition that active adaptation is required and taking action may be traced back to barriers to the implementation of adaptation options. The European-wide survey by Sousa-Silva et al. (2018) and a global survey of forest professionals on adaptation options (Himes et al., 2023) both highlighted that participants regard their current knowledge of adaptation options as insufficient for effective implementation. In this context, it is crucial to consider not just a lack of knowledge about technical knowledge to implement adaptation management but also the ecological factors that determine if an option is suitable and the specific socio-economic or regulatory circumstances that constrain or enable adaptation (D'Amato et al., 2023; Himes et al., 2023).

1.2. Barriers and enablers of adaptation in social-ecological systems

Adaptation of forests to global change can be described as a challenge embedded in social-ecological systems, which can be analysed with frameworks such as the social-ecological-technical-forestry-innovation systems (SETFIS, Sorge et al., 2022). SETFIS is an expansion of other frameworks of social-ecological systems (SESs). SES research employs systems thinking to facilitate a more profound understanding of complex processes by integrating a variety of subjects into interconnected systems. This framework enables a more comprehensive analysis of the intertwined relationships between human societies and ecosystems. Building on the work of Ostrom and colleagues, we structured the key elements influencing the forest adaptation process to align with this framework (McGinnis and Ostrom, 2014). Accordingly, the ecological component—comprising forest ecosystems that provide ecosystem services—is tightly interlinked with social components that include actors such as forest owners and professionals, and governance systems. The interactions between ecological and social components, as well as among actors, can play a decisive role in determining whether adaptation will be implemented.

Regarding the interactions in the social part of SESs, we assumed that implementation barriers may occur between different actors and the governance system. While Ostrom's SES Framework provides a good basis for analysing the relations between the different institutions in an SES, it displays the situation statically and may not capture the aspects of dynamic change that are important to understanding forest adaptation. Therefore, we employed the SETFIS framework, which integrates SESs with aspects from social-technical systems and innovation developments in order to represent the dynamics of forest adaptation processes (Sorge et al., 2022). The SETFIS analytical framework has been implemented to assess novel governance approaches across diverse forest contexts (Bussola et al., 2021; Sorge et al., 2022; Sorge et al., 2025). Through qualitative in-depth analysis of these governance innovations, the application of the SETFIS analytical framework has identified both context-specific factors and shared patterns underlying successful approaches. Critical determinants of successful adaptation included developing a robust understanding of local contexts and historical trajectories, facilitating knowledge sharing and collaborative learning through related innovations, strengthening institutional and individual capacities, mobilizing flexible and stable funding sources, and proactively preparing for disruptive events to minimize risks.

Such novel approaches for adaptation captured in SETFIS include adaptive governance. Adaptive governance refers to the structures and processes through which societies make decisions and share power in ways that enable collective action and social coordination to respond effectively to change and uncertainty in social-ecological systems. It addresses the broader social contexts, such as institutions, power dynamics, and decision-making frameworks that support ecosystem-based management. Adaptive governance involves resolving trade-offs, providing a shared vision for sustainability, and integrating feedback through monitoring to guide future actions (Dietz et al., 2003; Folke et al., 2005). Adaptive governance may also comprise decentralisation to regional governance systems that enable innovative solutions for region-specific problems and empowerment of local actors (Giessen, 2010).

The SETFIS framework identifies factors that enable or hinder changes that are also relevant for forest adaptation to global change. Forest owners and professionals may recognize the need to adapt either directly, through own observations of forest health decline, or indirectly, via media, state agencies, or research institutions. These **social-ecological interactions**, where ecological changes trigger social responses, can expose actors to the first major barrier: limited access to information, which is essential for understanding and applying appropriate adaptation options (Brunette et al., 2020; Himes et al., 2023; Sorge et al., 2022; Sousa-Silva et al., 2018). Information access has been widely recognized as a critical enabler across governance levels in forestry (Kolström et al., 2011).

Even with sufficient knowledge, institutional constraints, such as regulations imposed by governance bodies, may restrict how, where and when adaptation measures can be implemented. Institutional and social barriers were the most commonly reported barriers in a systematic review on climate change adaptation across different sectors (including forestry) (Biesbroek et al., 2013). Moreover, economic and market-related factors, such as implementation costs or uncertainty about returns, may influence decision-making. These financial barriers are closely linked with institutional and informational constraints, as market incentives and regulatory support often determine whether adaptation is feasible (Pakizer et al., 2023; Sousa-Silva et al., 2018; Winkel et al., 2022). Further potential constraints to adaptation detected in previous studies include ownership structures and the community's willingness to accept or embrace adaptation options (Andersson et al., 2017; Bouriaud et al., 2015; Himes et al., 2023; Sousa-Silva et al., 2018; van Gameren and Zaccai, 2015).

1.3. Study aim and research questions

While previous studies have identified barriers, we believe that linking them to specific adaptation options, as done in this study, is crucial for understanding the challenges of forest adaptation. This study aims to assess how forest owners and professionals perceive the effectiveness of adaptation efforts, as well as the factors that hinder or enable adaptation to global change. The following study questions guided our analysis:

- How do forest owners' and professionals' perceptions of the effectiveness of adaptation options, including passive adaptation, influence their implementation?
- Which implementation barriers and potential enablers of forest adaptation represent critical interactions in the social-ecological system that would need to be addressed to promote forest adaptation?

2. Methods

2.1. Choice of options and barriers, operationalisation, target group, and dissemination of the survey

In a workshop with stakeholder organisations representing forest practice and forest science from different European regions, the relevance of the two survey topics, adaptation options and implementation barriers, was assessed and potential ways to enable adaptation were discussed (see Table S1 in the Appendix for more details on the stakeholder workshop). Five adaptation options and six potential implementation barriers were chosen for the survey (Table 1, Table 2).

Subsequently, we created the survey in the online survey tool Unipark (Unipark, 2023). To account for diverse social and ecological forest contexts, we selected nine target regions using the Maximum Variation Sampling approach. These regions span a broad range of biogeographical areas, from boreal to Mediterranean forests, encompassing various disturbance regimes. Also, forest management practices differ substantially, reflecting regional preferences for specific ecosystem services and the demands of distinct forest value chains.

The target regions comprise the countries Ireland, Finland, Czech Republic, Croatia, France and the UK, as well as the regions Catalonia and Galicia in Spain and the federal state Baden-Württemberg in Germany (target region characteristics overview in Table S2). The survey was provided in the language spoken in the different target regions. The translation of the survey and the pretesting were conducted among the group of authors.

To obtain first-hand information about the problems of implementing adaptation options, we targeted the people who are directly responsible for forest management and implementing adaptation options in a specific forest with a stratified approach. For each target region, we searched for a) an organisation that represents forest owners, b) one association of professional foresters, c) one state forestry agency, and d) at least one private forest company (see Table S3 for the full dissemination plan). These organisations were asked to share the survey within their organisation/membership and motivate their employees/members to participate. Furthermore, authors working in the different target regions disseminated the survey to their network of stakeholders. Lastly, the survey was promoted on social media (LinkedIn and X) by the Communication team of the European Forest Institute, who also placed an invitation to participate on the project website (https://resonateforest.org/support-needed-survey-on-climate-change-adaptation-practices/). The survey was initially open for participation from 5.12.2023 to 8.01.2024 and subsequently, owing to low participation in the first round, for another period from 8.04.-10.05.2024.

The target participants of the survey were forest managers and forest owners. Nevertheless, through spreading the survey in professional networks in the target regions and online, we also gave people of other professions, such as forest consultants, researchers and administrators, the opportunity to respond and share their views on adaptation. Therefore, we named the participants of the survey in the following "forest owners and professionals".

We organised the questions of the survey to the participants into four themes: 1) demographic information and personal characteristics, including preferences on management objectives, 2) multiple choice questions about characteristics of the forest they are responsible for or familiar with, 3) multiple choice and open questions about the participant's opinion on the effectiveness and application of adaptation options, and 4) participant's degree of agreement that certain implementation barriers were hindering certain adaptation options on a Likert Scale from 1 to 5 (Likert, 1932). In section four, we also inquired

Table 1
Selected adaptation options with underlying rationale and supporting references. Short titles of adaptation options depicted in italics will be used in the following. Potential benefits of adaptation options are marked with a "+" and potential disadvantages with "-".

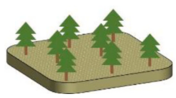
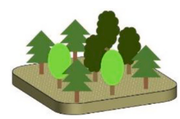
Reducing stand density *A1: Thinning*	Shortening production times *A2: Shorten rotation*	Enhancing and maintaining tree species diversity *A3: Mixing*	Introduction of more drought-tolerant species *A4: Introducing new species*	Cessation of management *A5: Non-management*
+ Enhancing resource availability for individual trees + Facilitation of regeneration and transformation processes	+ Reducing the risk of disturbance damage which increases with height and age of tree	+ Alleviate disturbances impacts through diversification of risks among species + Beneficial species interactions buffering disturbance impacts	+ Increasing the proportion of more drought-tolerant genotypes + More adapted species composition	+ Natural system's self-regulating capacity drives adaptation and strengthens resilience
- Increased exposure of individual trees to high irradiance and wind	- Less structural and species diversity due to more homogenous stand structures	- More complicated tending and harvest operations	- Potentially requires more knowledge for implementation - Risk of maladaptation or invasiveness of new species	- Mismatch between forests' inherent adaptive capacity and the pace of climate change
				
Millar et al. (2007); Sohn et al. (2016); Spittlehouse and Stewart (2003); Steckel et al. (2020)	Gardiner and Quine (2000); Roberge et al. (2016)	Grossiord (2020); Jactel et al. (2017); Messier et al. (2021)	Aitken et al. (2008); Chakraborty et al. (2024); Pötzelsberger et al. (2020); Royo et al. (2023)	Jandl et al. (2019); Lindner et al. (2020); Millar and Stephenson (2015); Puettmann (2011); Seidl et al. (2016)

Table 2
Selected implementation barriers with underlying rationale and supporting references.

B1: Lack of evidence	B2: Lack of capacity	B3: Regulatory restrictions	B4: Economic shortcomings	B5: Management trade-offs	B6: Low social acceptance
• Lack of evidence or experience for effectiveness of adaptation options • Ambiguous results of scientific studies • No local experience of application of adaptation options	• Lack of skilled workforce or equipment needed to implement adaptation options	• Legislation constrains the application of adaptation options • Bureaucratic efforts to implement adaptation are too high	• Investments for adaptation cannot be covered by financial resources • Adaptation options are not cost-efficient • Products resulting from adapted forest stands are not marketable	• Adaptation options are in conflict with other management objectives	• Adaptation options are not implemented because participants assume that applying the option would create adverse responses by stakeholders or the general public.
Bouriaud et al. (2015); Himes et al. (2023); Ostrom (2011); Sousa-Silva et al. (2018)	Ostrom (2011); Pakizer et al. (2023); Sousa-Silva et al. (2018)	Bouriaud et al. (2015); Ostrom (2011)	Bouriaud et al. (2015); Ostrom (2011); Pakizer et al. (2023); Sousa-Silva et al. (2018)	Bouriaud et al. (2015); Ostrom (2011)	Bouriaud et al. (2015); Ostrom (2011); Pakizer et al. (2023)

about additional implementation barriers and enablers in an additional open question. The full list of questions and reasoning for their choice can be found in the Supplementary Material (Table S4).

2.2. Statistical analysis

The dataset was downloaded from the online survey tool and cleaned by removing those participants who did not answer questions beyond section 1. We used the basic analyses package and the package *survey* in the software R to analyse the data (Lumley, 2004; R Core Team, 2022).

In total, 804 participants completed the survey. However, their distribution was not balanced between regions. In Germany, 318 participants filled out the questionnaire, followed by Croatia with 292 participants, Catalonia with 52, the Czech Republic with 42, Galicia with 29, Ireland with 26, France with 10, Finland with 6 and the UK with 3 (Fig. S2). In addition, 26 people who were not part of any target region participated.

Since this unbalanced distribution of participants did not allow for a meaningful comparison between regions, we analysed the perceived effectiveness and application of adaptation options (study question 1) across all participants. We visually assessed the relation between both factors with a heatmap (Fig. 1). We divided the adaptation options into active management (options A1 to A4) and passive management (option A5) and compared the relevance of implementation barriers between these two groups to answer study question 2. The mean agreement values to barriers for active management were calculated by averaging all indicated Likert scale values for the four options A1 to A4.

2.2.1. Cluster analysis

In addition, we conducted a cluster analysis to analyse the application of adaptation options among all participants and their perception of barriers according to their preferred management objectives (study question 3). Previous studies have shown that forest owners and professionals can be clustered into different groups in terms of their interests and attitudes towards forest management in general, in terms of the forest products and services they want to obtain and also regarding forest adaptation options (Ficko et al., 2019; Roitsch et al., 2023).

We clustered the participants by similarity in their answers regarding the importance of different management objectives: a) timber production, b) biodiversity/nature conservation, c) recreation and d) protection of water, soils and slopes, all of which were evaluated on a Likert scale from 1 "unimportant" to 5 "very important". Clustering was

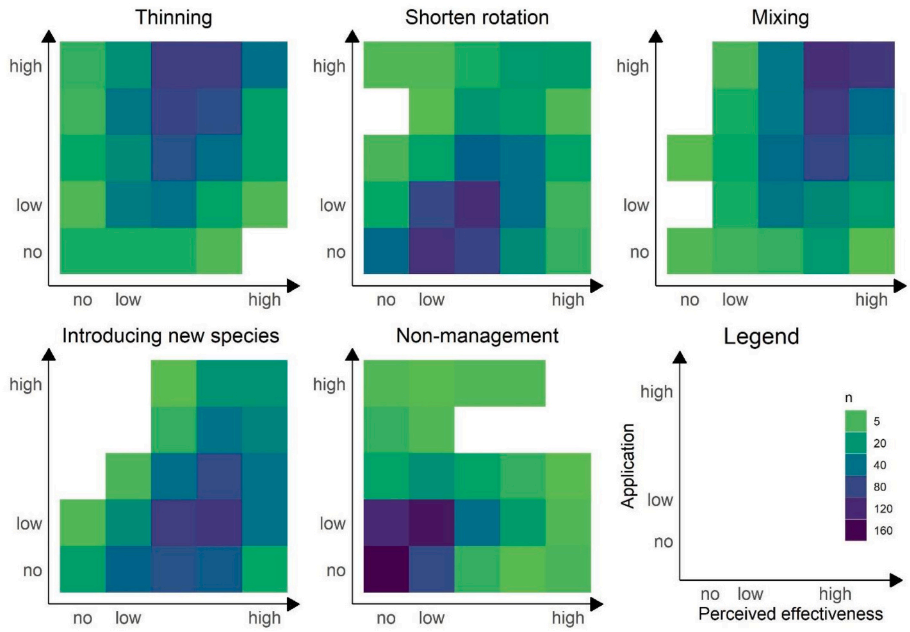


Fig. 1. Heatmaps of the relation between perceived effectiveness and estimated application. The darker the colour (from light green to dark blue), the more participants indicated the respective combinations. Combinations with no votes were left blank. Axis descriptions were reduced to low and high for better visibility, but the underlying data still refers to the Likert levels with five categories (see above). Note: Relating the scales in this way should not be confused with correlations between two continuous variables; please see section 4.4, Study limitations, for further explanations. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

conducted with the multidimensional scaling (MDS) approach. Therefore, the responses to the four objectives were converted into one multidimensional data point per participant and subsequently, the Euclidean distance between participants' data points was calculated. Using the function *fviz_nbclust* of the *factoextra* R package, three clusters were determined in an iterative process (Kassambara and Mundt, 2020). Following the k-means clustering methods, a centroid point was calculated for each cluster. Participants were assigned the cluster for which the Euclidean distance between the centroid and their data point was the closest. The analysis was conducted with the R package *cluster* and visualized in an MDS diagram (Fig. S3, Maechler et al., 1999). Other attempts to cluster responses based on other variables did not yield a meaningful characterisation of clusters. The three distinct clusters were named according to the respective management objectives: Multiple Use Cluster (MUC), Timber-oriented Cluster (TOC) and Cultural and Environmental Benefits Cluster (CEC). Participants that fell into the Multiple Use Cluster indicated a high importance of all management objectives, timber production as well as biodiversity, recreation and protection. Participants in the Timber-oriented Cluster prioritized timber production over the other three objectives, whereas participants in the Cultural and Environmental Benefits Cluster found it less important and indicated a higher importance to benefits from biodiversity, recreation and protection.

Generally, the participants were distributed in a balanced way across clusters, meaning that no cluster was dominated by participants from a certain target region, profession or ownership structure (Fig. S4, Fig. S5). Accordingly, we could use the clustering to analyse meaningful differences between forest owners and professionals across Europe depending on their management preferences.

To evaluate whether the clusters differed significantly in relation to key survey variables, we conducted one-way ANOVAs with cluster membership as the grouping factor. Where significant effects were found, we applied the post-hoc Tukey's Honestly Significant Difference (HSD) test to identify specific differences between clusters.

2.2.2. *Analysis of texts suggesting enablers to implementation barriers*

The texts which participants wrote in response to the open question of which enabler they could suggest to overcome barriers were translated and analysed. Similar suggestions were identified, counted and grouped under a typical term describing the suggestions. Suggestions that were mentioned more than ten times are listed and explained in Table 3.

3. Results

3.1. *Implementation of adaptation options*

There was an apparent relationship between the level of application of all five adaptation options and participants' perception of effectiveness (Fig. 1). For example, participants expressed low effectiveness of *A5: non-management* in preventing disturbance-driven tree mortality (Fig. 1). Accordingly, most of them did not apply it or limited its application to less than 10 % of the forest area. Likewise, *A2: shorten rotation* was regarded as little to moderately effective and was mainly applied on a small scale, if at all. In contrast, *A3: mixing* was evaluated as the most effective adaptation option by participants, reflected in its widespread application. While *A4: introducing new species* and *A1: thinning* were perceived as similarly effective, their levels of application differed significantly: *A1: thinning* was widely implemented, whereas *A4: introducing new species* was applied much less frequently. However, the application of *A4: introducing new species* still increased with participants' perception of effectiveness.

The indicated extent of application of *A1: thinning* was highest among respondents from the Multiple Use Cluster, followed by the Timber-oriented Cluster and the Cultural and Environmental Benefits Cluster (Fig. 2). The average values of indicated application differed

Table 3
Enabling factors to remove or overcome the respective implementation barriers suggested by participants. Similar suggestions were grouped under typical terms, which are displayed in bold and counted; the number of mentions is written in the text or displayed in brackets. Typical terms have the same meaning throughout barriers. Only suggestions that were mentioned more than ten times are displayed. The content of the table explaining the enablers is written from the perspective of the participants and does not represent the opinion of the authors.

Implementation Barrier	Enablers mentioned by participants
Lack of evidence	To overcome the lack of evidence 89 participants suggested that **more research** is necessary, in particular through the installation of research plots. Further, the **dissemination of research** should be strengthened (26). Likewise, the participants asked for **more information** on adaptation in general (19), **educational offers** to learn more about it (19) and opportunities for practitioners to **exchange experience** (15). Participants proposed that a **trial-and-error** management strategy may provide new evidence (14). Lastly, they advocated for **better communication,** meaning that the way information is shared with owners and professionals should be improved. (13)
Lack of capacity	39 participants suggested **paying higher salaries** in order to reduce the shortage of skilled workers. **Educational offers** for owners and professionals to acquire the required skills were mentioned 32 times. Therefore, **more investments in training and education** should be carried out (25). Participants proposed that **more state support** should be available, e.g. in forms of subsidies (17). Further, it was suggested that **more forestry jobs should be created** (11) and the **image of forestry jobs needed to be improved** so that forest workers receive more appreciation (11).
Regulatory restrictions	Participants suggested a **revision of current regulations** (40) and a **reduction of restrictions** imposed by regulations (34). Examples mentioned by survey participants included management constraints stemming from biodiversity conservation requirements as well as prescribed minimum periods for successful reforestation following disturbances. Furthermore, they demanded a **reduction of bureaucracy** in general (27). They suggested **increased flexibility and a simplification of current legislation** (23). **New (exotic) species should be supported** by lawmakers (17). Participants asked for a stronger dialogue between the government and practitioners (11). They suggest that **regulations are developed faster** to respond to sudden events (10). Lastly, they proposed **that access to state support was simplified** to be able to benefit, e.g. from funding programs (10).
Economic shortcomings	**More state support** to reduce the financial burden of forest adaptation was mentioned 46 times by participants. Furthermore, **compensation for the provisioning of ecosystem services** other than timber was suggested as a means to overcome the barrier (18). The participants proposed that **new markets or new sales opportunities should be explored** to be able to sell the wood assortments that they produce in future (18).
Management trade-offs	The participants recommended **adapting management objectives to future conditions** (21), by either promoting climate change adaptation as an objective or changing the balance between objectives such as timber production and conservation and others. To achieve this, they asked for more **educational offers** (10), which could for example also help to find decisions in situations with several objectives.
Low social acceptance	**Better communication** with owners and professionals (56) as well as the provision of **information to the general public** (48) were mentioned most often concerning removing this barrier. This may be achieved through **educational offers** (26) and **information events**, such as joined walks through the forests with interested citizens (12). Moreover, the participants proposed **media campaigns** to advertise forestry (10) and to **highlight the importance of forest usage** and wood products (12). Lastly, 10 participants suggested using **more facts instead of ideological arguments** in the public debate.

significantly between all three clusters for *A1: thinning*. Option *A2: shorten rotation* received a significantly lower mean value of application by respondents of the Cultural and Environmental Benefits Cluster compared to the other two clusters. For *A3: mixing*, the Multiple Use Cluster showed the highest average application; the difference between Timber-oriented Cluster and Cultural and Environmental Benefits Cluster was not statistically significant. The results for *A4: introducing new species* were less clear, showing only a slightly significantly higher indicated application in the Timber-oriented Cluster compared to Cultural and Environmental Benefits Cluster. *A5: non-management* was applied to a significantly greater extent by respondents from the Cultural and Environmental Benefits Cluster compared to the other two clusters.

3.2. Barriers to and enablers of forest adaptation

3.2.1. Barriers to forest adaptation

Participants generally rated implementation barriers for active adaptation options (A1 to A4) between “Disagree” and “Neutral” on the Likert scale (Fig. 3). Responses showed little variation across barriers, except for B2: *lack of capacity*, which leaned more clearly towards “Disagree”. There was greater variation among responses in relation to the passive adaptation option (*A5: non-management*). Participants indicated barriers to the implementation of passive adaptation on average as more relevant, in particular the barriers *B5: management trade-offs* and *B1: lack of evidence*. Not surprisingly, the agreement to the occurrence of barrier *B2: lack of capacity*, was even lower for passive management compared to active management.

Looking at the active adaptation option in detail (Fig. 4), the results for *A1: thinning* showed a distribution of the mean agreement values to the occurrence of implementation barriers between “Disagree” and “Neutral” (Fig. 4). Participants regarded B5: *management trade-offs* as the least relevant barrier for thinning compared to all other barriers. For the adaptation option *A2: shorten rotation*, the barriers *B6: low social acceptance*, *B5: management trade-offs* and *B1: lack of evidence* were indicated above the Likert scale level “Neutral”. Participants associated *A3: mixing* with the lowest occurrence of implementation barriers. The adaptation option *A4: introducing new species* received moderate average responses between the levels “Disagree” and “Neutral” across all barriers. Here, the most important anticipated implementation barrier was *B3: regulatory restrictions*.

Since the clustering of respondents was based on their management objectives, it was not surprising that the perception regarding barrier *B5: management trade-offs* varied across the different clusters for the adaptation options. Barriers that were also perceived quite differently by participants from the different clusters were *B4: economic shortcomings* and *B2: lack of capacity*. For the other barriers *B1: lack of evidence*, *B3: regulatory restrictions* and *B6: low social acceptance*, there was relatively little disagreement between clusters.

Owners and professionals in the Multiple Use Cluster generally perceived the implementation barriers to adaptation as less constraining than those from the other two clusters. Multiple Use-oriented participants consistently indicated fewer constraints from *B4: economic shortcomings*, especially considering the adaptation option *A3: mixing* (MUC = 2.06, TOC = 2.76, CEC = 2.41, Fig. 4). Also, they considered *B2: lack of capacity* as less constraining compared to the other clusters. One exception was the agreement to the occurrence of barriers considering option *A4: introducing new species*, which was similar between clusters.

Timber-oriented participants (TOC) strongly agreed with the relevance of the implementation barrier *B4: economic shortcomings*, and generally perceived most other barriers as more constraining compared to the other clusters. They were particularly sceptical about *A3: mixing*, for which they viewed all barriers, except for *B6: low social acceptance*, as more constraining than the other clusters. For *A5: non-management*, they identified *B5: management trade-offs* and *B4: economic shortcomings* as key hindrances to its application. Participants of the Cultural and Environmental Benefits Cluster assigned greater importance to

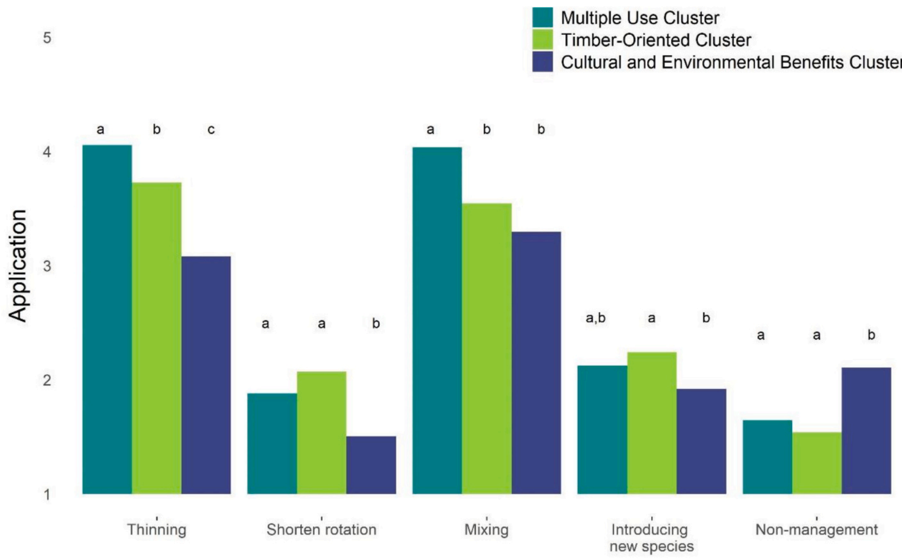


Fig. 2. Frequency of application of adaptation options by cluster. Application was indicated on the scale: 1 = not applied (on 0 % of the forest area), 2 = rare application (1–10 %), 3 = moderate application (11–40 %), 4 = regular application (41–80 %) and 5 = general application (>80 % of the forest area). Clusters with different letters for a given adaptation option were significantly different in Tukey test comparison ($p < 0.05$).

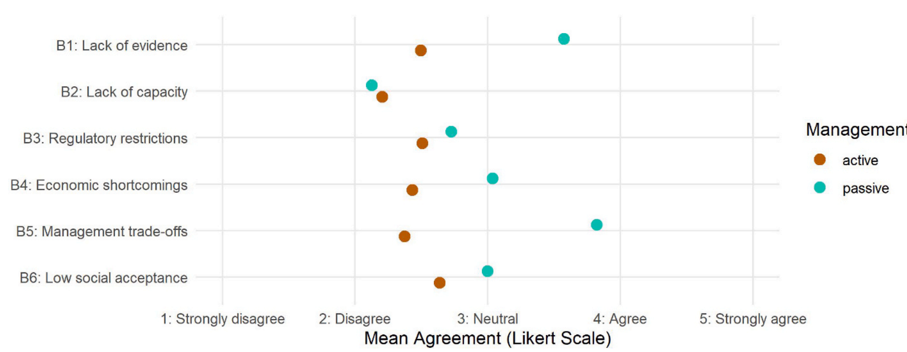


Fig. 3. Agreement to the occurrence of implementation barriers for active and passive adaptation options. The active management values (brown dots) are average values for all responses to the four active adaptation options (A1 to A4) per barrier, whereas the passive management value (turquoise dot) represents responses for the adaptation option *A5 non-management*. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

implementation barriers for the adaptation options *A1: thinning* and *A2: shorten rotation* compared to the other clusters. In contrast, they perceived fewer implementation barriers regarding *A5: non-management*. Overall, their responses were more variable. For example, participants viewed economic issues as a more significant barrier for some adaptation options (*A1: thinning*, *A2: shorten rotation*) compared to other clusters. However, they attributed less importance on *B4: economic shortcomings* for other adaptation options such as *A5: non-management*.

Enablers of forest adaptation

The open-text questions on potential enablers to overcome each implementation barrier yielded between 133 and 282 distinct and interpretable suggestions depending on the barrier (Table S4). Keeping in mind that some participants gave several suggestions per barrier, one can say that roughly one-fourth of the 804 participants answered the questions. Some suggestions were mentioned in relation to several barriers. For instance, the participants suggested that the barriers *B1: lack of evidence*, *B2: lack of capacity*, *B5: management trade-offs* and *B6: low social acceptance* could be reduced if education and training to inform and teach about forest adaptation and management would be offered (Table 3). The improvement of communication from policy and science to forest owners and professionals and the stronger or more simplified state support to realise forest adaptation was another suggestion in relation to several barriers.

4. Discussion

4.1. Summary of results

The results demonstrated that forest adaptation options that were perceived effective were, on average, more likely to be applied. The general agreement on the occurrence of barriers was low to neutral across the adaptation options. Passive forest adaptation (*A5: non-management*) was perceived as less effective and associated with more implementation barriers than active adaptation options. The analysis of application among clusters demonstrated that the social context of the participants strongly influenced the extent to which adaptation options were already applied and how barriers to application were perceived. Multiple-use-oriented managers generally applied the options to a greater extent and perceived most barriers as less relevant, whereas timber-oriented managers indicated to struggle more with barriers, especially the *economic barrier* (*B4*). Participants from the Cultural and Environmental Benefits Cluster showed the lowest application values except for *A5: non-management* and perceived particular options, namely *A1: thinning* and *A2: shorten rotation*, as more affected by barriers. Certain suggestions for overcoming barriers were ubiquitously mentioned, such as better communication, more educational offers and strengthening or streamlining state support.

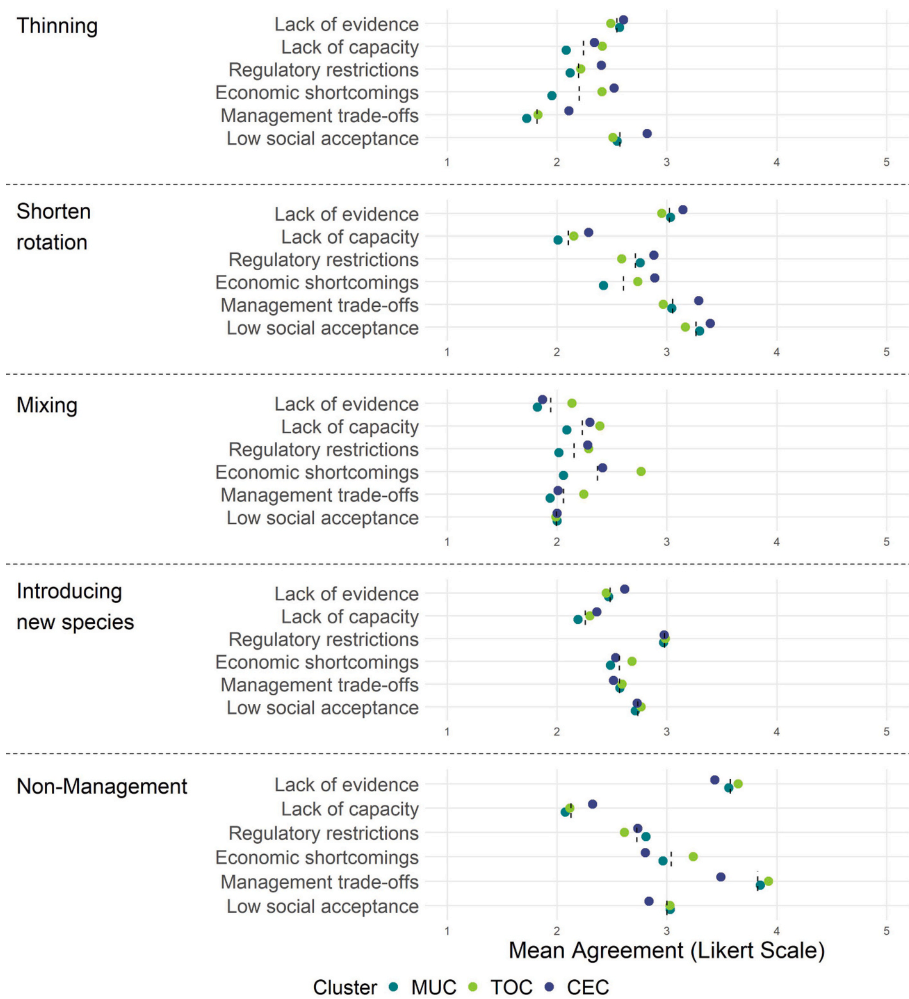


Fig. 4. Agreement to the occurrence of implementation barriers for different adaptation options by cluster. The dots display the mean agreement value of a cluster: Multiple Use Cluster (MUC) in turquoise, Timber-oriented Cluster (TOC) in light green and Cultural and Environmental Benefits Cluster (CEC) in purple. The vertical dashed line represents the overall mean agreement of all participants. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

4.2. Participants' evaluation and application of adaptation options

Previous studies found that management options that have been applied long before the recognition of the need to adapt forests to global change are more likely to be repurposed for adaptation (Bouriaud et al., 2015; Brunette et al., 2020). In the stakeholder workshop, a similar conclusion was drawn but from the opposite perspective: the openness to new options is limited due to uncertainty. Our survey results corroborate this observation, as we see a high application rate of both adaptation options, *A1: thinning* and *A3: mixing*, paired with the perception of greater effectiveness of the options and lower relevance of barriers (Fig. 2). This is particularly pronounced for multiple-use-oriented managers. In several other studies, the use of mixed-species forests also received a high acceptance and implementation rate (Hoeben et al., 2025; Roitsch et al., 2023; Sousa-Silva et al., 2018; Thomas et al., 2022; van Gameren and Zaccai, 2015). There seems to be a great reliance by practitioners on mixed forests due to the common perception that mixed forests provide more ecosystem services. However, scientific evidence on the functioning and management of mixed stands is less well developed than for monocultures of frequently cultivated tree species and remains inconclusive (Bauhus et al., 2017) with limited knowledge on underlying mechanisms, trade-offs, and long-term management implications (Carnol et al., 2014; Coll et al., 2018).

Option *A2: shorten rotation* was mostly applied on lower scale or not at all among participants, even though a bigger share of participants indicated it as at least moderately effective. Here, the barriers may explain this aversion further. Participants of the Cultural and Environmental Benefits Cluster, who prioritized recreation, protection, and biodiversity, showed significantly greater disagreement with shorter rotation times (A2) and their alignment with management objectives *(B5)*. This finding suggests that the conflict may originate from the appreciation of biodiversity and recreation, which rely to a large extent on old trees and less frequent disturbances (Lindenmayer, 2017; Suchocka et al., 2022). It is conceivable that forest owners and professionals across clusters assumed such a general appreciation of older trees by the general public and therefore also indicated the barrier *B6: low social acceptance* as more relevant for this option.

It may be surprising that adaptation option *A4: introducing new species* was not perceived to have greater implementation barriers since there are certain risks associated with this option, such as the influence of new species on biodiversity of semi-natural ecosystems and the risk of maladaptation (Bindewald et al., 2021). However, the indication of occurrences of implementation barriers was similar to *A1: thinning*, a much more widely applied option (Fig. 4). To capture the general opinion on introducing other species than the present ones, we deliberately left it open whether this barrier refers to rare native or non-native species. Perceptions of invasive species have been shown to depend on various factors, including participants' values, beliefs, and the perceived benefits of the species in question (Kapitza et al., 2019). For example, a Canadian study found that public support for reforestation strategies decreased with the distance of the origin of the species proposed for planting (Peterson St-Laurent et al., 2018). Since values and beliefs concerning these species likely differ between clusters, and the timber cluster, for instance, may perceive greater benefits due to superior growth performance (Pötzelsberger et al., 2020), we expected stronger divergence in perceived barriers across clusters. In addition, we assumed that participants of the Cultural and Environmental Benefits Cluster, owing to the above-mentioned perceived risks to natural ecosystems, would show higher dissent to this option (Bindewald et al., 2021). The high importance placed on *B6: low social acceptance* in relation to *A4: introducing new species* also aligns with a general reluctance towards adaptation options that involve transformation (D'Amato et al., 2023; Himes et al., 2023). However, for some actions such as assisted migration, barriers may have been perceived as less constraining simply because owners and professionals were less familiar with them or have limited experience with their implementation and associated challenges.

The results confirmed our second hypothesis, that *A5: non-management* is not seen as a relevant adaptation option by the vast majority of participants. From the participants' view, it is predominantly ineffective in adapting forests to climate change, and it was rarely implemented at larger scales. It was also indicated with the highest agreement values for barriers to occur. This clear rejection of the option may be related to strong shared opinions concerning set-aside areas in the forestry sector due to cultural identification and socialization among forest owners and professionals (Cichecki et al., 2025). Two European survey studies support the reluctance to this option: participants generally preferred adaptation options over non-management or a reduction in harvest (Mostegl et al., 2019; Vehola et al., 2022). Nevertheless, we need to acknowledge that the evidence base for passive forest adaptation is not well developed, and more research is needed to assess its effectiveness. However, there are circumstances where relying on certain natural processes for adaptation can be effective, such as during the post-disturbance recovery of forest stands (Lloret et al., 2012; Senf et al., 2019). *It should also be noted that passive management does not only occur in strictly protected reserves. In many cases, it is practiced in forests designated for wood production on private or public lands due to limited financial resources, difficult access, lack of personnel, and importantly also management prioritising conservation goals. Further, set-aside areas can be important for forest biodiversity conservation, and this consideration should be the primary rationale when designating strictly protected reserves.* Ideally, these areas may serve as climate change refuges and conserve locally adapted populations (Hoffmann et al., 2019).

4.3. Barrier-provoking SES interactions and strategies for research and policy

While some implementation barriers were specific to certain adaptation options, we also found commonalities in participants' indications of barriers and suggestions for enablers across options. Since these common issues may point to interactions within the SES that pose general challenges in the adaptation processes, we discuss them in the following sections.

4.3.1. Information access, capacity building & participation of actors

The *lack of evidence* (*B1*) appears to be a widely perceived implementation barrier to forest adaptation by forest owners and professionals, as it was also found in other studies (Brunette et al., 2020; Himes et al., 2023; Sousa-Silva et al., 2018). In most cases, the lack of evidence does not refer to a lack of basic technical or ecological understanding of the adaptation options but rather to the uncertainty about the effectiveness and consequences of implementing such an option within a specific setting. There is a substantial body of scientific literature, including systematic reviews on adaptation options (Table 1). Nevertheless, when asked about enablers, survey participants expressed a need for more information on adaptation options, including research findings and experiences from other forest owners or practitioners. This has also been shown in a study on the adoption of agroforestry in Ireland, in which farmers often favoured peer-to-peer learning and real-world examples (Irwin et al., 2025). Likewise, it is reflected in the demand for more education and training opportunities that was formulated in the participants' responses as measure to overcome numerous barriers. This apparent lack of information points to the erosion of experiential knowledge that accompanies global change and highlights the need for increased expert advice and peer-to-peer learning among forest owners as well as for continuing training of forest professionals. In the SES context, the suggested enablers point to an insufficient flow of information from forest governance systems, such as forest administration but also forest research facilities, to the relevant actors. This underlines the importance of translating scientific findings into forest management practice or employing co-creation processes between scientists and practitioners (see for example Nagel et al., 2017; or Petrokofsky et al., 2010). Therefore, it is critical to develop and implement new and/or more effective approaches to bridge the science/practice gap, such as platforms for exchange of experience and collaborative learning (Armitage et al., 2009; Berkes, 2017).

Improved efforts in research specifically but also communication of relevant forest topics should not only be targeted to forest owners and professionals but also the general public to reduce the barrier *low social acceptance* (*B6*) of forest adaptation. This barrier can be attributed to anticipated dissatisfaction by the general public, local communities or specific stakeholders about changes in forest appearance and functioning. For example, a Europe-wide review of public demands on forests identified forest appearance as a key factor influencing perceived attractiveness for recreational activities (Ciesielski and Stereńczak, 2018). A survey study on the public perception of dieback and adaptation in mountain areas in Bavaria found that the local population disfavoured adaptation options that would change forest appearance substantially, such as salvage logging, shortening rotations or introducing non-native tree species (Garms et al., 2024). To improve *social acceptance* and, more importantly, acknowledge concerns of local foresters, it has been recommended that stakeholders, particularly those from forest-dependent communities, be actively involved in the planning and development of adaptation strategies (Bouriaud et al., 2015; Sorge et al., 2022).

4.3.2. Tailoring adaptation to specific contexts

Participants' uncertainty about consequences of applying adaptation options may also come from the variable effects of adaptation options depending on the ecological context (Castagneri et al., 2021; Grossiord et al., 2014). For example, thinning in young stands may improve drought tolerance and wind firmness, whereas thinning in old stands may increase vulnerability to drought and windthrow (Montoro Girona et al., 2019; Moreau et al., 2022; Sohn et al., 2016). This challenge to break down the broad goal of forest adaptation to the specific contexts of different social-ecological systems across Europe was already revealed in the stakeholder workshop preceding the survey (Table S1). Survey participants suggested that more experimentation at the local level with a trial-and-error approach, as well as sharing these local experiences among forest owners and professionals, may reduce the lack of evidence they perceive. These suggestions confer with the ideas of experiments and learning of adaptive management (Bolte et al., 2009). To enable such learning through experimentation, forest owners' and professionals' room for manoeuvre should be increased and more diverse management styles be permitted (von Detten, 2022). However, emphasis should be placed on learning from existing experiments and approaches because, for many pertinent adaptation questions, the establishment of new experiments with slow-growing trees will yield results too late for effective adaptation. Here, much may be gained through developing European forest practitioner networks (e. g.

Integrate, Forêt Nature, FIRE-RES). These platforms enable, for example, Northern Europeans managing boreal forests to learn from the ongoing forest diversification efforts in temperate forests of Western and Central Europe. At the same time, Central European practitioners can benefit from Mediterranean experiences with forest fire adaptation.

Also, the specificity of local social contexts may exacerbate adaptation. General recommendations for adaptation options often fall short since they do not fit the very specific sets of management objectives and value systems of actors in an SES (Hagerman and Pelai, 2018). To reduce conflicts among management objectives in contexts of specific SESs, future research could explore the potential of more specific combinations of adaptation options appropriate to site conditions and variations within forest stands (D'Amato et al., 2023; Nagel et al., 2017). While this was not the focus of our survey, there is an opportunity for further studies to optimize overall adaptation strategies (but see for example Hildebrandt and Knoke (2011) and Gutsch et al. (2018) for optimising decision-making in forests).

The perception of relevance of the barriers *B3: regulatory restrictions* and *B4: economic shortcomings* varied across clusters of respondents and adaptation options. This may also be related to the different SES contexts across target regions. It is difficult to assess how far national forest related legislation and financial support schemes in Europe are effective in supporting forest adaptation, as they differ on a national and sometimes sub-national level. Since this heterogeneity, which can be largely attributed to the principle of subsidiarity within the EU and its member states, will not disappear in the short term, solutions tailored to the specific stakeholder group, forest type or region may be necessary to overcome the two barriers.

4.3.3. Enhancing adaptive capacity of actors and institutions

The adaptive capacity of forest owners and professionals is fundamental for flexible responses to changing conditions and uncertainties (Sorge et al., 2022). Our findings confirm that regulatory restrictions, especially on non-native tree species, remain significant barriers to adaptation. SETFIS highlights the need for institutions to provide flexible instruments, such as adaptable regulations and incentives, to allow experimentation and innovation in forest management, while safeguarding against maladaptation. For example, transnational seed exchange programs may be a helpful measure to enhance the choice of tree species or provenances, as suggested by some participants (Chakraborty et al., 2024).

Economic barriers also determine adaptive capacity. In our study, participants from publicly owned, multiple-use forests who typically do not invest their own financial resources, perceived fewer economic constraints, while private, timber-oriented owners perceived new adaptation options as less profitable. This is reflected in the SETFIS framework that links stable and adaptable funding sources to withstand disruptive events and changes with resilience in governance structures. As seen in case studies from different countries (Sorge et al., 2022), initial public funding (e.g., European Agricultural Fund for Rural Development or competitive project funds) was crucial for enabling adaptation and reducing its economic risks.

Bureaucratic burdens, including complex compliance and funding applications or regulatory fragmentation, further limit the implementation of adaptation management (Winkel et al., 2022). Practitioners repeatedly expressed the need for greater policy coherence at national and regional levels, as well as more regulatory flexibility to foster innovation. The need for adaptive governance to allow for temporary or short-term space for innovative solutions to emerge and develop is also captured in the SETFIS framework. Addressing these institutional and funding challenges through flexible governance innovations is essential for supporting adaptive forest management and ensuring the continued provision of ecosystem services (Sorge et al., 2022).

Enhancing adaptive capacity within the SETFIS framework requires a combination of simplified legislation, coherent policies, and flexible funding mechanisms. These measures, together with administrative support and opportunities for experimentation, can empower forest owners and managers to implement adaptation strategies more effectively and respond to future uncertainties with greater resilience.

4.3.4. Approaching barriers jointly

Lastly, we observed that most barriers were seen as equally constraining. Accordingly, applying the potential enablers targeted to fix single barriers separately will likely not be successful. For example, providing financial incentives for certain adaptation options without convincing information about their effectiveness or on the basis of a highly bureaucratic process would not be a promising approach. Instead, our study indicates that approaches need to be developed to overcome barriers jointly to motivate more forest owners and professionals to take action. When promoting specific adaptation options, specifically capacity building should be a key measure to enhance forest owners' and professionals' confidence in these options and provide them also with arguments to convince other stakeholders and the general public.

4.4. Study limitations

The participation in our survey across target regions was unbalanced, with around 300 participants in Germany and Croatia, respectively, while the remaining target regions had much fewer participants. In addition, the stratified dissemination approach may have resulted in gaps among certain target groups in specific regions if the designated contact persons within an organisation did not forward the survey invitation internally. Differences between regions could, therefore, not be explored. Despite these limitations, the survey results remain valid, as obtaining a quota-representative sample of forest owners and professionals is inherently challenging. While the sample may not be fully representative, it still provides valuable insights into the perspectives of forest owners and professionals, contributing to a broader understanding of the challenges and trends within this group. In addition, the clustering by management objective preferences helped to obtain further insights into participants' preferences.

In our effort to streamline the survey, we combined two elements into the economic barrier *B4*: the cost of investing in adaptation and the marketability of products resulting from adaptation. To further understand this barrier, it would be helpful to disentangle these factors and identify the specific junctures at which financial assistance to forest owners and professionals would be necessary. This could be, for example, assistance in initial investments in equipment or skill development, compensation for losses incurred during adaptation implementation, payments for ecosystem services, or a form of insurance to buffer uncertainty (Brunette et al., 2020). Likewise, the scale of barrier *B6: low social acceptance* is unclear. From participants' quantitative responses and their qualitative responses on enablers, we cannot assess whether they refer to stakeholders in their local forestry context who disfavour certain forest adaptation options or the general public. Here, further qualitative approaches, such as interviews, may contribute to a better understanding of the barrier. Lastly, one should also not overemphasize the relation between the perceived effectiveness of the options and their application because one cannot automatically conclude that participants would be willing to apply an option at larger scales because they think it is effective.

5. Conclusions and outlook

Active adaptation of forests requires forest owners and professionals with adaptive capacity; these include informational, technical and financial resources. Capacity building on forest adaptation options and outreach, especially research dissemination, need to be further supported to consider the local to regional contexts in which forest owners and professionals operate. We propose that much could already be achieved by synthesizing, translating and communicating the knowledge on adaptation options that has been accumulated already. Forest adaptation also needs adaptive governance, which provides forest owners and professionals, and other involved institutions with flexible instruments to respond to rapidly changing adaptation challenges. This requires a carefully selected mix of governance instruments at the different levels of governance (EU, member states, regions) to remove implementation barriers (e.g. overregulation, lack of resources, access to information).

We also experienced great interest and passion from many participants on this topic, from their answers to open questions on the enablers. In our view, this interest by local stakeholders should be embraced and could act as a starting point to initiate collaborative learning platforms, integrating local knowledge and experience to improve management for adaptation (Berkes, 2017; Sorge et al., 2022).

We identified that the Timber-oriented cluster, which has a strong pillar of private ownership, perceived economic issues as more constraining than other clusters. To encourage them to adapt their forests, it would be necessary to demonstrate the financial benefits of adaptation or provide financial incentives to implement adaptation.

The results of different behaviours and perspectives of certain clusters of forest owners and professionals identified in this study could serve as input to model the behaviour of actors in social-ecological systems, in which the social part is often underrepresented or strongly simplified as there are usually fewer data available compared to the ecological part (Brown et al., 2017; Rounsevell et al., 2021). The information may also contribute to developing governance options to enable target group-specific adaptation.

CRediT authorship contribution statement

Julius Willig: Writing – review & editing, Writing – original draft, Visualization, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Sabeth Häublein:** Writing – original draft, Methodology, Investigation. **Stefan Sorge:** Writing – review & editing, Writing – original draft, Methodology, Investigation. **Annechien Brudermann:** Writing – review & editing, Investigation. **Elena Cantarello:** Writing – review & editing, Validation, Project administration. **Josep Maria Espelta:** Writing – review & editing, Validation, Investigation. **Liina Häyrinen:** Writing – review & editing, Validation. **Tomás Hlasny:** Writing – review & editing, Validation. **Nina Horstmann:** Writing – review & editing, Conceptualization. **Silvija Krajter Ostoić:** Writing – review & editing, Validation. **Marie Lautrup:** Writing – review & editing, Writing – original draft. **Maša Zorana Ostrogović Sever:** Writing – review & editing, Visualization, Validation, Formal analysis. **Mikko Peltoniemi:** Writing – review & editing, Validation. **Juan Picos:** Writing – review & editing, Validation. **Yulia Poskakukhina:** Writing – review & editing, Conceptualization. **Björn Reineking:** Writing – review & editing, Validation. **Ian Short:** Writing – review & editing, Visualization. **Jonathan Spazzi:** Writing – review & editing, Validation. **Marie Vaney:** Writing – review & editing, Conceptualization. **Dijana Vuletić:** Writing – review & editing, Validation. **Jürgen Bauhus:** Writing – review & editing, Writing – original draft, Visualization, Supervision, Project administration, Methodology, Investigation, Conceptualization.

Declaration of competing interest

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

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.forpol.2025.103654.

Data availability

The data that has been used is confidential.

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