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Close-to-nature forestry and intensive forestry – Two response patterns of forestry professionals towards climate change adaptation

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ABSTRACT

Climate change poses a major challenge for forest management in Europe. Understanding how forestry professionals perceive climate change is critical to inform decision-making on climate change adaptation. The aim of this study was to explore the perceptions of forestry professionals regarding climate change and its effects on forests, as well as the importance of different forest management strategies for climate change adaptation. Using a survey, to which we received 565 [retained] responses, we determined regional differences in climate change perceptions across nine European countries and six professional groups. We found a North-South gradient in the perceptions of climate change effects for early 2019 – at the time of the survey – and when looking ahead to 2050. Perceptions of climate change effects and views on the possibility to adapt to climate change were particularly negative in Germany. According to respondents, the most important forest management strategies to adapt to climate change are diversification of tree species, artificial regeneration with improved forest reproductive material, and enrichment of natural regeneration with forest reproductive material better adapted to future climate changes. Two distinct clusters emerged from our analysis on how to adapt forests to climate change: a close-to-nature forestry cluster and an intensive forestry cluster. It appeared that the perception of public forestry regarding climate change effects and the possibility to adapt to climate change was significantly more pessimistic than those of private forestry and the forest industry. Recent extreme summer droughts and exceedances of ecological thresholds have manifested itself in profound changes in the perceptions of climate change by forestry professionals compared to findings of previous surveys in European regions.

1. Introduction

Anthropogenic climate change has led to an increase in extreme temperatures and persistent weather patterns in Europe, which are likely to become more frequent and intense in the future (IPCC, 2021). Globally, surface temperatures have warmed by about 1.15 [1.02 to 1.28] °C above pre-industrial levels (World Meteorological Organization, 2022). In Europe, the long-term trend since the 1950s indicates that heat stress and extreme temperatures have increased threefold, and extremely cold nights have warmed by >3 °C (IPCC, 2021; Lorenz et al., 2019). In addition, the probability of persistent weather patterns that were exceptional in the past, such as the extremely hot temperatures and drought observed in large parts of Central and North-Western Europe, has increased twofold (World Weather Attribution, 2018). It is *virtually certain* (Vogel et al., 2019) that the increasing frequency of such once-rare atmospheric patterns and meteorological extremes is a consequence of climate change.

1.1. The effects of climate change on forest ecosystems in Europe

Climate change and increasing CO_2 concentrations have complex and uncertain impacts on the potential of forests to provide ecosystem services, posing challenges to their resilience and economic value (Keenan, 2015; Hanewinkel et al., 2013). In Europe, 42.5% of the terrestrial area is covered by forests and woodlands providing society with important ecosystem services (FOREST EUROPE, 2020). These

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forests are increasingly under pressure from climate change, particularly since the 2018 drought (Senf and Seidl, 2021). Climate-induced abiotic disturbances (fires, droughts and windstorms) and biotic disturbances (insects and fungi) are increasingly notable across the continent, especially in coniferous forests, and are expected to challenge forest resilience in the future (Seidl et al., 2017). For example, it has been shown that increasing temperatures and changing precipitation patterns have far-reaching consequences such as large-scale early wilting (Brun et al., 2020) and drought-induced excess forest mortality (Brodribb et al., 2020; Senf et al., 2020). Across the continent, forest ecosystems are being subjected to changes in site suitability, species composition and biodiversity (Lindner et al., 2014).

1.2. Evolving forest owners and managers perceptions and responses to climate change in Europe

Given the pace and scale of climate change and its (projected) impacts on forests in Europe, the question of how forest management can contribute to climate change adaptation is critical (Keenan, 2015; Kolström et al., 2011).

The perceptions of climate change effects by forest owners and managers in Europe have shown to correlate with their responses to climate change adaptation, although the extent of changes in the choice of forest management strategies varies across the continent. The first comparative European study was conducted by Blennow et al. (2012), who examined the climate change perceptions of 845 private forest owners in Sweden, Portugal and Germany. The study showed that perceptions of climate change effects are an accurate predictor of human responses to climate change adaptation in three European countries. Furthermore, it showed that around half of the participating forest managers in Portugal and Germany had changed their forest management approach in view of climate change adaptation, compared to one-fifth in Sweden. Another study, with 1131 forest owners and managers in seven European countries, showed that 73% of the respondents expect climate change to affect their forest and are somewhat concerned about climate change overall (Sousa-Silva et al., 2018). Furthermore, the paper found that public managers were more supportive of adaptation measures compared to private managers and forest owners. The most important forest management strategies were forest regeneration with planting of better-adapted tree species and varieties, and promoting the diversification of tree species (Sousa-Silva et al., 2018).

Zooming down to specific regions of Europe, in Northern Europe, Eriksson (2014) conducted in-depth interviews with 20 private forest owners in Sweden and showed that the owners expressed a rather positive view on the effects of climate change now and for the future. Similarly, Vulturius et al. (2018) conducted a survey with 836 private forest owners in Sweden; they found that respondents were less concerned about their own forest than about global consequences, with only 20% indicating that they seriously considered climate change in the management of their own forests. Yet, about 40% indicated that they planned to take up adaptation measures in response to climate change within the next five years. An analogous perspective was reported in a study with private forest owners, managers and advisors in Norway (Heltorp et al., 2018). This study highlighted that the effects of climate change were not an important concern for private forest owners and that climate change was seen as an opportunity rather than a threat. Very few participants, mostly private managers, had taken measures to adapt. Overall, the study showed that there is concern about financial costs outweighing the benefits of climate change adaptation, i.e. in relation to the idea of currently changing management towards mixed and uneven stands. Additionally, the uncertainty around climate change effects was decisive for most forestry professionals in Norway to maintain their current forest management approach (Heltorp et al., 2018). A recent survey amongst private forest owners with 887 responses in Finland investigated support for seven different climate change mitigation strategies (increased conservation, reduced harvest, land use change, adaptation, wood products, intensified management, increased harvest). It found that private forest owners supported six of these strategies, all except reduced harvest (Vehola et al., 2022).

In Western Europe, a study by van Gameren and Zaccai (2015) investigated climate change adaptation practices through 46 semi-structured interviews with private forest owners in Wallonia. They described that forest owners use different ways of responding to climate change, with some owners using measures like diversification of tree species, replacement of vulnerable species, change of stand structure, shifting planting season, and planting in pots to counteract droughts. Another survey by Sousa-Silva et al. (2016), of 220 forest owners and 171 forest managers in Belgium, reported that foresters were worried about climate change, and that 71% were certain that climate change would impact their forests. They found, however, that less than one-third of the forestry professionals had modified their forest management in response to such worries. Public forest managers were more likely than private forest owners to adapt forest management practices because of climate change. In a study to determine the climate change perceptions of forestry professionals in south-west Germany, Yousefpour and Hanewinkel (2015) used an online questionnaire to gather 262 responses, with 80% from public foresters. Amongst all respondents, 80% were at least concerned about climate change impacts and 65% found them a crucial concern. The most important forest management strategy was the "selection of those tree species in the regeneration phase that are better adapted to the changing environmental conditions" (p. 277). More recently, Brunette et al. (2020) investigated the perceptions of 88 forestry professionals, mainly those managing public forests, in Germany and France. The study reported that almost 90% had already modified their forest management strategies for climate change adaptation or planned to do so in the near future. The most important forest management strategies were "More species mix" usually coupled with "Assist in tree regeneration" (p. 2165). In France, Thomas et al. (2022) investigated the predictors in decision-making processes in forest management adaptation by surveying 944 private forest owners. Of these respondents, 429 reported that they had no plans to change forest management practices and 107 reported that they had changed their forest management strategy in the past. Amongst the 107 owners that had changed, 67 respondents opted for thinning, 49 indicated to have reduced rotation age, and 66 respondents indicated to have applied forestry measures that maintain a diversity of age stands and mix of species. In the United Kingdom, a study using semi-structured interviews in Wales in 2014 revealed that private forest managers and advisors were not so much concerned about climate change, but rather, about other issues like tree diseases (Lawrence and Marzano, 2014). Accordingly, they were not committed to adapt their silvicultural approach with regard to a changing climate (Lawrence and Marzano, 2014). More recently, a report of the British Woodlands Survey with 1055 forestry professionals revealed that the awareness and observations of environmental change (pathogens, droughts, fires) had increased since 2015 (Hemery et al., 2020). Regarding adaptations for the future, most forest owners perceived the diversification of tree species as most important, with the majority favouring nationally sourced and nationally grown material. In contrast, the support for improved forest reproductive material (FRM)[1] was not strong (Hemery et al., 2020). While past efforts

[1] The term "improved FRM" describes FRM normally derived from breeding programs. It is always based on the selection of individual trees with characteristic seen as superior as parent material. These trees may be used to produce FRM either by sexual reproduction through seed (Seed Orchards, Parents of Families), or by asexual reproduction through vegetative propagation (Clones, Clonal Mixtures). This basic material has been tested and selected with the expectation to obtain one or several specific benefits in some environments, such as increased productivity, improved timber quality or better resilience to climatic conditions, pests and diseases. In line with Vinceti et al. (2020), we use the term "improved FRM" throughout this study.

have mostly targeted productivity traits, recent tree improvements and breeding programs have begun to integrate traits such as improved drought tolerance (Serrano-León et al., 2021). Specifically, (presumably) improved FRM with diverse gene structures within a population is considered by researchers to have some potential to increase the possibilities of trees being more resilient to biotic and abiotic changes (Alfaro et al., 2014).

Some important themes emerge from the literature discussed so far. First, taken together, the studies reviewed clearly indicate that forestry professionals show awareness of climate change, but there are significant differences in the extent to which climate change is perceived as a problem for forestry. Second, awareness only partially translates in taking up active adaptation measures – specifically, in Northern Europe, where forest owners and managers seem to perceive limited pressure to change management practices. Third, studies covering forestry professionals' views about climate change effects and adaptation pathways are mostly limited to Northern and Western Europe, but rare in Southern Europe. Fourth, most studies focus on specific regions or countries, and only a few explore perceptions of climate change comparing across multiple European countries. Interestingly, studies indicate an increasing readiness amongst forest owners and managers to change forest management practices to adapt to climate change over the years (cf. Blennow et al. (2012) and Brunette et al. (2020)).

1.3. Study aims

Understanding how forest owners and managers perceive climate change is critical for developing effective climate change adaptation strategies. In addition, it is important because perceptions and experiences of climate change directly influence decisions on adaptation and choice of forest management strategies (Seidl et al., 2015), which in turn influence efforts to maintain and enhance certain forest ecosystem services. Also, the forest sector involves many other stakeholders (NGOs, researchers, private industry, public administration) where a better understanding of their perceptions of climate change can facilitate their engagement in discussions and collaboration.

In light of this, and given the regional differences in the readiness to adapt forest management strategies in Europe, and the lack of cross-national studies, this study aims to fill gaps in the literature by analysing the perceptions of climate change and the importance of forest management strategies amongst different groups of forestry professionals in nine European countries. The obtained data will help to address the following research questions: a) How do forestry professionals perceive climate change effects on forests and the possibility to adapt forests? B) How do forestry professionals perceive the importance of different forest management strategies for climate change adaptation? And c) How do the perceptions from (a) and (b) differ with regard to different geographical patterns and by occupational groups within the forest sector?

2. Methods

2.1. Survey design & data collection

This study used an online survey to trace perceptions of forest managers and experts in nine European countries (Finland, France, Germany, Italy, Norway, Portugal, Spain, Sweden, and the United Kingdom). The questionnaire was designed in English and translated by native speakers and experts in forestry into respective national languages for more convenient sampling (Supplementary A). The questionnaire was also open to respondents from other countries than the nine target countries, but no translation in other languages was provided. Before data sampling, the survey was pre-tested by four researchers and foresters who were not directly involved in the survey design. Pre-testing helped to improve the content and to adapt the length of the survey. After two rounds of pre-testing, the survey was considered adequate for data collection.

Relevant forest management strategies aimed at disturbance mitigation and climate change adaptation were reviewed to inform the questionnaire (Hörl et al., 2020; Ogden and Innes, 2009). The following seven forest management strategies were integrated into the questionnaire: shortening of rotation periods to reduce risk, continuous cover forestry with prolonged regeneration cycles, natural regeneration, enrichment of natural regeneration with Forest Reproductive Material (FRM) better adapted to future climate changes, diversification of tree species, artificial regeneration with improved FRM, and development of clonal propagation of superior genotypes to speed up adaptation. The selection of forest management adaptation strategies surveyed in this study is also inspired by Vinceti et al. (2020). However, some modifications were made to explore the importance of improved FRM as an alternative strategy to those emphasizing autochthonous genetic material and/or natural regeneration.

Using the Survey Monkey online platform (SurveyMonkey Inc., 2021), data collection happened between January and March 2019. A mixed approach was employed to generate a maximum number of responses from individuals with a background in or related to forestry. In the above-mentioned countries, the questionnaire was distributed by phone and/or email to individuals in public forestry companies, different professional forestry associations and research institutions with the request to further distribute the survey amongst their colleagues. The access link to the survey was also freely available on the B4EST project webpage (https://b4est.eu/) and the European Forest Institute webpage (https://efi.int/articles/take-b4est-tree-breeding-survey) and was further distributed using the European Forest Institute's EUFORGEN (802 subscribers), EFIPLANT (about 500 subscribers) and Mediterranean newsletters (792 subscribers).

Table 1 shows the survey questions analysed in this study along with the corresponding Likert scale. Not every respondent answered each question, with the respective number of responses (N) given in the table.

2.2. Data analysis

The questionnaire closed with 639 responses. During subsequent data preparation for analysis, 74 answers were deleted, resulting in 565 valid responses that were further processed. Criteria deleting responses were: i) responses where respondents answered the same for a series of questions ("straight-lining"); and ii) entries with high levels of non-responses (e.g., respondents who did not complete the majority of the first twelve questions).

The questionnaire used twelve groups of forestry professionals, but to simplify the analysis and comparison between variables, we reduced the number of groups from twelve to six based on the similarity of their responses. The re-classified groups are: public forestry, private forestry, public administration, private sector and industry, NGOs & research, and other (Supplementary B, Table B.2). For the re-classification of groups, a Bartlett test was performed to determine the homogeneity of variances for each question on effects of climate change and forest management (Appendix A). The final step was to identify and merge combinations of groups that did not show significant differences in their answers using a Kruskal-Wallis test and a Dunn test with Bonferroni correction (Supplementary B, Table B.1).

In the following, descriptive statistics were used to calculate central tendency – mean ($\bar{x}$), median ($\tilde{x}$) and interquartile range (IQR) – for each question item for the groups and at country-level. The IQR measures the range from the 75th percentile to the 25th percentile of responses. A small IQR indicates that answers are within close range, implying higher agreement within the responses. For a large IQR, the opposite is true. In this study, an IQR = 0–1 constitutes high agreement, an IQR = 2 constitutes neither agreement nor disagreement, and an IQR = 3–4 constitutes low agreement given the overall Likert scale ranging from 1 to 7.

To identify significant differences in views on climate change and

Table 1
Likert scale used to assess views of forestry professionals on effects of climate change and forest management strategies. N indicates the number of responses.

Questions	Likert scale*			
	Value = 1	Value = 4	Value = 7	Additional answer option
How do you evaluate the effects of climate change on forests in your forest region today? (N = 563)	Very negative effects	Balance between positive and negative effects	Very positive effects	I do not observe effects of climate change
How do you expect a changing climate to affect the forests in your forest region by 2050? (N = 561)	Very negatively		Very positively	I do not expect the climate to change significantly
To what extent is it possible to adapt forests in your region to climate change through forest management measures by 2050? (N = 560)	Adaptation through forest management will not be possible		Adaptation through forest management is fully possible	No adaptation needed
How important are the following forest management strategies to adapt forests in your forest region to climate change?	Not at all important	Moderately important	Extremely important	Do not know

[*] The intermediate options on the Likert scale are interpreted as 2 = negative, 3 = slightly negative, 5 = slightly positive, 6 = positive. For the forest management strategies, the Likert scale is interpreted as 2 = not important, 3 = somewhat not important, 5 = somewhat important, 6 = important.

forest management strategies between the groups and between the countries, the responses to all questions were analysed using a Kruskal-Wallis and a Dunn post-hoc test with Bonferroni adjustment (Appendix E).

The sample was further explored using inductive clustering to see if groups and countries could be clustered based on the similarity of their answers to each question. Applying a k-medoids algorithm (Kaufman and Rousseeuw, 1990) and Spherical k-Means Partitions with Manhattan distance (Hornik et al., 2021) showed that the best grouping was a 2-cluster solution with an average silhouette width of 0.21 and 0.23, respectively. Lastly, to evaluate significant differences in the views about climate change and forest management strategies between the two clusters ($p < 0.05$), a Kruskal-Wallis test and a Pearson's Chi-squared test with simulated p-value (based on 2000 replicates) were conducted (Appendix F). The analysis was conducted using the statistics and analysis software R (R Core Team, 2017).

2.3. Ethics

During the entire research, the ethics and privacy of respondents were respected through the deliverable of clear and transparent information about objectives of the research, data protection and data collection. All respondents were informed that participation is voluntary and that responses are completely anonymous. Participants who were interested in the results were given the opportunity to provide their contact information at the end of the questionnaire; those that did, subsequently received a report of the summarised responses.

3. Results

As indicated above, a total of 565 valid responses were analysed from our survey of forestry professionals in over 13 countries. From the nine investigated countries, most responses were from Germany (42.7%), followed by France (17.2%), Italy (11.0%), Norway (6.9%), Finland (5.7%), Spain (5.3%), the United Kingdom (3.9%), Sweden (2.8%) and Portugal (2.7%). The (negligible) responses from international organizations (0.4%), Russia (0.4%), Latvia (0.4%), Romania (0.2%), Estonia (0.2%), and others (0.5%) are not discussed further in relation to those countries due to the very low number of responses per category. Yet, we do include these 11 responses as part of the groups (public forestry, private forestry, public administration, etc.).

For the professional groups, a total of 508 responses could be assigned and 57 were missing values (10%). Most responses came from private forestry (23.7%), followed by public forestry (20.7%), public administration (19.1%), private sector and industry (12.6%), NGOs & researchers (11.2%), and other (2.7%).

The sample consisted mostly of male respondents (82.3%); 16.4% of the respondents are female (1.3% answered "prefer not to say"). The respondents are predominantly in the age group 41–65 years (72.6%) and most hold a university degree in forestry (79.1%). When asked about their professional role, 36.8% indicated that they operate at the provincial/regional level, and 36.6% at the forest management level. Fewer respondents work at the national (23.2%) and at the international level (3.4%). Almost two-thirds (63.9%) of the respondents indicated that they have at least 20 years of professional work experience, followed by 18.6% of respondents with 10–20 years of professional work experience. About half of all respondents (46.4%) indicated that they are responsible for a forest area of 10,000 ha or larger, with the rest being responsible for a smaller area (38.6%) or not indicating an area (15%). The detailed socio-demographic and professional characteristics are shown in Table 2.

3.1. Perceptions of climate change and the possibility to adapt forests by 2050

We examined the perceived effects of climate change on forests at the time of the survey in early 2019, and the expected effects by 2050, as well as the possibility to adapt forests to climate change through forest management by 2050. Fig. 1 shows that overall, respondents evaluated the effects of climate change on forests in their forest region in early 2019 ($\tilde{x}$=3, IQR = 2) and by 2050 ($\tilde{x}$=3, IQR = 2) as slightly negative. When asked about the possibility of adapting forests to climate change by 2050, the respondents ($\tilde{x}$=5, IQR = 2) had a rather positive view that adaptation is possible by 2050.

Looking at the six professional groups we clustered, all groups viewed effects of climate change on forests in early 2019 as slightly negative ($\tilde{x}$=3). However, a closer look reveals that public forestry ($\tilde{x}$=3, IQR = 1) and respondents from public administration ($\tilde{x}$=3, IQR = 1) had significantly (p = 0.00007 and p = 0.01236, respectively) more negative views than respondents from the private sector and industry ($\tilde{x}$=3, IQR = 1).

When asked about the expected effects of climate change on their forest region by 2050, public forestry ($\tilde{x}$=2.5, IQR = 1) had a

Table 2
Sociodemographic and professional background of forestry professionals.

Variables	N	%
Country	**565**	
Germany	241	42.7
France	97	17.2
Italy	62	11.0
Norway	39	6.9
Finland	32	5.7
Spain	30	5.3
United Kingdom	22	3.9
Sweden	16	2.8
Portugal	15	2.7
Other	3	0.5
International organization	2	0.4
Russia	2	0.4
Latvia	2	0.4
Romania	1	0.2
Estonia	1	0.2
Gender	**440**	
Male	362	82.3
Female	72	16.4
Prefer not to say	6	1.3
Missing values	125	
Age (years)	**441**	
18–40	75	17.0
41–65	320	72.6
Older than 65	40	9.1
Prefer not to say	6	1.4
Missing values	124	
Education	**440**	
University degree in forestry	348	79.1
University degree not related to forestry	37	8.4
Other professional education in forestry	31	7.0
Other professional education not related to forestry	7	1.6
Other qualification	8	1.8
Prefer not to answer	9	2.0
Missing values	125	
Professional role	**565**	
Forest management level	207	36.6
Provincial level or regional level	208	36.8
National level	131	23.2
International level	19	3.4
Professional experience (years)	**565**	
<5	43	7.6
5–10	52	9.2
11–20	105	18.6
>20	361	63.9
Prefer not to answer	4	0.7
Size of forest that professional is responsible for (ha)	**565**	
< 5	14	2.5
5–50	15	2.7
51–200	25	4.4
201–1000	60	10.6
1001–10,000	104	18.4
>10,000	262	46.4
Prefer not to answer	85	15.0

significantly (p = 0.00011) more negative view compared to respondents from the private sector and industry ($\tilde{x}$=3, IQR = 1) and from public administration (p = 0.00572, $\tilde{x}$=3, IQR = 1).

Finally, regarding the possibility to adapt forests in their region to climate change by 2050, NGOs & research ($\tilde{x}$=6, IQR = 1) were the most confident professional groups, while all other groups were only slightly confident ($\tilde{x}$=5).

Looking at the responses per country to the question about climate change effects in early 2019, the most negative view with high consensus was shown by respondents in Germany ($\tilde{x}$=2, IQR = 1). This view is significantly ($p < 0.001$) different to the more positive views of respondents in the United Kingdom (UK) ($\tilde{x}$=4, IQR = 1), Finland ($\tilde{x}$=4, IQR = 1), Sweden ($\tilde{x}$=4, IQR = 1,25), Norway ($\tilde{x}$=4, IQR = 2) and France ($\tilde{x}$=3, IQR = 1). Another interesting result is that views in France ($\tilde{x}$=3, IQR = 1) and the Southern European countries Portugal ($\tilde{x}$=3, IQR = 1), Italy ($\tilde{x}$=3, IQR = 1) and Spain ($\tilde{x}$=3, IQR = 1,25) are significantly ($p < 0.05$) more negative than those in the Nordic countries Norway ($\tilde{x}$=4, IQR = 2) and Finland ($\tilde{x}$=4, IQR = 1).

In line with this, when asked about the expected climate change effects by 2050, the views by respondents from Germany ($\tilde{x}$=2, IQR = 1) were significantly (p < 0.05) more negative compared to respondents in Northern Europe, Sweden ($\tilde{x}$=4, IQR = 1) and Norway ($\tilde{x}$=4, IQR = 2), and neighbouring France ($\tilde{x}$=3, IQR = 1). Also, the expected climate change effects by 2050 were viewed as statistically significantly (p < 0.05) more negative in France ($\tilde{x}$=3, IQR = 1) and Southern European countries Italy ($\tilde{x}$=3, IQR = 1), Portugal ($\tilde{x}$=2.5, IQR = 1) and Spain ($\tilde{x}$=2, IQR = 2) than they were viewed in Northern Europe, Finland ($\tilde{x}$=4.5, IQR = 1) and Norway ($\tilde{x}$=4, IQR = 2).

Finally, when asked about the possibilities to adapt forests to climate change through forest management measures by 2050, respondents in Norway ($\tilde{x}$=6, IQR = 1), Finland ($\tilde{x}$=6, IQR = 1.25), Italy ($\tilde{x}$=6, IQR = 2) and France ($\tilde{x}$=5, IQR = 2) were significantly (p < 0.05) more confident that adaptation will be possible compared to respondents in Germany ($\tilde{x}$=4, IQR = 2). Along with respondents from Germany, the respondents from Portugal ($\tilde{x}$=4, IQR = 1.5) were the least positive about climate change adaptation by 2050.

The results of the descriptive statistics and Dunn's test with Bonferroni correction (p < 0.05) on perceptions of climate change effects today (early 2019), climate change effects by 2050 and climate change adaptation options by 2050 can be found in Appendix C and Appendix E, respectively.

3.2. Perceptions of forest management strategies for adapting forests to climate change

The results of the importance of seven forest management strategies for adapting forests to climate change are shown in Fig. 2. The most important strategies were *diversification of tree species* ($\tilde{x}$=6, IQR = 2), *artificial regeneration with improved FRM* ($\tilde{x}$=6, IQR = 2.25), and *enrichment of natural regeneration with Forest Reproductive Material (FRM) better adapted to future climate changes* ($\tilde{x}$=6, IQR = 3, short title: *Enriched natural regeneration with FRM*). The median of $\tilde{x}$=6 implies that they are all considered important to adapt European forests to climate change. The least prioritised forest management strategies in this study were *shortening of rotation periods to reduce risk* ($\tilde{x}$=4, IQR = 2, short title: *Shortening of rotation periods*) and *continuous cover forestry with prolonged regeneration cycles* ($\tilde{x}$=4, IQR = 4, short title: *Continuous cover forestry*). Both were seen as moderately important, but it is worth noting that there was moderate consensus amongst answers for *shortening of rotation periods* compared to the very high spread in answers for *continuous cover forestry*, indicating substantially diverging views amongst the respondents on this forest management strategy.

When looking at the responses by (professional) groups, *diversification of tree species* was viewed as significantly ($p < 0.05$) more important by public forestry ($\tilde{x}$=7, IQR = 1) and public administration ($\tilde{x}$=6, IQR = 2) than the by private sector and industry ($\tilde{x}$=6, IQR = 2.5).

Artificial regeneration with improved FRM was perceived as important ($\tilde{x}$=6) by all groups. However, it was seen as significantly more important by the private sector and industry (p = 0.00098, $\tilde{x}$=6, IQR = 1) and private forestry (p = 0.00071, $\tilde{x}$=6, IQR = 2) than by the public forestry group ($\tilde{x}$=6, IQR = 3).

Across almost all groups, *enriched natural regeneration with FRM* was viewed as important for climate change adaptation ($\tilde{x}$=6), with the only notable exception of the private sector and industry ($\tilde{x}$=5, IQR = 2) who

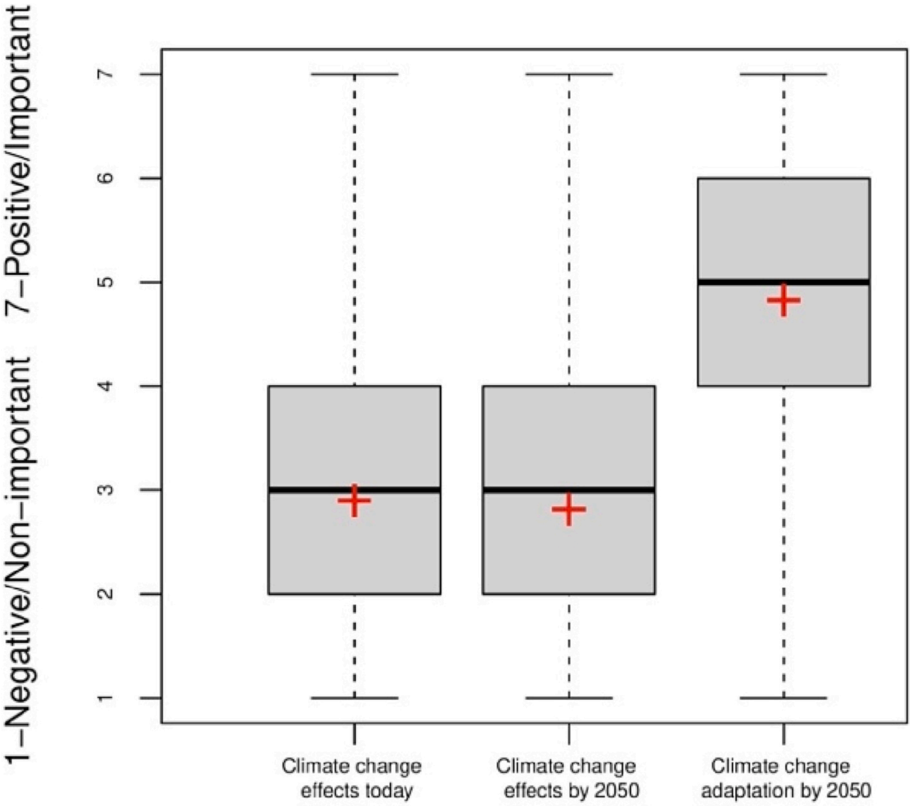

Fig. 1. Boxplots on perceptions of climate change effects today (early 2019), climate change effects by 2050 and climate change adaptation options by 2050. The box indicates the 1st and 3rd quartile, the dark line is the median, the red cross is the mean, the whiskers extend to the maximum and minimum of the data. The exact questions were: i) How do you evaluate the effects of climate change on forests in your forest region today? (1 = Very negative effects, 7 = Very positive effects; not included in the analysis were additional responses: “I do not observe effects of climate change” (2.7%)); ii) How do you expect a changing climate to affect the forests in your forest region by 2050? (1 = Very negatively, 7 = Very positively; not included in the analysis were additional responses: “I do not expect the climate to change significantly” (2.1%)); iii) To what extent is it possible to adapt forests in your region to climate change through forest management measures by 2050? (1 = Adaptation through forest management will not be possible, 7 = Adaptation through forest management is fully possible; not included in the analysis were additional responses: “No adaptation needed” (1.3%)). The results of the descriptive statistics can be found in Appendix B. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

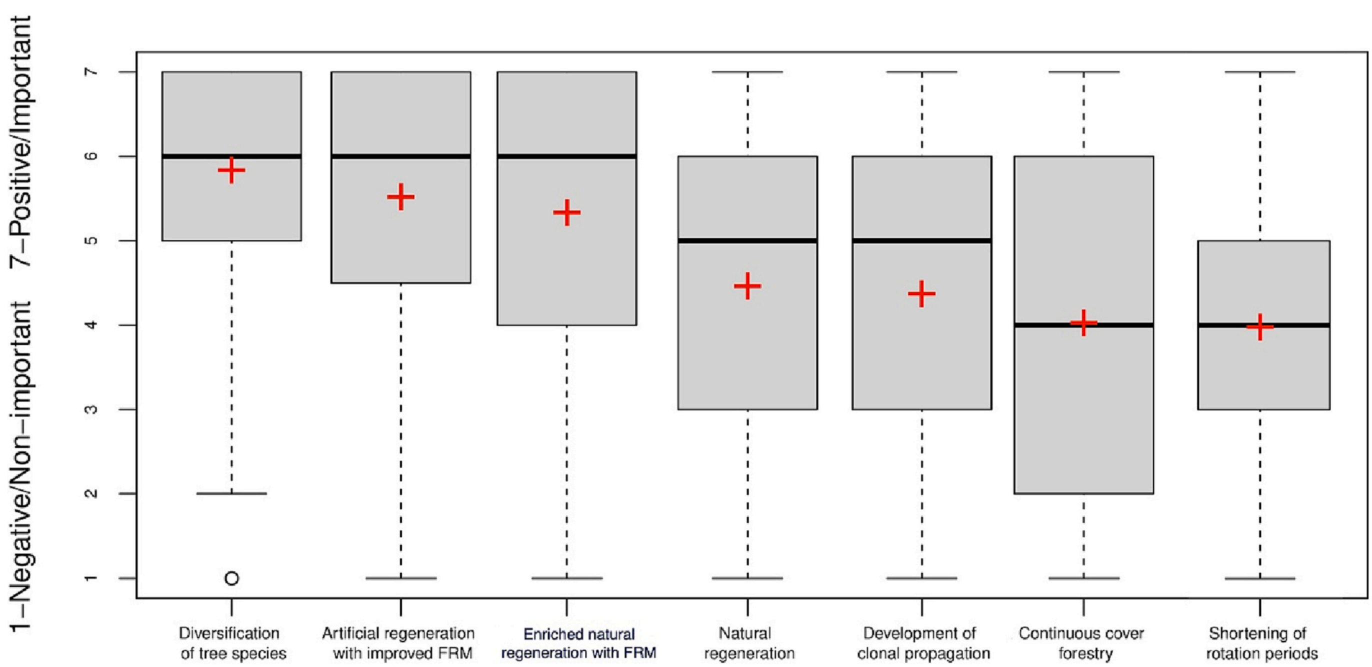

Fig. 2. Boxplots showing differences in the importance of forest management strategies for climate change adaptation. The box indicates the 1st and 3rd quartiles, the dark line is the median, the red cross is the mean, the whiskers extend to 1.5 times the interquartile range. Data points outside that range are shown with hollow circles. Question from the questionnaire: i) How important are the following forest management strategies to adapt forests in your forest region to climate change? (Scale: 1 = Not at all important, 4 = Moderately important; 7 = Extremely important). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

viewed it only as somewhat important.

Natural regeneration was viewed as significantly more important by public forestry ($\tilde{x}$=6, IQR = 3) than it was seen by private forestry (p = 0.00075, $\tilde{x}$=4, IQR = 4) and private sector and industry ($p < 0.0001$, $\tilde{x}$=2, IQR = 2.75).

The *development of clonal propagation* was ranked as significantly more important by private forestry ($p < 0.0001$, $\tilde{x}$=6, IQR = 3) and by the private sector and industry ($p = 0.00036$, $\tilde{x}$=5, IQR = 4) than it was seen by the group of public forestry ($\tilde{x}$=4, IQR = 3), who considered it as moderately important.

Furthermore, *continuous cover forestry* was viewed as significantly more important in public forestry ($\tilde{x}$=5, IQR = 2) than it was seen amongst NGOs & research ($p = 0.00014$, $\tilde{x}$=4, IQR = 2), private forestry ($p = 0.00031$, $\tilde{x}$=4, IQR = 3), and private sector and industry ($p < 0.0001$, $\tilde{x}$=2, IQR = 2).

For *shortening of rotation periods,* we found that it was seen as significantly less important amongst public forestry ($\tilde{x}$=3, IQR = 2) than amongst NGOs & research ($p = 0.03771$, $\tilde{x}$=4, IQR = 3), private forestry ($p = 0.00001$, $\tilde{x}$=5, IQR = 3), and private sector and industry ($p = 0.00042$, $\tilde{x}$=5, IQR = 2).

Reviewing the data with respect to countries revealed some differences in the importance of forest management strategies. For instance, *diversification of tree species* was perceived as extremely important in the Southern European countries of Italy ($\tilde{x}$=7, IQR = 1) and Spain ($\tilde{x}$=7, IQR = 1). Furthermore, it was viewed as important in Sweden ($\tilde{x}$=6, IQR = 1), Germany ($\tilde{x}$=6, IQR = 1), France ($\tilde{x}$=6, IQR = 2) and the UK ($\tilde{x}$=6, IQR = 2). At the other end of the spectrum, it was only seen as somewhat important in Portugal ($\tilde{x}$=5, IQR = 1.5), Norway ($\tilde{x}$=5, IQR = 2) and in Finland ($\tilde{x}$=5, IQR = 3).

Artificial regeneration with improved FRM was considered as extremely important to adapt forests to climate change in Finland ($\tilde{x}$=7, IQR = 1), Sweden ($\tilde{x}$=7, IQR = 1.25), and in Portugal ($\tilde{x}$=7, IQR = 1.75). It was seen as important in Norway ($\tilde{x}$=6, IQR = 1), Spain ($\tilde{x}$=6, IQR = 2), the UK ($\tilde{x}$=6, IQR = 2), France ($\tilde{x}$=6, IQR = 2) and Germany ($\tilde{x}$=6, IQR = 3), but only somewhat important in Italy ($\tilde{x}$=5, IQR = 3).

Adopting *enriched natural regeneration with FRM* was considered important in the Southern European countries of Spain ($\tilde{x}$=6, IQR = 1.75) and Portugal ($\tilde{x}$=6, IQR = 2), but also in France ($\tilde{x}$=6, IQR = 2), Germany ($\tilde{x}$=6, IQR = 2) and the UK ($\tilde{x}$=6, IQR = 2). In Norway ($\tilde{x}$=5, IQR = 2) and Italy ($\tilde{x}$=5, IQR = 3) it was still seen as somewhat important. In contrast, it was viewed as only moderately important in Finland ($\tilde{x}$=4.5, IQR = 3.25) and Sweden ($\tilde{x}$=4, IQR = 2.25).

Natural regeneration was viewed as important in Germany ($\tilde{x}$=6, IQR = 3) and Italy ($\tilde{x}$=6, IQR = 3). This was very different in Norway ($\tilde{x}$=2.5, IQR = 2), Finland ($\tilde{x}$=2, IQR = 2.5) and Sweden ($\tilde{x}$=2, IQR = 3.25) where *natural regeneration* was seen as unimportant. Furthermore, it was considered as somewhat important in Spain ($\tilde{x}$=5, IQR = 2.25), as moderately important in France ($\tilde{x}$=4, IQR = 4) and the UK ($\tilde{x}$=4, IQR = 3), and as somewhat unimportant in Portugal ($\tilde{x}$=3, IQR = 2).

The *development of clonal propagation* was viewed as extremely important only by respondents in Portugal ($\tilde{x}$=7, IQR = 1), while it was viewed as moderately important in Germany ($\tilde{x}$=4, IQR = 3), the least important of all the countries studied. It was viewed as important in Sweden ($\tilde{x}$=6, IQR = 2.75), as somewhat important in Norway ($\tilde{x}$=5, IQR = 2), Finland ($\tilde{x}$=5, IQR = 2), the UK ($\tilde{x}$=5, IQR = 2), France ($\tilde{x}$=5, IQR = 3), Italy ($\tilde{x}$=5, IQR = 3), Spain ($\tilde{x}$=5, IQR = 3).

Continuous cover forestry was regarded as somewhat important in Germany ($\tilde{x}$=5, IQR = 3) – the most important of all countries studied. This view differed from the view that this strategy was considered not important (least important of all countries studies) to adapt forests to climate change in the Northern European countries of Norway ($\tilde{x}$=2, IQR = 1), Sweden ($\tilde{x}$=2, IQR = 1.75) and Finland ($\tilde{x}$=2, IQR = 2). Moreover, it was seen as moderately important in Italy ($\tilde{x}$=4, IQR = 2), Spain ($\tilde{x}$=4, IQR = 2), the UK ($\tilde{x}$=4, IQR = 2), Portugal ($\tilde{x}$=4, IQR = 2.5) and in France ($\tilde{x}$=3.5, IQR = 3).

Shortening of rotation periods was seen as somewhat important in Norway ($\tilde{x}$=5, IQR = 1), France ($\tilde{x}$=5, IQR = 2) and Sweden ($\tilde{x}$=5, IQR = 2), while it was viewed as least important amongst respondents from Spain ($\tilde{x}$=3.5, IQR = 2). Additionally, in the group of Finland ($\tilde{x}$=4, IQR = 2), Italy ($\tilde{x}$=4, IQR = 2), the UK ($\tilde{x}$=4, IQR = 2), Portugal ($\tilde{x}$=4, IQR = 2.75) and Germany ($\tilde{x}$=4, IQR = 3), this strategy was seen as moderately important.

The results of the descriptive statistics and Dunn's test with Bonferroni correction ($p < 0.05$) on the importance of seven forest management strategies to adapt forests to climate change can be found in Appendix C and Appendix E, respectively.

3.3. Hierarchical clustering: Two major response strategies towards climate change in forest management

Hierarchical clustering identified two distinct clusters across all respondents and questions (Table 3). First, a close-to-nature forestry cluster, composed mostly of respondents from the groups public forestry

Table 3
Results from hierarchical clustering: Perceptions by cluster of respondents.

	Close-to-nature forestry cluster (242 cases)			Intensive forestry cluster (179 cases)		
	Median	**Mean**	**IQR**	**Median**	**Mean**	**IQR**
How do you evaluate the effects of climate change on forests in your forest region today?* (1 = Very negative effects, 7 = Very positive effects)	2.00	2.44	1.00	3.00	3.46	1.00
How do you expect a changing climate to affect the forests in your forest region by 2050?* (1 = Very negatively, 7 = Very positively)	2.00	2.38	1.00	3.00	3.49	1.00
To what extent is it possible to adapt forests in your region to climate change through forest management measures by 2050?* (1 = Adaptation through forest management will not be possible, 7 = Adaptation through forest management is fully possible)	5.00	4.62	3.00	5.00	5.29	2.00
How important are the following forest management strategies to adapt forests in your forest region to climate change? (1 = Not at all important, 4 = Moderately important, 7 = Extremely important)						
Diversification of tree species*	7.00	6.19	1.00	6.00	5.37	3.00
Natural regeneration*	6.00	5.72	2.00	2.00	2.74	2.00
Enriched natural regeneration with FRM*	6.00	5.67	2.00	5.00	4.89	2.00
Artificial regeneration with improved FRM*	5.00	5.12	2.00	6.00	6.06	1.00
Continuous cover forestry*	5.00	5.17	2.00	2.00	2.49	2.00
Development of clonal propagation*	4.00	3.79	3.00	6.00	5.21	3.00
Shortening of rotation periods*	3.00	3.38	2.00	5.00	4.66	2.00

*Indicates statistically significant answers ($p < 0.001$)

(33.02%), private forestry (25%) and public administration (23.6%), mostly from Germany (59.5%), Italy (14.05%), France (11.57%) and Spain (6.61%). Second, an intensive forestry cluster composed of private forestry (23.58%), private sector and industry (17.92%) and public administration (16.4%), mostly from France (22.35%), Germany (20.67%), Norway (15.05%) and Finland (14.53%). Respondents in both clusters differ significantly in their perceptions of climate change, forest management adaptation possibilities, and how forest management can best respond (Table 3).

Respondents in the close-to-nature forestry cluster viewed the effects of climate change in early 2019 ($\tilde{x}$=2, IQR = 1) and by 2050 ($\tilde{x}$=2, IQR = 1) as negative with high consensus. Furthermore, respondents in this cluster indicated that climate change adaptation through forest management will somewhat be possible ($\tilde{x}$=5, IQR = 3), albeit with low consensus. On the other hand, the respondents in the intensive forestry cluster were of the opinion that the effects of climate change are (only) somewhat negative in early 2019 ($\tilde{x}$=3, IQR = 1) and by 2050 ($\tilde{x}$=3, IQR = 1). Similar to the close-to-nature forestry cluster, they also indicated that adaptation through forest management will somewhat be possible ($\tilde{x}$=5, IQR = 2).

When it came to forest management strategies, some interesting similarities and differences emerged. The respondents in the close-to-nature forestry cluster perceived the *diversification of tree species* ($\tilde{x}$=7, IQR = 1) as extremely important with high level of consensus. *Natural regeneration* ($\tilde{x}$=6, IQR = 2) and *enriched natural regeneration with FRM* ($\tilde{x}$=6, IQR = 2) were both considered important to adapt forests to climate change amongst the respondents of the close-to-nature forestry cluster. *Artificial regeneration with improved FRM* ($\tilde{x}$=5, IQR = 2) and *continuous cover forestry* ($\tilde{x}$=5, IQR = 2) were viewed as moderately important in this cluster, while the *development of clonal propagation* ($\tilde{x}$=4, IQR = 3) was perceived as neither important nor unimportant, followed by *shortening of rotation* ($\tilde{x}$=3, IQR = 2), which was considered moderately unimportant.

In turn, respondents in the intensive forestry cluster perceived *artificial regeneration with improved FRM* ($\tilde{x}$=6, IQR = 1), *development of clonal propagation* ($\tilde{x}$=6, IQR = 3), and *diversification of tree species* ($\tilde{x}$=6, IQR = 3) as important to adapt their forests to climate change. From these three forest management strategies, *artificial regeneration with improved FRM* had the highest consensus. Respondents in the intensive forestry cluster were further of the opinion that *enriched natural regeneration with FRM* ($\tilde{x}$=5, IQR = 2) and *shortening of rotation* ($\tilde{x}$=5, IQR = 2) were moderately important. Finally, the respondents in this cluster perceived *continuous cover forestry* ($\tilde{x}$=2, IQR = 2) and *natural regeneration* ($\tilde{x}$=2, IQR = 2) as moderately unimportant. All reported differences between the responses of the intensive forestry cluster and the close-to-nature forestry cluster are statistically relevant at the $p < 0.001$ level.

4. Discussion

4.1. North-south gradient in perceptions of climate change effects in Europe

Our study revealed significant geographical differences in the perceptions of climate change effects on forests now (2019) and in 2050, with a North-South gradient in Europe. Perceptions ranged from balanced negative and positive effects on forests in Northern Europe (Norway, Sweden, Finland) and the UK, to rather sceptical views in Southern Europe (Italy, Portugal, Spain), France, and (most) negative views in Germany. With the exception of Germany, these findings are in accord with previous studies that have observed a similar North-South gradient of climate change effect perceptions in Europe (Blennow et al., 2012; Sousa-Silva et al., 2018). For instance, Blennow et al. (2012) showed that private forest owners in Southern Europe (Portugal) were more likely to be concerned about climate change effects than they were in Northern Europe (Sweden). Little concern about climate change was reported in Northern Europe (Vulturius et al., 2018), on the contrary, even a rather positive view on the effects of climate change on forests and forestry now and in the future was shown in earlier studies (Eriksson, 2014; Heltorp et al., 2018). Our data is mostly consistent (except for Germany) with these findings and ultimately add more weight to this claim as our study showed a similar trend and covered additional countries in Europe. This finding could be explained by earlier research indicating that a warming climate can, at least in part, have positive effects on forestry in Northern Europe due to higher forest productivity resulting from longer forest growing seasons. However, these positive effects may be counterbalanced by (also) increasing disturbance risks (Lindner et al., 2014).

In contrast, in Southern Europe, respondents generally showed a rather negative view towards the effects of climate change in early 2019 and in the future; particularly respondents from Spain expected to experience negative effects of climate change in 2050. This can be correlated with increasing disturbances, such as fires leading to production losses, which are amongst the greatest challenges related to climate change in this region (Schelhaas et al., 2015).

Finally, it is remarkable that the findings for Germany depart from the North-South gradient in our study. Respondents from Germany showed the most negative view, with high consensus on the effects of climate change in early 2019 and the expected effects by 2050. This is in contrast to previous studies where the risks of climate change were not perceived as very high by forest practitioners in this country (Yousefpour and Hanewinkel, 2015). A shift towards a more pessimistic view of climate change effects may be explained in part by the extraordinary weather conditions in this country in 2018 and 2019, combined with the vulnerable forest structure. Evidence suggests that concrete experiences of weather extremes (most likely influenced by climate change) influence perceptions of climate change, and willingness towards climate change adaptation (Demski, 2017; Seidl et al., 2015). During the summer of 2018, extremely hot and dry conditions prevailed in Central Europe (Drouard et al., 2019; Vogel et al., 2019), subsequently causing major forest dieback, specifically in Norway Spruce plantations in Germany which were planted outside their natural distribution range but have been economically profitable so far. This situation has been interpreted as a forest crisis and a turning point for the forest sector in Germany (Schuldt et al., 2020), greatly effecting its economic viability. The negative view of German forest experts and practitioners is probably directly connected to this – at the time of the survey, fresh and shocking – experience of an extreme weather (and most likely climate change) induced forest disturbance. The unprecedented extreme climatic events occurring in Central Europe since 2018 may constitute more than a temporary negative perception of climate change effects. The stark climate-induced ecological changes, including long-lasting droughts, major bark beetle outbreaks and increased tree mortality, indicate a change in the disturbance regimes (Senf et al., 2020; Senf and Seidl, 2021; Thonfeld et al., 2022), which may continue or even accelerate with continuing climatic warming (Hlásny et al., 2021; Seidl et al., 2017).

4.2. Forest owner types influencing climate change perceptions and management preferences

When looking at different patterns within occupational groups in the forest sector, this study found that opinions repeatedly differed significantly between those of private forestry/forest industry and the more negative views of public forestry. These differences concern questions about climate change effects in early 2019, and by 2050, as well as whether adaptation to climate change through forest management will be possible. Public forestry and public administration also tended to attach more importance to *diversification of tree species*, *natural regeneration*, and *continuous cover forestry*. The variations of opinions on climate change amongst forestry professionals is not a new phenomenon (Nelson, 2016). One possible explanation is that public forestry tends to manage the forest focusing on maximizing ecosystem services for society at large, while private forestry may manage with a stronger focus on maximising profits from marketing timber as raw material, hence the latter's preference of more economic output-oriented forest management strategies. In contrast to our results, Sousa-Silva et al. (2018) found no observable difference between the views of forest owners and private and public managers regarding how climate change impacts their forests, nor any significant difference regarding future effects. There is also a potential bias in our study given the large number of respondents from the public sector from Germany, which particularly suffered from drought and high temperatures during the summer of 2018. Yet, the difference between public and private owners could also be observed on a country-by-country basis.

4.3. Between close-to-nature forestry and intensive forestry for climate change adaptation

This study supported the importance of seven (based on existing literature) selected forest management strategies for climate change adaptation, and found agreement amongst forestry professionals and experts on three of these. The top-evaluated strategy was the *diversification of tree species*, which also had the highest agreement amongst our respondents. This finding is broadly in line with other (local) studies investigating forest management strategies for climate change adaptation, for example in Wallonia (van Gameren and Zaccai, 2015) and in south-west Germany (Yousefpour and Hanewinkel, 2015). Strong support for more diverse species composition has also been found in national studies, for Sweden (Lidskog and Löfmarck, 2015) and France (Thomas et al., 2022), and in multi-national studies, for France and Germany (Brunette et al., 2020) and across seven countries in Europe (Sousa-Silva et al., 2018). While the support for tree species diversification is not surprising given its potential to reduce risks and uncertainty related to individual tree species, an interesting question is which tree species will be considered for diversification – namely, how far non-native tree species will be considered.

As Winkel et al. (2011) have shown for the case of Germany, there is remarkable disagreement at the policy level on this question. In their study, a nature conservation coalition emphasized "natural" adaptation including non-intervention approaches or close-to-nature forestry approaches with only individual tree or group selection cuttings in structurally rich forests, using native tree species. In contrast, a forest/wood production coalition emphasized the necessity to introduce fast-growing non-native tree species such as Douglas fir and advocated for shorter rotation periods to reduce disturbance risks. Such divergent views on climate change adaptation have been mapped in other contexts, e.g. for the EU biodiversity conservation policy Natura 2000 and its implementation in forests (de Koning et al., 2014; Harrinkari et al., 2016). The nature conservation/environmental/close-to-nature forestry coalition emphasizes the need for more governmental regulation of forestry, giving more space to natural dynamics, and the importance of protecting old and volume-rich stands (old-growth forests) with high amounts of deadwood (Aszalós et al., 2022; Harrinkari et al., 2016). The forestry/timber coalition, in turn, argues for the necessity to reduce the rotation periods/harvesting ages of trees, as well as the growing stocks of forests, to reduce (timber production) risks (Jandl et al., 2019). Remarkably, these diverging policy perspectives are mirrored, to some degree, in the two clusters we could identify in our study (Table 3). We found that *natural regeneration* and *continuous cover forestry* were perceived as important by respondents in the *close-to-nature forestry cluster*, but not important by respondents in the *intensive forestry cluster*. Reversely, the *development of clonal propagation* and the *shortening of rotation periods* were perceived as important by respondents in the *intensive forestry cluster*, but only moderately or not important by respondents in the *close-to-nature forestry cluster* ($p < 0.001$). Similar to what has been mapped at the policy level as main paradigms in European forestry before, the two clusters in our survey differ fundamentally in their main strategy for climate change adaptation. While one cluster follows the rationale to largely draw on natural adaptation processes to adapt to climate change, the other cluster follows the logic of strong nature intervention to optimise the resilience of the timber production system for successful climate change adaptation. This is a key finding of our study.

4.4. Methodological considerations

This study used an online survey to collect data, which can have drawbacks. First, it is not possible to give a response rate to the questionnaire because we distributed the survey as widely as possible by using *E*-mail lists, the European Forest Institute website and the B4EST project website, and distributing it via contacts at associations, ministries and within the private sector. Given the relatively larger number of forest sector employees in Central-West Europe compared to Northern Europe and Southern Europe (FOREST EUROPE, 2020), it could be expected that this study would receive more responses from Germany and France. However, the strong discrepancy in responses is probably also due to varying success in implementing the sampling strategy, as the number of responses for each country differed strongly (Table 2). For instance, respondents from Germany are overrepresented (42.7% of our sample). Moreover, private foresters are underrepresented: while they make up 14% of our sample, about 46.5% of forests in Europe are privately owned (FOREST EUROPE, 2020).

Second, this study is not representative of the forest sector in Europe. Comparing the biographical patterns of our sample with those of the entire forest-sector workforce shows some deviations, but also some alignment. For instance, female respondents make up 16.4% in our study compared to between 13% and 16% in the forestry and wood manufacturing workforce in Europe (FAO and UNECE, 2020). Respondents with high education in the form of a university degree in forestry are, in turn, overrepresented in our study (79.1%), while in the forest sector this figure is around 19% (FAO and UNECE, 2020). This may be explained by the fact that our survey mostly reached forestry experts in management positions, be it a the local, regional or national level, and not, for instance, forestry workers. As studies have shown, gender and education are decisive factors in risk perceptions of climate change, with female and more educated citizens being on average more concerned about climate change risks (Lujala et al., 2015). Arguably, our sampling strategy reached a disproportionate number of large-scale professional forestry enterprises in comparison to small-scale private forest owners. Our sample consists of 46.4% of forestry professionals that are responsible for a forest area > 10,000 ha, whereas the size of forest holdings varies much more in Europe, e.g., smaller ones in South-East Europe compared to larger ones in Northern Europe (FOREST EUROPE, 2020). Furthermore, our sampling strategy and survey targeted forests that are actively managed (forestry), hence we did not include, for instance, strictly protected forests or forests mostly managed for conservation purposes, which we consider justified as our main interest is adaptation within forestry (and not forests as a whole) in Europe.

In sum, our sample cannot be considered fully representative for forest management in the nine countries investigated, and we caution against reading our findings as being fully representative of the perceptions of forest managers in terms of absolute numbers and for individual countries. This is an important limitation of our study.

Finally, while we provided survey respondents with the definition of FRM at each location where FRM was mentioned, we did not provide further explanation of the forest management strategies queried. It is therefore possible that some respondents may have a different interpretation of the forest management strategies compared to the researchers who designed it.

Despite these limitations, we argue that the main trends we found – namely a North-South gradient in the perception of climate change effects (less and more ambiguous effects in Northern Europe) and in the confidence of being able to adapt forest management (more confidence in the North) and the existence of two main clusters of forest management responses (close-to-nature forestry versus intensive forestry) – are significant findings.

4.5. Policy and practice implications and research needs

The findings of this study have practical and policy implications. Climate change related policies on forests should consider the reported awareness of climate change, including the North-South gradient in perceptions of climate change effects and possibilities to adapt. Given the widespread awareness of climate change, adaptation strategies may increasingly move from creating awareness to climate change adaptation measures, which, however, need to be regionally contextualized.

In Southern Europe, where the perceptions of climate change and its impacts on forests are generally negative, policies need to provide crisis response and preparedness mechanisms, thus focussing on rapid adaptation and mitigating the intensity of climate change effects on forests (e.g., forest fires). Suitability of traditional and adaptive forest management approaches needs to be evaluated considering recent climatic extreme events and future forest growth projections and increasing risks.

In Germany, where perceptions are very negative, there have already been significant policy responses, making substantial funding available for forest restoration after disturbances and supporting the implementation and scaling up of climate resilient forestry measures such as the diversification of tree species. Still, as in other contexts, it will be interesting to observe how forest practitioners "on the ground" will respond in terms of adaptation strategies.

In Northern Europe, perceptions are generally more positive, in line with modelling projections of a (at least temporarily) positive impact of a warming climate on forest growth. Still, increasing disturbances risks may increasingly necessitate adaptation measures also here, some of them offering potentially significant co-benefits (e.g., the diversification of tree species).

The opinions between private and public forestry repeatedly significantly differed concerning the effects of climate change and possibility to adapt forests to climate change. This is an interesting finding and again underlines the necessity to develop target-group specific policies and policy instruments. For private forest owners, financial support mechanisms and strategies that underline future possibilities to gain economic returns from their forest resources, including a diversification of income streams beyond biomass production (e.g., carbon offset markets, nature-based tourism), may be more important than for public forestry, which already places more emphasis on multiple benefits for society.

Finally, the observed dichotomy of response mechanisms – close-to-nature forestry and intensive forestry – is highly interesting and relevant for forest policy making. One could argue that both response lines represent traditional patterns of action that are reinforced also in the light of new challenges. This, however, necessitates a critical reflection on how suitable both response lines will be under a changing climate. For instance, natural regeneration may no longer be sufficient as natural adaptation to a changing climate is often too slow. Previously well adapted tree species may not be able to cope with future climate conditions. Arguably, further (natural science) research is needed to not only model, but also empirically assess the impacts of the changing climate and the effectiveness of climate change response strategies. Practical observations by forest managers could be integrated in such research to gather a growing and continuously updated evidence base given accelerating change.

Altogether, our findings call for increased attention to different pathways of adaptation in European forest policy – including those not covered in this study, related to (strict) forest protection and non-intervention. Arguably, different reported adaptation measures and adaptation pathways will result to different degrees of synergies and trade-offs with respect to the provision of multiple ecosystem services. Conversely, the necessity to adapt unlocks new synergies to implement forest management strategies that meet plural societal demands for ecosystem services (Winkel et al., 2022).

Further research is needed to assess the perceptions of climate change adaptation strategies in forest management practices beyond the scope of this study, including in protected areas and amongst small-scale private forest owners. Moreover, in light of ongoing and further increasing climate change impacts and related disturbances such as drought, expanding bark beetle outbreaks in the southern boreal region, and forest fires, it is likely that some of the patterns revealed in this study will alter in the coming decades.

5. Conclusions

Climate change is increasingly affecting forests across the globe, and the question of how forests – and forestry – will adapt is an urgent one. The perceptions and actions of forestry professionals are of critical importance for managed forests, as they – along with climate change – will determine future forests' resilience and their potential to deliver multiple ecosystem services to society. The purpose of the current study was to explore the perceptions of climate change and the importance of forest management strategies amongst different forestry professionals in nine European countries. Our study has shown that awareness of climate change exists across Europe, albeit with significant regional variations in the perceptions of climate change effects and regarding the confidence in the possibility to adapt forests and forest management. These regional patterns seem to be related to regionally different current effects of climate on forests (in terms of forest growth and disturbances). Our work has also demonstrated the existence of two main "adaptation paradigms" in forest management, contributing to fill a gap in the literature by spanning nine countries in Europe. Which paradigm is followed may be decisive for the potential of forests and forestry to deliver multiple forest ecosystem services, including the conservation of forest biodiversity. Disentangling evidence from interest-driven positions in the related policy debate is critical for future forest policies to support adaptation in forest management that can serve multiple societal needs.

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CRediT authorship contribution statement

Dennis Roitsch: Writing – original draft, Formal analysis, Writing – review & editing. **Silvia Abruscato:** Writing – review & editing. **Marko Lovrić:** Formal analysis. **Marcus Lindner:** Writing – review & editing. **Georg Winkel:** Supervision, Conceptualization, Writing – review & editing.

Declaration of Competing Interest

The authors declare no conflicting interests.

Data availability

Data will be made available on request.

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Appendix A. Results from the re-classification of respondents to a smaller number of classes

Table A.1
Results of Bartlett's Test for Homogeneity of Variances ($p > 0.05$ means that group variances are equal). The Homogeneity of Variances is an assumption of the Kruskal-Wallis test (non-parametric ANOVA). Table A1 below shows these p values per variable. The Kruskal-Wallis test can be done on all variable except on the variable *Artificial regeneration with improved FRM*.

Variable name	p-value
Climate change effects today	0.06284
Climate change effects by 2050	0.3325
Climate change adaptation by 2050	0.8011
Shortening of rotation periods	0.9427
Continuous cover forestry	0.9509
Natural regeneration	0.6719
Enriched natural regeneration with FRM	0.1708
Diversification of tree species	0.5023
Artificial regeneration with improved FRM	0.0002177
Development of clonal propagation	0.9007

Appendix B. Results of descriptive statistical tests

Table B.1
Results from descriptive statistics (mean, median and interquartile range).

	Mean	Median	Interquartile range
Climate change effects today	2.911	3.000	2
Climate change effects by 2050	2.831	3.000	2
Climate change adaptation by 2050	4.841	5.000	2
Shortening of rotation periods	3.991	4.000	2
Continuous cover forestry	4.039	4.000	4
Natural regeneration	4.478	5.000	3
Enriched natural regeneration with FRM	5.347	6.000	3
Diversification of tree species	5.849	6.000	2
Artificial regeneration with improved FRM	5.533	6.000	2.25
Development of clonal propagation	4.384	5.000	3

Appendix C. Results of descriptive statistics

Table C.1
Descriptive statistics for each question by groups of respondents.

		Climate change effects today	Climate change effects by 2050	Climate change adaptation by 2050	Shortening of rotation periods	Continuous cover forestry	Natural regeneration	Enriched natural regeneration with FRM	Diversification of tree species	Artificial regeneration with improved FRM	Development of clonal propagation
NGOs & research	Median	3.00	3.00	6.00	4.00	4.00	4.00	6.00	7.00	6.00	5.00
	mean	3.22	2.77	5.29	4.20	3.42	4.15	5.44	6.00	5.64	4.57
	IQR	1.00	2.00	1.00	3.00	2.00	3.00	2.75	2.00	2.00	3.00
Other	Median	3.00	3.00	5.00	5.00	3.00	4.50	6.00	6.00	6.00	5.00
	mean	3.21	3.13	5.47	4.47	3.57	4.21	5.27	6.07	5.36	4.29
	IQR	2.00	1.00	1.50	2.00	3.00	4.50	2.50	1.00	2.75	3.75
Private forestry	Median	3.00	3.00	5.00	5.00	4.00	4.00	6.00	6.00	6.00	6.00
	mean	2.92	2.91	5.08	4.52	3.77	4.22	5.56	5.70	5.94	5.12
	IQR	2.00	2.00	2.00	3.00	3.00	4.00	2.00	2.00	2.00	3.00
Private sector and industry	Median	3.00	3.00	5.00	5.00	2.00	2.00	5.00	6.00	6.00	5.00
	mean	3.35	3.36	5.07	4.48	3.06	2.96	4.79	5.48	6.11	4.84
	IQR	1.00	1.00	2.00	2.00	2.00	2.75	2.00	2.50	1.00	4.00
Public administration	Median	3.00	3.00	5.00	4.00	4.00	5.00	6.00	6.00	6.00	4.00
	mean	2.80	2.78	4.52	3.83	4.18	4.75	5.45	6.03	5.39	4.22
	IQR	1.00	1.00	3.00	2.50	3.00	3.00	2.50	2.00	2.25	2.00

(continued on next page)

Table C.1 (*continued*)

		Climate change effects today	Climate change effects by 2050	Climate change adaptation by 2050	Shortening of rotation periods	Continuous cover forestry	Natural regeneration	Enriched natural regeneration with FRM	Diversification of tree species	Artificial regeneration with improved FRM	Development of clonal propagation
Public forestry	Median	3.00	2.50	5.00	3.00	5.00	6.00	6.00	7.00	6.00	4.00
	mean	2.55	2.56	4.50	3.40	4.82	5.29	5.37	6.01	5.10	3.60
	IQR	1.00	1.00	3.00	2.00	2.00	3.00	3.00	1.00	3.00	3.00

Table C.2
Descriptive statistics by country.

		Climate change effects today	Climate change effects by 2050	Climate change adaptation by 2050	Shortening of rotation periods	Continuous cover forestry	Natural regeneration	Enriched natural regeneration with FRM	Diversification of tree species	Artificial regeneration with improved FRM	Development of clonal propagation
Estonia	Median	5.00	4.00	4.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00
	mean	5.00	4.00	4.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00
	IQR	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Finland	Median	4.00	4.50	6.00	4.00	2.00	2.00	4.50	5.00	7.00	5.00
	mean	4.25	4.41	5.88	4.10	2.27	2.65	4.22	5.25	6.22	4.77
	IQR	1.00	1.00	1.25	2.00	2.00	2.50	3.25	3.00	1.00	2.00
France	Median	3.00	3.00	5.00	5.00	3.50	4.00	6.00	6.00	6.00	5.00
	mean	3.16	2.74	5.03	4.89	3.45	3.81	5.65	5.88	5.84	4.38
	IQR	1.00	1.00	2.00	2.00	3.00	4.00	2.00	2.00	2.00	3.00
Germany	Median	2.00	2.00	4.00	4.00	5.00	6.00	6.00	6.00	6.00	4.00
	mean	2.39	2.47	4.32	3.65	4.75	5.18	5.57	6.00	5.25	3.80
	IQR	1.00	1.00	2.00	3.00	3.00	3.00	2.00	1.00	3.00	3.00
Italy	Median	3.00	3.00	6.00	4.00	4.00	6.00	5.00	7.00	5.00	5.00
	mean	2.71	2.67	5.53	3.71	4.34	5.38	5.32	6.16	5.25	5.09
	IQR	1.00	1.00	2.00	2.00	2.00	3.00	3.00	1.00	3.00	3.00
Latvia	Median	3.50	4.00	6.00	6.00	5.00	3.50	6.50	6.50	5.50	6.00
	mean	3.50	4.00	6.00	6.00	5.00	3.50	6.50	6.50	5.50	6.00
	IQR	0.50	1.00	1.00	1.00	1.00	0.50	0.50	0.50	1.50	0.00
Norway	Median	4.00	4.00	6.00	5.00	2.00	2.50	5.00	5.00	6.00	5.00
	mean	4.10	4.03	5.34	4.26	2.00	2.79	4.59	5.15	5.92	4.73
	IQR	2.00	2.00	1.00	1.00	1.00	2.00	2.00	2.00	1.00	2.00
Other	Median	3.00	2.00	7.00	4.00	4.00	7.00	7.00	7.00	7.00	5.00
	mean	3.00	2.67	6.67	4.67	5.00	6.33	6.00	7.00	6.00	4.33
	IQR	1.00	2.00	0.50	2.00	1.50	1.00	1.50	0.00	1.50	3.00
Other International organization	Median	3.00	2.50	5.50	7.00	3.00	4.50	6.50	5.50	7.00	7.00
	mean	3.00	2.50	5.50	7.00	3.00	4.50	6.50	5.50	7.00	7.00
	IQR	1.00	1.50	1.50	0.00	1.00	2.50	0.50	1.50	0.00	0.00
Portugal	Median	3.00	2.50	4.00	4.00	4.00	3.00	6.00	5.00	7.00	7.00
	mean	2.73	2.71	4.40	3.79	3.67	3.21	5.40	5.13	6.29	6.38
	IQR	1.00	1.00	1.50	2.75	2.50	2.00	2.00	1.50	1.75	1.00
Romania	Median	4.00			2.00	4.00	5.00	2.00	3.00	1.00	1.00
	mean	4.00			2.00	4.00	5.00	2.00	3.00	1.00	1.00
	IQR	0.00			0.00	0.00	0.00	0.00	0.00	0.00	0.00
Russia	Median	1.00	2.50	4.00	3.50	4.00	2.00	6.50	7.00	5.50	3.50
	mean	1.00	2.50	4.00	3.50	4.00	2.00	6.50	7.00	5.50	3.50
	IQR	0.00	0.50	2.00	0.50	1.00	1.00	0.50	0.00	0.50	1.50
Spain	Median	3.00	2.00	5.00	3.50	4.00	5.00	6.00	7.00	6.00	5.00
	mean	2.64	2.31	4.63	3.17	4.04	5.14	5.60	6.27	5.57	4.79
	IQR	1.25	2.00	2.00	2.00	0.50	2.25	1.75	1.00	2.00	3.00
Sweden	Median	4.00	4.00	5.50	5.00	2.00	2.00	4.00	6.00	7.00	6.00
	mean	3.75	3.69	5.25	5.06	2.20	2.69	4.38	5.44	6.19	5.57
	IQR	1.25	1.00	1.25	2.00	1.75	3.25	2.25	1.00	1.25	2.75
UK	Median	4.00	3.00	5.00	4.00	4.00	4.00	6.00	6.00	6.00	5.00
	mean	3.65	3.30	5.25	3.86	4.50	4.23	4.95	5.50	5.35	4.95
	IQR	1.00	1.00	1.00	2.00	3.00	3.00	2.00	2.00	2.00	2.00

Appendix D. Variability of responses within groups

Table D.1
Comparison of in-group variability for groups and countries*

Static	Groups	Countries
Median	0.07242	0.05556
Mean	0.07276	0.06195
SD	0.02753817	0.04777185
-1.96 SD	0.01879	-0.03168283
+1.96 SD	0.12673481	0.155582826

*To define 'significantly' deviating values of variance in the two tables D1 and D2, the criterion was set at $p < 0.05$, or ± 1.96 SD from the mean. These values are stated in table D3 where the truly cohesive answers are coded in green, and truly divergent in red. A subsequent Mann-Whitney *U* test, where $p = 0.003077$, revealed that there is a significant difference between responses by countries and groups, hence there was no need to join groups and country-level responses together.

Appendix E. Results for variability of responses between groups of respondents and country

Table E.1
Significant differences in views of climate change between groups of respondents. Significant values (i.e. pointers where there is a significant difference in responses) are marked in red.

		Private sector and industry	Other	NGOs & research
Climate change effects today	Public forestry	0.00007	1.00000	0.00720
	Public administration	0.01236	1.00000	0.30831
Climate change effects by 2050	Public forestry	0.00011	1.00000	1.00000
	Public administration	0.00572	1.00000	1.00000
	Private sector and industry		1.00000	0.03230
Climate change adaptation by 2050	Public forestry	0.16267	0.35725	0.00846
	Public administration	0.13358	0.02123	1.00000

Table E.2
Significant differences in views of forest management strategies between groups of respondents. Significant values (i.e. pointers where there is a significant difference in responses) are marked in red.

Forest management strategy		Private sector and industry	Private forestry	NGOs & research
Shortening of rotation periods	Public forestry	0.00042	0.00001	0.03771
Continuous cover forestry	Public forestry	0.00000	0.00031	0.00014
	Public administration	0.00337	1.00000	0.31674
Natural regeneration	Public forestry	0.00000	0.00075	0.00652
	Public administration	0.00000	0.73475	0.97012
	Private sector and industry		0.00052	0.01636
Enriched natural regeneration with FRM	Private sector and industry		0.04484	1.00000
Diversification of tree species	Public forestry	0.00955	0.17537	1.00000
	Public administration	0.04638	0.69557	1.00000
Artificial regeneration with improved FRM	Public forestry	0.00098	0.00071	1.00000
	Public administration	0.02689	0.03897	1.00000
Development of clonal propagation	Public forestry	0.00036	0.00000	0.03166
	Public administration	0.33805	0.00347	1.00000

Table E.3
Significant differences in views of climate change by country. Significant values (i.e. pointers where there is a significant difference in responses) are marked in red.

		Spain	Norway	Italy	Germany	France	Finland
Climate change effects today	UK	0.32307	1.00000	0.09296	0.00014	1.00000	1.00000
	Sweden	0.44069	1.00000	0.16531	0.00081	1.00000	1.00000
	Spain		0.00061	1.00000	1.00000	1.00000	0.00001
	Portugal		0.04077	1.00000	1.00000	1.00000	0.00238
	Norway			0.00001	0.00000	0.03771	1.00000
	Italy				1.00000	0.93146	0.00000
	Germany					0.00000	0.00000
	France						0.00062
Climate change effects by 2050	Sweden	0.01152	1.00000	0.10193	0.00259	0.10267	1.00000
	Spain		0.00007	1.00000	1.00000	1.00000	0.00000
	Portugal		0.26171	1.00000	1.00000	1.00000	0.00411
	Norway			0.00046	0.00000	0.00021	1.00000
	Italy				1.00000	0.00000	1.00000
	Germany					0.00000	1.00000
	France						0.00000
Climate change adaptation by 2050	Norway			1.00000	0.00655	1.00000	1.00000
	Italy				0.00000	1.00000	1.00000
	Germany					0.02068	0.00000

Table E.4
Significant differences in views of forest management strategies by country. Significant values (i.e. pointers where there is a significant difference in responses) are marked in red.

Forest management strategy		Spain	Norway	Italy	Germany	France	Finland
Shortening of rotation periods	Spain		1.00000	1.00000	1.00000	0.00245	1.00000
	Italy				1.00000	0.00586	1.00000
	Germany					0.00000	1.00000
Continuous cover forestry	UK	1.00000	0.00054	1.00000	1.00000	1.00000	0.00667
	Sweden	1.00000	1.00000	0.10393	0.00330	1.00000	1.00000
	Spain		0.01015	1.00000	1.00000	1.00000	0.09231
	Norway			0.00000	0.00000	0.02411	1.00000
	Latvia			1.00000	1.00000	0.82976	0.00020
	Germany					0.00001	0.00000
Natural regeneration	Sweden	0.02135	1.00000	0.00028	0.00034	1.00000	1.00000
	Spain		0.00060	1.00000	1.00000	0.39479	0.00064
	Portugal		1.00000	0.04088	0.07134	1.00000	1.00000
	Norway			0.00000	0.00000	0.89444	1.00000
	Italy				1.00000	0.00022	0.00000
	Germany					0.00001	0.00000
Enriched natural regeneration with FRM	Norway			1.00000	0.00376	0.00629	1.00000
	Germany					1.00000	0.01315
	France						0.01687
Diversification of tree species	Norway			0.00492	0.00777	0.75377	1.00000
Development of clonal propagation	Portugal		0.63485	1.00000	0.00023	0.04451	0.86811
	Italy				0.00160	1.00000	1.00000

Appendix F. Results of hierarchical clustering

Table F.1
Composition of two clustered groups according to professional groups and countries.

	Close-to-nature forestry cluster (242 cases)	Intensive forestry cluster (179 cases)
GROUP OF RESPONDENTS*	Public forestry: 33.02% Private forestry: 25.00% Public administration: 23.58% NGOs & research: 8.96% Private sector and industry: 6.60% Other: 2.83%	Private forestry: 23.58% Private sector and industry: 17.92% Public administration: 16.04% NGOs & research: 12.74% Public forestry: 7.08% Other: 2.36%
COUNTRY*	Germany: 59.50% Italy: 14.05% France: 11.57% Spain: 6.61% UK: 3.72% Finland: 1.24% Other: 1.24% Portugal: 1.24% Norway: 0.41% Sweden: 0.41% Other International organization: 0.00% Latvia: 0.00% Estonia: 0.00%	France: 22.35% Germany: 20.67% Norway: 15.08% Finland: 14.53% Italy: 8.38% Sweden: 5.03% UK: 4.47% Portugal: 4.47% Spain: 2.79% Estonia: 0.56% Latvia: 0.56% Other International organization: 0.56% Russia: 0.56%

Appendix G. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.forpol.2023.103035.

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