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# Report on Improved Forest models with enhanced representation of behavior and behavioral change of forest owners and conservation managers

(Deliverable 3.1)

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## Disclaimer

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# 1.Introduction

The complex nature of human decision making has been the focus of studies for decades across several themes, including environment modelling (Groeneveld et al., 2017). Forest management decisions are shaped by many socio-ecological factors and result in different behavioural responses. There are diverse types of forest owners and managers, hereafter collectively referred to as ‘agents’, with a variety of objectives, preferences and behaviour that affect forest management decision-making. It is important to consider these differences in behaviour and behavioural change in forest management decision support tools when assessing the impact of policies, market drivers, and conservation goals on forest environments (e.g., see Brodrechtova et al., 2018 and Sotirov et al., 2019).

Distinct methods have been used to represent agent behaviour through integration of influence factors for decision making (e.g., economic, social, environmental factors) into modelling of land use change and decision support systems to the provision of ecosystem services (Groeneveld et al., 2017). In the context of the BIOCONSENT project, behaviour is defined as being forest management practices opted to be implemented by the forest owners and conservation managers. Within the project, the factors that shape forest management decision making will be covered by the analysis of behaviour of forest owners and conservation managers, as they act as primary agents of change by making and implementing management decisions. The BIOCONSENT project, aims to design an effective and integrated decision support tool, supported by more in-depth knowledge that will be gained on (i) analysing policy objectives and identifying implementation instruments (ii) the behavioural responses from agents of change and (iii) the outcomes of forest conservation and restoration measures.

To better understand how alternative policies and management actions affect forest biodiversity conservation and restoration, WP3 seeks to integrate biophysical, social, economic, and policy/governance aspects into forest modelling tools. WP3 will quantify scenario outcomes on regional and EU levels, by interpreting and upscaling policy and management scenarios.

The aim of this report is to describe:

(1) the correlation between variables influencing forest management behaviour and the different agent typologies.

(2) how to improve the representation of behaviour and behavioural change of forest owners and conservation managers in biophysical forest models.

(3) further improvements made to forest models to simulate biodiversity outputs, as consequence of the implementation of different policy and management scenarios.

# 2. General methodology

Models are important decision support tools which help deal with complexity under uncertain conditions. Many forest models have been developed to simulate forest stand development and guide forest management (e.g., see Fontes et al. 2010; Schelhaas et al. 2017). These existing models often rely on “textbook” management practices. The general approach for including forest management decision-making in forest models is schematically shown in Figure 1.

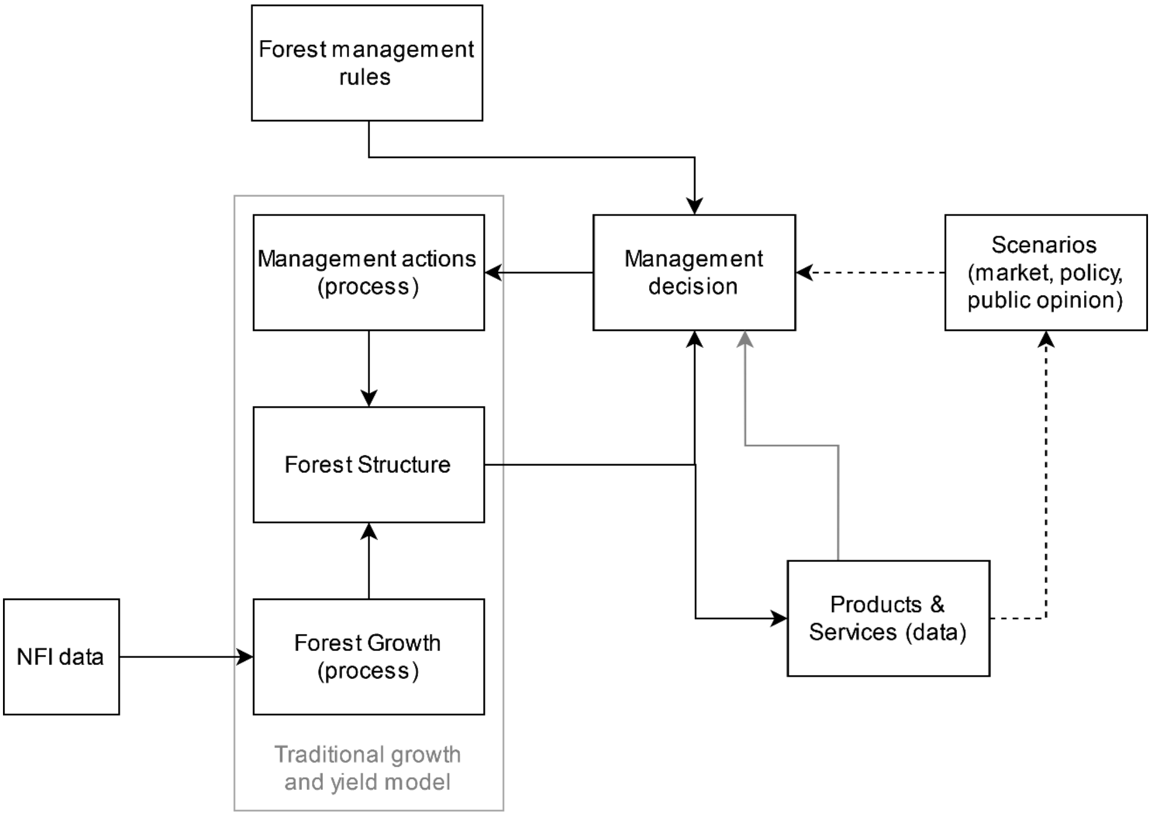



*Figure 1. General approach for including forest management in traditional forest models, where forest management rules are general silviculture possibilities. Management decisions are the owner decisions based on textbook management and Management actions are the implementation of the textbook management into the forest structure being modelling.*

The approach in Figure 1 contemplates only some of the aspects that can influence the different agents’ behaviours. In this schema, the forest model only takes into consideration the biophysical aspects of a forest stand and the related management objectives. Such an approach assumes rational decision-making by implementing management practices which maximize an expected utility function corresponding to their management objective (Bernoulli, 1954; Groeneveld et al., 2017). In this way, the approach illustrated in Figure 1 ignores the complex social scenarios in which forest management decisions are made. In other words, while the approach shown in Figure 1 may be useful to look at the effects of specific management actions, it ignores the overall complexity of reality. For example, Schelhaas et al. (2018a) concluded that textbook management does not exist within Europe. Socio-economic conditions are generally not incorporated in existing forest models, or only to a limited extent.

Therefore, the objective of this report was to improve the representation of behaviour and behavioural change of forest owners and managers in biophysical forest models to provide better decision support. This was done at regional level in Bulgaria, Germany, Spain and Sweden, as well as at a national level across the EU-27.

An approach to improve the representation of behaviour and behavioural change in BIOCONSENT is shown in Figure 2. Multiple factors influence management decision-making of agents, including information from scenarios (e.g., assumptions on market, policy, public opinion, etc.), the products and services provided by the forest, as well as the structure of the forests. An agent would select actions from (pre-defined) forest management interventions to apply to their forest, while taking into consideration the behavioural-defining factors. Therefore, an important development in the models is a module to decide which management option or alternative to select, depending on scenarios specifications, forest structure and agent type.

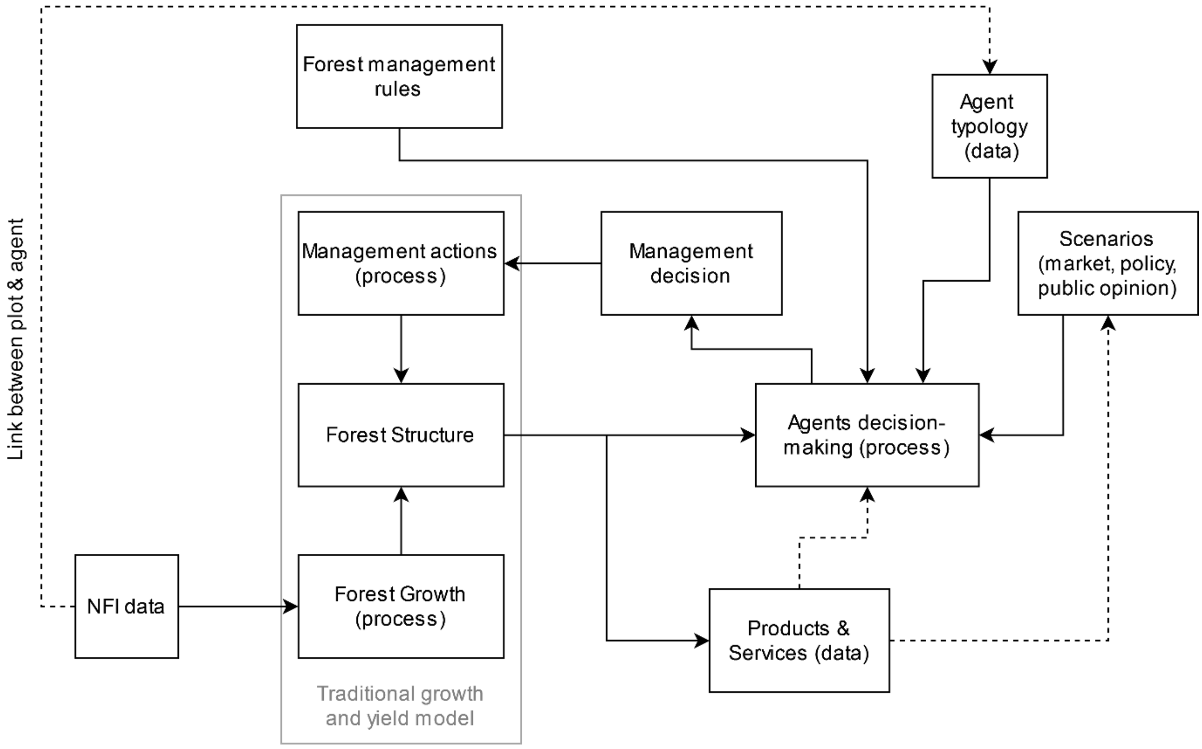



*Figure 2. Proposed approach for including forest management behaviour and behavioural change in forest models.*

In this first step of the work, focus was given on improving the representation of agent behaviour in forest management models. In the approach developed in BIOCONSENT, the agent typology and their decisions were defined by the results of a survey conducted by Sotirov et al. (2025). The survey assessing forest characteristics, management, and socio-economic factors, that affect forest management, was carried out in each case study regions (Table 1).

*Table 1. Multi-level case study research design in BIOCONSENT.*

| National scale | Subnational scale | Regional (Landscape and forest stand scale) |
|---|---|---|
| Bulgaria | Yundola and Teteven | Mixed (spruce, fir, pine, beech) forests in Rila-Rhodope high mountains and beech forests in the Balkan high mountains; forest use for timber, bioenergy, biodiversity (Natura 2000), drinking water (WFD); old growth forests; restoration needs after climate change impacts. |
| Germany | Baden-Württemberg (Southwestern Germany) | Mixed (douglas fir, spruce, beech) forests in the Back Forest low mountains and lowlands riparian deciduous (oak, beech, hornbeam) forests along the Rhine river; active forest use for timber, biodiversity (Natura 2000 sites), drinking water (WFD) and recreation; restoration needs after climate change impacts (storms; bark beetle). |
| | North Rhine-Westphalia (Western Germany) | Low mountain spruce forests and lowlands riparian deciduous (oak, beech) forests along the Rhine River; very active forest use for timber, biodiversity (Natura 2000), drinking water and recreation; severe restoration needs after climate change impacts (storms, bark beetle). |
| Spain | Catalonia | Pine forests in central Catalonia in mountains and lowland; little active forest use for timber, but important services such water (WFD), biodiversity (Natura 2000), noon wood forest products and recreation; restoration needs after climate change driven drought and wildfires. |
| Sweden | Norrbotten County | Spruce and pine dominated forests in lowland and mountainous areas; intensively used for timber production but also including protected (nature reserves; Natura 2000) and non-protected old growth forests with high conservation/biodiversity values. Also, recreation, non-wood products, reindeer pastures and cultural values. Restoration needs exist in intensively used forest areas. |

Among the survey questions, two of them that related to forest management objectives and decision-making principles were used to categorize forest owners and managers, through hierarchical clustering, into four different agent types. Further details on the survey and the agent typology methodology and results, including agent typology descriptions, are given by Sotirov et al. (2025).

Based on the survey's results and proposed approach to improve agent's behaviour representation in models (Figure 2), forest management and change in forest management are generally described in the form of these set of equations:

*Equation 1*

$$current\_forest\_management = f(forest\_structure, agent\_type)$$

*Equation 2*

$$change\_forest\_management = f(current\_forest\_management, forest\_structure, agent\_type)$$

Where forest structure is the variables, gather in the survey, that described the characteristics of forest stands, such as the age structure, the species diversity (mono or multiple species stand), as well as the dominant, second and third species present on the stand. Agent typology, as mentioned previously, is the result of a hierarchical clustering exercise considering the forest management objectives and decision-making principles questions from the survey. The forest management is set of activities encompassing different practices along a forest stand rotation, the different practices options covered by the BIOCONSENT project are shown in the Definitions chapter of this report on Table 27. However, each case study has adapted these general equations according to their dataset and chosen methodologies.

In summary, based on the survey results, each case study-specific algorithm (e.g., regression model, machine learning technique) was developed to predict the behaviour of distinct agent types, being adjustable to be implemented on different scenarios. In the proposed approach, the socio-economic factors serve as lever for defining the reaction of forest agents to different policy and socioeconomic scenarios (defined in WP1 and WP2). With the understanding of the behavioural change specifications, BIOCONSENT will include human agency and behavioural change in forest models, quantifying scenario outcomes on regional and EU levels, through interpreting and upscaling techniques.

The methodologies and results from each case study, focusing on enhancing the representation of behaviour and behavioural change of forest owners and conservation managers in forest models, are detailed in their respective chapters throughout this document. Furthermore, different forest models are used in each case study: SIBYLA in Bulgaria, EFISCEN-space in Germany, FORMES in Spain and, Heureka in Sweden, as well as the G4M+FLAM used across the EU-27. Table 2 provides a summary of these models and detailed descriptions of the developments are given in chapters 3-6. No results are available for the Bulgarian case study.

*Table 2. Overview of models used in BIOCONSENT.*

| | **Sweden** | **Germany** | **Spain** | **Bulgaria** | **EU** |
|---|---|---|---|---|---|
| **Model used** | HEUREKA | EFISCEN-space | FORMES | SYBILLA | G4M + FLAM |
| **Reference** | Lämås et al. 2023 | Schelhaas et al. 2022 | Trasobares et al. 2022 | - | Kindermann et al. 2013 |
| **Spatial coverage** | Regional, Norrbotten County | Grid / regional, Baden Wuerttemberg and North Rhein Westphalia | Regional, Catalonia | Yundola: coniferous mountain forests Teteven: mixed broadleaved | Grid, EU-27 |
| **Temporal coverage** | ~2020-2120 (or shorter) | ~2020-2050 | 2020-2050 | 2020-2050 | ~2020-2050 |
| **Biodiversity indicators and ecosystem service indicators quantified** | • growing stock<br>• wood removals<br>• carbon stocks and storage | • growing stock<br>• wood removals<br>• carbon stocks and storage<br>• Tree microhabitats | • growing stock<br>• wood removals<br>• carbon stocks and storage | • growing stock<br>• wood removals<br>• carbon stocks and storage<br>• age structure<br>• deadwood and litter<br>• water availability | • growing stock<br>• wood removals<br>• carbon stocks and storage<br>• burned areas (wildfire) |

# 3. Germany

## 3.1. EFISCEN-space model description

EFISCEN-Space (Schelhaas et al. 2022) is a spatially explicit simulation model for understanding forest development in Europe under climate and management scenarios. The model relies on tree-wise plot data from forest inventories. Projections are driven by environmental conditions and forest management. EFISCEN-Space is modular, such that depending on the aim of the application and resources available, modules can operate on different levels of detail or can be excluded if not relevant. EFISCEN-Space is intended to be used for regional to European scale studies on the development of forest resources and the delivery of ecosystem services.

Within the model, forest development is modelled at the level of individual plots with a known (or approximate) location and results are scaled to a 1-ha stand. The state of this stand at any moment in time is expressed as the distribution of the number of trees over diameter classes, per species or species group. The model includes tree growth, tree mortality, tree ingrowth and decomposition in soils, and the management processes tree harvesting and tree species selection. Diameter increment (Schelhaas et al. 2018b) is modelled as the transition of trees to a higher diameter class. Mortality (Pugh et al. 2024) and harvesting (Filipek et al. 2025) are modelled as the removal of trees from specific diameter classes. Ingrowth (König et al. 2022) is modelled as the increase in stem number in specific diameter classes (ingrowth/planting). Intensity and frequency of harvesting activities are derived from repeated measurements from the 2nd and 3rd Bundeswaldinventur (Filipek et al. 2025). Within BIOCONSENT, EFISCEN-space is initialised for Baden Wuerttemberg and North Rhein Westphalia based on the 3rd Bundeswaldinventur (Thünen-Institut, 2012).

## 3.2. Agent typologies, behaviour and management in EFISCEN-space

The approach used to include behaviour and behavioural change in EFISCEN-space is shown in Figure 3 and consisted of three main activities. Firstly, we investigated the correlation between agent typologies and socio-economic aspects, in an effort to predict behavioural change. Secondly, we developed models to predict the current forest management and possible changes in these activities. Thirdly and finally, we developed a model to allocate agent typologies across the forest landscape for the two German regions. Together, these activities resulted in the stepstones to predict forest management change under alternative socio-economic scenarios.

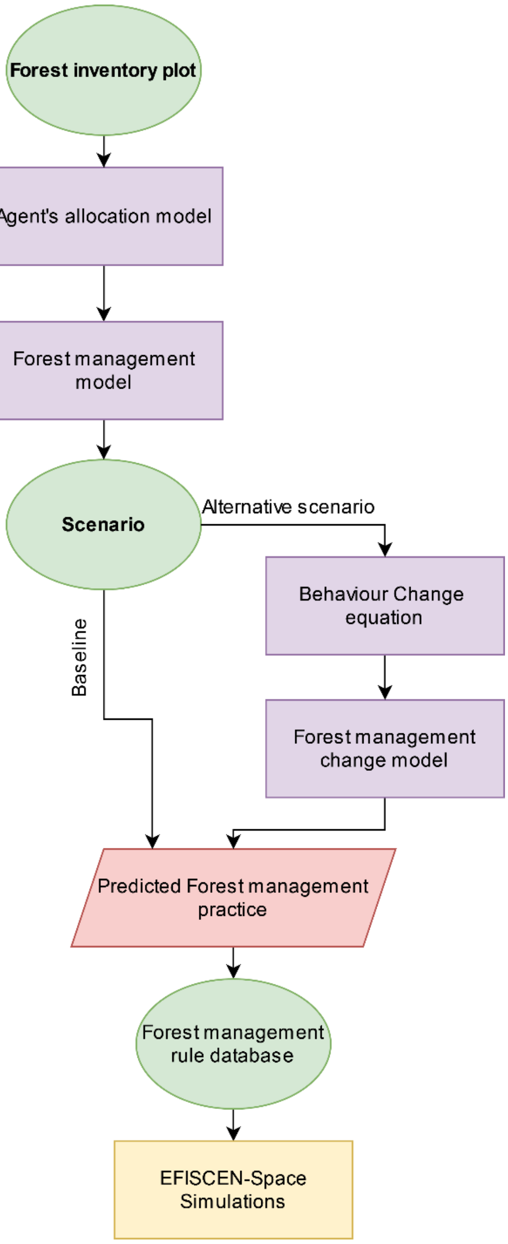



*Figure 3. Process flow diagram for the German case-study.*

As mentioned previously, the WP2 survey has collected data on real forest owners and managers' forest characteristics, management, and socio-economic factors for Baden-Wuerttemberg and North Rhein-Westphalia. The data gathered in this survey was the basis for the development of the main activities within the effort of improving the representation of behaviour and behavioural change in EFISCEN-space. Figure 4 presents a summary scheme of how the different questions were used throughout the activities.

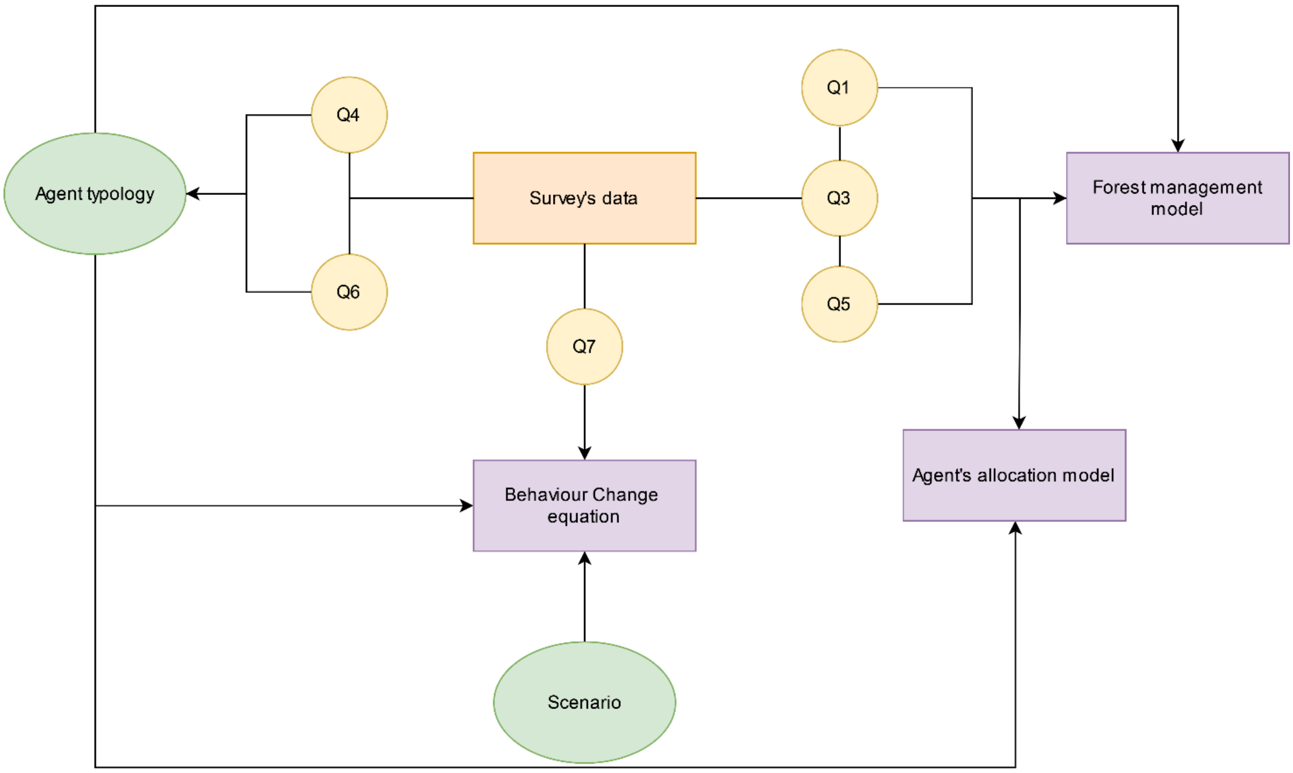



*Figure 4. Survey's questions used for the German case-study, where Qn represents the corresponding survey question.*

The survey collected a total of 232 valid responses for these two German regions, the responses were considered valid when the questions 1, 3, 4, 5, 6 and 7 were fully answered by the survey respondents and an agent typology could be assigned. As shown in Figure 4, among the survey questions, two of them that related to forest management objectives (Question 4) and decision-making principles (Question 6) were used by WP2 to categorize forest owners and managers. Four agent typologies were identified among the surveyed forest owners and managers, which were labelled as: Multi-functionalists (43%), Optimizers (31%), Traditionalists (19%), and Environmentalists (7%). According to the theorical framework by Sotirov et al. (2019), two other typologies (Passives, Maximisers) could be theoretically present, but they could not be identified from the survey results. Further details on the survey and the agent typology methodology and results, including agent typology descriptions, are given by Sotirov et al. (2025).

According to Sotirov et al. (2025), the agent typology encompasses behaviour characteristics that are crucial to determining decision-making. Therefore, we utilized the identified agent typologies in addition to other sections of the survey dataset to analyse the decision-making behaviour involved in forest management activities, as described in sections 3.2 and 3.3.

### 3.2.1. Factors that shape the current behaviour of owners and managers and their willingness to change

To assess the impact of socio-economic factors on forest management decisions, the distributed survey included a targeted question addressing this aspect. Question 7, assed the influence of 26 different socio-economic factor by order of importance for making a management decision (see Annex). Table 3 shows the top 10 most important socio-economic factors, identified as independent values among the different agent's typologies, that currently shape management in the German case study, according to the survey results. According to the survey results, all ecological factors were highlighted as important drivers in decision-making processes for forest management. Additionally, economic-related factors, such as items 7 and 8, along with item 5 were also recognized as critical by forest owners and managers. Among the social category factor items 13, 14 and 15 were highlighted as being important for influencing management decisions.

*Table 3. Top 10 most important factors that currently shape management in the German case study.*

| Socio-economic factors | Category |
|---|---|
| Item 5: Economic instruments (subsidies, compensation payments, taxes) | Policy |
| Item 6: Informational instruments (advisory services, knowledge, research, know-how transfer) | Policy |
| Item 7: Forest management costs and revenues | Economic |
| Item 8: Timber prices | Economic |
| Item 13: Forest property structure (property size and fragmentation) | Social |
| Item 14: My values, objectives, knowledge and experiences | Social |
| Item 15: Generational shift on my property and/or my management organisation) | Social |
| Item 19: Technologies and innovations in forest management (e.g., digitalisation, timber harvesting, tree breeding, planting) | Technological |
| Item 22: Availability of labour (e.g., labour forces) | Technological |
| Item 23: Silvicultural state of forest (e.g. age classes, productivity, forest growth, bio-physical conditions) | Ecological |
| Item 24: Health status of forest (e.g., disturbances and/or damages after drought, storm, fire, insects and pathogens) | Ecological |
| Item 25: Ecological and biodiversity status of forest (e.g., ecological processes, favourable or non-favourable conservation status, functionality and connectivity of the forest ecosystem) | Ecological |
| Item 26: Climate change impacts (e.g., tree distribution shifts, forest growth shifts) | Ecological |

To better understand the implications of grouping forest owners and managers based on their decision-making principles and forest objectives we explored the relationship between socio-economic variables (Question 7) and the determined agent's typology. We conducted an analysis to assess meaningful differences or identifiable patterns among the agent's group and the assessed socio-economic factors (i.e. policy, economic, social, technological and ecological factors).

First, the variance between each socio-economic factors gathered through Question 7, which was composed by 26 items in total, and the agent typology data was analysed through the Kruskal-Wallis test. The variance analysis test indicated a significant difference among most of socio-economic factors (16 out of 26), which includes policy, economic, social, technological, and environmental aspects, when compared between the agent typologies. To have a better understanding of these significant differences and the relationship between agents, the post-hoc Dunn's test was performed where significant differences were previously found. However, due to the large number of socio-economic variables considered in the survey, no clear conclusions were possible to be drawn from this analysis (Table 4). As a result, aiming to capture the variability of the observed data and illustrate better the socio-economic factors in fewer variables, a Factor analysis was conducted. Unfortunately, possibly due to the data distribution and the design of the survey questions, which were not originally planned for Factor analysis, the results of this effort did not yield significant results.

*Table 4. Results of the Kruskal-Wallis test and Dunn test pairwise comparisons.*

| **Factor** | **p-value (1)** | **Significance of differences obtained from the Dunn test pairwise comparison between each pair of agent types (2)** | | | | | |
|---|---|---|---|---|---|---|---|
| | | **ENVI-TRAD** | **ENVI-MULTI** | **ENVI-OPTI** | **TRAD-MULTI** | **TRAD-OPTI** | **MULTI-OPTI** |
| Regulatory forestry policy | 0.0000 | | * | | *** | *** | |
| Regulatory biodiversity policy | 0.0000 | | * | | *** | * | * |
| Regulatory climate policy | 0.0002 | | * | | *** | | |
| Regulatory water policy | 0.0002 | | | | *** | * | |
| Economic instruments | 0.0022 | | | | | *** | |
| Informational instruments | 0.0127 | | | | * | * | |
| Forest management costs and revenues | 0.0027 | | | ** | | * | |
| Timber prices | 0.0023 | | | ** | | | |
| Energy wood prices | 0.0379 | | | | | | |
| Requirements set by forest management certification standards | 0.0025 | | | | ** | * | |
| Market demand for certified forest products | 0.0124 | | | | | | * |
| My values, objectives, knowledge and experiences | 0.0445 | | | | | | |
| Media and social pressure | 0.0002 | | * | | ** | | |
| Technologies and innovations in forest-based industries | 0.0056 | | * | * | | | |
| Availability of labour | 0.0023 | | | * | | * | |
| Ecological and biodiversity status of forest | 0.0480 | | | | * | | |

(1) P-value obtained from the Kruskal-Wallis test on all four categories
(2) Dunn test results. P-value < 0.001, ***; < 0.01, **; < 0.05, *; > 0.05, ns

Therefore, no definitive conclusion could be drawn from this analysis, which aimed to assess the relevance of the agent typology classification in determining the influence that various socio-economic aspects have on forest management behaviour. One of the possible reasons for this is that the agent typology is not solely based on decision-making principles (Question 6), but also incorporate forest objectives (Question 4), making the comparison between this classification system and the socio-economic influence less straightforward.

### 3.2.2. Behaviour change equation

Considering the statistical limitations of the dataset, where nonspecific patterns were observed among the relationship of different agents to socio-economic factors, we applied a probabilistic approach instead. In this approach the 26 socio-economic related items gathered in the survey are individually used to estimate how much a forest manager, belonging to a specific agent type, would be influenced to change by different sets of socio-economic aspects.

To capture changes in behaviour by forest owners and managers, we parameterized an equation using a combined probability distribution. The parameterization was based on the survey's average replies, by agent typology, to the stated importance of each socio-economic items to forest management decision (see Annex – Question 7). Equation 3 determines the probability that an agent, belonging to a certain typology group, decides to implement changes in their forest management according to socio-economic conditions, which will be determined by policy driver scenarios.

To apply the values gathered in the survey in the Equation 3, we converted the stated importance of each socio-economic factor from a Likert scale (1 - not important at all; 3 – neutral; 5 - very important) to a linear probability scale, where 1 equals to 0% and 5, to 100%.

*Equation 3*

$$P(Change \mid Importance_1 \cup Importance_2 \ldots \cup Importance_{n-1}) = 1 - \prod_{i=1}^{n-1} 1 - P(Change \mid Importance_i)$$

Each future scenario incorporates a different combination of socio-economic factors. Table 5 provides an example of the method applied to the fictional scenario "Foo", which encompasses socio-economic factors Item 1 (i.e., Regulatory forestry policy) and Item 8 (i.e., Timber prices).

*Table 5. Example of behaviour change prediction according to scenario "Foo".*

| Agent type | Mean $Importance_1$ | Mean $Importance_8$ | Probability of change |
|---|---|---|---|
| Multi-functionalists | 3.63 (65%) | 4.22 (80%) | 93% |
| Optimizers | 3.31 (57%) | 4.47 (86%) | 94% |
| Traditionalists | 2.63 (40%) | 4.15 (78%) | 87% |
| Environmentalists | 2.81 (45%) | 3.56 (74%) | 80% |

The application would be done per plot, where after estimating the probability of an agent changing in a certain future scenario, a random number will be drawn, between 0 and 100%. In case this number falls within the probability obtained by Equation 3, it indicates that a change would be made, and the relevant forest management model will be applied in that plot. A sufficiently large number of plots would ensure the expected number of changes is preserved.

### 3.2.3. Forest management decision model

By observing the proportion that each agent typology indicated concerning their different management activities through the survey, it is possible to notice an overall similarity among the proportion of agents for each current practice category (Table 6). However, a notable exception is observed in current cutting methods, while most agents prefer Single-tree selection (75% or higher), the Environmental typology distinctly favored Group selection (88%). Regarding thinning methods, most of the agent's indicated that they perform mostly either thinning from above or from all size classes. Among the environmentalist, no one has selected thinning from below, and also this group had the highest proportion on no thinning practices (12%), when compared to the others. In addition to that, the environmentalist was also the only group that hasn't indicated that they would perform a shift to coniferous dominated forest, on the species selection practice category.

Regarding regeneration methods, none of the agents had indicated coppicing, as their current regeneration practice. The minority of the proportions, among the different agents, had indicated to perform planting with regular material, while most of them rely on natural regeneration of enrichment planting. Concerning biodiversity management, most of the proportions were distributed along increasing deadwood and tree size diversity in the stand. The multi-functionalists and the traditionalist had a small adherence to setting aside forest (2%), while Optimizers were omitted on that practice, and the Environmentalists had the biggest adherence (25%). Compared to the other agents, the traditionalists, had the biggest proportion on the none applying specific biodiversity management techniques.

Finally, regarding post-disturbance management, the most common practices for all categories was to do salvage logging with planting or with natural regeneration. Optimizers were the only group that indicated that do not leave wood on the disturbed areas, while Environmentalists were the only group to indicate (6%) that do not perform post-disturbance management.

*Table 6. Current management practices per typology (%) in the German case-study. MULTI represents Multifunctionalists, OPTI represents Optimizers and ENVI represents Environmentalists.*

| Current practices | | MULTI n=100 | OPTI n=72 | TRAD n=44 | ENVI n=16 | ALL n=232 |
|---|---|---|---|---|---|---|
| Cutting method | A. Clear felling | - | 10% | 2% | 6% | 4% |
| | B. Group selection | 18% | 15% | 23% | 88% | 17% |
| | C. Single tree selection | 81% | 75% | 75% | 6% | 78% |
| | D. No cutting | 1% | - | - | - | 1% |
| Thinning regime | A. Thinning from above | 54% | 47% | 27% | 31% | 45% |
| | B. Thinning from below | 6% | 4% | 2% | - | 4% |
| | C. Thinning from all size classes | 38% | 46% | 64% | 56% | 47% |
| | D. No thinning | 2% | 3% | 7% | 12% | 4% |
| Species selection | A. Maintain current composition | 6% | 15% | 18% | 12% | 12% |
| | B. Shift to broadleaves dominated forest | 39% | 21% | 11% | 19% | 27% |
| | C. Shift to conifers dominated forest | 2% | 7% | 7% | - | 4% |
| | D. Shift to mix species forest | 52% | 53% | 48% | 62% | 52% |
| | E. Use of non-native tree species | 1% | 4% | 16% | 6% | 5% |
| Regeneration method | A. Planting with regular planting material | 1% | - | 2% | 6% | 1% |
| | B. Planting with material obtained from tree breeding | 17% | 25% | 25% | 12% | 21% |
| | C. Enrichment planting | 50% | 49% | 32% | 50% | 46% |
| | D. Natural regeneration | 32% | 26% | 41% | 31% | 32% |
| | E. Coppice | - | - | - | - | - |
| Biodiversity management | A. Set aside forest, with no active management | 2% | - | 2% | 25% | 3% |
| | B. Increasing deadwood and microhabitats | 48% | 36% | 32% | 31% | 40% |
| | C. Increase diversity in tree sizes | 49% | 58% | 48% | 44% | 51% |
| | D. None | 1% | 6% | 18% | - | 6% |

| Current practices | | MULTI n=100 | OPTI n=72 | TRAD n=44 | ENVI n=16 | ALL n=232 |
|---|---|---|---|---|---|---|
| Post-disturbance management | A. Salvage logging with planting | 62% | 57% | 66% | 38% | 59% |
| | B. Salvage logging with natural regeneration | 36% | 43% | 32% | 50% | 38% |
| | C. Leaving all wood with natural regeneration on the forest area affected by disturbances | 2% | - | 2% | 6% | 1% |
| | D. No post-disturbance management | - | - | - | 6% | 1% |

Therefore, although there were some differences among the agent typologies, most of the proportions of agent's current management practices had overall similarity distribution among the options presented in the survey.

To better represent the forest management activities applied in the Baden-Wuertemberg and North Rhein-Westphalia by different forest owners and managers, we developed a forest management decision model. The forest management decision model predicts (i) the current forest management and (ii) how management would change, once an agent is triggered to change management. These models can predict which management activities (Table 27) will be implemented in a plot, while frequencies, intensities and other features regarding these activities are likely to be determined through a combination of repeated forest inventory observations, management prescription guidelines, or expert input.

The initial step in developing the forest management decision model involved identifying which variables from the survey data could be utilized for this purpose. Therefore, to understand better the collected data and which variables would be used as input for training the model, a Pearson's Chi-square correlation test was performed at a significance level of 0.05 to assess the correlation between the categorical variables related to forest characteristics, ownership and agent typology (Table 7).

*Table 7. Results of the Chi-square correlation test.*

| | Agent | Age-structure | Biodiversity | Cutting | Disturbances | Dominant spp. | Mono/Multi spp. | Ownership | Second spp. | Spp. selection | Thinning | Third spp. |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Agent | - | 0.04 | 0.00 | 0.01 | 0.07 | 0.00 | 0.26 | 0.00 | 0.00 | 0.00 | 0.05 | 0.25 |
| Age-structure | 0.04 | - | 0.22 | 0.11 | 0.01 | 0.11 | 0.00 | 0.08 | 0.95 | 0.06 | 0.62 | 0.85 |
| Biodiversity | 0.00 | 0.22 | - | 0.04 | 0.00 | 0.00 | 0.72 | 0.05 | 0.00 | 0.35 | 0.00 | 0.00 |
| Cutting | 0.01 | 0.11 | 0.04 | - | 0.00 | 0.00 | 0.00 | 0.01 | 0.00 | 0.62 | 0.00 | 0.41 |
| Disturbance | 0.07 | 0.01 | 0.00 | 0.00 | - | 0.00 | 0.26 | 0.55 | 0.00 | 0.30 | 0.00 | 0.00 |
| Dominant spp. | 0.00 | 0.11 | 0.00 | 0.00 | 0.00 | - | 0.22 | 0.20 | 0.00 | 0.00 | 0.00 | 0.00 |
| Mono/Multi spp. | 0.26 | 0.00 | 0.72 | 0.00 | 0.26 | 0.22 | - | 0.03 | 0.57 | 0.43 | 0.80 | 0.54 |
| Ownership | 0.00 | 0.08 | 0.05 | 0.01 | 0.55 | 0.20 | 0.03 | - | 0.61 | 0.02 | 0.03 | 0.20 |
| Second spp. | 0.00 | 0.95 | 0.00 | 0.00 | 0.00 | 0.00 | 0.57 | 0.61 | - | 0.10 | 0.03 | 0.00 |
| Spp. selection | 0.00 | 0.06 | 0.35 | 0.62 | 0.30 | 0.00 | 0.43 | 0.02 | 0.10 | - | 0.07 | 0.07 |
| Thinning | 0.05 | 0.62 | 0.00 | 0.00 | 0.00 | 0.00 | 0.80 | 0.03 | 0.03 | 0.07 | - | 0.07 |
| Third spp. | 0.25 | 0.85 | 0.00 | 0.41 | 0.00 | 0.00 | 0.54 | 0.20 | 0.00 | 0.07 | 0.07 | - |

Where:

Forest owner classification variables

Forest structure variables

Forest management variables

Correlation found (at significance level 0.05)

According to the results shown in Table 7, it is possible to observe that many correlations were found among the different variables. The agent typology variable, developed by Sotirov et al. (2025) was correlated with diverse forest structure and managements variables, therefore being a good candidate for being used as a forest management predictive variable. As expected, many forests structural variables were correlated to management variables. In particular, dominant species were correlated to all of the forest management variables. The second species most frequent in the stand also correlated to the forest management variables, expected by the species selection management activities. The age-structure variable, although theoretically important to predict management, has only correlated with post-disturbance management activities. However, it is important to note that the data was not evenly distributed and arguably not independent, as some variables may be potentially linked.

According to the Chi-square test, forest ownerships type was also correlated to management variables, that is why the Equation 1 and Equation 2 were adjusted for the German case studies, by including forest ownership type as a predictor for forest management activities, as shown on the following equations.

*Equation 4*

$$current\_forest\_management = f(forest\_structure, agent\_type, ownership\_type)$$

*Equation 5*

$$change\_forest\_management = f(current\_forest\_management, forest\_structure, agent\_type, ownership\_type)$$

In these equations, forest structure comprise the variables included in the survey that describe the characteristics of forest stands, such as the age structure, the species diversity (mono or multiple species stand), as well as the dominant, second and third species present in the stand. Agent typology is the result of the classification work described in Sotirov et al. (2025). The forest management is set of activities encompassing different practices along a forest stand rotation, described in the Definitions chapter (see Table 27). The ownership type refers to the categorization of forests based on the entity that holds its legal ownership, such as private individuals, corporations, communal groups, or governmental organizations. Therefore, 7 variables were considered in Equation 4 and 12 in Equation 5.

### Current forest management

Following Equation 4, different machine learning techniques such as, Random Forest, Support Vector Machine, Gradient Boosting Classifier were calibrated and tested. Among these techniques, Random Forest provided the most accurate overall results and was therefore selected as the classifier technique for the management model. The literature indicates that decision-tree-based methods, such as Random Forests, are recommended classifiers for categorical data, as they can perform categorical predictions without requiring preliminary transformation processes (Au, 2018). Taking as input forest characteristics, agent typology and, ownership type the model was evaluated using 5-fold cross-validation approach to predict forest management activities. The Random Forest features were set to have a maximum tree's depth of 16 and forest size of 64 trees, the Gini impurity was used as our goodness-of-split measure and since the data was unbalanced, the weights were adjusted based on proportions of class frequency of the input data. Since the variables to be predicted are categorical in nature.

As Random Forest models split data randomly and thereby produce slightly different results each time they are trained and evaluated, to minimize this randomness effect during the split and stabilised the results, the model accuracy was defined as the mean of 128 runs of the classifier. The results of the Random Forest showed that the models trained with the survey data can produce meaningful forest management predictions with 46-73% accuracy, depending on the management practise considered (Table 8).

*Table 8. Management practice model accuracy, where n is the number of options per management practice.*

| Management practice (n) | Accuracy |
|---|---|
| Cutting regime (4) | 73% |
| Thinning regime (4) | 48% |
| Regeneration type (5) | 48% |
| Species selection (5) | 46% |
| Biodiversity measure (4) | 49% |
| Post-disturbances measure (4) | 52% |

Alternative Random Forest models were also trained taking as input all possible combinations of the 7 input variables, resulting in different 127 models evaluated. The results of this effort showed that overall accuracy was mostly dependent on the tree species (with dominant tree species being most important and followed by third and second species) present in the forest. The agent typology had a general impact of only 2% in accuracy, which could indicate that forest owner and manager typologies had overall little effect on a management choice. Overall accuracy was the highest when all the input variables were included, therefore all the input variables were maintained in the model. This was also supported by the feature's importance for splitting decisions in the Random Forest (Figure 5).

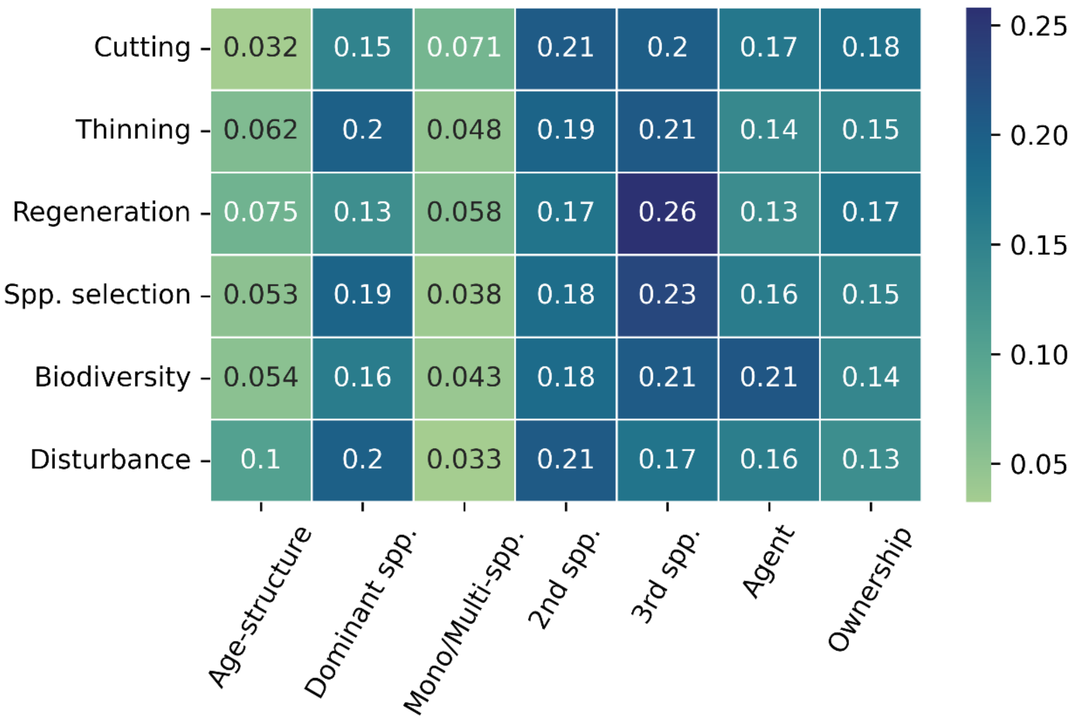



*Figure 5. Importance of features in a classification model by mean decrease in impurity.*

The features importance, measured as the mean decrease impurity, was defined as the total decrease in node impurity, according to the Gini impurity criterion, and weighted by the probability of samples reaching that node, averaged over all trees in the forest (Breiman et al., 1984). Figure 5 indicates that the most important variables used to predict the different management activities were dominant, second, and third species present in the forest, while the least important was Age-structure and Mono/Multi species variables. In contrast with the previous analysis where it was identified that the agent typology and ownership type had little effect on accuracy, in this analysis these variables were considered important to the decision criteria of the model.

**Forest management change**

Following Equation 5, the same approach was followed to predict changes in forest management practices, and we trained a Random Forest model with the survey data. Since the survey categorized changes in management into (i) improving biodiversity restoration and conservation, and (ii) adapting management to climate change impacts, two separate models were developed for each of these groups. Taking as input forest characteristics, agent typology, ownership type, and current management practices the models were also evaluated using a randomly split 5-fold cross-validation approach to predict changes in forest management activities. The Random Forest features were set to be the same as the one used for predicting current management practices. The results showed that the change in management models can produce more accurate predictions (Table 9) compared to predicting current management practices (Table 8). To minimize the effect of randomness during the split, the model accuracy was defined as the mean of 128 runs of the classifier and varied between and among themselves, according to the target management practice (Table 9).

*Table 9. Changes in management practice models accuracy, where n is the number of practices possibilities.*

| **Management practice (n)** | **Changes for Biodiversity (Accuracy)** | **Changes for Adaptation to Climate Chance (Accuracy)** |
|---|---|---|
| Cutting regime (4) | 88% | 81% |
| Thinning regime (4) | 84% | 80% |
| Regeneration type (5) | 57% | 59% |
| Species selection (5) | 77% | 66% |
| Biodiversity measure (4) | 70% | 75% |
| Post-disturbances measure (4) | 68% | 82% |

The three Random Forest models together are capable of predicting the current management activities, as well as the management in case of change towards improving biodiversity restoration and conservation and adapting management to climate change impacts. The accuracy considerably varied between the models and management practices, however, all of them scored clearly better than if attributed randomly. Consequently, the models were considered suitable for implementation in the subsequent parts of the study.

## 3.3. Spatializing agent typologies

To be able to apply the agent behaviour change equation and the Forest management decision model in EFISCEN-space, it is necessary to assign a typology to each inventory plot and to spatially allocate the agent typologies to the landscape. A Random Forest model was calibrated taking as input forest characteristics and ownership type from the survey data to predict agent typology. The model was evaluated using 5-fold cross-validation approach to predict agent typology. The Random Forest features were empirically set to have a maximum tree’s depth of 16 and forest size of 64 trees, and since the data was unbalanced, the weights were adjusted based on proportions of class frequency of the input data. To minimize the effect of randomness during the split, the model accuracy was defined as the mean of 128 runs of the classifier, was of around 43%. Considering that there are 4 different agents, this model accuracy shown to be better than randomly attributing agents to plots (i.e. 25% of accuracy). Then, we applied the Random Forest model to assign a typology to each forest inventory plot, using the plots' information on tree species and ownership, results can be observed in Figure 6 and Table 10.

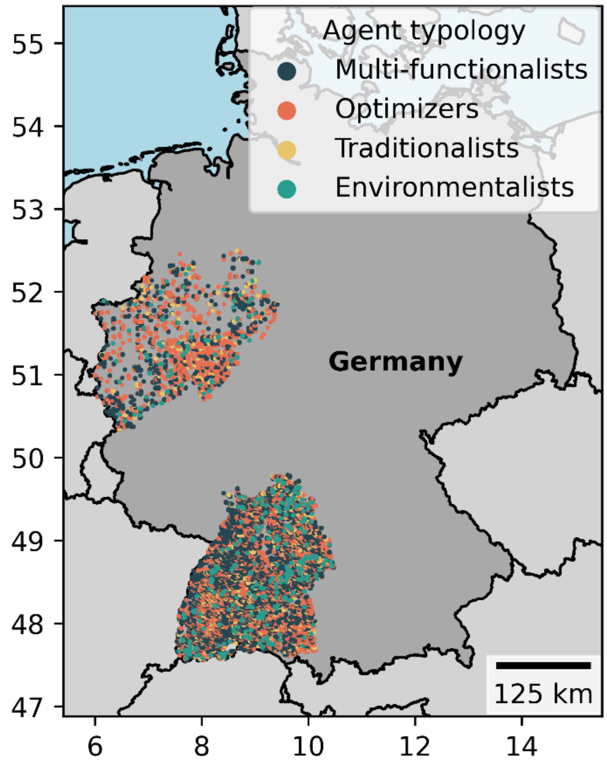



*Figure 6. Allocation of agent typologies in North Rhine-Westphalia and Baden-Württemberg.*

We collected NFI-plot information for Baden-Wuerttemberg and North Rhine-Westphalia based on the 3rd Bundeswaldinventur (Thünen-Institut, 2012). Firstly, the German NFI design was examine, since each plot is divided in 4 different tracts. The NFI measurements are taken from these 4 sub-plots, which are 150 meters apart from each other, arranged in a square shape. Analysing the NFI plot data, we were able to detect important differences between sub-plots, which were part of the same plot, referring to ownership type, dominant species and others. For that reason, we decided to consider each sub-plot as an individual plot, as it would not be straightforward to find some sort of average between these categorical variables that are the key to classify and allocate agent typology.

Observing Figure 6, it is possible to notice that North Rhine-Westphalia has considerable fewer plots (1,965) (here considered as each sub-plots of the region) when compared to Baden-Wuerttemberg (11,920), together totalizing valid 13,885 plots. A plot was considered invalid if it contained missing data for any of the forest characteristics or ownership type variables required as input for the allocation model.

Table 10. Proportion of different agent's typologies allocated in each focused region and the overall results.

| Agent type | North Rhine-Westphalia | Baden-Wurttemberg | Overall |
|---|---|---|---|
| Multi-functionalists | 41% | 52% | 50% |
| Optimizers | 42% | 33% | 35% |
| Traditionalists | 12% | 12% | 12% |
| Environmentalists | 5% | 3% | 3% |

Table 10 shows the proportion of different agent's typologies that were allocated by region and an overall results considering both regions together. The allocation model classified most of the plots as being part of the Multi-functionalist and Optimizers agent's typology, while traditionalist and especially environmentalists present a smaller proportion. A possible explanation for that can be due to the fact that similar unbalanced proportions were already present on the model's training data, where most of the data was initially classified as Multi-functionalist and Optimizers typologies. Since these data was collected through the survey, here that is taken as the observed proportion in the field, at least when following the methodology proposal by Sotirov et al. (2025) to classify agent's typologies.

## 3.4. Additional model developments

In addition to improving the representation of behaviour and behavioural change in forest models to better estimate biodiversity in forests, we developed a procedure to estimate the probability of tree microhabitats occurrence on EFISCEN-Space outputs. Tree-related microhabitats (TreM) are an important part of forest Biodiversity, as it provides crucial habitats and resources for a diverse array of species, including insects, fungi, birds, and small mammals (Larrieu, et al., 2018). Therefore, when assessing biodiversity, it is important that the presence of TreM to be considered in forest stands, as well as the impact of forest management activities on these structures.

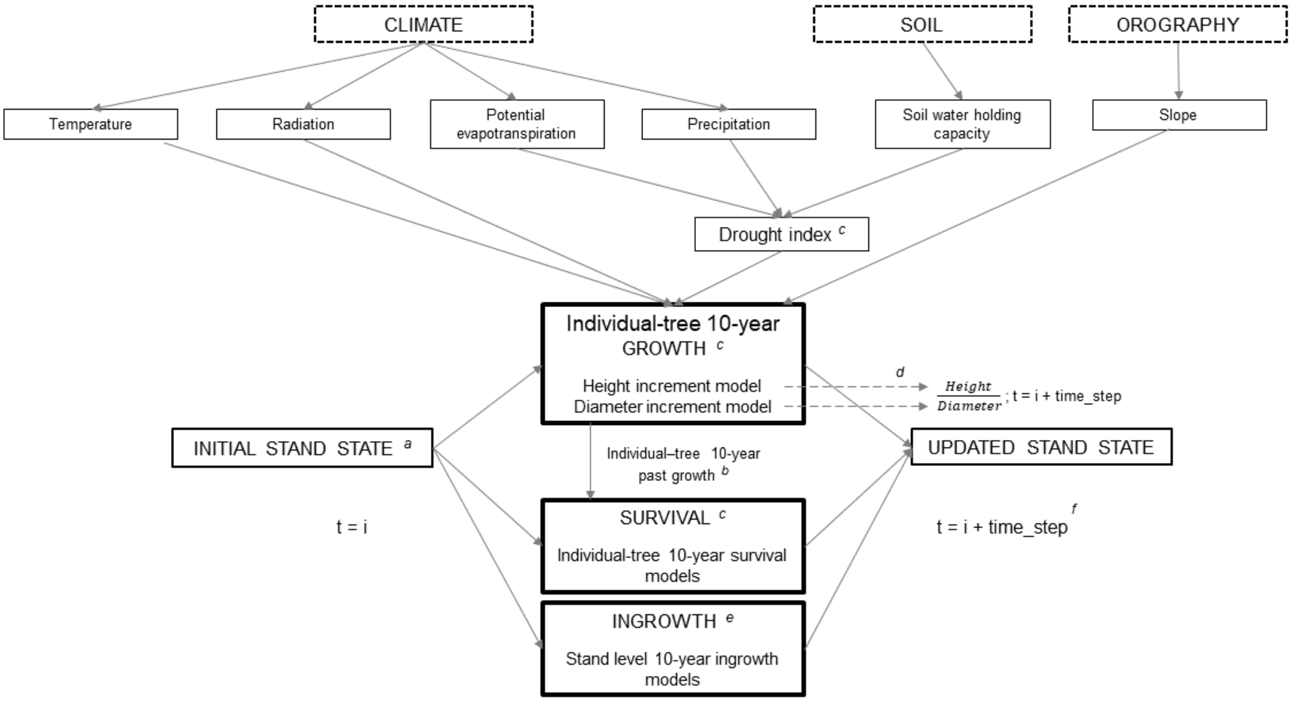
The inclusion of TreM in EFISCEN-Space's Forest simulations was based on the work of Courbaud et al. 2022, where the authors adjusted a Weibull probability density function for 11 different TreM groups for 19 different tree species groups present in Europe. The TreM contemplated in their work are: bark loss, woodpecker breeding cavity, rot holes, dendrotelm, root concavity, exposed heartwood, cracks, dead crown wood, burr and cankers, polypore and, sap run. Courbaud et al. (2022) model takes as input to predict the occurrence of TreM on a stand: the tree's species group, tree's diameter at breast height, and the occurrence of forest management in the stand. Since these variables are included in the outputs of EFISCEN-Space, we were able to directly apply the Courbaud et al. (2022) model.

# 4. Spain

## 4.1. FORMES model description

The FORMES projection system for multi-objective forest planning is a modular modelling framework that simulates forest dynamics under changing climatic conditions and forest management (Trasobares et al., 2022). It has been specially designed to understand and explore the medium and long-term effects of alternative forest management approaches, fire, and climate on forest structure and composition. The forest dynamics models included in FORMES allow the estimation of the variation of the live mass for a determined period/simulation scenario, and combined with other existing models, they also allow the prediction of other goods and services such as carbon sequestration, fire risk reduction, or water supply (De Cáceres et al., 2015; González et al., 2007; Roces-Díaz et al., 2018). To do so, FORMES includes a set of empirical, climate-sensitive, individual-tree, distance-independent models to simulate forest stands dynamics. Tree-level models consider individual trees as the basic unit for simulating growth, mortality, and ingrowth processes, which enables a more detailed and flexible description of stand structure, composition, and simulation of alternative management treatments than stand-level models. Distance-independent models operate assuming an average spatial pattern of individuals and have similar predictive performance than distance-dependent (which require explicit tree spatial coordinates) but are less computationally demanding than the latter. The forest management module included in FORMES allows to specify the levels of target timber (or wood demand) for each forest species at a provincial or national scale. It includes a series of species-level silvicultural prescriptions that are applied at the stand scale according to the stand dominant species or any other classification of the forest stands in different forest typologies. Thus, even if induvial-tree growth, mortality, and ingrowth models were developed at the species (or group of species) level it is then possible to customize silvicultural prescriptions for any forest typology classification or management units' schema to accurately capture the potential forest management applied to these forest typologies.

The set of empirical models incorporated in FORMES includes the simulation of diameter increment, height increment, total height, survival, local ingrowth, and ingrowth by colonization from the neighbourhood of the target stand with potentially new species (Figure 7). Likewise, the developed models include the possibility of estimating the incorporation of species initially absent in the target plot but present in neighbouring plots, in a similar way to landscape dynamics models (García-Valdés et al., 2013), which is relevant to consider the processes of forest diversification along time. These models allow the prediction of the development of tree communities in Spain for the tree species most abundant in the Spanish territory or in particular regions (like the Pinus canariensis in the Canary Islands). Thus, 11 separate target entities were considered, whereas less frequent species were grouped into 16 species groups according to taxonomic and functional criteria ending up in the following 27 tree species or group of species: *Pinus pinea*, *Pinus sylvestris*, *Pinus uncinata*, *Pinus pinaster*, *Pinus halepensis*, *Pinus nigra*, *Pinus canariensis*, *Pinus radiata*, *Abies/Picea/Pseudotsuga* spp., *Juniperus thurifera*, *Juniperus* spp., *Cupressus/Taxus* spp., other conifers, *Quercus ilex*, *Quercus suber*, *Quercus faginea*, *Quercus robur/petraea/rubra*, *Quercus pyrenaica/pubescens/canariensis*, *Populus/Platanus* spp., *Fraxinus/Salix* spp., *Eucalyptus* spp., *Erica arborea*, laurisilva, *Fagus sylvatica*, *Castanea sativa*, *Betula/Acer* spp., and other broadleaves.




[a] Diameter class distribution or diameter distribution of measured individual trees
[b] Used after the first 10-year simulation period
[c] Models based on tree size, competition, and environmental variables effects
[d] Independent height increment and diameter increment models allow calculating changes in stem height/diameter ratios
[e] Models based on competition and environmental variables. Used in uneven-aged stands/forestry. Height of ingrowth trees calculated using static height models
[f] If time_step < 10 years, height and diameter increments are linearly interpolated, and logistic probability of survival and ingrowth are re-calculated

*Figure 7. FORMES workflow.*

The individual-tree models included in FORMES have been calibrated and validated for these 27 main species and groups of species in Spain with data from the 2nd, 3rd, and 4th Spanish National Forest Inventories (NFI2, NFI3, NFI4, respectively). For each of the two periods NFI2-NFI3 and NFI3-NFI4, we selected permanent forest plots with at least 10% of forest cover and presence of trees with a DBH larger than 7.5 cm in the final survey, and with geographic coordinates determined at < 100 m of precision. These criteria resulted in 50,359 and 21,987 plots selected for the NFI2-NFI3 and NFI3-NFI4 periods, respectively, entailing a total of 72,346 re-sampled forest plots, and 838,620 and 514,460 tree measurements, for the same periods respectively. The lower number of plots for the second period is explained by the fact that the NFI4 is not finished for all the Spanish provinces. We considered three types of explanatory variables. Namely, factors related to tree-size and vitality, descriptors of forest structure and competition, and site-quality indicators to assess the overall growth conditions.

The forest management module included in FORMES allows to specify the levels of target timber (or wood demand) for each forest species at a provincial or national scale. It includes a series of species-level silvicultural prescriptions that are applied at the stand scale according to the stand dominant species or any other classification of the forest stands in different forest typologies such as those defined according to the forest owner typologies derived from the survey. Thus, even if individual-tree growth, mortality, and ingrowth models were developed at the species (or group of species) level it is then possible to customize silvicultural prescriptions for any forest typology classification to accurately capture the potential forest management applied to these forest typologies. Being forest dynamics based on individual-tree models allows a detailed description of the stand structure and its dynamics, which confers flexibility for simulating all sort of sylvicultural treatments for both even- and uneven-aged stands, and pure and mixed stands. The combination of different timber harvesting levels, variations in the silvicultural prescriptions (such as the rotation period or the mean DBH for final cuts) allow the simulation of possible management alternatives at the local scale. Specifically, silvicultural treatments are defined by:

- Types of thinning/cutting. Four types are considered: intermediate (same proportion of trees by diameter class are removed), below-intermediate (more proportion of trees of lower diameter class are removed), above-intermediate (more proportion of trees of higher diameter class are removed), and selection cutting (different proportion of trees are removed depending on the diameter class).
- Minimum basal area when thinning is implemented (related to the periodicity of thinning application).
- Percentage of basal area to be removed during thinning (related to the intensity of thinning).
- Target diameter or rotation period in even-aged management, that is the mean DBH of forest stand when regeneration cutting starts.
- Percentage of BA to remove in regeneration cutting (shelterwood method) and period (years) involved in regeneration cutting.
- Maintenance of retention trees in final cutting.

## 4.2. Agent typologies, behaviour and management in FORMES

### 4.2.1. Classification of forest owners' and their characterization

Four agent types based on the survey to forest owners' analysis (n=315) were defined. The main criteria to define those categories have been: i) the given importance of different forest functions/aims; and ii) the given weight to different decision-making rationalities. This analysis resulted in four categories, labelled as following: multifunctionalists (MULTI, 38.1%), optimizers (OPTI, 19.4%), traditionalists (TRAD, 22.7%) and environmentalists (ENVI, 19.8%). We did not find any maximisers in our sample. One plausible explanation could be found in the attributes of Mediterranean forests – with lower productivity than forests in other European regions, and hence offer limited opportunities to market forest products. Instead, traditionalists appear in this context as a typology that only seeks to cover their own needs of fuel and wood consumption from the forest. They generally assign low importance to forest functions, except for the provision of fuel wood. Their decision-making is guided mainly by personal values and beliefs, financial benefits, and professional knowledge, with less consideration given to social pressure. The optimizers appearing are the ones that seed to enhance the productivity of the forests even though the economic opportunities in the Mediterranean sector might differ substantially from the ones in other European forests.

*Table 11. Summary of main features by identified category in Catalonia.*

| | | 1 MULTI | 2 ENVI | 3 OPTI | 4 TRAD |
|---|---|---|---|---|---|
| | | **Multi functionalists** Integral approach Professional knowledge | **Environmentalists** Nature protection Biodiversity conservation | **Optimizers** Conventional forestry | **Traditionalists** Family based Live close to the forest |
| **N** | | **94** | **49** | **48** | **56** |
| **Forest functions** | | High importance of all forest functions. | High importance of biodiversity conservation and related functions. | Higher importance of functions related to provision of fuel wood, biodiversity conservation and related functions. | Low importance of all forest functions, except for provision of wood. |
| **Decision-making principles** | | Integrate own values and beliefs, professional knowledge, financial benefits and regulations. | Mainly own values and beliefs, secondly professional knowledge and regulations | Financial benefits, regulation, own values and beliefs and professional knowledge. | Own values and beliefs, professional knowledge and financial benefits. |
| **Type of ownership** | | 86.17% Private 13.83% Public | 95.92% Private 4.08% Public | 95.83% Private 4.17% Public | 96.43% Private 3.57% Public |
| **Surface (ha)** | **Mean ± sd** | 1392 ± 8534 | 478 ± 2172 | 2865 ± 13137 | 396 ± 942 |
| | **Intervals** | [0,50] 25.53% (50,250] 44.68% (250,Inf] 22.34% | [0,50] 46.94% (50,250] 30.61% (250,Inf] 16.33% | [0,50] 27.08% (50,250] 39.58% (250,Inf] 25.00% | [0,50] 26.79% (50,250] 39.29% (250,Inf] 17.86% |
| **Distance residence-forest (km)** | **Mean ± sd** | 32 ± 44 | 19 ± 32 | 33 ± 89 | 22 ± 33 |
| | **Intervals** | [0,10] 56.38% (10,100] 23.40% (100,Inf] 7.45% | [0,10] 42.86% (10,100] 38.78% (100,Inf] 8.16% | [0,10] 50.00% (10,100] 43.75% (100,Inf] 4.17% | [0,10] 58.93% (10,100] 26.79% (100,Inf] 1.79% |
| **Management Plan** | | YES 80% NO 20% | YES 67% NO 33% | YES 79% NO 21% | YES 74% NO 26% |
| **Motivations** | | Family heritage, biodiversity conservation and wildfire prevention as main motivations. | Family heritage, biodiversity conservation and wildfire prevention as main motivations. | Family heritage, biodiversity conservation and wildfire prevention as main motivations. | Family heritage as main motivation. Economic yield, biodiversity conservation and wildfire prevention are also important. |
| **Grants** | | 55% apply for grants and subsidies | 37% apply for grants and subsidies | 42% apply for grants and subsidies | 48% apply for grants and subsidies |

This classification of owners into typologies is the foundation for the identification of differential or common drivers that will be effective for modifying their behaviour, since it is indeed constructed after their behaviour. The main assumption is that they will respond differently according to different policy factors. We aimed at identifying those factors that would be effective for changing their forest management practices to increase biodiversity.

Once the categories were identified, an analysis of other variables obtained through the survey was performed for each typology separately. No significant association was found between categories and current management practices in their forests. However, some relevant findings described next should be considered.

### 4.2.2. Current management practices

Regarding current cutting methods, no intervention has notable presence across all categories, with the highest in the traditionalists (17.86%) and the lowest in multifunctional (6.38%). Uniform shelterwood cutting is dominant in the traditionalists (41.07%) and the multifunctional (37.23%). Environmentalists have similar proportions of uniform shelterwood cutting (26.53%), group selection (26.53%) and single tree selection (28.57%). Single tree selection is the most common cutting method across the traditionalist (39.58%), followed by uniform shelterwood cutting (14.58%).

Similar patterns are presented for the current thinning regime. No intervention is higher in the traditionalist (25.00%), while the multifunctional are the ones with the lowest proportion (8.5%). Thinning from all size classes is the most common practice among the multifunctional (42.55%), followed by thinning from above (23.40%) and thinning from below (18.05%). Among the optimizer, the most common practice is again thinning from all size classes (29.16%), followed by thinning from above (25.00%), no intervention (18.75%) and thinning from below (16.66%). The most common thinning regime for the traditionalists is thinning from below (25.00%), followed by thinning from above (21.43%) and thinning from all size classes (21.43%). Thinning from all size classes is the most common practice in the environmentalists (34.69%), followed by thinning from below (26.53%) and from above (18.36%).

For species selection, the most common practices in all groups are to maintain current composition, followed by shift to broadleaves dominated forest, except for the optimizers, where the shift to broadleaves is slightly more common. Most common forest regeneration method is natural regeneration for all typologies (more than 45% for all categories), followed by coppice. Finally, regarding biodiversity management, the most common practice for all categories is to set the forest aside, with no active management.

*Table 12. Current management practices per typology (%) in Catalonia.*

| Current practices | | MULTI n=94 | OPTI n=48 | TRAD n=56 | ENVI n=49 |
|---|---|---|---|---|---|
| Cutting method | A. Clear felling | 1.06% | 0.00% | 1.78% | 2.04% |
| | B. Uniform shelterwood cutting | 37.23% | 29.17% | 41.07% | 26.53% |
| | C. Group selection | 20.21% | 14.58% | 7.14% | 26.53% |
| | D. Single tree selection | 26.60% | 39.58% | 26.79% | 28.57% |
| | 0. No intervention | 6.38% | 12.50% | 17.85% | 14.28% |
| | 99. Don’t know | 1.06% | 0.00% | 0.00% | 2.04% |
| | *NA* | 7.45% | 4.17% | 5.35% | 0.00% |
| Thinning regime | A. Thinning from above | 23.40% | 25.00% | 21.42% | 18.37% |
| | B. Thinning from below | 18.08% | 16.67% | 25.00% | 26.53% |
| | C. Thinning from all size classes | 42.55% | 29.17% | 21.43% | 34.69% |
| | 0. No intervention | 8.51% | 18.75% | 25.00% | 16.33% |
| | 99. Don’t know | 1.06% | 2.08% | 1.78% | 2.04% |
| | *NA* | 6.38% | 8.33% | 5.36% | 2.04% |
| Species selection | A. Maintain current composition | 39.36% | 31.25% | 37.50% | 32.65% |
| | B. Shift to broadleaves dominated forest | 25.53% | 33.33% | 26.79% | 30.61% |
| | C. Shift to conifers dominated forest | 2.13% | 0.00% | 0.00% | 4.08% |
| | D. Shift to mix species forest | 18.08% | 16.67% | 14.29% | 12.24% |
| | E. Use of non-native tree species | 0.00% | 2.08% | 0.00% | 0.00% |

| Current practices | | MULTI n=94 | OPTI n=48 | TRAD n=56 | ENVI n=49 |
|---|---|---|---|---|---|
| | 0. No intervention | 4.25% | 12.5% | 7.14% | 16.33% |
| | 99. Don't know | 2.13% | 0.00% | 7.14% | 2.04% |
| | *NA* | 8.51% | 4.17% | 7.14% | 2.01% |
| **Regeneration method** | A. Planting with regular planting material | 1.06% | 0.00% | 3.57 | 4.08 |
| | B. Planting with material obtained from tree breeding | 1.06% | 2.08% | 0.00% | 2.04% |
| | C. Enrichment planting | 6.38% | 0.00% | 0.00% | 4.08% |
| | D. Natural regeneration | 53.19% | 45.83% | 53.57% | 53.06% |
| | E. Coppice | 24.47% | 43.75% | 26.77% | 28.57% |
| | 0. No intervention | 3.19% | 4.16% | 3.57% | 6.12% |
| | 99. Don't know | 2.12% | 0.00% | 5.35% | 0.00% |
| | *NA* | 8.51% | 4.17% | 7.14% | 2.04% |
| **Biodiversity management** | A. Set aside forest, with no active management | 32.98% | 25.00% | 51.79% | 40.82% |
| | B. Increasing deadwood and microhabitats | 16.15% | 12.50% | 8.93% | 10.20% |
| | C. Increase diversity in tree sizes | 20.21% | 18.75% | 19.64% | 10.20% |
| | D. None other than the practices described in previous questions | 12.77% | 18.75% | 7.14% | 10.20% |
| | 0. No intervention | 7.45% | 16.67% | 5.36% | 16.33% |
| | 99. Don't know | 4.26% | 6.25% | 3.57% | 6.12% |
| | *NA* | 3.19% | 2.08% | 3.57% | 6.12% |

### 4.2.3. Factors that shape the current behaviour of owners and their willingness to change

For each agent type, we can descriptively assign different shares of factors appearing as most influential to change their management with the aim of improving biodiversity are as follows. Factors have been ranked according to the proportion of "important" and "very important" answers (Table 13). Proportions in brackets indicate the share of responses that stated this factor would be very relevant for modifying their forest management, out of the total number of responses.

Referring to the ranking of drivers that currently shape their management the most, all agent types present similar results. Forest road infrastructure and transport, own knowledge and experiences and silvicultural state of the forest appear in the top five of the ranking for all categories. Damage after a natural disaster appears for all the categories except for the multifunctional. Forest cost and revenues appear for all categories except for the environmentalist, and climate change impacts appears only for the environmentalists. Availability of labour appears as important only for the multifunctional owners. It must be considered that a factor not appearing as important here for any of the categories does not mean that it does not matter at all for them, but it is less important than the mentioned factors.

*Table 13. Top 5 most important factors that currently shape management, by categories in Catalonia. Percentage in brackets indicates the proportion of respondents in each category that stated this factor is "important" or "very important" for them.*

| Multifunctional | Optimizer | Traditionalist | Environmentalist |
|---|---|---|---|
| 1. Forest road infrastructure and transport (78%)<br>2. Own knowledge and experiences (72%)<br>3. Silvicultural state of forest (65%)<br>4. Availability of labour (64%)<br>5. Forest management costs and revenues (63%) | 1. Silvicultural state of forest (67%)<br>2. Damage after a natural disaster (64%)<br>3. Forest management costs and revenues (64%)<br>4. Own knowledge and experiences (64%)<br>5. Forest road infrastructure and transport (62%) | 1. Own knowledge and experiences (56%)<br>2. Damage after a natural disaster (53%)<br>3. Forest road infrastructure and transport (51%)<br>4. Silvicultural state of forest (45%)<br>5. Forest management costs and revenues (43%) | 1. Forest road infrastructure and transport (60%)<br>2. Own knowledge and experiences (56%)<br>3. Climate change impacts (56%)<br>4. Silvicultural state of forest (54%)<br>6. Damage after a natural disaster (52%) |

Additionally, respondents were asked if they would be willing to change their management, with the necessary technical assessment, towards a management contributing to biodiversity conservation. Optimizers were the group with the most respondents saying they would not change their management (32.9%), but still a majority said they would do so (54.2%). Similarly, most of the multifunctional owners (52.6%) said that they would be willing to change their management, while 23.6% said they would not, and 8.5% stated they did not know. Similar results were found for the traditionalists (24.3% No, 53.2% Yes, 10.4% Don't know). Finally, the environmentalists were the category with more proportion of respondents saying they would be willing to change (58.4%), while they were also the ones with higher proportion of respondents say they do not know (16.3%) and the ones with less proportion of people saying they would not change their management to improve biodiversity (17.6%).

### 4.2.4. Factors that would be influential in changing their management to improve biodiversity

The prioritization of drivers changes when referring to those that would modify their management to improve biodiversity. For **multifunctional owners**, the most important **factors are related with financial support, labour availability, and technical guidance.** Subsidies for forest management are the most important (66%), followed subsidies for natural evolution (63%) and availability of labour (61%). Innovations that facilitate forest exploitation (60%) and joint technical management and forest improvement plans (60%) go after them.

For **optimizers**, subsidies for natural evolution go first as most important for modifying their forest management. Joint technical management and forest improvement plans (67%) and availability of labour (66%) go next, followed by subsidies for forest management (63%) and innovations that facilitate forest exploitation (58%).

For **traditionalists**, again subsidies for forest management (59%) and natural evolution (55%) are the most important factors, but after them, different factors appear as rated important. These are **timber prices** (54%) **innovations that facilitate forest exploitation (46%), and availability of labour (44%).** This reinforces the idea that the management of this agent type is often limited by the economic profitability of their forest plots.

Finally, **environmentalists also consider subsidies for forest management (59%) and joint technical management and forest improvement plans (59%) as very important.**

Availability of labour (57%), subsidies for natural evolution (55%) and innovations that facilitate forest exploitation (50%) are also very important for them.

In summary, there are some factors that are similarly important for more than one agent type, while others only appear in one of the types. For instance, subsidies appear as important in all agent types, but technical advice and availability of labour have different importance.

To identify if there was any significant difference among factors and agent types, we performed a Kruskal-Wallis test for each of the factors and the four categories (Table 14). This comparison allowed to determine which factors are more determinant in engaging each agent type. Once these factors showing significant differences were identified, Dunn test pairwise comparisons were applied to these, allowing us to observe that these differences usually appear between MULTI or OPTI and ENVI or TRAD, but rarely between ENVI and TRAD or MULTI and OPTI.

*Table 14. Results of the Kruskal-Wallis test and Dunn test pairwise comparisons in Catalonia.*

| **Factor** | **p-value** (1) | **Significance of differences obtained from the Dunn test pairwise comparison between each pair of agent types** (2) | | | | | |
|---|---|---|---|---|---|---|---|
| | | **ENVI-TRAD** | **ENVI-MULTI** | **ENVI-OPTI** | **TRAD-MULTI** | **TRAD-OPTI** | **MULTI-OPTI** |
| Regulatory biodiversity policy | 0.0228 | | | | * | | |
| Regulatory climate policy | 0.0018 | ** | | | *** | * | |
| Regulatory water policy | 0.0067 | ** | | | ** | | |
| Informational instruments | 0.0408 | | | | * | | |
| Forest management costs and revenues | 0.0163 | | | | | | |
| Timber prices | 0.0099 | | ** | | | | |
| Income from other marketable goods than timber | 0.0464 | | | | | | |
| Requirements set by forest management certification standards | 0.0066 | | | | ** | * | |
| Forest property structure | 0.0094 | * | | | ** | | |
| Media and social pressure | 0.0222 | | | | | | * |
| Forest road infrastructure and transport | 0.0091 | | * | | ** | | |
| Availability of labour | 0.0241 | | | | ** | | |
| Silvicultural state of forest | 0.0254 | | | | * | | |
| Ecological and biodiversity status of forest | 0.0004 | | | | **** | | |

(1) P-value obtained from the Kruskal-Wallis test on all four categories
(2) Dunn test results. P-value < 0.001, ***; < 0.01, **; < 0.05, *; > 0.05, ns

As a result, we consider merging MULTI and OPTI under the label group 1, as well as grouping TRAD and ENVI as group 2. Aiming at increasing the significance of the selected factors to explain different behavioural responses, the analysis of the most important factors for each group was repeated. The results of this joining contribute to simplifying the interpretation of the importance of factors for each group. In Table 15, the most important factors for each agent group are shown.

*Table 15. Multi-level case study research design in BIOCONSENT. Most important factors to improve biodiversity for each group of typologies. The percentage value indicates the proportion of responses "important" or "very important" in each typology. If factor shows a significant difference between groups, a (*) is added.*

| MULTI + OPTI (GROUP 1) | TRAD + ENVI (GROUP 2) |
|---|---|
| 1. Subsidies for natural evolution (66%)<br>2. Subsidies for forest management (65%)<br>3. Availability of labour (63%) (*)<br>4. Joint technical management and forest improvement plans (62%)<br>5. Innovations that facilitate forest exploitation (59%) | 1. Subsidies for forest management (59%)<br>2. Subsidies for natural evolution (55%)<br>3. Availability of labour (50%) (*)<br>4. Joint technical management and forest improvement plans (50%)<br>5. Innovations that facilitate forest exploitation (48%) |

Only factors that have a proportion of respondents indicating that it is important or very important for them higher than 50% will probably have an actual effect on the behaviour of each agent type.

The first five most important factors are the same for both groups. These are subsidies, both for forest management and natural evolution, availability of labour, joint technical management and forest improvement plans and innovations that facilitate forest exploitation. Availability of labour is the only factor that shows a significant difference between group 1 and group 2.

### 4.2.5. Developments in the model to include agency according to different behavioural responses

To represent forest owner behaviour and behavioural change according to policy instruments in the FORMES projection system for multi-objective forest planning three actions have been done:

(1) Associate at least one NFI4 plot to each forest owner typology according to the location (either the municipality or failing that, the county) of the forest, the type of property right (public or private), whether it has a protection figure, it is a mono-species or multi-species forest, and the main tree species (up to 3) reported in the survey. 234 survey responses had all the required variables for doing such correspondence with NFI plots.

(2) Add the variable 'management unit' to gather the set of NFI plots representing an ownership typology in the dataset gathering the plots' descriptors.

(3) Associate to each management unit, and according to the forest owner typology if applies, the sylvicultural prescription applied if a multi-functional management with a business-as-usual perspective is adopted or if a close-to-nature with the aim to improve biodiversity conservation is adopted. Each perspective will be applied to each typology if the defined scenarios include the factors that trigger change in the respective typologies or not. Outputs of the model will be compared for the application of BAU or close-to-nature management to each typology, showing if there are any differences when owners change their management as a results of a response to other factors.

Thus, the model is ready to simulate either a business-as-usual (BAU) or a close-to-nature (C2N) silvicultural approach for any set of management units (Table 4 and 5, respectively). Natural regeneration is the predominant regeneration type for all the species, both in the BAU and the C2N approach. Despite this, in the BAU approach, tree species that commonly growth in plantation regimes are regularly planted after the final cutting at a mean density of 600 trees/ha (*Castanea sativa* and *Pinus pinaster*) or 200 trees/ha (*Populus* spp. and *Platanus* spp.), and a standard initial DBH of 5 cm. Under the C2N approach, only are maintained *Populus* spp. and *Platanus* spp. plantations with the same artificial regeneration characteristics.

The BAU silvicultural prescriptions are based on the Guidelines for Sustainable Forest Management in Catalonia (ORGEST) developed for the main tree species present in the region (Centro de la Propiedad Forestal, 2025). The ORGEST series constitute a set of technical tools to help forest management planning. They collect a series of decision elements, models and management recommendations, adjusted to Catalan conditions, which constitute a body of practical and up-to-date information on forest management. They aim to support the manager in the decision-making process regarding the allocation of preferential objectives and the planning and execution of management actions.

Following the same philosophy, a new set of management guidelines was developed to adopt close-to-nature principles for the dominant alpine and mountain conifers species in Catalonia (Beltrán et al. 2020), that include *Abies* spp., *P. nigra*, *P. sylvestris* and *P. uncinata*; as well as, for the most abundant species in Mediterranean forest ecosystems such as *Pinus halepensis*, *Quercus ilex*, *Q. pubescens*, *Q. canariensis*, *Q. petraea*, and *Q. faginea* (Baiges et al. 2023). Based on these close-to-nature management guidelines and expert criteria we stablished the silvicultural treatments for the dominant tree species of Catalan forest stands (Table 5).

Finally, scenario definition is the linking element to simulate forest owner behaviour and behavioural change according to policy instruments in the FORMES modelling platform. Thus, to each scenario describing the policy instruments implemented to promote and reinforce biodiversity conservation through forest management, a set of owner typologies will respond to them according to the survey analysis. For those management units belonging to such owner typologies sensible to the policy instruments proposed, C2N silvicultural prescriptions will be followed, and BAU prescriptions otherwise.

*Table 16. Silvicultural prescriptions regarding cutting regimes for the main tree species in Catalonia region (NE Spain) for the business-as-usual (BAU) forest management approach.*

| **Tree species** | **Management system** | **Thinning** | | | **Regeneration cutting** | |
|---|---|---|---|---|---|---|
| | | **Type** | **BA threshold ($m^2$ $ha^{-1}$)[a]** | **Reduction in BA (%)** | **Mean DBH (cm)[b]** | **Reduction in BA (%)[c]** |
| Abies/Picea/Pseudotsuga spp. | Uneven-aged | Above-intermediate | 37 | 35 | - | - |
| Betula/Acer spp. | Uneven-aged | Intermediate | 25 | 25 | - | - |
| Castanea sativa | Even-aged | Below-intermediate | 40 | 33 | 30 | 100 |
| Fagus sylvatica | Even-aged | Intermediate | 35 | 25 | 50 | 40 - 60 - 95 |
| Pinus halepensis | Even-aged | Below-intermediate | 35 | 33 | 35 | 60 - 100 |
| Pinus nigra | Uneven-aged | Above-intermediate | 27 | 32 | - | - |
| Pinus pinaster | Even-aged | Below-intermediate | 32 | 35 | 45 | 100 |
| Pinus sylvestris | Even-aged | Intermediate | 33 | 35 | 45 | 45 - 55 - 100 |

Continue in next page

| Tree species | Management system | Thinning | | | Regeneration cutting | |
|---|---|---|---|---|---|---|
| | | Type | BA threshold (m$^2$ ha$^{-1}$)[a] | Reduction in BA (%) | Mean DBH (cm)[b] | Reduction in BA (%)[c] |
| Pinus uncinata | Even-aged | Above-intermediate | 33 | 45 | 35 | 60 - 100 |
| Populus/Platanus spp. | Even-aged | Intermediate | 20 | 35 | 25 | 100 |
| Quercus faginea | Uneven-aged | Intermediate | 25 | 30 | - | - |
| Quercus ilex | Uneven-aged | Intermediate | 30 | 40 | - | - |
| Quercus suber | Uneven-aged | Below-intermediate | 25 | 20 | - | - |
| Quercus spp. | Even-aged | Below-intermediate | 30 | 25 | 60 | 30 - 65 - 95 |
| Other conifers | Even-aged | Below-intermediate | 30 | 30 | 30 | 40 - 60 - 95 |
| Other deciduous | Uneven-aged | Intermediate | 25 | 25 | - | - |

*Note*: BA: basal area; DBH: diameter at the breast height; and DC: diameter class. DC 10 cm = [7.5–12.5), DC 15 cm = [12.5-17.5), DC 20 cm = [17.5– 22.5).
[a] It determines the periodicity of the cuts.
[b] It determines the initiation of the regeneration cutting.
[c] Reduction of BA from the total BA of the stand in the 1st cut, 2nd cut (after 10 years) and 3rd cut (after 20 years from 1st cut), shelterwood method.

*Table 17. Silvicultural prescriptions regarding cutting regimes for the main tree species in Catalonia region (NE Spain) for the close-to-nature (C2N) forest management approach.*

| Tree species | Management system | Thinning | | | Regeneration cutting | |
|---|---|---|---|---|---|---|
| | | Type | BA threshold (m$^2$ ha$^{-1}$)[a] | Reduction in BA (%) | Mean DBH (cm)[b] | Reduction in BA (%)[c] |
| Abies/Picea/Pseudotsuga spp. | Uneven-aged | Above-intermediate | 44 | 35 | - | - |
| Betula/Acer spp. | Uneven-aged | Intermediate | 32 | 35 | - | - |
| Castanea sativa | Uneven-aged | Intermediate | 35 | 38 | - | - |
| Fagus sylvatica | Uneven-aged | Above-intermediate | 30 | 28 | - | - |
| Pinus halepensis | Even-aged | Below | 40 | 33 | 40 | 60 - 90 |
| Pinus nigra | Uneven-aged | Above-intermediate | 32 | 32 | - | - |
| Pinus pinaster | Even-aged | Below | 37 | 35 | 50 | 60 - 90 |
| Pinus sylvestris | Uneven-aged | Intermediate | 27 | 25 | - | - |
| Pinus uncinata | Uneven-aged | Intermediate | 27 | 25 | - | - |

Continue in next page

| Tree species | Management system | Thinning | | | Regeneration cutting | |
|---|---|---|---|---|---|---|
| | | Type | BA threshold ($m^2$ $ha^{-1}$)[a] | Reduction in BA (%) | Mean DBH (cm)[b] | Reduction in BA (%)[c] |
| Populus/Platanus spp. | Even-aged | Below-intermediate | 20 | 35 | 25 | 100 |
| Quercus faginea | Uneven-aged | Below | 30 | 30 | - | - |
| Quercus ilex | Uneven-aged | Below | 35 | 40 | - | - |
| Quercus suber | Uneven-aged | Below | 30 | 20 | - | - |
| Quercus spp. | Uneven-aged | Intermediate | 25 | 30 | - | - |
| Other conifers | Uneven-aged | Intermediate | 27 | 25 | - | - |
| Other deciduous | Uneven-aged | Below | 30 | 25 | - | - |

*Note*: BA: basal area; DBH: diameter at the breast height; and DC: diameter class. DC 10 cm = [7.5–12.5), DC 15 cm = [12.5-17.5), DC 20 cm = [17.5– 22.5).
[a] It determines the periodicity of the cuts.
[b] It determines the initiation of the regeneration cutting.
[c] Reduction of BA from the total BA of the stand in the 1st cut, 2nd cut (after 10 years) and 3rd cut (after 20 years from 1st cut), shelterwood method.

According to the above-described developments forest evolution will be modelled under three qualitative different scenarios, which have been defined through the analysis of factors that are important for each agent type:

- Scenario 1: Multi-functional management with a business-as-usual perspective. Conditions similar to the current context will be applied to the long term to see its effect on biodiversity.
- Scenario 2: Promotion of close-to-nature silviculture, with the aim to improve biodiversity conservation. In this case, alternative forest management will be promoted through the factors identified as most effective to achieve so, presented above.

The qualitative description of each scenario and the projections and resulting indicators will be presented to different forest owners in a workshop. This workshop will serve to test their responses to different policy drivers to improve their management towards more biodiversity-oriented practices. The model will be improved based on the results and feedback of the workshop. If there are any biodiversity conservation differences in the long-term projections (estimated 120 years) for each scenario, these will be reflected in the indicators that the model provides in this sense. The indicators that have been chosen to show changes in biodiversity are based on the new restoration law (see next section 4.3.).

## 4.3. Spatializing agent typologies

The above-mentioned agent types have been linked to forest areas in Catalonia using the information on forest areas with public ownership, private forest areas with management plan and total forest area (Figure 8). The proportion of each typology per type of forest area (public or private) has been extracted from the collected responses (Table 18). The obtained proportions are estimates as equivalent to the proportions of surface occupied by each typology in each surface type.

Besides the agent types identified from the cluster analysis (group 1 and 2), passive owners will also be included in the modelling as those forest owners who apply no management in their forests. Their location has been estimated out of public information on whether forests have Forest Management Plan. Forests without this Management Plan are assumed to be owned by passive owners. In summary, we will include three groups of forest owners' typologies that represent a gradient from forest owners more active and responsive to policy drivers (group 1 followed by group 2) to owners that are passive and do not respond to current policy drivers (group 3).

*Table 18. Proportion of each agent type by property type in Catalonia.*

| | | **PUBLIC** | | **PRIVATE** | | |
|---|---|---|---|---|---|---|
| | | | | **with management plan** | | **without management plan** |
| **Group 1** | **MULTI** | 72% | 78% | 36% | 56% | - |
| | **OPTI** | 6% | | 20% | | |
| **Group 2** | **TRAD** | 11% | 22% | 22% | 44% | - |
| | **ENVI** | 11% | | 22% | | |
| **Group 3** | **PASSIVE** | - | | - | | 100% |

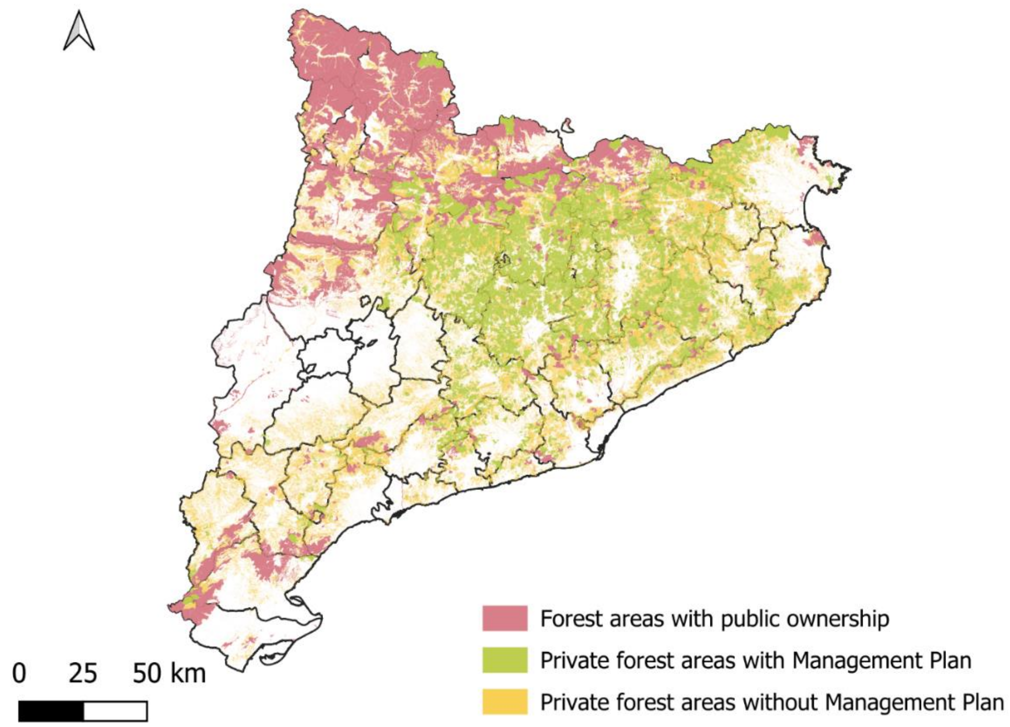



*Figure 8. Total forest area in Catalonia, differentiating by forest areas with public ownership, private forest areas with management plan and without management plan.*

## 4.4. Additional model developments

In addition to improving the representation of forest owner behaviour and behavioural change in FORMES model, other improvements were made to be able to report biodiversity and wood production related indicators. A complementary FORMES module has been developed to estimate:

(1) Wood productivity expressed as rate of cut volume ($m^3$/ha/year) and total cut volume, the number of harvesting interventions done during the simulation period, and the distribution of wood assortments for the first transformation in trituration, roundwood of 1st and 2nd class, poles, and/or fuelwood. Wood allocation in the different assortments categories depends on the species and the DBH of cut trees.

(2) Amount of deadwood (in biomass units) with a fixed decomposition rate for conifer and deciduous species, expressed as 1-exp-rate.

(3) Above- and below-ground stock of organic carbon

To account for the forest resources of any forest stand as biomass (kg/ha) or volume ($m^3$/ha), FORMES includes the most recent set of allometric equations for the main tree species in Spain (Ibáñez et al. 2002, Montero et al. 2005, Ruíz Peinado et al. 2011, Ruíz Peinado et al. 2012). This module includes allometric equations for each biomass fraction (i.e. compartment) and species code, deriving the biomass (kg/ha) of stem, roots, branches, leaves/needles and bark of species in the Spanish National Forest Inventory. All equations are calculated form height and diameter at breast height (DBH) of trees (either living, cut or dead). Biomass values from equations refer to individual trees, but within the module, the result is multiplied by the density of individuals N, so the resulting value is in units of kg/ha. Similarly, the module includes static models for the wood volume (i.e., volume with bark - VB, volume without bark - VWB, firewood volume - FWV, and annual increase in volume with bark - AIVB) by species and province in the National Forest Inventory.

The volumetric equation used for each tree record depends on province, species, cubic content form and volume parameter (VB, VWB, FWV and AIVB). Volumes are given as per hectare, as the result of the volumetric equation is multiplied by the density of individuals N. In FORMES, forest stands are described by the distribution of diameter classes per species, i.e., a tree list as recorded in the Spanish National Forest Inventory, where each record accounts for a representative tree with sampled species, DBH, and height, and estimated N (Alberdi et al. 2016).

The forest management module in FORMES returns a tree list of cut trees (as the one describing standing, living trees), and by applying the same set of allometric equations, it is possible to derive the total volume (or biomass) harvested and the annual wood productivity rate (by averaging the total volume cut by year). Besides that, the classification of wood assortments for first transformation considered in the Catalan case, considers shredding (the lowest quality destination, for which wood of small dimensions (i.e. DBH< 15 cm) or with defects that prevent another use is destined), roundwood of 2nd class (it includes intermediate quality wood that can be industrially processed for packaging (boxes, cable drums or pallet) and other products based on small solid pieces, such as panels for frameworks), roundwood of 1st class (that are good quality pieces, with large dimensions, i.e., DBH > 18 cm and length > 5 m, good straightness and little or no knots, and it is intended for wood products for structural use (solid or laminated) or carpentry and woodworking with long processing chains), poles (Mediterranean conifers are well suited to be impregnated with mineral salts to generate products of great durability outdoors and both small, i.e. DBH=15 cm, length=2 m, or large, i.e., DBH=30 cm, length=12 m, are suitable), and fuelwood (being the main destination for Quercus spp. because of their high quality as firewood). Other primary processing uses for these species in Catalonia, such as unrolling, veneer or construction in contact with water, are rare and of little relevance in the total volume of wood harvested from these forests. Table 19 shows the percentage of wood volume of each diameter class and species that is classified in each first processing destination for commercial conifer species in Catalonia based on the DBH of the trees felled and extracted in any simulated silvicultural action. The determination of the volume percentage of each destination has been based on the experience from different real silvicultural actions, information from different forest management plans, where harvesting forecasts are made, technical publications on the classification of timber by destination according to quality and species (Mundet and Capó 2007; Correal et al. 2017), and standardised norms for the classification of wood products (UNE and ISO).

*Table 19. Wood assortment distribution, in percentage, per diameter class (DC) applied to conifer species in Catalonia. DC are 5 cm width each and only the mid-point is indicated. A 20% of wood per DC is allocated to slash.*

| DC | Shredding | Roundwood 2nd class | Roundwood 1st class | Poles |
|---|---|---|---|---|
| 10 | 80.00 | 0.00 | 0.00 | 0.00 |
| 15 | 80.00 | 0.00 | 0.00 | 0.00 |
| 20 | 52.00 | 16.00 | 4.00 | 8.00 |
| 25 | 32.00 | 20.00 | 12.00 | 16.00 |
| 30 | 18.40 | 24.00 | 17.60 | 20.00 |
| 35 | 6.40 | 29.60 | 28.00 | 16.00 |
| 40 | 4.80 | 33.60 | 33.60 | 8.00 |
| 45 | 4.80 | 29.60 | 45.60 | 0.00 |
| 50 | 4.80 | 21.60 | 53.60 | 0.00 |
| 55 | 4.80 | 16.00 | 59.20 | 0.00 |
| 60 | 4.80 | 8.00 | 67.20 | 0.00 |
| 65 | 4.80 | 8.00 | 67.20 | 0.00 |
| 70 | 4.80 | 16.00 | 59.20 | 0.00 |
| 75 | 8.80 | 12.00 | 59.20 | 0.00 |
| 80 | 12.00 | 8.80 | 59.20 | 0.00 |
| 85 | 12.80 | 8.00 | 59.20 | 0.00 |
| 90 | 16.80 | 4.00 | 59.20 | 0.00 |
| 95 | 16.80 | 4.00 | 59.20 | 0.00 |
| 100 | 16.80 | 4.00 | 59.20 | 0.00 |

Above-ground and below-ground stock of organic carbon of living trees is derived from biomass fractions, adding up stem, branches, leaves/needles and bark to get above-ground biomass, and root fraction makes up below-ground biomass. Percentage of organic carbon per dry weight biomass by species is taken from Montero et al. (2005), ranging from 47.2% and 50.9%.

# 5. Sweden

## 5.1. Heureka model description

Heureka projects the future forest development and the effects of forest management on, e.g., timber and biofuel production, carbon sequestration, dead wood dynamics, habitat for species, recreation and susceptibility to forest damages. The projections use a common core of growth and yield models for simulating forest dynamics but are handled by three different software: StandWise is used for stand-level simulations, PlanWise is mainly used for simulation and optimization of forest management on estate and landscape level, and Regwise is used for simulation on regional and national level. Heureka can use different types of forest input data, mainly from two types of sources: 1) Sample plot data (e.g., from the Swedish National Forest Inventory or other inventories), and 2) stand-level data (e.g., data from a traditional forest management plan or a stand register). In RegWise and PlanWise, the user can define which management strategies should be applied when projecting the state of the forest into the future and group treatment units based on either their spatial location or their characteristics (e.g., dominant species, management class, protection status) and then assign one or several different management strategies to these groups. A variety of management strategies can be simulated, including different variants of final felling, thinning and selective harvesting, nature conservation-focused management, retention practices and no management. Forest development and management actions are normally simulated in five-year time steps over a 20-to-100-year time horizon, depending on the focus of the study. More detailed information on Heureka can be found in Lämås et al. (2023).

In this project Heureka PlanWise is used for projecting forest development under different scenarios. The modelling in Heureka PlanWise typically involves several steps (for a comprehensive overview of the process, see Eggers and Öhman, 2020), starting with import of data for the initial state of the forest. We use data from the Swedish National Forest Inventory (NFI), gathered during 2016–2020 from 3 470 plots in Norrbotten County, representing 3,896,625 ha of productive forests (for an overview of the Swedish NFI, see Fridman et al., 2014). Next, a range of settings will be defined to reflect the forest management in various scenarios. The forest is divided into subsections, referred to as forest domains, based on ownership and forest type. Then, one or several management strategies are assigned to each forest domain. Management strategies can differ in management system (unmanaged, even-aged, and uneven-aged), or details within each system, e.g. in type of regeneration, minimum rotation length, number of thinnings or the proportion of broadleaves retained in thinnings. Based on these settings, Heureka generates up to twenty treatment programs per management strategy and treatment unit. Treatment programs are simulations of treatments and their timing over the next 100 years, divided into twenty five-year periods. Optimization will then be used to select treatment programs and associated management strategies based on the goal formulations set up for a particular scenario.

## 5.2. Agent typologies, behaviour and management in HEUREKA

Data on forest owners, forest characteristics, management, and socio-economic factors for Norrbotten County in the north of Sweden was collected through a survey by Sotirov et al. (2025) and used as the basis for representing agent behaviour and behavioural change in Heureka. In total, there were 178 responses to the survey for Norrbotten County, which is a rather low response rate.

Two of the questions in the survey related to forest management objectives (Question 4) and decision-making principles (Question 6), respectively, and were used by Sotirov et al. (2025) to categorize forest owners and managers in different behavioural types. The framework proposed by Sotirov et al. (2018), which describes six different forest owner behavioural models (Optimizers, Traditionalists, Maximisers, Passives, Multi-functionalists, and Environmentalists), was used for this categorization. Three of these behavioural models (or agent typologies, as we refer to them from here on) were identified in the survey data from Norrbotten: Optimizers, Multi-functionalists, and Environmentalists. The three other typologies in the framework − Traditionalists, Maximisers, and Passives − could not be found in the data. The distribution of the different types of forest owners over the agent typologies is shown in Table 20. This distribution is the basis for the spatialization of agent types, using the ownership data for the NFI plots (see section 5.3). However, for each forest owner type there is a large proportion, 62%, that could not be assigned to any of the agent typologies. This is mainly due to the statistical effects from the relatively small number of complete responses to the WP2 survey.

*Table 20. Distribution of forest owner types over agent typologies based on the WP2 survey for the Swedish case-study.*

| **Forest owner type** | **Agent typologies** | | | **Not assigned to typology** |
|---|---|---|---|---|
| | **Optimizers** | **Multifunctionalists** | **Environmentalists** | |
| State National | 14.3% | 14.3% | 14.3% | 57.1% |
| State Sub-national | - | - | 50% | 50% |
| Local Government | 33.3% | 6.7% | - | 60% |
| PFO Ind or Family | 12.1% | 21.5% | 7.8% | 58.6% |
| PFO Business Entity | 14.3% | - | - | 85.7% |
| PFO Private Institution | 14.3% | 14.3% | - | 71.4% |

Next, data from the WP2 survey was used to define the typical forest management for the agent typologies based on the question on main forest management practices (Question 5). First, current management practices were defined (Table 21). To a large extent, Optimizers and Multifunctionalists have similar management practices, i.e., the main cutting regime is clear felling and the dominant regeneration method is planting. This is most likely due to the Swedish forest policy and practice that have promoted clear felling followed by planting for a long time, which has made clear felling the main and, until recent years nearly the only, cutting regime used in Sweden. These results may also reflect a long Swedish tradition of "multifunctional", or "multiple use forestry" which in the Swedish contemporary context include large scale rotation forestry with retention of trees and patches of forest. Environmentalists differ by much larger proportions of single tree selection, no cutting and natural regeneration.

The forest area not belonging to any of the three agent types was assigned to standard forest management for the region, as it is defined in the most recent National Forest Assessment (Swedish National Forest Agency, 2022).

*Table 21. Forest management regimes for the three agent typologies under current management in the Swedish case-study. MULTI represents Multifunctionalists, OPTI represents Optimizers and ENVI represents Environmentalists.*

| Current practices | | MULTI | OPTI | ENVI |
|---|---|---|---|---|
| **Cutting method** | A. Clear felling | 93.3% | 81.8% | 27.3% |
| | B. Group selection | - | - | - |
| | C. Single tree selection | 6.7% | 13.7% | 54.5% |
| | D. No cutting | - | 4.5% | 18.2% |
| **Thinning regime** | A. Thinning from above | 10.0% | 19.0% | 36.4% |
| | B. Thinning from below | 60.0% | 52.4% | 27.3% |
| | C. Thinning from all size classes | 30.0% | 28.6% | - |
| | D. No thinning | - | - | 36.4% |
| **Species selection** | A. Maintain current composition | 56.7% | 76.2% | 81.8% |
| | B. Shift to broadleaves dominated forest | 13.3% | 19.0% | - |
| | C. Shift to conifers dominated forest | 13.3% | - | - |
| | D. Shift to mix species forest | 13.3% | 4.8% | 18.2% |
| | E. Use of non-native tree species | 3.4% | - | - |
| **Regeneration method** | A. Planting with regular planting material | 16.7% | 13.0% | 9.1% |
| | B. Planting with material obtained from tree breeding | 56.7% | 73.9% | 18.2% |
| | C. Enrichment planting | - | 4.4% | - |
| | D. Natural regeneration | 26.7% | 8.7% | 72.7% |
| | E. Coppice | - | - | - |
| **Biodiversity management** | A. Set aside forest, with no active management | 26.7% | 41.0% | 18.2% |
| | B. Increasing deadwood and microhabitats | 36.6% | 22.7% | 18.2% |
| | C. Increase diversity in tree sizes | 26.7% | 13.6% | 18.2% |
| | D. None | 10.0% | 22.7% | 45.4% |
| **Post-disturbance management** | A. Salvage logging with planting | 66.7% | 68.2% | 20.0% |
| | B. Salvage logging with natural regeneration | 26.6% | 18.2% | 30.0% |
| | C. Leaving all wood with natural regeneration on the forest area affected by disturbances | 6.7% | 4.5% | 30.0% |
| | D. No post-disturbance management | - | 9.1% | 20.0% |

The information in Table 21 was combined with existing data on forest management practices from the NFI and used to define treatment programs for simulation of forest management in Heureka.

Information on potential changes in forest management implemented due to biodiversity restoration and conservation or climate change adaptation were also provided from responses on the question on main forest management practices (Question 5) in the survey by Sotirov et al. (2025). Table 22 shows the changes in forest management regimes due to biodiversity restoration and conservation. The willingness to change cutting and thinning regimes is relatively low for all agent types, whereas especially Optimizers and Multifunctionalists seem willing to change to natural regeneration and to shift tree species (especially to broadleaves). Possibly, all types consider their cutting and thinning regimes to be adapted to biodiversity preservation in general but still think it could be improved by some adjustments of the management.

In Heureka, forest management was simulated according to the adaptation indicated for each agent type. The change from current management was set to take place at the start of the simulation, to make it possible to see the effects of changed management within the simulation period.

*Table 22. Forest management regimes for the three agent typologies with adaptation to biodiversity restoration and conservation in the Swedish case-study. MULTI represents Multifunctionalists, OPTI represents Optimizers and ENVI represents Environmentalists.*

| Current practices | | MULTI | OPTI | ENVI |
|---|---|---|---|---|
| **Cutting method** | A. Clear felling | 10.7% | 15.0% | 18.2% |
| | B. Group selection | 7.2% | 10.0% | 9.1% |
| | C. Single tree selection | 25.0% | 40.0% | 18.2% |
| | D. No cutting | - | 5.0% | - |
| | E. No change from current management | 57.1% | 30.0% | 54.5% |
| **Thinning regime** | A. Thinning from above | 3.4% | 5.3% | - |
| | B. Thinning from below | 37.9% | 15.7% | 9.1% |
| | C. Thinning from all size classes | 27.6% | 26.3% | 9.1% |
| | D. No thinning | - | 5.3% | 27.3% |
| | E. No change from current management | 31.1% | 47.4% | 54.5% |
| **Species selection** | A. Maintain current composition | 31.1% | 40.0% | 27.3% |
| | B. Shift to broadleaves dominated forest | 34.5% | 40.0% | 27.3% |
| | C. Shift to conifers dominated forest | 3.4% | - | - |
| | D. Shift to mix species forest | 27.6% | 5.0% | 9.1% |
| | E. Use of non-native tree species | 3.4% | - | - |
| | F. No change from current management | - | 15.0% | 36.4% |
| **Regeneration method** | A. Planting with regular planting material | 10.3% | 4.8% | 9.1% |
| | B. Planting with material obtained from tree breeding | 20.7% | 33.3% | - |
| | C. Enrichment planting | - | 4.8% | 9.1% |
| | D. Natural regeneration | 34.5% | 38.1% | 27.3% |
| | E. Coppice | - | - | - |
| | F. No change from current management | 34.5% | 19.0% | 54.5% |
| **Biodiversity management** | A. Set aside forest, with no active management | 17.2% | 33.3% | 9.1% |
| | B. Increasing deadwood and microhabitats | 41.4% | 9.5% | 27.3% |
| | C. Increase diversity in tree sizes | 13.8% | 14.3% | 27.3% |
| | D. None | - | 4.8% | - |
| | E. No change from current management | 27.6% | 38.1% | 36.4% |
| **Post-disturbance management** | A. Salvage logging with planting | 27.6% | 23.8% | 10.0% |
| | B. Salvage logging with natural regeneration | 6.9% | 33.3% | 30.0% |
| | C. Leaving all wood with natural regeneration on the forest area affected by disturbances | 17.2% | 14.3% | 10.0% |
| | D. No post-disturbance management | 6.9% | - | 10.0% |
| | F. No change from current management | 41.4% | 28.6% | 40.0% |

Table 23 shows the changes in management due to climate change adaptation. The responsiveness concerning cutting and thinning regimes is especially low for the Environmentalists, who most likely consider climate adaptation to already be part of their management in general. In line with their response on biodiversity preservation, all types seem to favor a shift to broadleaved forest. The Optimizers and Multifunctionalists will adapt to climate change by shifting to natural regeneration as well as planting material obtained from tree breeding.

As for adaptation to biodiversity restoration and conservation, forest management was simulated according to the changes indicated for each agent type. Again, to see the effects of changed management within the simulation period, the change from current management was set to take place at the start of the simulation.

*Table 23. Forest management regimes for the three agent typologies with adaptation to climate change impacts in the Swedish case-study. MULTI represents Multifunctionalists, OPTI represents Optimizers and ENVI represents Environmentalists.*

| Current practices | | MULTI | OPTI | ENVI |
|---|---|---|---|---|
| **Cutting method** | A. Clear felling | 10.7% | 30.0% | 9.1% |
| | B. Group selection | - | 10.0% | 9.1% |
| | C. Single tree selection | 28.6% | 20.0% | 18.2% |
| | D. No cutting | - | - | - |
| | E. No change from current management | 60.7% | 40.0% | 63.6% |
| **Thinning regime** | A. Thinning from above | - | 10.4% | 9.1% |
| | B. Thinning from below | 32.1% | 21.1% | - |
| | C. Thinning from all size classes | 35.7% | 21.1% | - |
| | D. No thinning | 7.1% | - | 9.1% |
| | E. No change from current management | 25.1% | 47.4% | 81.8% |
| **Species selection** | A. Maintain current composition | 28.6% | 50.0% | 27.3% |
| | B. Shift to broadleaves dominated forest | 28.6% | 20.0% | 36.3% |
| | C. Shift to conifers dominated forest | 3.6% | 5.0% | - |
| | D. Shift to mix species forest | 35.6% | 10.0% | 9.1% |
| | E. Use of non-native tree species | - | - | - |
| | F. No change from current management | 3.6% | 15.0% | 27.3% |
| **Regeneration method** | A. Planting with regular planting material | 10.3% | 9.5% | 9.1% |
| | B. Planting with material obtained from tree breeding | 34.5% | 38.1% | 18.2% |
| | C. Enrichment planting | 3.4% | 4.8% | 9.1% |
| | D. Natural regeneration | 24.2% | 33.3% | 18.2% |
| | E. Coppice | - | - | - |
| | F. No change from current management | 27.6% | 14.3% | 45.4% |
| **Biodiversity management** | A. Set aside forest, with no active management | 17.2% | 19.0% | 9.1% |
| | B. Increasing deadwood and microhabitats | 24.2% | 4.8% | 9.1% |
| | C. Increase diversity in tree sizes | 27.6% | 28.6% | 45.4% |
| | D. None | 3.4% | 9.5% | - |
| | E. No change from current management | 27.6% | 38.1% | 36.4% |
| **Post-disturbance management** | A. Salvage logging with planting | 37.9% | 42.8% | 10.0% |
| | B. Salvage logging with natural regeneration | 13.8% | 14.3% | 20.0% |
| | C. Leaving all wood with natural regeneration on the forest area affected by disturbances | 13.8% | 9.5% | 30.0% |
| | D. No post-disturbance management | - | 4.8% | 10.0% |
| | F. No change from current management | 34.5% | 28.6% | 30.0% |

Concerning responsiveness to various socio-economic factors, the results from the survey for this question (Question 7) do not show any clear patterns for the various agent typologies. Sensitivity analysis could be used to assess the effects of different levels and patterns of responsiveness.

## 5.3. Spatializing agent typologies

The agent types described above were assigned to inventory plots in Norrbotten county based on ownership type and forest characteristics of the inventory plots in the initial state. The proportion of each agent type per ownership type was set according to the results of the questionnaire (Table 20).

The NFI plots were then, based on agent type, assigned to different forest domains, to which different forest management was applied through the simulation of different sets of treatment programs.

## 5.4. Additional model developments

No additional developments have been made.

# 6. European Union

## 6.1. G4M model description

The Global Forest Model (G4M; Kindermann et al., 2013) is a dynamic forest growth and evolution model that is designed principally for the purpose of simulating the evolution of forests on continental and global scales under a range of climate and management scenarios. The model breaks down the geographical area being considered into a finite set of grid cells (typically using the WSG84 projection). Within each grid cell, the spatial distributions of forests are not given. Forests are broken down by species with the default species categories distinguishing between coniferous and broadleaved forests, and between evergreen and deciduous forests and by ecoregion (tropical, subtropical, temperate, and boreal) what gives in total 16 forest types on global scale. Within each forest type it is possible to distinguish between slow, average, or fast culminating species. At local or regional scale, the growth pattern of some tree species like spruce, beach, fir, oak, or pine are explicitly represented in the model but yield estimates need to be provided from external sources. The forest structure within each cell and species is represented as a set of cohorts with different ages, each of which has an associated area, biomass stand density, tree diameter, and tree height.

Forest growth is determined by two submodels within G4M. Firstly, spatially explicit distributions of site productivity for each species group is estimated using climate (temperature, precipitation, radiation) and soil (water holding capacity, nitrogen and phosphorus content, acidity, and salinity) properties. Secondly, empirical yield tables are used to describe as functions of species, local productivity, and age the changes of forest properties such as growth, stock, removals, tree height, and tree diameters. Forest evolution is additionally determined for managed forest by local management practices. Simulated forest managers decide on thinning intensities, when to harvest, how much to harvest from each species and cohort, and which species to select for regeneration.

To capture natural disturbances (wildfires, specifically), G4M will be coupled with the wildFire cLimate impacts and Adaptation Model (FLAM) which captures impacts of climate, population, and fuel availability on burned areas and associated emissions. FLAM uses a process-based fire parameterization algorithm that was originally developed to link a fire model with dynamic global vegetation models. The key features implemented in FLAM include fuel moisture computation based on the Fine Fuel Moisture Code (FFMC) of the Canadian Forest Fire Weather Index (FWI), a procedure to calibrate spatial fire suppression efficiency, and the ability to include additional variables in fire modelling and prediction (Krasovskii et al., 2016; Jo et al., 2023).

The G4M model will be applied on the EU level, which is a larger scale than the models used in the regional case studies. This will be done by establishing a correlation between management decisions and the local forest conditions for different agent types. We will explore how the interactions of agent type and forest conditions influence final outputs to better understand how agent type and forest parameters influence decision-making and eventually how this influences forest growth and structure.

## 6.2. Agent types and management in G4M

A fundamental assumption in the calculations done for modelling management behaviors in the EU-27 context is that a forest practitioner's behavior is determined by two factors. One factor is the kind of forest manager the practitioner is, which we describe using a classification scheme with six categories corresponding to separate forest owner/manager types (optimizers, traditionalists, maximizers, passives, multi-functionalists, environmentalists, see Sotirov et al. 2019). The other factor is the local conditions in the forest the practitioner is responsible for. We consider in this case only natural location factors such as soil properties and climate conditions. An improvement could include also financial incentives for the forest practitioners.

We used the survey responses from all of the countries included in BIOCONSENT (excl. Bulgaria), as well as two countries in the Learn4Climate project (Poland and Slovenia) to develop a European-wide typology and predict agent management behaviour in a spatially explicit and time-dependent way for each of the relevant agent types. Since our aim is to determine separate models for management behaviour for each agent type, an important part of this task is the determination of the agent type for each of the survey respondents. This gives us a set of responses for each agent type from which the models can be derived. We have done this in two ways. Firstly, we combine the results of the clustering analysis performed on the results of each individual country by the individual national teams (see Sections 3-5), meaning that for example the set of respondents classified as maximizers is the combination of the sets of respondents classified as maximizers for each country. Secondly, we combine the responses for each country and perform the hierarchical clustering on the entire dataset. The first method has the advantage that the clustering is done in such a way that regional differences in the properties of each agent type have less of an effect on the clustering results, whereas the second method has the advantage of the clustering being done on a larger dataset. The second method is described here.

Based on the examples of the analysis done by the individual national teams, we do not consider passive and maximizer agent types as they are not considered to be sufficiently represented (or even absent altogether) in the survey responses. This means that we are looking for four clusters when performing the clustering. Similar to the regional/national case studies, we used hierarchical clustering on the answers to Questions 4 (“Forest management objectives”) and 6 (“Decision making rationalities”) of the survey to develop the clusters.

We compiled the survey responses for all respondents in Catalonia, Germany, Poland, Slovenia, and Sweden. The full sample contains 1573 respondents. There are 13 questions in Question 4 and 6 questions in Question 6, and the responses for all of these are categorical in nature. The hierarchical clustering method first calculates the distances between each of the respondents. Since the types of all responses are ordinal, the distance between two answers of a single question is defined to be proportional to the number of categories between them (such that the distance between answers 1 and 3 is double the distance between answers 1 and 2). Based on the examples of the individual national teams, the distance between two respondents is calculated using the Euclidean distance metric in such a way that respondents with missing values in any of the relevant questions are removed. Hierarchical clustering using this distance matrix and Ward’s method is performed

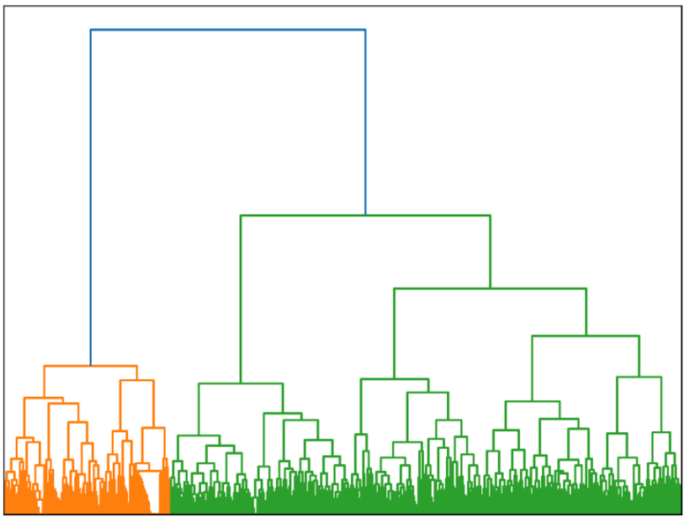


*Figure 9. Dendrogram showing hierarchical clustering on the entire European dataset.*

until there are four clusters. The dendrogram demonstrating the hierarchical clustering is shown in Figure 9. Based on the results of the individual national teams, we assume these clusters represent the optimizers, traditionalists, multi-functionalists, and environmentalists. The estimated number of respondents in each of the clusters and each of the countries is shown in Table 24.

*Table 24. The number of respondents in each country and each cluster.*

| | *Sweden* | *Germany* | *Catalonia* | *Poland* | *Slovenia* |
|---|---|---|---|---|---|
| **Cluster 1** | 74 | 44 | 168 | 14 | 88 |
| **Cluster 2** | 14 | 59 | 15 | 223 | 107 |
| **Cluster 3** | 32 | 26 | 62 | 50 | 133 |
| **Cluster 4** | 51 | 214 | 69 | 60 | 70 |
| **Total** | 171 | 343 | 314 | 347 | 398 |

Each of these four clusters is assumed to represent a single owner/manager category. For each cluster individually, we used the responses to Question 5 of the survey from the respondents to derive a model for predicting management decisions as a function of local properties that can be implemented as management behaviour in our G4M model.

Question 5 of the survey is designed to capture various aspects of forest management practices, including cutting and thinning regimes, species selection for regeneration, methods to improve biodiversity, and post-disturbance management strategies. Respondents provide information on current practices, changes they would make for biodiversity purposes, and adjustments they would adopt in response to climate change. Each sub-question offers four to five multiple-choice options.

Given that G4M models forests on scales larger than individual trees, there are limitations on how specific management actions can be represented, and many fine-scale decisions cannot be directly distinguished within G4M. Below, we outline how we address these limitations and map survey responses to model parameters.

- **Cutting Regimes:** The cutting regime question has the options 'clear felling', 'group selection', 'single tree selection', and 'no cutting'. Since G4M does not distinguish between the first three options, we simplify the responses to a binary choice of 'cutting' and 'no cutting'.
- **Thinning Regimes:** Similarly, G4M does not model the distribution of tree sizes within a cohort so it cannot distinguish between thinning from above, below, and all size classes and we therefore only distinguish between the options 'thinning' and 'no thinning'.
- **Species Selection for Regeneration:** The species selection aspect is crucial for forest composition and dynamics. We define dominance by species groups (broadleaf vs. needleleaf) using a 75% threshold for forested area within a model pixel. Forests with more than 75% of their area covered by one group are considered dominated by that group.
- **Regeneration Method:** Since planting with material obtained from tree breeding or doing enrichment planting is associated with enhanced forest growth, we account for these methods by applying a 25% increase (based on Isaac-Renton et al. 2020) in the forest growth productivity in pixels where these methods are chosen. The unique regrowth dynamics when doing coppicing is not implemented within G4M and so

respondents this response is not considered in the regression method and is instead treated as missing data.

- **Biodiversity Enhancement:** If the respondent indicates that they would set aside forest with no active management, we consider the forest unmanaged regardless of the responses to other parts of the question. If they indicate that they would increase deadwood, we add 10% of harvested stemwood to the deadwood pool in the fuel model used for coupling G4M and FLAM.
- **Post-Disturbance Management:** The post-disturbance management question is simplified into two outcomes: removal or retention of carbon from trees that die. This influences the deadwood pool post-disturbance.

Table 25 gives the scheme for converting from survey responses to management decisions resolvable by G4M.

*Table 25. Detailed scheme for converting responses of Q5 of the survey to management options that can be modelled by G4M. In the final column, the letters in parentheses give the corresponding options in the original responses.*

| Question | Original options | G4M management options |
|---|---|---|
| Main cutting regime | A) Clear felling<br>B) Group selection<br>C) Single tree selection<br>D) No cutting | 1) Cutting (A, B, C)<br>2) No cutting (D) |
| Main thinning regime | A) Thinning from above<br>B) Thinning from below<br>C) Thinning from all size classes<br>D) No thinning | 1) Thinning (A, B, C)<br>2) No thinning (D) |
| Main tree species selection | A) Maintain current composition<br>B) Shift to broadleaves dominated forest<br>C) Shift to conifer dominated forest<br>D) Shift to mix species forest<br>E) Use of non-native tree species | 1) Replant as the same species (A)<br>2) Replant with share of 75% broadleaf and 25% needleleaf if the broadleaf share is <75% (B)<br>3) Replant with share of 75% needleleaf and 25% broadleaf if the needleleaf share is <75% (C)<br>4) If broadleaf share is <25%, replant as 25% broadleaf and if needleleaf share is <25%, replant as 25% needleleaf (D)<br>5) Replant as same species but with 10% increase in increment (E) |
| Main regeneration method | A) Planting with regular planting material<br>B) Planting with planting material obtained from tree breeding<br>C) Natural regeneration<br>D) Enrichment planting<br>E) Coppice | 1) Increase productivity by 25% (B, D)<br>2) Keep same productivity (A, C, E) |
| Main biodiversity improvement method | A) Set aside forest, with no active management<br>B) Increasing deadwood and microhabitats in managed forests<br>C) Increase diversity in tree sizes<br>D) None | 1) Do no management, overriding any options from other question (A)<br>2) Shift 10% of harvested wood to harvest residuals, increasing deadwood (B)<br>3) Do nothing (C, D) |

| Question | Original options | G4M management options |
|---|---|---|
| Post-disturbance management | A) Salvage logging with planting<br>B) Salvage logging with natural regeneration<br>C) Leaving all wood with natural regeneration on the forest area affected by disturbances<br>D) No post-disturbance management | 1) Do not add killed carbon to deadwood for fuel model (A, B)<br>2) Add all killed carbon to deadwood for fuel model (C, D) |

For each agent type, we derive a model to predict management behaviors as a function of local conditions. It is therefore necessary to derive locations for the forests of all respondents.

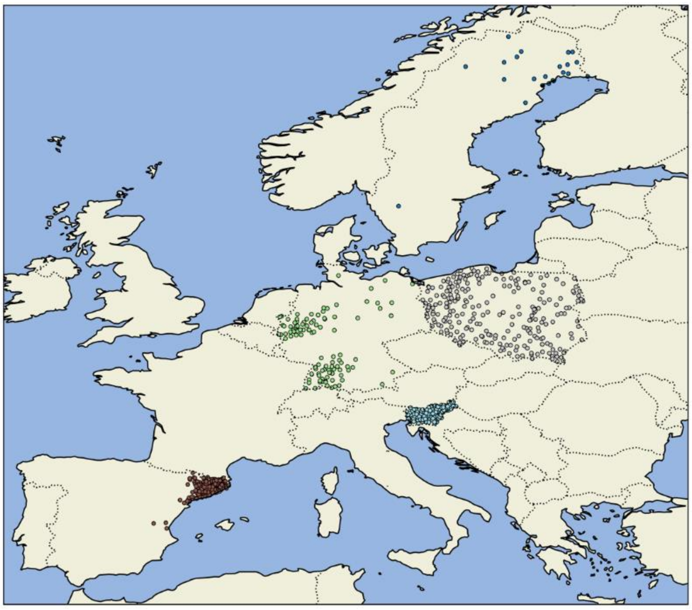


*Figure 10. Locations of survey respondents based on municipality.*

We did this using Question 10 of the survey, which asked respondents to name the municipality in which their forest is located. Each response is given to the Python package GeoPy which can take a location name and return latitude and longitude of the location. As a test of the results, each set of coordinates is then given to the reverse_geocoder Python package to determine that the results are in the correct country. The derived locations are shown in Figure 10. For Poland and Slovenia, the distributions of responses give a relatively good even coverage of the entire country. For the other countries the distributions are more biased to specific regions. However, the sample still spans most of geographic Europe and can plausibly be considered representative of most regions of Europe. We note that since each point represents a single municipality in which a single respondent's location was found, each point on the figure can correspond to multiple survey responses if multiple respondents were found to be in the same municipality. This is especially important for Sweden where 84 respondents were located within only 18 municipalities.

We derive a predictive machine learning model for the responses to each of the answers to Question 5. The question has six parts, with three responses given for each corresponding to current practice and how they would change their management for biodiversity improvement purposes and for to adapt to climate change impacts. We therefore have 18 parts of Question 5 that we take as the dependent variables (i.e. the quantities we are predicting) in our model. Predictions for these 18 quantities are done for each of the four agent types separately and as a comparison for the entire sample of respondents. For the individual agent types, the analysis is performed both on the results of clustering with the responses from individual nations separately and on the results of clustering with the entire pooled dataset together. Since this leads to a very large number of management maps being produced, we only show a subset of results in here.

Due to the nature of G4M, we are not able to use the exact set of response options for each question. For example, the survey options for the main cutting regime question in Question 5 has the options clear felling, group selection, single tree selection, and no cutting. The first three options are not distinguished in G4M  and we cannot use all options separately. We therefore categorize the responses to this question as simply cutting and no cutting and derive models for these two options. Table 25 gives for all parts of Question 5 the conversions from the catatorizations of the answers in the survey (‘Original options’) to cateogorizations that can be used by G4M (‘G4M Management Options’).

Our model predicts the categories from the G4M management options using spatially explicit maps of forest coverage and forest growth productivity as the independent variables. The forest coverage maps are taken from the MODIS combined land cover product and represented as a percentage of each pixel covered in each species category. The forest productivity maps are calculated using the productivity model within G4M which calculates net primary productivity (NPP) in units of tC year$^{-1}$ ha$^{-1}$ for each species category as a function of local climate (precipitation, temperature, solar radiative flux) and surface (elevation, soil N and P concentrations, soil pH and salinity, water availability) parameters. The species categories considered are evergreen needleleaf, evergreen broadleaf, deciduous needleleaf, deciduous broadleaf, and woody savannah. The use of climate parameters means that we can make time dependent predictions of management decisions for different climate scenarios. For each of the respondents in the survey with coordinates identified, the local values of the independent variables are derived by taking the values from the closest pixels in these spatially explicit maps.

We consider it likely that there are regional differences in the behaviours of forest practitioners, such that a practitioner of a certain agent type in one part of Europe does not always behave the same as a practitioner of the same agent type in another part of Europe, even when presented with similar local conditions. To take into account these regional differences, we also include as an independent variable in our model the region of Europe that a given respondent is in using the regions adopted from Winkler et al. (2023) and discussed below in Section 6.3. This should have the effect of strengthening the influence of responses from a given region on the management decisions within that region.

*Table 26. Cross-validation accuracy scores for the random forest fits to each part of the G4M management options (summarized in Table 21). These fits are based on the answers to Question 5. The fits were performed for assuming the entire set of survey responses (All agents), and filtering responses separately for each individual agent category (Agents 1-4). For each of the individual agents, fit scores are given for the cases of the agents determined from clustering on the entire pooled data (upper rows labelled ‘Pool’) and for clustering done on each country separately (lower rows labelled ‘Nat’). For each agent type, fits are done to the questions regarding current practice and how they would change their management for biodiversity improvement purposes and for to adapt to climate change impacts. Each column gives the values for the subsections of Question 5 with the $n_{opt}$ value in parentheses giving the number of options in each category.*

| | | | **Cutting ($n_{opt}$=2)** | **Thinning ($n_{opt}$=2)** | **Species ($n_{opt}$=5)** | **Regen. ($n_{opt}$=2)** | **Biodiv. ($n_{opt}$=3)** | **Disturb. ($n_{opt}$=2)** |
|---|---|---|---|---|---|---|---|---|
| **All agents** | **Current practice** | | 0.87 | 0.84 | 0.45 | 0.64 | 0.51 | 0.84 |
| | **Biodiversity purposes** | | 0.87 | 0.82 | 0.49 | 0.54 | 0.57 | 0.78 |
| | **Climate change** | | 0.87 | 0.82 | 0.48 | 0.53 | 0.58 | 0.82 |
| **Agent 1** | **Current practice** | **Pool:** | 0.68 | 0.63 | 0.49 | 0.78 | 0.56 | 0.66 |
| | | **Nat:** | 0.95 | 0.95 | 0.45 | 0.66 | 0.49 | 0.89 |
| | **Biodiversity purposes** | **Pool:** | 0.71 | 0.62 | 0.44 | 0.66 | 0.57 | 0.58 |
| | | **Nat:** | 0.94 | 0.90 | 0.46 | 0.51 | 0.53 | 0.85 |
| | **Climate change** | **Pool:** | 0.66 | 0.58 | 0.56 | 0.69 | 0.65 | 0.62 |
| | | **Nat:** | 0.91 | 0.91 | 0.45 | 0.52 | 0.57 | 0.89 |
| | **Current practice** | **Pool:** | 0.93 | 0.94 | 0.53 | 0.65 | 0.54 | 0.94 |
| | | **Nat:** | 0.92 | 0.88 | 0.44 | 0.72 | 0.49 | 0.88 |

| | | | Cutting ($n_{opt}$=2) | Thinning ($n_{opt}$=2) | Species ($n_{opt}$=5) | Regen. ($n_{opt}$=2) | Biodiv. ($n_{opt}$=3) | Disturb. ($n_{opt}$=2) |
|---|---|---|---|---|---|---|---|---|
| **Agent 2** | **Biodiversity purposes** | **Pool:** | 0.92 | 0.89 | 0.51 | 0.54 | 0.56 | 0.86 |
| | | **Nat:** | 0.90 | 0.94 | 0.47 | 0.56 | 0.57 | 0.76 |
| | **Climate change** | **Pool:** | 0.89 | 0.91 | 0.49 | 0.52 | 0.55 | 0.87 |
| | | **Nat:** | 0.90 | 0.90 | 0.46 | 0.55 | 0.63 | 0.88 |
| **Agent 3** | **Current practice** | **Pool:** | 0.77 | 0.75 | 0.51 | 0.69 | 0.55 | 0.73 |
| | | **Nat:** | 0.79 | 0.73 | 0.46 | 0.72 | 0.63 | 0.72 |
| | **Biodiversity purposes** | **Pool:** | 0.73 | 0.76 | 0.47 | 0.64 | 0.61 | 0.65 |
| | | **Nat:** | 0.82 | 0.70 | 0.48 | 0.70 | 0.63 | 0.70 |
| | **Climate change** | **Pool:** | 0.77 | 0.71 | 0.45 | 0.53 | 0.70 | 0.66 |
| | | **Nat:** | 0.81 | 0.68 | 0.49 | 0.63 | 0.72 | 0.73 |
| **Agent 4** | **Current practice** | **Pool:** | 0.96 | 0.92 | 0.47 | 0.63 | 0.53 | 0.89 |
| | | **Nat:** | 0.73 | 0.63 | 0.50 | 0.88 | 0.48 | 0.77 |
| | **Biodiversity purposes** | **Pool:** | 0.97 | 0.89 | 0.49 | 0.59 | 0.61 | 0.84 |
| | | **Nat:** | 0.76 | 0.61 | 0.46 | 0.80 | 0.56 | 0.63 |
| | **Climate change** | **Pool:** | 0.94 | 0.87 | 0.43 | 0.61 | 0.64 | 0.91 |
| | | **Nat:** | 0.69 | 0.64 | 0.54 | 0.71 | 0.51 | 0.68 |

To predict the management decisions for the entire sample and for each agent type from the independent variables, we use the random forest method as implemented in the SciPy package. Since the variables to be predicted are categorical in nature, we use the Gini impurity as our goodness-of-split measure. The additional hyperparameters that we determine are the number of decision trees and the maximum tree depths to be used. We fit these parameters by fitting a grid of models with different values of these two quantities. For each for each set of values, we use 5-fold cross-validation and the accuracy criterion (i.e. the fraction of predictions from the model that are correct) to determine the goodness-of-fit. The chosen set of these two hyperparameters are the ones that give the highest goodness score. We also tested a modified version of the cross-validation method in which the set of respondents are partitioned by country, meaning that we train the model on four of the five countries and then test the model on the country left out. The results using this cross-validation method are similar to those found when using normal cross-validation. Cross validation scores for each of the model fits are given in Table 26. Note that the results presented in this section assume current climate conditions and the maps shown can change in the future due to climate change.

Europe-wide maps of management decisions for each of the questions in Q5 and each of the three cases (current management, management for biodiversity improvement purposes, and management to adapt to climate change impacts) are shown in Figure 11. These maps are from the model that is trained on the entire set of respondents. The maps show that when considering all respondents together, the management maps are similar for the three scenarios. The largest differences between the methods can be seen for the main regeneration method and biodiversity management questions. When aiming for biodiversity improvement and climate change adaption, practitioners would not significantly change their decisions on whether to harvest and perform thinning, as well as which species to select for replanting and post-disturbance management, but would change their regeneration methods and biodiversity management in much of Europe.

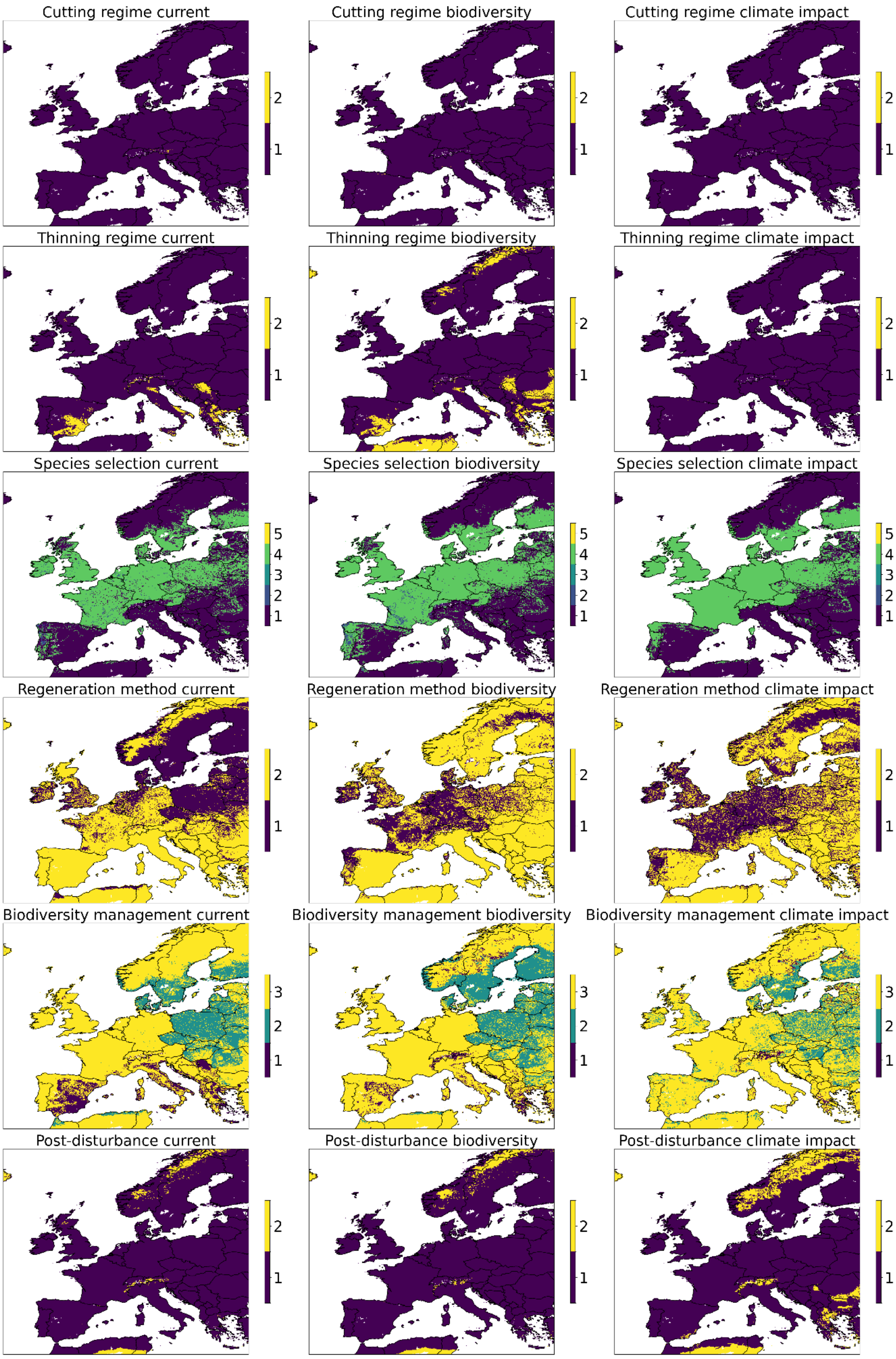



*Figure 11. Spatially explicit maps of management decisions as predicted for our machine learning regression model trained on all survey responses pooled (n=1573). The rows correspond to the questions from Question 5 and the columns correspond to current management (left), management for biodiversity improvement purposes (middle), and management to adapt to climate change impacts (right). In each panel, the colours corresponding to the G4M management options given in Table 21 (third column). In the cutting and thinning panels, blue shows where cutting/thinning is performed and yellow where it is not performed. In the species selection panels, the two most common colours are blue for replanting as the same species and green for shifting to mix species forest. In the*

*regeneration method panels, blue corresponds to management decisions that increase productivities and yellow to decisions that do not influence productivities. In the biodiversity management panels, blue shows no management, green shows management that leaves some harvested wood on the ground, and yellow shows no action taken. In the post disturbance management panels, blue corresponds to removal of deadwood and yellow to leaving the deadwood on the ground.*

For both the cutting and thinning regime questions, cutting/thinning is done in almost all locations as is expected for managed forested, with some regions of no thinning being predicted in southern Europe and additionally in the far north for the biodiversity improvement scenario. Note that in our European-wide forest models, we will exclude cutting and thinning in protected forests. For the regeneration method question, most of western Europe and much of eastern Europe chooses to shift to mixed forest, whereas southern and northern Europe typically chooses to maintain current composition. For the main biodiversity improvement method, most practitioners choose to either increase deadwood and microhabitats in western Europe and the far North or to do nothing in eastern Europe and southern Sweden and Finland.

Management maps for the models fitted to the individual agent types are shown in Figure 12 and Figure 13 for the cutting regime question and Figure 14 and Figure 15 for the species selection question. We only show the answers to two questions to reduce the number of figures shown and choose these two questions to show almost arbitrarily. Figure 12 and Figure 14 show the results with the agent type assignment performed using the clustering on the entire pooled dataset and Figure 13 and Figure 15 show the results for the agent assignment performed using the clustering on each individual national team separately. While these results are mostly similar on a European scale to results where single models are fit to all respondents without considering agent type, some quite significant differences can be seen. Differences between the three scenarios are larger when considering the different agent types separately and in many cases quite large differences can be seen between the agents, meaning that it is possible that breaking forest practitioners down into individual agent types improves our description of how practitioners respond to incentives for biodiversity improvements and climate adaption. In particular, we find that in some of Europe, agents often choose to use non-native tree species, whereas in the description that does not considers all agent types together, this option is rarely seen. We find a similar thing for the choice to shift to broadleaf dominated forests.

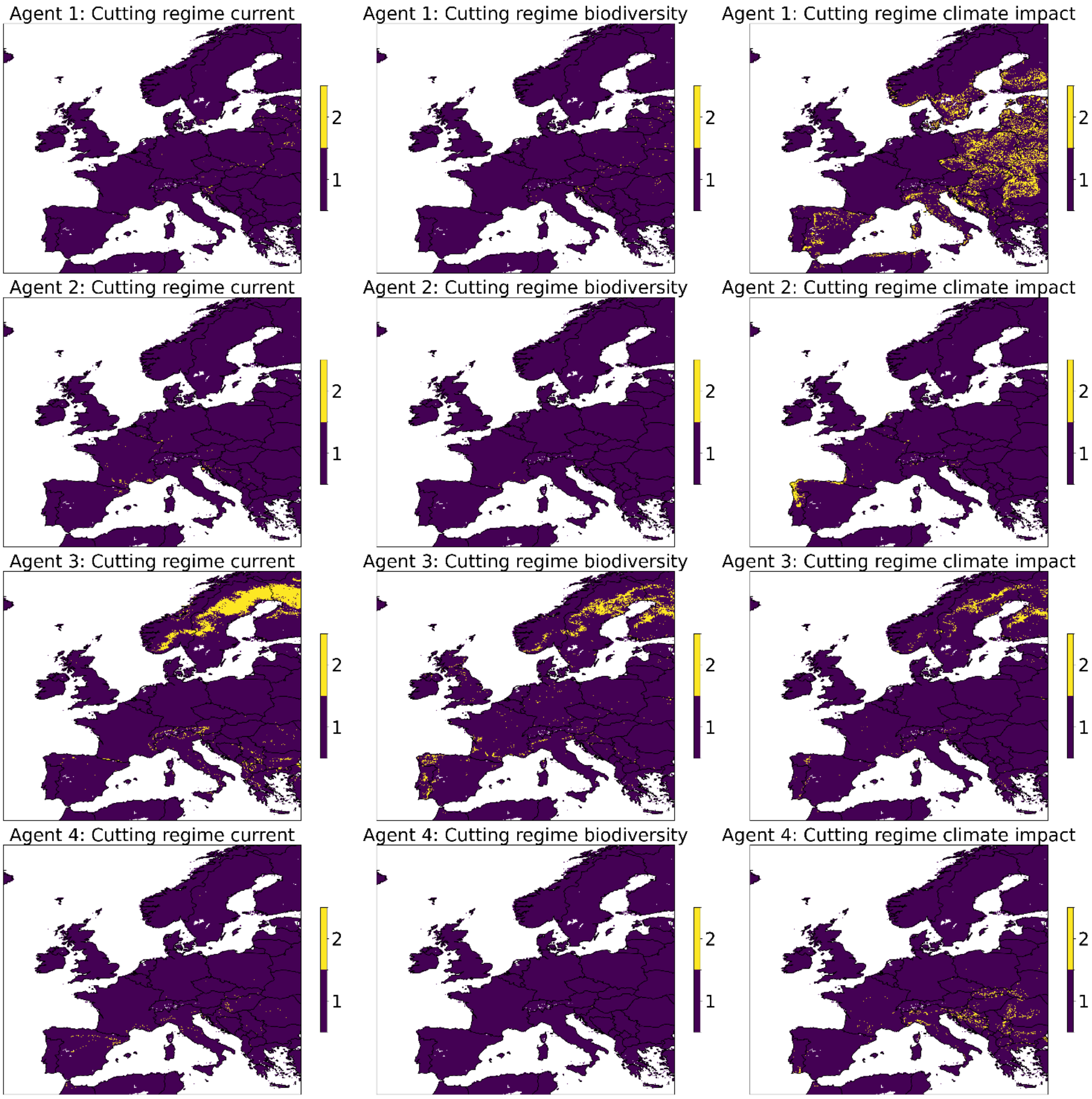



*Figure 12. Predicted distribution of cutting regimes. Each column is as in Figure 11 and the rows show the results for each of the four identified agent types (optimizers, traditionalists, multi-functionalists, and environmentalists).For each agent type, these show if cutting is done in each pixel if that agent is present. Blue shows where cutting is performed and yellow where it is not performed.*

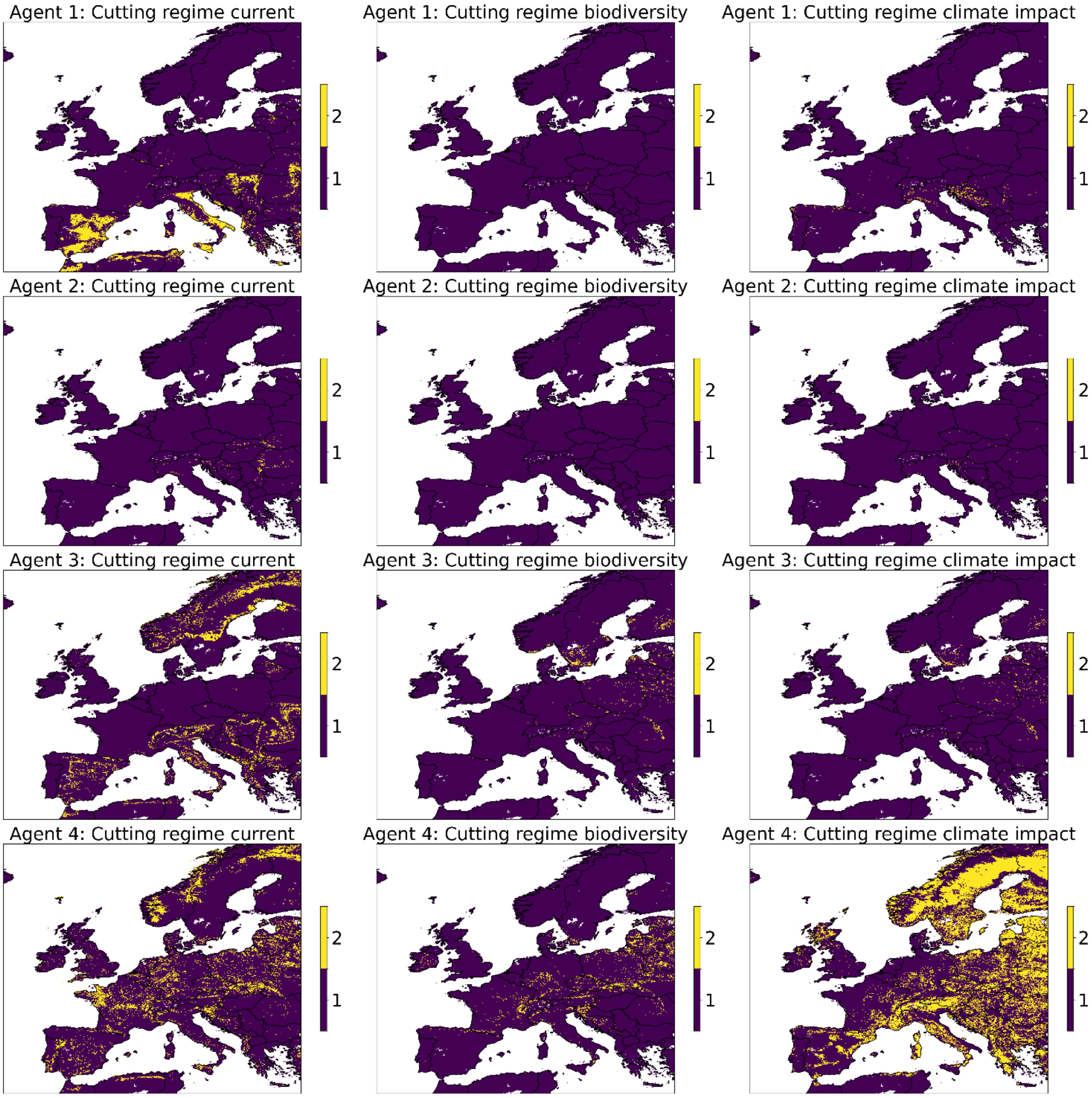



*Figure 13. Same as Figure 12 but using the clustering results from the individual national teams to assign survey respondents to each agent type. Blue shows where cutting is performed and yellow where it is not performed.*

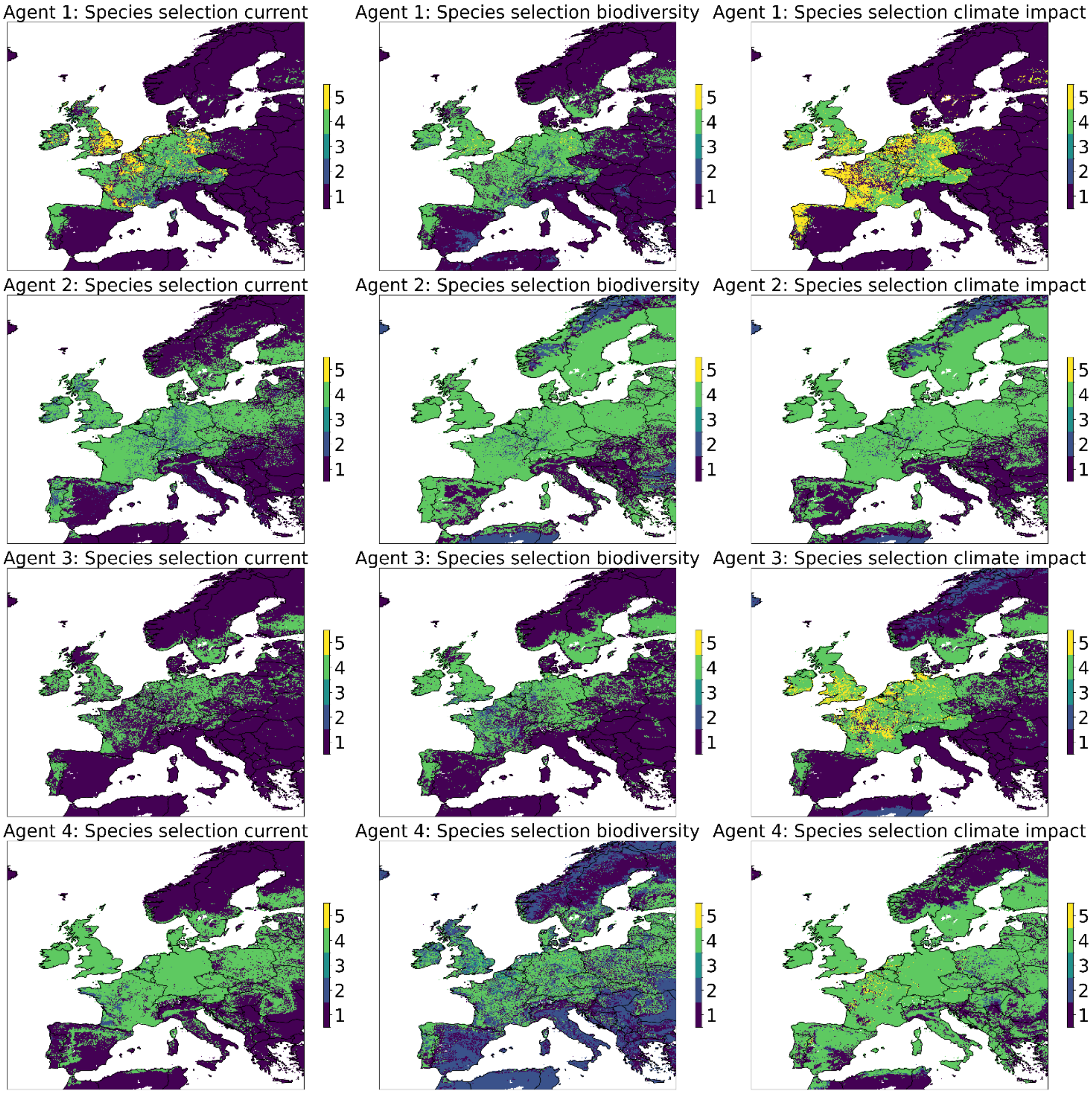



*Figure 14. Predicted distribution of tree species selection. Each column is as in Figure 11 and the rows show the results for each of the four identified agent types (optimizers, traditionalists, multi-functionalists, and environmentalists). For each agent type, these show the species selection regime (see Table 21 for the meanings of the values) in each pixel if that agent is present. The management options shown are replanting as the same species (dark blue), switching to broadleaf dominated forests (light blue), switching to needleleaf dominated forests (dark green), switching to mixed forests (light green), and use non-native species (yellow).*

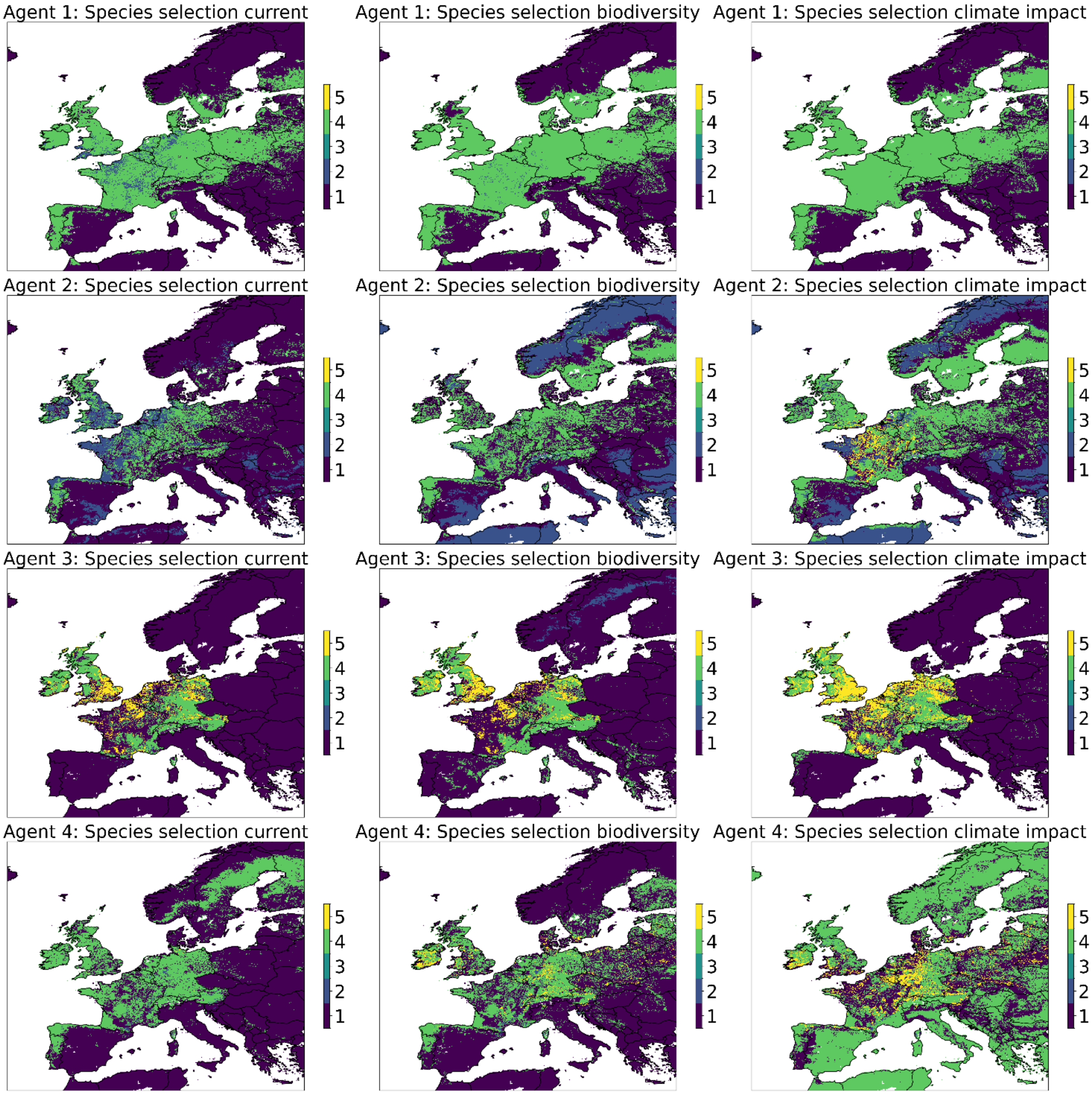



*Figure 15. Same as Figure 14 but using the clustering results from the individual national teams to assign survey respondents to each agent type. The management options shown are replanting as the same species (dark blue), switching to broadleaf dominated forests (light blue), switching to needleleaf dominated forests (dark green), switching to mixed forests (light green), and use non-native species (yellow).*

## 6.3. Spatializing agent typologies

Using the results of the previous section, we will run dynamic forest models with G4M for each of the agent types separately assuming all forested area is covered in that agent type. To get the final model, we will combine the results of these individual agent models. It is therefore necessary to determine the distribution of these agent types across Europe. Within each modelled pixel, we need the fraction of forested area managed by each agent type. We estimate this distribution by breaking down Europe into four regions named Europe-North, Europe-East, Europe-South, and Europe-West. The definitions of these regions are adopted from Winkler et al. (2023) and shown in Figure 16. The regions Europe-North, Europe-East, and Europe-West each contain one country represented in the survey (Sweden, Poland, and Germany respectively), and the region Europe-South contains two countries represented in the survey (Slovenia and Spain).

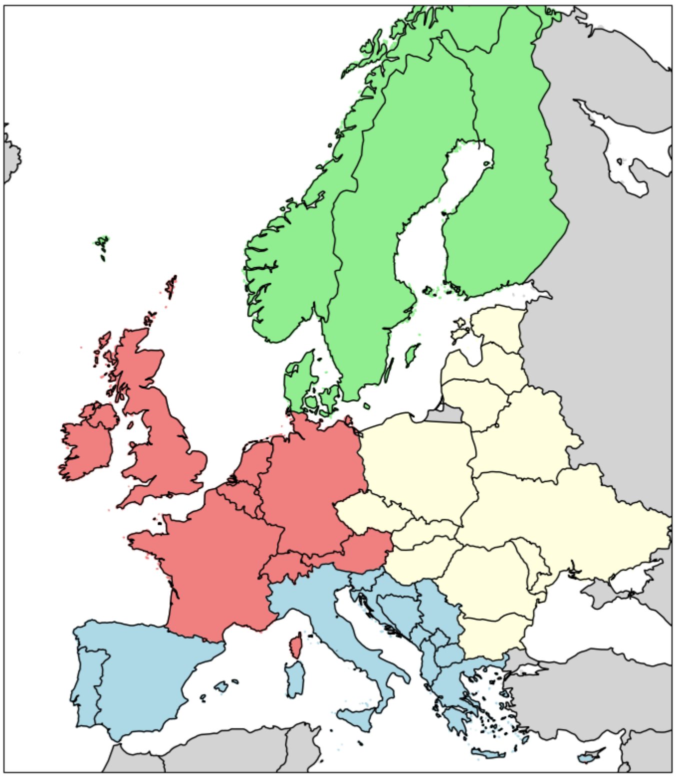


*Figure 16. The four regions of Europe that we assume for spatialising agent types. The regions are Europe-North (green), Europe-East (yellow), Europe-South (blue), and Europe-West (red).*

We assume that the fractional area covered by each agent type in each pixel is uniform within a region. For each region, we can therefore derive the fractional area coverage of agent type from the survey responses of the country or countries representing that region and assume this for all countries in that region. The area of forest that each survey respondent is responsible for was asked in Question 9 of the survey. To get the fractional area distribution, we therefore additionally assume that the actual distribution of areas among the agent types is the same as the distribution of areas implied by the sample of survey respondents. This method has the advantage that it means that in the countries where the survey was conducted the agent distribution matches our expectations from the survey responses exactly. The distributions for the four regions are shown in Figure 17.

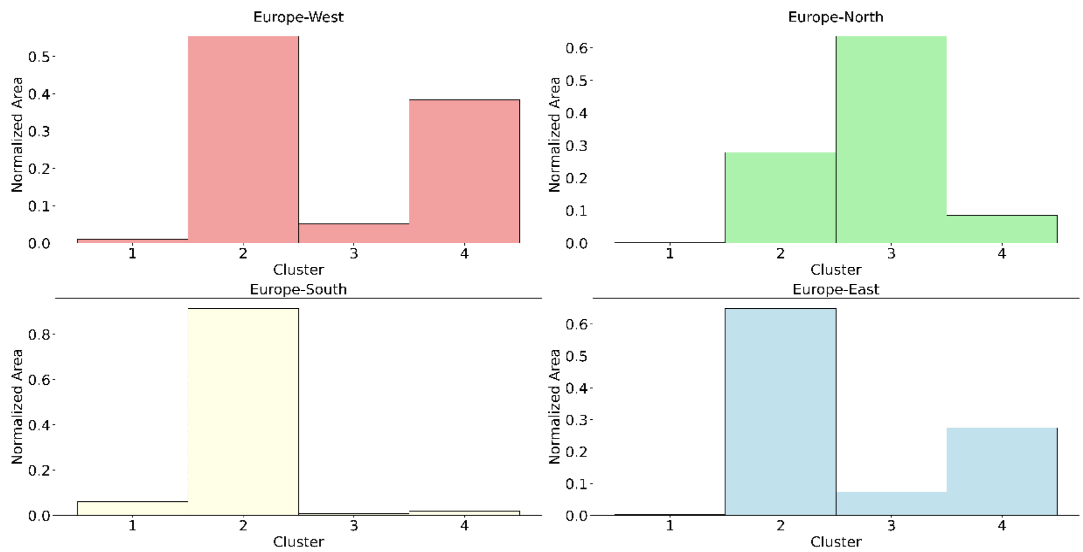



*Figure 17. Distributions of area among the four agent types for each of the regions shown in Figure 11.*

## 6.4. Additional model developments

The G4M model was designed to simulate the effects of forest management and changing climate conditions on forest development. Integrating the survey results into the Europe-wide forest modelling requires a high level of flexibility for how the model handles management decisions. For this reason, we have developed a new, more flexible Python implementation of the G4M model to replace the older C++ code. This allows us to model a broader range of management options.

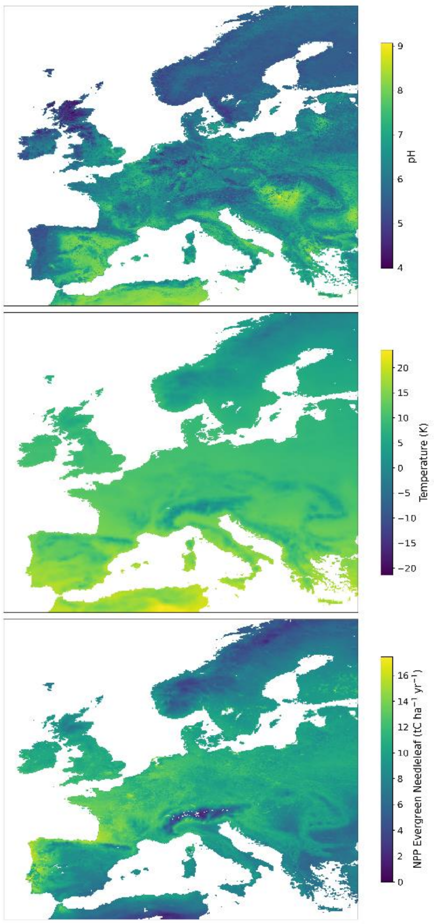



*Figure 18. Figures of soil pH (upper panel), yearly average surface temperature (middle panel), and theoretical evergreen needleleaf NPP (lower panel).*

Another important part of the G4M model is the calculation of forest growth productivity in the form of potential net primary production for each species category considered. For each species, this quantity can be understood as the NPP assuming that species covers the entire map. This quantity is used in BIOCONSENT for two purposes. Firstly, it is used as an independent variable in the regression analysis presented above for predicting management behaviour in a spatially-explicit and time-dependent way. Secondly, it is used to quantify growth productivity in the growth equations used for the forest development algorithm.

The productivity model requires a range of surface and climate parameters as input. For the Europe-wide G4M runs to be done as part of BIOCONSENT, we have collected and processed all of the necessary input data, producing surface maps of soil nitrogen and phosphorus concentrations, soil pH and salinity, surface elevation, and the climate parameters precipitation, temperature, and solar radiative flux. The climate parameters are calculated as monthly average from 2015 to 2100 and have been prepared for the climate scenarios SSP126, SSP245, SSP370, and

SSP585. The climate data used originates from the NASA Earth Exchange Global Daily Downscaled Projections (NEX-GDDP-CMIP6), specifically derived from the GFDL-ESM4 model. For the purpose of consistency with other modelling groups in BIOCONSENT, we might rederive the input parameters using data from other climate models. Europe-wide maps of one of the soil parameters (pH), one of the climate parameters (temperature), and the resulting productivity maps for one of the species categories considered (evergreen needleleaf) are shown in Figure 18.

The task that has required the most original development has been for the dynamic coupling between the G4M and FLAM models in order to take into account disturbances and post-disturbance management. The primary issue is the need for G4M to include a model for deadwood and litter produced by forests to be used as fuel in the FLAM fire algorithm. Previously G4M was only concerned with the living biomass in forests and contained no prescription for deadwood and litter. While a simple and common first approximation based on the assumption that the surface density of fuel is a fixed fraction of the living biomass is often sufficient, it would not capture some of the effects necessary for our purposes in this project. Most importantly, in the final part of Question 5 of the survey, the respondents indicated if they would harvest or leave dead trees after a disturbance, which is important for the fuel model.

We extended G4M to contain also a coupled dynamic model for fuel that evolves the carbon surface densities of deadwood and litter considering the effects of background accumulation, mortality, decomposition, harvests, and disturbances. The fuel densities are broken down into a fast decomposition component and a slow decomposition component, corresponding approximately to the litter and the deadwood respectively. In the near future, the model will be updated to distinguish also between lying deadwood and standing deadwood since the latter has a much slower decomposition rate. The rate of background accumulation is assumed to be proportional to the living biomass and the rate of decomposition (in mass of carbon decomposed per unit time per unit area) is proportional to the fuel surface densities. The effects of harvests and disturbances come naturally from the G4M model. An important parameter in determining the effects of disturbances is the fraction of killed carbon that remains in the forest as deadwood. The difference in the fuel post-disturbance for the extreme cases of all killed carbon being removed and all killed carbon remaining in the forest is shown in Figure 19. The extreme cases are used for the purposes of demonstrating the model, and our model is flexible for how much of the carbon is killed in a disturbance and how much of that is let in the forest post-disturbance.

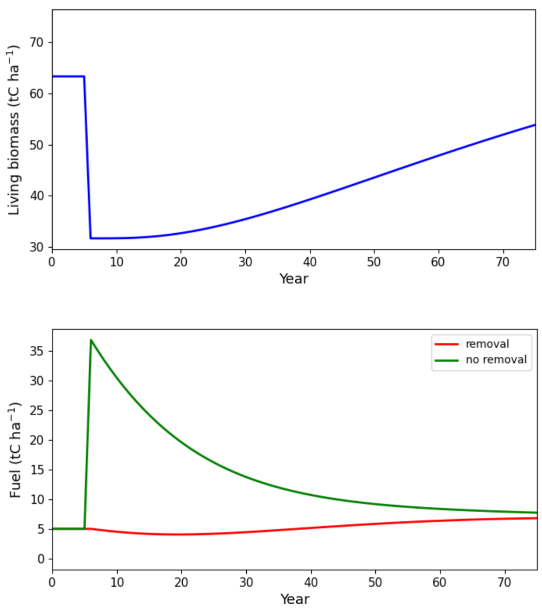



*Figure 19. Upper panel: evolution of living biomass in a forest over 75 years assuming a disturbance that kills half of the living biomass in year 5. Lower panel: evolution of fuel densities in this scenario separately assuming for the purposes of demonstrating the model the extreme cases of all killed carbon remaining in the forest (green) and assuming all killed carbon being removed (red).*

The fraction of killed carbon that remains dependents heavily on the post-disturbance management employed. This is probed in the final part ('Post-disturbance management') of Question 5 of the survey in which answers A and B would indicate much of the killed carbon is removed and answers C and D would indicate the remaining carbon will be left. This dynamic fuel model will therefore allow us to probe the difference between the answers in this part of the survey.

# 7. Synthesis

This report describes how four biophysical forest models (EFISCEN-space, FORMES, HEUREKA and G4M) were improved with regards to the representation of behavior and behavioral change of forest owners and managers. Human agency is often mostly included in such forest models through scenarios, but in this study, we tried to include human agency in the models themselves. In the four models, this was achieved based on a survey conducted by Sotirov et al. (2025) who identified agent typologies across Europe. We extended their analysis by analysing the main management practices applied by these agent types (in all four case studies) and what factors are shaping the decision-making (in the German and Catalan case studies only).

Based on the survey results, three to four agent types could be identified by Sotirov et al. (2025), which included Multi-functionalists, Optimizers, Traditionalists (not in the Swedish case study), and Environmentalists. According to the theorical framework by Sotirov et al. (2019), two other typologies (Passives, Maximisers) could be theoretically present, but they could not be identified from the survey results. As a results, these types could not be considered in the models. Only in the Catalan case study, Passives could be identified with the help of complementary data on forest management plans. In general, our analyses revealed rather minor differences in management practices between agent typologies.

Surprisingly, our analyses revealed that the type of forest management is mostly determined by the type and structure of the forests. More specifically, our results indicate that agent typologies add little (German case study, section 3.2) to no (Catalan and Swedish case studies, section 4.2 and 5.2, resp.) information in addition to forest structure in understanding which management practise is applied by a forest owner or manager. This finding could be related to the survey design and timing, for example due to current concerns on the effects of recent droughts and bark-beetle outbreaks, it but may also reflect that there are existing management prescriptions and guidelines that prescribe how forests should be managed and that these influence the choice of an owner or manager to adopt a certain practise. Moreover, the structure of the forest is, at least partly, the result of past management decisions and therefore also indirectly reflects human behaviour in the past.

The analyses of the German and Catalan case studies revealed that, according to the survey results, only a limited set factors drive management behavior and behavorial change. According to the results for the German case study, ecological variables are among were most important for all agent types, complemented by the respondents' own values, objectives, knowledge and experience, as well as economic variables such as timber prices and forest management revenues and costs (Table 3). This was also confirmed by the Random Forest models that were developed, and which highlighted the importance of forest structure over ownership or agent type (section 3.2.1). Except for information instruments, policy variables had generally lesser importance in shaping your forest management decisions in Germany compared to other variables. Nevertheless, among the policy variables, there were some significant differences between traditionalists and multifunctionalists and between traditionalists and optimisers (see Table 4). In a context of recent large-scale disturbances, the importance of ecological variables (e.g., the health, ecological, and silvicultural status of forests, climate change impacts) over policy variables in the German case studies might support the finding by Erdozain et al. (2025) that natural disasters trigger change.

Somewhat similar results were obtained for the Catalan case study. Based on the ranking of the variables, forest road infrastructure and transport, own knowledge and experiences and silvicultural state of the forest appeared among the most important factors for all agent types. Damage after a natural disaster appears for all the types except for the multifunctionalists. Forest cost and revenues appear for all categories except for the environmentalist, and climate change impacts appears only for the environmentalists. Availability of labour appeared as important only for the multifunctional owners. With regards to important factors for changing to improve biodiversity restoration and conservation in forest management, subsidies for forest management and natural evolution, availability of labour, joint technical management and forest improvement plans and innovations were among on the most important factors, whereas the availability labour is the only factor that showed a significant difference between multifunctionalists and optimisers versus traditionalists and environmentalists.

Altogether, these findings indicate that, according to our results, many factors shape the decisions by forest owners and managers with regards to their forest management. The importance of policy factors appears to be relatively limited. Instead, traditions in forest management, as well as other factors that determine the structure of forests (e.g., climate change), appear to play a very important role in current forest management decision-making.

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# Definitions

In this section, we provide comprehensive definitions for the key terms and concepts used throughout this document in order to promote clarity and understanding through WP3 and the BIOCONSENT project.

For the purposes of this document, the following definitions apply:

(1) 'agent' means a diverse groups of forest owners and conservation managers.

(2) 'behaviour' means the set of forest management practices opted to be implemented by the forest owners and conservation managers.

(3) 'forest management' practices are defined by the combination of the following options:

*Table 27. Forest management practices considered in the BIOCONSENT project.*

| Forest Management practice | Species selection | Regeneration | Thinning | Harvesting | Biodiversity improvements methods | Post-disturbance management |
|---|---|---|---|---|---|---|
| **Option 1** | Maintain current composition | Planting with regular planting material | Thinning from above | Clear felling | Set aside forest | Salvage logging with planting |
| **Option 2** | Shift to broadleaves dominated forest | Planting with planting material obtained from tree breeding | Thinning from below | Group selection | Increasing deadwood and microhabitats | Salvage logging with natural regeneration |
| **Option 3** | Shift to conifers dominated forest | Natural regeneration | Thinning from all size classes | Single tree selection | Increase diversity in tree sizes | Leaving all wood with natural regeneration on the forest |
| **Option 4** | Shift to mix species forest | Enrichment planting | No Thinning | No cutting | | No post-disturbance management |
| **Option 5** | Use of non-native tree species | Coppice | | | | |

The options shown in the table are vertically self-excluding options. Agents can choose only one option for each Forest management practice (columns).

(4) 'socio-economic factors' means the set of different policy, economic social, technological and ecological factors described in the table below.

*Table 28. Socio-economic factors considered in the BIOCONSENT project.*

| Policy | Economic | Social | Technological | Ecological |
|---|---|---|---|---|
| Regulatory forestry policy (objectives, targets, standards in law and bylaw) | Forest management costs and revenues | Forest property structure (property size and fragmentation) | Monitoring, assessment and availability of data (e.g. on forests, on biodiversity status, effects of climate change and natural disasters) | Silvicultural state of forest (e.g. age classes, productivity, forest growth, bio-physical conditions) |
| Regulatory biodiversity policy | Timber prices | My values, objectives, | Technologies and innovations in | Health status of forest (e.g., disturbances |

| Policy | Economic | Social | Technological | Ecological |
|---|---|---|---|---|
| (objectives, targets, standards in law and bylaw) | | knowledge and experiences | forest management (e.g., digitalisation, timber harvesting, tree breeding, planting) | and/or damages after drought, storm, fire, insects and pathogens) |
| Regulatory climate policy (objectives, targets, standards in law and bylaw) | Energy wood prices | Generational shift on my property and/or my management organisation) | Forest road infrastructure and transport | Ecological and biodiversity status of forest (e.g., ecological processes, favourable or non-favourable conservation status, functionality and connectivity of the forest ecosystem) |
| Regulatory water policy (objectives, targets, standards in law and bylaw) | Income from other marketable goods than timber (water, recreation, biodiversity, carbon sequestration) | Media and societal pressure by the public, environmental NGOs and other civil society groups | Technologies and innovations in forest-based industries (e.g., timber processing, new bio-economy products) | Climate change impacts (e.g., tree distribution shifts, forest growth shifts) |
| Economic instruments (subsidies, compensation payments, taxes) | Requirements set by forest management certification standards | Advice from a consultant, managing company or forest owner association that I am member of | Availability of labour (e.g., labour forces) | |
| Informational instruments (advisory services, knowledge, research, know-how transfer) | Market demand for certified forest products | | | |

# Annex

This annex includes the survey questions used in the research presented in this report. Each question was translated into the official language of the respective country to ensure clarity and effective distribution.

**Question 1**: **What type of forest ownership are you representing?** (*Please mark the most relevant option*).

1.1. Public ownership by the state at national level (incl. state-owned corporations)
1.2. Public ownership by the state at sub-national (regional) level
1.3. Public ownership by local government (municipality or equivalent)
1.4. Private ownership by individual or family
1.5. Private ownership by private business entity
1.6. Private ownership by private institution (e.g., church, foundation, etc.)
1.7. Other (*please specify*):………………………………………………………

**Question 3: Please indicate the main forest type on your property, or holding that you own/manage:**

| Forest characteristics | Answer |
|---|---|
| Even-aged / uneven-aged | *Tick box* |
| Mono-species / multi-species | *Tick box* |
| Dominant tree species (select one) | *Species (drop down list provided by national team)* |
| Second the most important species (select one) | *Species (drop down list provided by national team)* |
| Third the most important species (select one) | *Species (drop down list provided by national team)* |
| Approximate average productivity [$m^3$ with bark / ha / year] | |
| Approximate average growing stock [$m^3$ with bark / ha] | |
| Approximate share of your forest area covered by the forest type (%) | |
| Site productivity class **(only for Sweden case)** | *Swedish soil bonity classes (drop down list)* |

**Question 4: Please evaluate, how important are the following objectives and functions (forest ecosystem goods and services) that you are currently manage in your forest?**

| **Forest functions (forest ecosystem goods and services)** | **Relative importance** *(1 – not important at all; 3 – neutral; 5 very important; 99- I do not know)* | | | | | | **Does the provision of this function need active management** (*yes, no*) | |
|---|---|---|---|---|---|---|---|---|
| 6.1. Timber or pulp wood production (material use) | 1 | 2 | 3 | 4 | 5 | 99 | 1 | 2 |
| 6.2. Fuel wood or other biomass for energy production | 1 | 2 | 3 | 4 | 5 | 99 | 1 | 2 |
| 6.3. Non-timber forest products (e.g., berries, mushrooms, nuts, fruits, medicinal plants) | 1 | 2 | 3 | 4 | 5 | 99 | 1 | 2 |
| 6.4. Hunting | 1 | 2 | 3 | 4 | 5 | 99 | 1 | 2 |
| 6.5. Indigenous livelihoods and businesses | 1 | 2 | 3 | 4 | 5 | 99 | 1 | 2 |
| 6.6. Recreation (e.g., hiking, cycling, landscape view) | 1 | 2 | 3 | 4 | 5 | 99 | 1 | 2 |
| 6.7. Biodiversity conservation (e.g., habitats, animal and plant species protection) | 1 | 2 | 3 | 4 | 5 | 99 | 1 | 2 |

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| 6.8. Water and soil protection (e.g., water filtration, soil erosion reduction, shelterbelts) | 1 | 2 | 3 | 4 | 5 | 99 | 1 | 2 |
| 6.9. Carbon sequestration in standing (old-growth) forests and soils | 1 | 2 | 3 | 4 | 5 | 99 | 1 | 2 |
| 6.10. Carbon sequestration in growing forests and harvested wood products from forests | 1 | 2 | 3 | 4 | 5 | 99 | 1 | 2 |
| 6.11. Climate change adaptation (e.g., climate resilient forest) | 1 | 2 | 3 | 4 | 5 | 99 | 1 | 2 |
| 6.12. Cultural, educational, emotional and spiritual values (e.g., eco-trials, historical site, religious site, burial forests) | 1 | 2 | 3 | 4 | 5 | 99 | 1 | 2 |
| 6.13 Other services: *(please specify)* | 1 | 2 | 3 | 4 | 5 | 99 | 1 | 2 |

**Question 5: What are your main forest management practices to meet your forest management objectives?** *(Please provide your answers for the main forest type you have defined in Question 3).*

| Forest management practice | How do you manage your forest currently? | If you were to change your management to improve biodiversity restoration and conservation, what forest management practices would you implement? | If you were to adapt your management to climate change impacts, what forest management practices would you implement? |
|---|---|---|---|
| **Main Cutting regime** *(drop down list)* | | | |
| A) Clear felling | | | |
| B) Group selection | | | |
| C) Single tree selection | | | |
| D) No cutting | | | |
| E) No change from current management[1] | | | |
| **Main Thinning regime** *(drop down list)* | | | |
| A) Thinning from above (selects the larger trees for harvest, leaving smaller trees on site) | | | |
| B) Thinning from below (selects the smaller trees for harvest, leaving the larger trees on site) | | | |
| C) Thinning from all size classes | | | |
| D) No Thinning | | | |
| E) No change from current management | | | |
| **Main Tree species selection** *(drop down list)* | | | |
| A) Maintain current composition | | | |
| B) Shift to broadleaves dominated forest | | | |
| C) Shift to conifers dominated forest | | | |
| D) Shift to mix species forest | | | |
| E) Use of non-native tree species | | | |
| F) No change from current management | | | |
| **Main Regeneration method** *(drop down list)* | | | |
| A) Planting with regular planting material | | | |
| B) Planting with planting material obtained from tree breeding | | | |
| C) Natural regeneration | | | |
| D) Enrichment planting | | | |

[1] This option will show up only for biodiversity conservation/restoration changes in forest management and climate change impact changes in forest management

| |
|---|
| E) Coppice |
| F) No change from current management |
| **Main Biodiversity improvement method** *(drop down list)* |
| A) Set aside forest, with no active management |
| B) Increasing deadwood and microhabitats in managed forests |
| C) Increase diversity in tree sizes |
| D) None |
| E) No change from current management |
| F) Other *(please specify)* |
| **Post-disturbances management** *(drop down list)* |
| A) Salvage logging with planting |
| B) Salvage logging with natural regeneration |
| C) Leaving all wood with natural regeneration on the forest area affected by disturbances |
| D) No post-disturbance management |
| E) No change from current management |
| F) Other *(please specify)* |

**Question 6: How important are the following decision-making principles for your forest management practices?** *(Please evaluate these principles along the degree of importance for your forest management decisions*).

| **Decision-making principle** | **Relative importance** *(1 – not important at all; 3 – neutral; 5 very important; 99- I do not know)* | | | | | |
|---|---|---|---|---|---|---|
| Financial benefits such as generating income/profit or avoiding costs (“the economically rational thing to do”) | 1 | 2 | 3 | 4 | 5 | 99 |
| Own values and beliefs (“the right thing to do”) | 1 | 2 | 3 | 4 | 5 | 99 |
| Need to comply with applicable regulations (“the legally appropriate thing to do”) | 1 | 2 | 3 | 4 | 5 | 99 |
| Social pressure or social appreciation (“the socially expected thing to do”) | 1 | 2 | 3 | 4 | 5 | 99 |
| Professional knowledge and experience (“the thing I am taught and know to do”) | 1 | 2 | 3 | 4 | 5 | 99 |
| Habit and tradition (“the thing I am used to do”) | 1 | 2 | 3 | 4 | 5 | 99 |
| Other: *(please specify)* | 1 | 2 | 3 | 4 | 5 | 99 |

**Question 7: How important are the following factors for shaping your forest management decisions?** (*Please evaluate factors along the degree of importance for your forest management decisions using a 5-point Likert scale: 1 - not important at all; 3 – neutral; 5 - very important).*

| **Policy** | **Which factors are shaping your current forest management?** | | | | |
|---|---|---|---|---|---|
| Item 1: Regulatory forestry policy (objectives, targets, standards in law and bylaw) | 1 | 2 | 3 | 4 | 5 |
| Item 2: Regulatory biodiversity policy (objectives, targets, standards in law and bylaw) | 1 | 2 | 3 | 4 | 5 |
| Item 3: Regulatory climate policy (objectives, targets, standards in law and bylaw) | 1 | 2 | 3 | 4 | 5 |
| Item 4: Regulatory water policy (objectives, targets, standards in law and bylaw) | 1 | 2 | 3 | 4 | 5 |

| | | | | | |
|---|---|---|---|---|---|
| Item 5: Economic instruments (subsidies, compensation payments, taxes) | 1 | 2 | 3 | 4 | 5 |
| Item 6: Informational instruments (advisory services, knowledge, research, know-how transfer) | 1 | 2 | 3 | 4 | 5 |
| **Economic** | | | | | |
| Item 7: Forest management costs and revenues | 1 | 2 | 3 | 4 | 5 |
| Item 8: Timber prices | 1 | 2 | 3 | 4 | 5 |
| Item 9: Energy wood prices | 1 | 2 | 3 | 4 | 5 |
| Item 10: Income from other marketable goods than timber (water, recreation, biodiversity, carbon sequestration) | 1 | 2 | 3 | 4 | 5 |
| Item 11: Requirements set by forest management certification standards | 1 | 2 | 3 | 4 | 5 |
| Item 12: Market demand for certified forest products | 1 | 2 | 3 | 4 | 5 |
| **Social** | | | | | |
| Item 13: Forest property structure (property size and fragmentation) | 1 | 2 | 3 | 4 | 5 |
| Item 14: My values, objectives, knowledge and experiences | 1 | 2 | 3 | 4 | 5 |
| Item 15: Generational shift on my property and/or my management organisation) | 1 | 2 | 3 | 4 | 5 |
| Item 16: Media and societal pressure by the public, environmental NGOs and other civil society groups | 1 | 2 | 3 | 4 | 5 |
| Item 17: Advice from a consultant, managing company or forest owner association that I am member of | 1 | 2 | 3 | 4 | 5 |
| **Technological** | | | | | |
| Item 18: Monitoring, assessment and availability of data (e.g. on forests, on biodiversity status, effects of climate change and natural disasters) | 1 | 2 | 3 | 4 | 5 |
| Item 19: Technologies and innovations in forest management (e.g., digitalisation, timber harvesting, tree breeding, planting) | 1 | 2 | 3 | 4 | 5 |
| Item 20: Forest road infrastructure and transport | 1 | 2 | 3 | 4 | 5 |
| Item 21: Technologies and innovations in forest-based industries (e.g., timber processing, new bio-economy products) | 1 | 2 | 3 | 4 | 5 |
| Item 22: Availability of labour (e.g., labour forces) | 1 | 2 | 3 | 4 | 5 |
| **Ecological** | | | | | |
| Item 23: Silvicultural state of forest (e.g. age classes, productivity, forest growth, bio-physical conditions) | 1 | 2 | 3 | 4 | 5 |
| Item 24: Health status of forest (e.g., disturbances and/or damages after drought, storm, fire, insects and pathogens) | 1 | 2 | 3 | 4 | 5 |
| Item 25: Ecological and biodiversity status of forest (e.g., ecological processes, favourable or non-favourable conservation status, functionality and connectivity of the forest ecosystem) | 1 | 2 | 3 | 4 | 5 |
| Item 26: Climate change impacts (e.g., tree distribution shifts, forest growth shifts) | 1 | 2 | 3 | 4 | 5 |

**Question 9: Please state the total size of the forest property you own and/or manage.**
*For public or joint ownership, please refer to the forest area that you are directly responsible for:*

____ (number of ha)

**Question 10: Where is your forest located?**

Municipality: ______________________________