ForestPaths

Co-designing holistic forest-based policy pathways for climate change mitigation

D1.1 Forest management approaches across Europe

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Key takeaway messages

- Even-aged forestry is more common in Nordic countries but national forest strategies in these countries are increasingly promoting the implementation of biodiversity and habitat restoration measures.
- Trends in forest management in the North Europe is showing a significant shift from a singular focus on maximizing timber production to embracing and balancing multiple objectives.
- Forest management is strictly ruled by forest management plans in Bulgaria, Romania, Czechia, and Hungary.
- Land abandonment, with no management, has been reported in Italy, Spain, Portugal, and Hungary.
- Most country forest policies are aligned with the principles of sustainable forest management but there is lack of evidence on the wider adoption of sustainable forest practices in private forests.
- The most common types of forest owners found in the literature, in Europe, are economic-oriented, tradition-oriented, environmentalists, non-active/passive and multi-objective forest owners.
- There are very few studies considering forest owners' typologies in South European countries.
- Most typology studies classify public managers as multi-objective and do not distinguish between public and private multi-objective forest managers.
- There is sparce information on current forest management per type of forest owner/manager and on the percentage of forests managed per type of forest owner/manager per country.
- Environmental conditions (topography, climate) have clear impacts on observed harvest rates across Europe, constraining the possibilities and choices forest owners/managers have.
- Given similar environmental conditions, clear differences in observed harvest intensity exist between countries, probably related to differences in (among others) forest history, forest management culture, ownership, and importance of the forest industry.
- It is difficult to assign a forest management strategy to an NFI plot just based on (repeated) tree observations, while it is impossible to assign an ownership class.

- Existing definitions of Climate-Smart Forestry (CSF) vary considerably, and insufficiently consider the importance of biodiversity. This report introduces a new concept of Climate and Biodiversity- Smart (CBS) Forestry.
- Indicators to assess CSF can potentially be used for CBS, but additional indicators are needed for biodiversity, the entire forest sector, and substitution effects in other sectors.
- The comparison of demo cases underlines that measures for CBS need to be tailored according to regional conditions.

Summary

The National Forestry Accounting Plans (NFAP) by all EU member states, the FACESMAP country reports and other relevant published literature were reviewed to identify current forest management approaches and trends across Europe, as well as silvicultural practices implemented. Even-aged forestry is the most common forest management regime in Nordic countries such as Finland, Sweden, Norway. Multifunctional forest management is implemented in France, Belgium, Spain. Agroforestry is implemented in Spain and Portugal. Coppicing is implemented in Portugal, United Kingdom, and Greece. Closer-to-nature forest management is implemented in Slovenia and Germany, for example. Many countries are following the principles of sustainable management principles, namely Germany, the Netherlands, Austria, France, and Czechia.

Typology studies of forest managers in Europe were reviewed. Most types of forest owners fall within 5 main categories, namely economic-oriented, tradition-oriented, environmentalists, non-active/passive and multi-objective forest owners. Even though most studies on typologies do not associate actual forest management approaches to forest owner or manager types, scattered information on forest management intensity, size of forest holding, silvicultural practices implemented, tree improvement, tree species, implementation of nature protection measures, ownership type, resistance to change, advisory sources, exist and was collated and associated to forest owner types. Based on available literature and expert knowledge, the percentage of forest managed per type of forest owner/manager in each country was derived, however with low confidence. According to the literature, other potential forest owner types exist (e.g., female forest owners, new forest owners) and these should be further investigated to understand if they can be considered as a separate type of owner or if their characteristics would place them within any of the five forest owner types identified. Distinctive forest management approaches can be associated to each of these emerging types such as managing forest only for the purpose of offsetting greenhouse gas emissions.

Harvest patterns in repeated national forest inventory data from 11 countries were analysed following the fate of individual trees on over 230 thousand plots for 2-4 cycles. The average annual harvest rate (i.e., the probability that a certain tree is harvested) per 1-degree grid cell, which we used as a reference showing the real (spatial) differentiation in harvest rate was calculated and mapped. This map was then visually compared to various alternatives, where harvest rates were calculated and mapped using groupings from a range of potential explanatory variables such as biogeographic zone, country, protection, topography, and population characteristics. A clear effect of constraining external factors on the harvest rate that works in a similar way all over Europe was found, with elevation as the best predictor. However, within these constraints, a very clear difference between countries was also found, which makes

it difficult to generalize management approaches across borders. These inventory-based observations can be connected in a straightforward way to the forest resource models (LPJ-GUESS and EFISCEN-Space) but give only information on the combined effect of the behaviour of the individual forest owners. Since no information is available on the individual owners of the plots, it is currently impossible to assign them to one of the classes as defined in the literature review. A further analysis of observed harvest events at the plot level (intensity, frequency) combined with observed forest structure and tree species composition may give some more information on the possible ownership and/or management approach at the plot level. Results from the interviews and the survey will be needed to bridge the gap between the observation-based approach and the literature review.

Based on a review of Climate-Smart Forestry (CSF) definitions and biodiversity management literature, a comprehensive definition for Climate and Biodiversity-Smart (CBS) Forestry was developed. CBS incorporates four main pillars: climate change mitigation, adaptation, biodiversity, and other ecosystem services provisioning. To implement CBS in practice, criteria are needed to assess what measures can qualify as CBS. So far, CSF assessment has mostly relied on criteria and indicators of sustainable forest management. However, the existing indicator lists refer mostly to forests and lack information on CBS forest management impacts on forest value chains and wood product use. Assessing biodiversity impacts of forest management also requires further method development, e.g., by specifying minimum requirements of key parameters such as amount of deadwood in the forest or maintenance of retention trees. A review of potential CBS forest management practices was carried out. The measures were categorized and evaluated on the relevance to CBS. CBS needs to be tailored according to regional conditions. This was illustrated using the ForestPaths demo cases as examples. Further research is needed to elaborate a wider framework to assess and weigh CBS indicators and to guide CBS assessment (e.g., in the context of ForestPaths forest simulation modelling) and its implementation in practical decision-making across the European countries.

List of abbreviations

EU	European Union
CBS	Climate and Biodiversity Smart Forestry
CSF	Climate-Smart Forestry
CCF	Continuous Cover Forestry
CNF	Closer-to-Nature Forestry
GBF	Global Biodiversity Framework
GHG	Greenhouse Gases
FACESMAP	Forest Land Ownership Change in Europe: Significance for Management and Policy
FMA	Forest Management Approaches
FSC	Forest Stewardship Council
PEFC	Programme for the Endorsement of Forest Certification
NFAP	National Forestry Accounting Plan
NFI	National Forest Inventory

1 Introduction

Forests provide numerous ecosystem services for society and can thereby help deliver numerous policy objectives, such as the Paris Agreement's goal to reduce global greenhouse gas (GHG) emissions, the EU's target to achieve climate neutrality by 2050 and the Kunming-Montreal Global Biodiversity Framework (GBF) to "take urgent action to halt and reverse biodiversity loss" by 2030. In the case of climate change, it is well understood that forests play a key role in the Earth's biogeochemical cycling of carbon via the sequestration of carbon from the atmosphere and formation of carbon sinks (Hurteau, 2021; Nabuurs et al., 1997). In addition, forest products can contribute to the reduction of anthropogenic carbon emissions by substituting more emissions intensive materials (e.g., Verkerk et al., 2022; Hurmekoski et al., 2022a, 2022b; Leskinen et al., 2018).

The provisioning of these services is largely influenced by the way forests are managed (Felipe-Lucia et al., 2018). Inevitably, not all services can be provided at the same location at the same time. Important trade-offs exist for example between biodiversity and wood provisioning, but also between carbon storage in biomass and carbon storage and substitution effects in harvested wood products. It is therefore essential to understand how forests are currently managed, and how management could be changed to optimize the delivery of ecosystem services, in line with the policy objectives. In this respect, forest owners are key decision makers because they are the primary agents of forest management activities (e.g., Deuffic et al., 2018). The way a forest is managed is to a great extent influenced by the aims of the forest owner and his/her capabilities of managing the forest. Moreover, the type of ownership will also be decisive in the way an owner could be persuaded to change the management to be in line with the (national) policy objectives. However, this is a great challenge, considering differences in socioeconomic profiles of forest owners and forest governance across EU regions (Winkel and Sotirov, 2016).

Within the ForestPaths modelling system, the models LPJ-GUESS and EFISCEN-Space simulate the development of the forest resource and ecosystem provisioning, under scenarios of current and future management. Information on how forests are managed under different scenarios is generated by the agent-based model CRAFTY, which simulates the behaviour of an array of different agents, in this case forest owners, in response to external pressures, such as changes in demands and new policies or policy instruments. To do so, CRAFTY needs information on the current distribution of forest ownership over a limited number of classes, harmonized over Europe. Each class should be characterized in terms of how they manage their forest, their goals and how responsive they are to external pressures.

In this report, Chapter 3 is to provides a review of existing forest ownership typologies in Europe, and a characterization of the management and behaviour of the underlying types of forest owners. The descriptions of the management approaches in the literature are often rather descriptive (Chapter 2), while the resource models need concrete information on for example tree species to be planted and harvest frequency and intensity. Although many countries have published management guidelines (for example France: *Fiches itinéraires techniques par essence (cnpf.fr)*), it is clear that such "textbook" management is often not implemented in practice (Schelhaas et al. 2018). The aim of Chapter 4 is to provide more quantitative information on how forests are managed in Europe, based on observations from repeated national forest inventories (NFIs). ForestPaths aims at to find new, effective, and feasible types of management that can contribute to climate change mitigation and adaptation, and to biodiversity protection. In the proposal this is defined as Climate and Biodiversity-Smart (CBS) Forestry. Chapter 5 aims to develop a comprehensive definition of CBS forestry and to review potential CBS forestry practices to be studied in the scenarios.

2 Forest management approaches implemented in Europe.

The forest management concept has evolved over the years, with social, ecology, and environmental aspects becoming more important over the years. The UNECE (2019) defines forest management as *"a system of measures to protect, maintain, establish, and tend forest, ensure provision of goods and services, protect forest against fire, pests, and diseases, regulate forest production, check the use of forest resources, and monitor forests; as well as to plan, organize and carry out the above-mentioned measures*." Forest management in Europe plays a critical role in ensuring sustainable use of forest resources, protecting biodiversity, and mitigating climate change. European forests, from boreal forests in Scandinavia to temperate deciduous forests in Central Europe and Mediterranean woodlands in south Europe (Mason et al., 2022; Fridén et al., 2014; Larsen, 2012) provide a diverse range of forest ecosystems and each region reflects its forest management approach, adapted to its environmental, social, and economic contexts. European countries, while sharing common goals for sustainable forestry, employ a variety of management techniques shaped by historical practices, ecological conditions, and policy frameworks (Larsen et al., 2022; Paletto et al., 2015; Fauchald et al., 2014).

Forest management approaches implemented across Europe can be broadly classified into several categories, depending on management objectives, dominant tree species/variety, and silvicultural methodologies. The choice of silvicultural method is often dependent on the specific ecological, social, and economic context of the forest area. Di Fulvio et al (2023) in their discussion of forest management approaches across Europe, classified the management approaches according to main forest types and dominant tree species. Ameray et al. (2021) in their study on the impact of forest management techniques on carbon storage and sequestration in Europe, classified forest management approaches widely used in the EU into three categories: extensive forest management, intensive forest management and old-growth forest conservation. Duncker et al. (2012) in their work on classification of forest management approaches (FMA) in Europe used the criteria of the gradient of intensity of intervention to classify the EU FMA into five FMAs (Table 1).

The FMAs identified by Duncker et al. (2012) are used as a framework to report which forest management approaches occur in Europe and where, the main trends of implementation, as well as main silvicultural systems associated to these forest management approaches. Silvicultural systems (e.g., shelterwood[1], selection, clear felling) are means of implementing the chosen management approaches and objectives. Six major regions in Europe are considered

[1] The shelterwood system is a silvicultural system in which trees are removed in a series of cuts designed to achieve a new stand under the shelter of remaining trees (*Encyclopaedia of Forest Sciences, 2004*).

for reporting, namely North Europe, Baltic countries, South Europe, Balkans, West Europe, Central Europe.

Table 1 Overview of major FMAs used across Europe (Adopted from Duncker et al., 2012).

Forest Management Approaches Description	Intensity of management
Nature reserve	No intervention
Closer-to-nature	Intervention mimics natural processes
Combined objective (multi-objective) forestry	Limited interventions
Even-aged forestry	Interventions follow production forestry goals
Short rotation forestry	Intensive management for maximum biomass

These FMAs can be described as following:

- **Nature reserve, and/or unmanaged forest** management involves a multifaceted strategy aimed at conserving biodiversity, protecting ecosystems, and promoting sustainable use of resources. Nature reserve FMA is mostly used to address environmental issues and biodiversity conservation concerns in forest management. The Nature reserve FMA is implemented across Europe through several strategies including strict protection, set asides, conservation of old growth forest, and woodland key habitat. Human intervention in a forest ecosystem is minimal or entirely excluded, allowing natural ecological processes to govern the development and dynamics of the forest. It relies on natural ecological processes, succession, and disturbance regimes to shape the structure and composition of the forest. It arises as the consequence of an active decision not to manage (reserve) or a lack of interest of the owner to manage the forest. An unmanaged forest reserve is a designated area where natural processes and disturbance regimes unfold without human intervention. In this space, ecological and societal objectives take precedence, with the primary goal of preserving ecologically significant habitats and their associated biodiversity. The overarching aim is to serve as a reference point for the advancement of silviculture practices closely aligned with natural ecosystems, maintaining a delicate balance between conservation and sustainable land use (Duncker et al., 2012).

- **Multi-objective** forest management refers to the management of forests for multiple societal and political demands such as climate change mitigation, wood production, biodiversity conservation, recreation, water protection and soil protection. rather than maximising individual objectives (Nabhani et al., 2024; Wolfslehner et al., 2020). Multi-objective forest management across Europe aims to balance various objectives, including timber production, biodiversity conservation, recreation, and climate regulation. Each country implements this approach uniquely, considering their specific ecological, social, and economic contexts (Winkel et al., 2022; Wolfslehner et al., 2020). This approach involves a comprehensive assessment of forest ecosystems, recognizing the interdependencies among different objectives. For instance, maintaining biodiversity often supports ecosystem resilience, which can benefit timber production in the long term. Similarly, protecting water resources can enhance recreational opportunities and ensure the sustainability of other ecosystem services (Díaz-Yáñez et al., 2021; Dunker 2012).

- **Even-aged Forest management (EFM)** is a silvicultural approach that involves the cultivation of trees in a uniform age class, typically resulting from practices such as clear-cutting followed by regeneration. This method is characterized by the simultaneous establishment of a new cohort of trees after the previous stand has been harvested, creating a landscape dominated by trees of similar age. Forest regeneration is achieved by natural regeneration, sowing, or planting and stand development controlled by thinning and regeneration felling. During the regeneration felling in the clear-cutting method most trees in the area are removed. In case of natural regeneration, individual seed trees are left in the area (i.e., seed tree cutting is performed) (Savilaakso et al., 2021). This results in forests arranged in a series of age classes, each composed of regular stands dominated by one or very few productive tree species. The main objective is the production of timber, and the provision of other ecosystem services is considered a 'by-product' of management (Biber et al., 2015). The primary objective of EFM is to optimize timber production and economic returns, as it allows for easier management and harvesting of trees that are of similar size and maturity (Chatterjee et al., 2010; Metzler, 2023). One of the significant advantages of EFM is its potential for economic profitability. Studies have indicated that EFM can yield higher economic returns compared to uneven-aged management, especially in the absence of carbon credit markets (Chatterjee et al., 2010; Pukkala, 2016). The systematic approach of EFM facilitates the efficient use of machinery and resources, thus enhancing productivity (Kuuluvainen et al., 2012).

- **Short rotation forestry (SRF)** involves the cultivation of fast-growing tree species in short cycles, typically ranging from 3 to 10 years, with the aim of producing biomass for energy and other uses. This method has gained prominence as a sustainable alternative to traditional forestry practices, particularly in response to increasing demands for renewable energy sources and the need for carbon sequestration to mitigate climate change (Schulze et al., 2016; Krēsliņa et al., 2020). SRF consists of planting a site and then felling the trees when they have reached a size of typically 10-20 cm diameter at breast height. Depending on tree species this usually takes between 8 and 20 years. It is intermediate in timescale between Short Rotation Coppice (SRC) and conventional forestry (Forestry Research, 2023b). In SRF, the crops (e.g., Eucalyptus spp., Nothofagus spp., Populus spp., Acer spp., Fraxinus spp.) are grown as an energy crop for use in power stations, alone (biomass power stations) or in combination with other fuels such as coal and it is like historic fuelwood coppice systems. SRF is a cultivation practice in which high-density, fast-growing tree species are planted to regular and constantly renewable supply of fuel in a significantly shorter period than from conventional forest tree species plantations (European Commission, 2023).

- **Closer-to-nature forest management** also known as 'ecologically sound forestry' or 'continuous cover forestry,' is characterized by less intrusive forest management, which relies on mimicking nature's own processes and aims to minimize risks in production. The system has a long-term planning character due to the long lifespan of trees (Mason et al.,2022). While the overarching principles of close-to-nature forest management exhibit a degree of uniformity across various regions of Europe, the specific management strategies and silvicultural practices employed can diverge significantly. This divergence is influenced by several factors, including the distinct types of forests present throughout the continent, variations in the intensity and scale of natural disturbance regimes, and the specific objectives guiding forest management (Mason et al., 2022; Roberge et al., 2020). Several common characteristics define the close-to-nature forest management approach across Europe. These include the retention of habitat trees, which serve as critical resources for biodiversity; the preservation of special habitats and dead wood, which are essential for numerous forest-dwelling species; and the promotion of native tree species alongside site-adapted non-native species that do not disrupt local ecosystems (Larsen et al., 2022; Mason et al., 2022; Korhonen et al., 2021). Furthermore, this management approach emphasizes the importance of natural tree regeneration processes, the implementation of partial harvesting techniques, and the enhancement of stand structural heterogeneity. Additionally, there is a concerted effort to promote diversity among tree species and to maintain genetic variability within those species. This is crucial for fostering resilience against pests, diseases, and changing environmental conditions (Larsen et al., 2022; Mason et al., 2022; Roberge et al., 2020).

Unmanaged forest nature reserve, multi-objective, and closer-to-nature FMAs can also be classified under the umbrella of the continuous cover forestry (CCF). This forest management approach intends to create more diverse forests, both structurally and in terms of species composition, by avoiding clear felling (Arcangeli et al., 2024). The development of more diverse forests is expected to reduce the risks posed by future and present climate change and by biotic threats (Forestry Research, 2023a). Continuous cover forestry may be regarded as a variant of the uneven-aged management system, or a conversion phase from even-aged to uneven-aged management. Mason et al. (2022) found out that the most common silvicultural systems associated with continuous cover forestry are single stem selection, group selection and irregular shelterwood. These authors estimated that between 22 and 30 per cent of European forests are managed through continuous cover forestry. Figure 1 present the estimated percentage implementation of continuous cover forestry in several countries of the European Union.

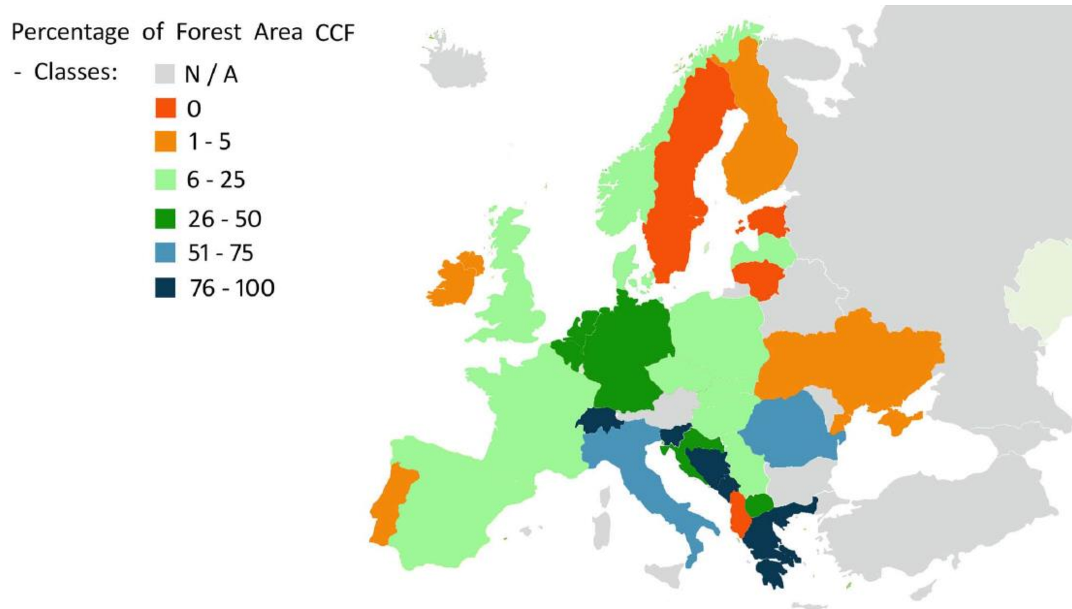

Figure 1: Estimated percentage use of CCF compared to other silvicultural systems in high forests in the Atlantic region (Source: Mason et al., 2022)

Literature review on forest management approaches in Europe

Published literature (e.g., European Commission 2023), the NFAPs and the FACESMAP joint country report (Zivojinovic et al., 2015) were reviewed to identify current forest management approaches and trends across countries in Europe, as well as silvicultural practices implemented (e.g., the regeneration approach, the selection of forest reproductive material, thinning and cutting regimes, treatment of forest residues or soil treatments). Information on coppice forests in Europe was provided by the report published for the project EuroCoppice (Unrau et al., 2018), which was authored by 115 experts, researchers, and practitioners from 35 countries across Europe. The report mainly focusses on traditional types of coppice, but also addresses more recent forms such as short rotation coppice. Further literature search was conducted using the databases: ISI Web of Science, Scopus, and Google Scholar. The search method used was, for example, “Even-aged forestry” *AND* “Sweden” keywords or “forest management” *AND* “Finland” or “closer-to-nature forest management” *AND* “Portugal”. The search was repeated for each of the 5 FMAs identified by Duncker et al. (2012) and all countries considered. The information was structured using the FMA’s described by Dunker et al. (2012), for all the mainland EU countries plus Norway, Switzerland, United Kingdom, and Bosnia and Herzegovina. Information available in English is unbalanced for the different countries across Europe.

2.1 **North Europe:** Finland, Sweden, Norway, Denmark

Finland

Forest cover
Forests cover 73.7% of the total land (Forest Europe, 2020).

Even-aged Forest management (EFM):
EFM has been the primary management regime (Siiskonen et al., 2007). According to the NFAP (Ministry of Economy and Forestry & Luke, 2019), forest management in Finland aims at promoting the growth of valuable stands and improve the quality of roundwood. EFM with clear-cutting is extensively practiced in Finland. Commercially managed even-aged forests are typically thinned periodically 2 to 3 times during the rotation period, with some 25−30% of the trees removed during thinning (Ministry of Economy and Forestry & Luke, 2019). In 2014, CCF and uneven forest management, was enabled. In CCF, regeneration is performed by light selection felling or small-scale group selection system with the aim of generating a forest stand with a diverse age structure and to maintain forest cover. In recent years, EFM with tree retention is becoming the dominant management system (Vauhkonen et al., 2019). The most used methods of management in commercial forests include leaving retention trees in regeneration felling, and preserving vital habitats, such as the habitats of special importance for biological diversity that are defined in the Forest Act (Ministry of Economy and Forestry & Luke, 2019). Finnish forests are managed by compartments, the average size of a compartment being less than two hectares. The rotation periods vary between 60 and 120 years, depending on the tree species and the site characteristics (Zivojinovic et al., 2015). Natural regeneration and artificial regeneration are implemented in 15% and 85% of the forest area, respectively (Zivojinovic et al., 2015).

Multi-objective forest management
Takala et al. (2019) found evidence that the hegemony of the wood production discourse has been weakening In Finland, especially due to the rise of the multi-objective forestry paradigm and the rise of the recreation discourse. Multi-objective forestry entails integrated planning with input from multiple stakeholders, including industry, environmental groups, and local communities, ensuring a balance of economic, ecological, and social objectives. (Pynnönen et al., 2019). The prominence of the *pro nature* discourse expanded between the 1990's and the 2010's (Takala et al., 2019). The biodiversity of forests is promoted by maintaining the characteristics of the valuable habitats, both in even and uneven-aged forests. Korhonen et al. (2020) indicates that several biodiversity indicators show positive development between 1980s and 2015, namely the area of protected forests, amount of retention trees, number of large trees, especially large aspens, and in southern Finland, also the amount of deadwood. Climate change mitigation and adaptation has also become more significant objectives to be integrated in both forest policy and management (Ministry of Economy and Forestry & Luke, 2019).

Nature reserve
This forest management approach is implemented through several strategies including strict protection, conservation of old growth forest, and woodland key habitat (Mason et al., 2022; Heinonen, 2013). National parks and strict nature reserves constitute the backbone of the Finnish network of nature conservation areas. In total, 2.46 million hectares are protected by law (Latsa, 2024). No forest harvesting is allowed in conservation areas to safeguard the biodiversity and several measures for maintaining and enhancing the biodiversity of production forests have been established and are being promoted. Public forests are managed by Metsähallitus, a forest enterprise previously owned by the Finish State. The Best Practices for Sustainable Forest Management are prepared in cooperation with private forest owners, forestry experts and researchers, and include guidance for the protection of waters, peatland forestry, biodiversity, and climate change adaptation. The national strategy and in the action plan for the conservation and sustainable use of biodiversity, “Saving Nature for People” (2012), highlights

the importance of safeguarding the biodiversity of forest ecosystems (Ministry of Economy and Forestry & Luke, 2019). The protected area management principles are partly determined directly by national legislation and partly by Metsähallitus (Latsa, 2024).

Short rotation forest (SRF) management

In this forest management approach fast-growing species such as hybrid aspen, willow, and birch are used. The rotation periods are typically between 10 to 20 years, depending on the species and site conditions. The primary objective is to produce biomass for bioenergy, this contributing to Finland's renewable energy targets and reducing reliance on fossil fuels (Jylhä et al., 2015).

Sweden

Forest cover

Forests cover about 68.7% of the country's territory (Forest Europe, 2020).

Even-aged Forest management (EFM)

This forest management approach is the most common method for managing forests in Sweden and is used by most of the country's 320,000 forest owners (Fahlvik et al., 2022). The silvicultural application of the EFM tends to vary with the main forest policy discourse per time. Between 1940s and 2014, the forest legislation and forest management guidelines (FMG) mainly supported EFM based on clearcutting (Göran, 2023). However, in recent years, EFM with tree retention is becoming the dominant management system (Felton et al. 2019; Mäkelä et al., 2023), in line with growing policy discourse on biodiversity conservation and ecological forestry (Roberge et al., 2020). This is driven by growing number of research suggesting that EFM can have negative impacts on biodiversity and forest dwelling species. There is growing interest in alternative management methods, such as selective logging and **CCF**, which may benefit biodiversity and forest ecosystem services (Fahlvik et al., 2022; Savilaakso et al., 2021).

Multi-objective forest management

This was the most common management approach until the beginning of 20th century. It was practiced until 1948 when a new law with detailed regulations regarding regeneration of forests was declared and from 1950 selective logging was forbidden in state owned forests (Lundqvist et al., 2009). In the 1993 Forest Act, multiple-objective forestry became recognized as a distinct notion promoting other forest management practices than those stemming from the dominant industrial paradigm (Karjalainen et al., 2009; Zhang et al., 2022). In recent years, multi-objective forestry has become more prominent in national political discussions surrounding Swedish forestry. This resurgence is particularly evident in the 2018 Swedish National Forest Program (NFP) and the 2020 Forest Inquiry (Skogsutredningen, SOU 2020:73 cited in Zhang et al., 2022). Multi-objective forestry is identified as one of the five key focus areas in the NFP and is frequently highlighted throughout the Forest Inquiry (Zhang et al., 2022). Multiple-use forestry has always existed in Sweden, even during the intensive timber production-oriented periods in the second half of the twentieth century. During that period, however, other uses of the forest tended to complement the production-oriented norm (Zhang et al., 2022).

Closer-to-nature forest management

In this approach practices include CCF systems, retention forestry, protection of key habitats and transition zones, and preserving species mixture in all development phases (Korhonen et al., 2021; Roberge et al., 2020). Sweden employs CCF, such as single-tree selection and group selection methods, to maintain an uneven-aged forest structure. In Sweden, the shift towards a more nature-oriented forest management approach is reflected in the 1993 Forest Act, which gave equal space and emphasis to biodiversity and the social values inherent in forests. According to Hengeveld et al. (2017), CCF is actively implemented on only 10% of the forest land but is increasing in importance and area cover. The Swedish Forestry Act regulates that deadwood should be retained after clear-cutting, especially older wind-felled trees, high-stumps, and snags (Ministry for the Environment, 2018). Trees and tree groups are also left at harvest. This measure together with deadwood is a key part of the certification standards in Sweden. Forest policy is increasingly complying with the Convention on Biological Diversity (CBD) and the EU forest strategy, and more forests have been designated for nature conservation and sustainable forest management in the past 10 years.

Nature reserve

This forest management approach is implemented through several strategies including large network of reserves, non-intervention management strategy, habitat restoration, species protection, and conservation of old growth forest (Heinonen, 2013; Angelstam et al., 2020). The proportion of old forests has increased by 80% since the early 1990s, when it reached its lowest point. This is due to the Swedish forestry model, which was introduced in 1994 and prioritizes both environmental and production goals (Hannerz and Simonsson, 2023). Approximately 9% of forest land and 6% of productive forest land are formally protected in Sweden. Voluntary set-asides are not formally protected, but landowners can choose how long to protect them for (Laudon et al., 2024).

Short rotation forestry (SRF)

The Swedish energy forestry approach is well aligned with SRF. The main species consist of different willows, grey alder, and poplars, of which the willow species *Salix viminalis* dominates (90–95%). During the oil crisis in the 1970s, the Swedish society invested considerably in research on alternative energy sources, of which SRF was considered the most realistic and long-lived (Perttu, 1998). SRF produce biomass for energy purposes, mainly as fuelwood and fiber for the industry, which, requires larger dimensions (preferably diameters >10 cm) (Perttu, 1998). In Sweden there are limited areas where traditional coppice forest management has been implemented, while coppice with standards does not exist at all. There are several sites of simple (low) coppice managed forest in the South (Scania) and in the mountainous areas, but these are not very extensive when compared to ‘conventional’ forestry. The species used for simple coppice are alder (*Alnus spp.*), birch (*Betula spp.*), aspen (*Populus tremula*), willow (*Salix spp.*) and poplar (*Populus spp.*). The most common coppice system in is willow (*Salix spp.*) short rotation coppice (SRC), which is used to produce biomass for energy. Approximately 11,500 hectares of SRC are being grown in Sweden. Willow cultivation is fully mechanized, from planting to harvest (Löf et al., 2018).

Norway

Forest cover

Forest area accounts for about 40% of the total area of the country (Forest Europe, 2020).

Even-aged Forest management

is commonly based on based on clear-cutting and shelterwood systems (Mason et al., 2022; Savilaakso et al., 2021). Clear-cutting is the common management practice although forest owners have relatively greater freedom to manage their forests according to their own objectives within the legal framework (Sundnes et al., 2020). Forests are managed as small-scale forestry, partly due to varying topography, different production conditions and the ownership structure. Of the total forest area 58% are conifers trees and 42% are deciduous trees (Zivojinovic et al., 2015). The rotation period generally ranges from 60 to 120 years, depending on the site productivity and species involved. Natural regeneration is encouraged where feasible, reducing the need for planting (Bashir et al., 2024; Mason et al., 2022; Savilaakso et al., 2021). According to the NFAP (Norwegian Ministry of Climate and Environment, 2020), all forests are considered managed, either for wood harvesting, protection and protective purposes, recreation, and to a greater or lesser extent, hunting and berry picking. On more marginal and less productive land, the various management practices may be less intense, but still present. The intensity of management practices varies greatly within the forested area. High management intensity occurs in areas of high productivity dominated by conifers trees (spruce and pine). Very low management intensity occurs in low productive forests, hardwood forests and areas with poor infrastructure (road network). The Norwegian Government has a goal to protect 10% of the forest area with 5% of the total forest area, including 3.8 % of the productive forest area, being protected in January 2020 (FAO, 2020). As a signatory to FOREST EUROPE, Norway is committed to promote and to implement the sustainable forest management framework and no forest harvesting is allowed in areas protected for biodiversity purposes. **Error! Reference source not found.** presents the forest management approaches most implemented in Norway.

Closer-to-nature forest management

This forest management approach often involves CCF, shelterwood system, and retention forestry (Fluvio et al., 2023; Szymański, 2007). The shelterwood management system is used primarily in coniferous forests, particularly with spruce and pine species. This method focuses on natural regeneration by gradually removing mature trees over a series of cuts, allowing young saplings to grow under the protection of remaining trees, which act as a "shelter" (Larsen et al., 2022; Mason et al., 2022; Szymański, 2007). Norway's shelterwood system is favoured in areas with high rainfall, where soil and environmental conditions support natural regeneration. It helps maintain forest structure, biodiversity, and soil stability, while also providing timber over time (Fulvio et al., 2023; Novichonok et al., 2020).

Nature reserve

This forest management approach is implemented through several strategies including extensive network of protected areas, minimal-intervention management strategy, habitat restoration, and protection of cultural heritage landscapes (Nerhus, 2016). Norway's initial focus on forest conservation began with the establishment of protected areas and national parks in the early 20th century. In the 1990s, Norway had adopted more comprehensive conservation policies, emphasizing sustainable forestry that balanced timber production with ecosystem preservation. The discourse shifted towards understanding forests not only as timber resources but also as providers of essential ecosystem services, such as carbon sequestration, water regulation, and recreation. In recent years, conservation discourses have increasingly focused on climate change mitigation, with forest conservation seen as a critical tool for carbon storage (Gundersen et al., 2022; Helseth et al., 2022; Haavik and Dale, 2012). Table 2 presents the percentage area where clear cutting, seed trees stand felling and shelterwood felling is implemented in Norway.

Table 2 Silvicultural systems in Norway in 2012 (in Zivojinovic et al., 2015)

Silvicultural systems	Area implemented (harvesting and regeneration area) (%)

Clear-cutting	65.5
Seed trees stand felling	21.7
Shelterwood felling (retention harvest, small-scale clear-cutting, edge cutting, selection harvest, mountain selection system)	12.2

Short rotation forestry (SRF)

SRC does not exist in Norway as the Norwegian forestry sector is essentially dominated by conifers (Aalmo, 2018).

Denmark

Forest cover
Forest area covers about 15% of the total forest area (Forest Europe, 2020).

Even-aged Forest management
More than 70% of the forest area is managed as even-aged forests (EFM), 6% of forests are managed for biodiversity, and only 10% are managed as uneven-aged (Johannsen et al., 2019). Plantations comprise an appreciable proportion of the forest resource (Forest Europe, 2020). Due to the milder climate and fertile soils, rotation periods are often shorter (compared to Norway, Finland, and Sweden), ranging from 40 to 80 years. While clear-cutting is practiced, there is also a growing emphasis on CCF, which aims to always maintain a forest cover (Schou et al., 2012). CCF is implemented in 13% of the forest area (European Commission, 2023) and the country has reported appreciable proportions of coppice stands or plantations being transformed to CCF (Mason et al., 2022). Forest management practices applied, differ per owner type, forest type and forest objectives. The species composition by area, results in approximately 50/50 distribution of broadleaved and conifers forests. For most of the conifers, most of the area is in <65 years age class. A significant share (1/3) of the volume of broadleaved, especially beech, has diameters > 60 cm, indicating (as well as the age class distribution), an accumulation of large old trees. In conifers plantations, intensive planting is adopted, followed by intermediate thinning, leading to the final harvest. Some broadleaved forests are managed in a similar way, with more frequent intermediate thinning. Supported natural regeneration is sometimes applied in broadleaved stands, instead of planting, if suitable for tree species and sites, as for example beech species (Johannsen et al., 2019).

Nature reserve
This approach is implemented in through several strategies including extensive network of smaller intensively managed reserves, integration of nature reserves with agricultural landscapes, and no-intervention management strategies (Schifferdecker, 2018; Danish Ministry of the Environment, Danish Nature Agency, 2014). Biodiversity and ecosystem services are the main objective for public forests. The Danish Forest Act ensures protection of biodiversity on designated areas according to local conservation decisions and designation of forest habitat areas. Some of the biodiversity objectives have resulted in deforestation, for the benefit of restoration of open nature types. However, for most of the forest area there are no restrictions on species choice, cutting cycle or regeneration strategy. In 2016, the Danish Parliament agreed on a “nature package” aiming at designating 13,800 ha forest areas in State owned forests for primarily biodiversity purposes and set aside from wood supply (Johannsen et al., 2019).

Closer-to-nature forest management

The Nature Agency manages public forests according to closer-to nature principles since 2005 (Larsen, 2012). The transition from classical even-aged plantation forestry to closer-to-nature silviculture was facilitated with the development of 19 Forest Development Types (FDTs) and different conversion models in a participatory process with forest practitioners, scientists, forest workers, contractors, and other stakeholders. Many forests belonging to municipalities have also changed management strategies to closer-to-nature forest management (Larsen, 2012). According to Larsen (2012), the private forest sector has been reluctant in applying closer-to-nature management. Some forest owners are implementing with enthusiasm, while a majority implements classical age-class plantation system (Larsen, 2012).

Short rotation forestry (SRF)

Short rotation forestry (SRF) in the form of short rotation coppice (SRC) is slowly finding its way into Danish agriculture. It is believed that some 2,000 ha of mainly willow plantations exist (Kofman et al., 2018). Between 2010 and 2012, a national subsidy program was established to support the cultivation of 30,000 hectares of energy crops, including SRC willow (Nord-Larsen et al., 2015; Ministry of Economic and Business Affairs, 2009).

2.2 **Baltic countries:** Lithuania, Latvia, Estonia

Lithuania

Forest cover

Forests cover about 35.1% of the country's territory (Forest Europe, 2020). The distribution of forests by functional groups was, in 2016, as follows: I – strict reserves (1 %); II – special purpose forest with primary function of either environmental conservation or recreation (12 %); III – protective forest for protection of soil, water etc. (15 %); IV – commercial forest (72 %) (Šatinskas, 2019; Aleinikovas et al., 2018). The most common tree species are Scots pine (Pinus sylvestris), silver and downy birch (*Betula pendula*, *B. pubescens*), Norway spruce (*Picea abies*), black and grey alder (*Alnus glutinosa*, *A. incana*), aspen (*Populus tremula*) and oak (*Quercus spp*) (Aleinikovas et al., 2018). Commercial forests occupy around 72% of the total forest area and the main objective is the production of wood for the industry and energy sectors in compliance with environment protection requirements (Ministry of Environment, 2018).

Even-aged Forest management

EFM is widely implemented in commercial forestry to ensure efficient timber production and predominantly employs the clear-cutting system. Lithuanian Law states the mandatory reforestation of clear-cuts and the expansion of the forest area through afforestation of abandoned lands and clear-cut areas should be reforested within 3 years after cutting (Aleinikovas et al., 2018). In the early 2000s, Lithuania increasingly embraced European Union directives and international conservation norms, leading to a stronger focus on sustainable and ecologically based forest management. National policies began to incorporate principles of climate change adaptation, ecosystem restoration, and public use of forests for recreation and tourism (Zivojinovic et al., 2015; Hjortsø and Stræde, 2001).

Nature reserve

There are many protected areas such as strict reserves, reserves, regional parks, national parks with specific restrictions (e.g., no silvicultural practices allowed in strict reserves) and limitations for forest resource use, and where the main objective is biodiversity protection. Natural forests have expanded rapidly, by about 65,000 ha of new forest, because of both natural growth and planting on abandoned agricultural land (Zivojinovic et al., 2015; Aleinikovas et al., 2018). Rotational forest management in special-purpose forests and protective forests is strictly controlled by policies such a having higher stand harvesting age and limiting clear cuttings. Around half (49.6%) of all forest land in is state-owned. Lithuania's main legal Forest Act adopted in 1994 establishes the basic principles of forest management. State forests are managed by 42 State Forest Enterprises (SFEs) and 1 national park, under the Ministry of Environment. State forest enterprises reforest ~10,000 hectares of clear-cuts per year, and private owners reforest 4000–7000 hectares per year, depending on the area of clear-cuts (Zivojinovic et al., 2015). The rotation age for commercial forest in state forests it is 121 years for oak, 101 years for pine, larch, ash, maple, beech, elm, 71 years for spruce, 61 years for birch, black alder, lime, hornbeam, 41 years for aspen, 31 years for grey alder, sallow and willow (Aleinikovas et al., 2018).

Short-rotation Forest management (SRF)

Coppice and coppice with standards (SRC) are rare and the national forest inventory authority of Lithuania (State Forest Service) does not include these types of forest. Research on SRC has been established 20 years ago. The most common coppice is a willow (*Salix sp*.) short rotation coppice system, used to produce biomass for energy. The short rotation woody crop area is 3,027 ha, with an additional willow plantation area of 2,477 ha (NMA, 2014). Another coppice culture in is hybrid aspen. Breeding of hybrid poplars has also been started and the clones best adapted to Lithuanian climatic conditions are be used to establish short rotation plantations (Pliūra et al., 2014).

Latvia

Forest cover

In Latvia, there is 54.9% of forest cover (Forest Europe, 2020). There are two main types of deciduous forests in the South, elements of boreal forests – unmixed forests of pines, and fir-trees in the North. The main tree species are pine, fir-tree, and birch (Tērauds et al., 2011).

Even-aged Forest management

EFM is commonly based on based on clear-cutting and shelterwood systems. Norway spruce is the second most widespread conifer tree species in Latvia (Ozols, 2024; Jansons, 2019). The rotation periods in for major tree species is typically 100 years for Scot pine, 80 years for Norway spruce, 70 years Black alder, 70 years for Birch, and 40 years for Aspen. Common tree species include Scots pine, Norway spruce, and birch. Forest managers, consultants and logging companies almost always prioritise clearcutting and easily persuade forest owners with their financial offers (Fern, 2024).

Unmanaged forest

Many private forests have no management (unmanaged) (Zivojinovic et al., 2015). Small and fragmented holdings are typical in the private forest sector and the principles of sustainability are not always implemented in the management of small forest properties. Management with selective cuttings is common and there are several regulations inherited from the Soviet period. More recently, non-clear cutting forest management considers environmental considerations and follows the principles of nature friendly management. The state-owned forests are managed in line with sustainability criteria and with the certification from the Forest Stewardship Council (FSC) (Zivojinovic et al., 2015). The Forest Policy was adopted in 1998 with the main goal of ensuring the sustainable management of forests and forests lands (Ministry of the Agriculture, 2019).

Closer-to-nature forest management

In Latvia lack of money is the biggest obstacle preventing foresters from adopting alternative forest management methods, such as closer-to-nature forestry (Fern, 2024).

Multi-objective forest management

In the 2000s, multi-objective management became central to forestry policy, focusing on conserving biodiversity, protecting water resources, and enhancing the social and recreational value of forests. EU directives, such as the Natura 2000 network, further influenced Latvia’s approach to forest conservation (Pukkala, 2002; Simončič and Bončina, 2015; Hoogstra-Klein et al., 2017; Ozols, 2024).

Short-rotation Forest management (SRF)

SRF is promoted for its potential to contribute to Latvia's renewable energy targets and reduce GHG emissions by providing a sustainable source of biomass. Research and experimentation with fast-growing species continue, and SRF is seen to balance energy production with environmental sustainability, although it remains a niche practice compared to traditional forestry (Lindegaard et al., 2016).

Estonia

Forest cover

Over a half (56.1%) of the country’s area is covered with mostly semi-natural forests (Forest Europe, 2020).

Even-aged Forest management

Forests are mostly even aged, and the predominant final felling type is clear felling in forests where the objective is wood supply. Rotation ages do not exceed 100 years (Lõhmus et al., 2005). Shelterwood cuttings are being used seldom. Scots pine, Norway spruce, and birch are commonly managed species (Forest Platform, 2024; Ministry of Environment (2019). While EFM are still widely used, there is a stronger emphasis on ensuring sustainability, enhancing forest resilience, and promoting biodiversity (Mason et al., 2022; Ministry of the Environment, 2021). Environmental groups and policymakers have pushed for more diversified approaches to forest management, including selective logging, mixed-species planting, and reducing clear-cuts. Forest management has evolved significantly (Zivojinovic et al., 2015). During the Soviet period the main harvest method was the whole-stem method with cut-to-length method largely introduced at the end of the 1980s and has remain the prevailing method for logging (Zivojinovic et al., 2015).

Multi-objective forest management

Both PEFC and FSC schemes are implemented in Latvia and the PEFC is mostly used in private forests (~110,000 hectares of private forests certified in 2015). The main forest policy goal is to harmonise the intensive use of timber with environmental and recreational requirements, following the principles of sustainable forest management, adopted in the Estonian Forestry Development Plan. According to the Forest Act and the Estonian Forestry Development Plan, equal priority is given to various production and environmental functions and goals, as well as the social aspects of sustainable forest management. However, a major challenge hindering the adoption of new and innovative forest management approaches is the low profitability associated with fragmented ownership (Zivojinovic et al., 2015).

Nature reserve

Protected forests accounts for 25.6% of the total forest land area (in 2017) and includes protection forests where forest management activities are limited but not prohibited (12.5%) and strictly protected forests where all forest management activities are prohibited (13.1%) (Ministry of Environment, 2019). Under the Forest Management Regulation, it is compulsory to leave retention trees on clear-felling sites to protect biodiversity and it is forbidden to damage retention trees, forest ecosystem, water bodies and forest soil during forest management (Ministry of Environment, 2019). Major forestry operations in public forests are outsourced to private companies or entrepreneurs (mainly thinning, clear-felling, timber transport to buyers' yards) while forest planting and some types of thinning (e.g., cleaning) were undertaken by workers from the RMK forest districts in combination with outsourcing to private companies. Around 7% of forest land is strictly protected in Estonia (Lõhmus et al., 2005).

Short-rotation Forest management (SRF)

The first sets of Short Rotation Coppice (SRC) plots of willow species were established in Estonia about 20 years ago to promote the local economy and renewable energy production (Heinsoo et al., 2020). Although there is potential to promote widespread adoption of SRC in Estonia through the usage of SRC for woodchip production (Heinsoo et al., 2002), and the provisioning of ecosystem services (Poplars and willows, 2016), the widespread adoption has stalled due to legislative limitations on the establishment of SRC, the lack of a supporting scheme for SRC management and very volatile wood residue prices (Heinsoo et al., 2020).

2.3 **South Europe:** Portugal, Spain, Greece, Italy

The Mediterranean bioregion

The Mediterranean bioregion includes a unique cultural, silvopastoral and agroforestry system shaped by humans named "*Dehesa*" and "*Montado*" in Spain and Portugal, respectively. These systems include holm oak, cork oak, chestnut, and stone-pine forests, which accounts for nearly 3 million ha, are open-canopy systems combining trees with natural pasture, low tree cover, and often simplified stand composition and structure, enabling production of livestock or crops (European Commission, 2023). Forests are managed for its **multiple functions** (Spiecker et al., 2009). The spontaneous forest expansion following the rural exodus in the 1950s to 1970s led to abandonment of land, with no silvicultural tending or thinning to reduce stem density and increase structural heterogeneity (Wittenberg and Malkinson, 2009). Forest management practices in these areas include reducing fire hazards, increasing stand resistance to fire disturbance (Espinosa et al., 2019) and mitigating fire intensity to support firefighting in shaded fuel breaks (Musio et al., 2022) with the objective of promoting less vulnerable and more fire-resilient landscapes (Moreira et al., 2011).

Portugal

Forest cover
In Portugal, forest cover about 36.2% of the total mainland area (Forest Europe, 2020).

Even-aged Forest management
According to the NFAP (APA and Ministry of Environment, 2019), most Eucalyptus (*Eucalyptus spp*.) and to a certain degree Maritime Pine (*Pinus pinaster*) are under EFM, and about 36% and 44% of these stands, are uneven aged and irregular, respectively. Eucalyptus is an exotic, fast-growing species (maximum net increment <5 years old) that grows exceptionally well in Portugal. Most of the stands are planted and plantations are mainly managed as short-rotation coppice (SRC) systems, with an average cutting cycle of 10-12 years, to produce high quality wood for pulp and paper production (Duncker et al., 2012).

Multi-objective forest management
Most of the forest area in Portugal have silvopastoral uses (agroforestry), either under tree cover (mainly in the "*montado*") or in improved pastures (e.g., in the forest perimeters in the Azores islands), or in shrublands and spontaneous pastures, representing 2.3 million hectares. Some forest stands such as holm oak (*Quercus rotundifolia*), umbrella pine (*Pinus pinea*), carob tree (*Ceratonia siliqua*), strawberry tree (*Arbutus unedo*), chestnut tree (*Castanea sativa*) and walnut tree (*Juglans regia*) are managed mostly for non-wood purposes, namely for seed production for human and/or animal consumption. Cork oaks (*Quercus suber*) are managed mostly for cork (bark) production, and harvestable surface, rather than volume is the correct production unit. There is no incentive for harvest, as wood has a very low value compared to cork, and cork production increases with tree size. The promotion of sustainable forest practices has been one of the priorities for the forest policy and one of the reasons for creation of the “forest intervention zones” (ZIF) which are areas of cooperative management of the forest lands. Since 2005 there has been a significant expansion ZIFs with these currently covering around 1.1 million hectares and including more than 23,000 forest owners and managed by more than 70 different organisations, such as forest owners’ associations, cooperatives, and private companies (APA and Ministry of Environment, 2019). The contribution of forests to biodiversity and habitat conservation is achieved by both forest and nature conservation legislation and programs. The Forest Management Plans (PGF) include a mandatory “management programme” specifically addressing the management of biodiversity whenever the forest holding is located within a “classified area” for nature conservation (i.e., a “classified area” includes protected areas under Natura 2000 and/or Sites of Community Interest and/or under the Ramsar Convention).

Closer-to-nature forest management
In Portugal, where only 3% of the forest is owned by the State, the oldest and largest public forest in Portugal “*Pinhal de Leiria*”, with an area of approximately 11,000 hectares, is managed by the national authority for nature conservation and biodiversity, namely, the Institute of Conservation of Nature and Forests (ICNF). Portugal’s integration into the European Union in

1986 and adherence to EU environmental policies led to a stronger emphasis on sustainability in forest management. In the 2000s, the “closer-to-nature” approach began to gain momentum. The “closer-to-nature” forest management discourse has been mainly driven by the country’s severe problem of wildfire risk. Natural forest structures and diverse, resilient ecosystems are seen as key strategies to mitigate fire risk. The approach also emphasizes promoting biodiversity, soil, and water conservation, and enhancing ecosystem services like carbon sequestration. Certification schemes such as FSC and PEFC have supported the adoption of these practices (European Commission, 2023).

Short-rotation Forest management (SRF)
In Portugal, short rotation coppices are not common (Carvalho et al., 2018).

Spain

Forest cover
In Spain, forest covers about 37.2% of the country’s territory (Forest Europe, 2020). Conifers account for approximately 55% of the wood volume over bark, with the remaining 45% corresponding to broadleaved species.

Even-aged Forest management
Even-aged Forest Mmanagement is typically based on clear-cutting. The rotation periods vary by species, with pines typically harvested at 30-40 years and eucalyptus at 10-15 years. The silvicultural systems of EFM are traditionally geared towards maximizing timber production, primarily using fast-growing species in monocultures. The most common silvicultural systems within EFM include clear-cutting, shelterwood, and coppice (Vadell et al., 2022).

Multi-objective forest management
In Spain, forests are mostly managed for multifunctional purposes. The protective and regulating (hydrological cycle and biodiversity) roles of forests prevail, but their productive ability is also important. Forest products include wood, firewood, biomass for energy, cork, resin, edible mushrooms, pine nuts, livestock, and hunting are often underexploited due the low profitability of the forest holdings (Ministerio para la Transicion Ecologica, 2019).

Unmanaged forest
Due to lack of labour availability for forest management, because of rural depopulation, and low profitability from forests (high costs and low timber prices) land has been abandoned, and the forest vulnerability to disturbances such as drought and fires has increased. The creation of large and sustainable management units is a political priority, but with little impact on-the-ground (European Commission, 2023). Public and private owners have little interest in cultivating and maintaining their forests (Palahí et al., 2008).

Closer-to-nature forest management
In the Galicia region (Spain), mercantile associations of limited liability, named Forest Development Societies (SOFOR is the Spanish acronym), were established to promote sustainable forest management with an emphasis on economic sustainability. The Law 43/2003 on Forests ensures the conservation of Spanish forests and the promotion of their restoration,

improvement, and rational use. This law is based by the principles of sustainable forest management (Ministerio para la Transicion Ecologica, 2019).

Short-rotation Forest management (SRF)

Coppice forests cover around 4 million hectares, which constitutes around 50% of the total area covered by spontaneous hardwood, and more than 20% of the total forest area. The most important species are Quercus, mainly *Quercus ilex* and *Quercus pyrenaica*. Since 1950, coppice forest management has been gradually abandoned all across Spain and, at present, only particular species and regions still maintain a significant use of coppices (e.g. Q. ilex in the North East, *Quercus pyrenaica* in the North West and Castanea sativa in the North of Spain). As a result of this general abandonment, all current coppices have exceeded the usual age of rotation, most of them doubling that age (Piqué et al., 2018). In the 2000s, initiatives to increase sources of renewable energy at a global scale provided the impetus to explore possibilities to produce biomass as a renewable resource (Oliveira et al., 2020). The climatic, edaphic, and demographic characteristics of some parts of the country are suitable for the cultivation of SRC, with an expected high productivity exceeding that obtained in other European countries (Oliveira et al., 2020). The main species of interest at a commercial or pre-commercial level are those belonging to the genera *Populus* spp. and *Eucalyptus* spp. However, regarding poplar in SRC, there is only a token presence in Spain (Oliveira et al., 2020).

Greece

Forest cover

In Greece, forest cover amounts to about 30.3% of the total land area (Forest Europe, 2020).

Even-aged Forest management

EFM forestry systems have been a predominant approach to forest management, particularly for species such as *Pinus halepensis* and *Pinus brutia,* which are well-suited to the Mediterranean climate. These systems typically involve practices such as clearcutting followed by replanting, which allows for uniform growth and easier management of timber resources. Clear cuts and coppicing are predominantly implemented in non-state forests (municipal, church-owned, and other private lands).

Multi-objective forest management

High uneven-aged forests comprise the second mostly applied management practice where natural regeneration is implemented. Planting and seeding are used only for reforestation and afforestation purposes and seeds are collected by natural forest stands surrounding the reforested areas (Ministry of Environment and Energy, 2019). The average growing stock is approximately 62 m3/ha, with approximately 70% of harvested wood used as firewood (Spanos et al., 2021). Oak (*Quercus* spp.) forests are partly under conversion to high forests by application of selective negative thinning. Forests are mainly managed for wood and non-wood purposes (e.g., resin, honey, wild plants, livestock) (Koulelis et al., 2020; Spanos et al., 2015). As a great proportion of forest land is state-owned (74.1%), the Greek authorities are the main actors ensuring the implementation of sustainable forest management. Private forests owners (6.5% of the total area) require an approved forest management plan to operate, which ensures some degree of forest protection (Koulelis et al., 2020). Forest management in Greece is mainly characterized as sustainable and complies with approved forest management plans overseen by the Forest Service. Multi-objective forestry is essential for sustainable forest management in the context of the diverse and often fragile Mediterranean ecosystems found in Greece (Pynnönen et al., 2018). The provision of multiple ecosystem services is central to Greece.

Closer-to-nature forest management
Greece is rich in biodiversity (~1600 endemic species) and about 41,5 % of the forest area is under the Natura 2000 network. Conservation and biodiversity enhancement and protection of endemic species and their biotopes is of high priority in the country (Ministry of Environment and Energy, 2019).

Short-rotation Forest management (SRF)
About 50% of the total forest area in Greece is covered by forests managed and regenerated as coppice forests and as coppice with EFM characteristics. These include mainly oak (*Quercus* spp.) forests with a 15-30-yr-rotation period and *Castanea sativa* forests with a 20-25-yr-rotation period, except in Mount Athos where longer rotation periods can be implemented. Coppiced forests, comprising around 48% to 50% of the total forested area, are under political and societal pressures to be converted to seedling-based forest management (Spanos et al., 2021).

Italy

Forest cover and characteristics
In Italy, forests land amounts to about 32.5% of the territory (Forest Europe, 2020). Forests are characterised by a high variety of species, structure, and management. Forest resources are non-homogeneously distributed throughout the national territory, being instead polarized along the elevation gradient, and concentrated in mountainous districts (62.3% of Italian forests grow in hilly and mountainous areas at more than 500m above sea level). The remaining forest resources, located in flat or hilly areas up to 500m above sea level, show a heterogeneous spatial distribution, with less than 10% of these wood areas concentrated in relatively flat areas (<100 m a.s.l.). The exploitation of forest stocks concentrated in hilly and mountainous areas faces, therefore, systematic accessibility issues which increase the costs of cutting and clearing operations. On the other hand, the forests in flat areas, with high potential productivity and more suited to advanced mechanization, have declined since the 1950s because of the intrinsic urbanization of coastal areas and agricultural intensification of inland areas (*cited in* Lanfredi et al., 2023).

Even-aged Forest management
EFM is predominantly characterized using coppice silvicultural systems, which have a long-standing tradition in the region. Approximately 35% of Italy's forest cover is managed under these systems, which are particularly effective in integrating wood production with other forest uses, thereby addressing societal demands for multifunctional forests (Mairota et al., 2016). The coppice system typically involves clearcutting at the end of a rotation period, followed by rapid vegetative resprouting from stumps, which is a hallmark of the management practices in Italian forests (Chirici et al., 2020). This method is especially prevalent in the Apennine region, where about 43% of the forest area consists of stands aged between 10 and 30 years, reflecting the short rotation periods commonly employed (Frate et al., 2016). Coppiced stands are more

subjected to intervention than high-forest, but the wood mass harvested in high-forest is more than 50% greater than in coppices (RAF Italia, 2019). The discourse surrounding EFM in Italy has evolved to incorporate ecological considerations and the need for sustainable management practices. Traditional silvicultural practices have often prioritized the production of timber, leading to simplified forest structures that compromise biodiversity (Ciancio and Nocentini, 2011).

Nature reserve
Approximately 3.5 million hectares of woodland (representing 32% of the national forest area) fall within protected areas, testifying to an extensive protection regime characteristic of Italian forests, which can limit their exploitation (*cited in* Lanfredi et al., 2023). This protection regime can be justified with the high ecological diversification that makes Italy the first country of the European Union in terms of tree and ecosystem diversity, due to its peculiar bio-geographical location (*cited in* Lanfredi et al., 2023). Italian forests are mainly associated with pure broadleaved formations, for nearly 90% of the national forest area, with some exceptions related to the Alpine regions, where coniferous forests prevail (*cited in* Lanfredi et al., 2023). A total of about 180 different species (corresponding to a total volume of 1.5 billion cubic meters of tree biomass) were recorded in the latest national forest inventory, although four species—three of which are deciduous: beech (*Fagus sylvatica* L.), chestnut (*Castanea sativa* Mill.) and Turkey oak (*Quercus cerris*) and a conifer: spruce (*Picea abies*) (*cited in* Lanfredi et al., 2023). Forest ownership is predominantly private (66%), but publicly owned forests cover large portions of the forest area (34%). Italy is characterised by a relatively low level of utilisation of national forest resources; most silvicultural interventions take place in broadleaf stands, while in terms of wood mass there is no substantial difference compared to coniferous forests (RAF Italia, 2019).

Multi-objective forest management
A silvicultural alternative to conventional management is systemic silviculture. This model promotes the management of forests as complex adaptive systems for sustainability and resilience, thereby enhancing their functional efficiency and multi-functionality (Barbati et al., 2010; Ciancio and Nocentini). This shift is aligned with the Ecosystems Approach, which promotes integrated management of land and resources while ensuring conservation and sustainable use (Barbati et al., 2010). Until 2018, Italy did not have a proper national forestry policy and the protection, management and valorisation of the forest heritage were dealt with under other policies, primarily environmental and landscape policies. Moreover, as enshrined in the Constitution (Title V), competences on land management and productive development of forests are delegated to the Regions. This process of regionalisation has had different speeds and implications across the territory, including differences on (i) the application of planning tools, which are very important for ensuring sustainable land management and governance, (ii) appropriate forest training, (iii) lack of dedicated economic resources, (iv) forest monitoring. To address this situation, a legislative decree entitled "*Testo Unico in materia forestale e di filiere forestali*" was published in 2018, providing clear national guidelines for the creation of a unified coordination system for the sustainable management of Italian forests and the development of supply chains linked to them. In particular, the decree includes the drafting of the National Forest Strategy (NFS, issued in 2022), which aims to promote, with a long-term vision and in implementation of Italy's international and European commitments, the sustainable management of the national forest heritage and thus the development of the sector and its productive, environmental, and socio-cultural resources. In particular, the NFS aims to

contribute effectively, in line with the European Green Deal, to the pursuit of the priorities and commitments undertaken in the international arena in the fields of climate, environment and biodiversity, energy and sustainable socio-economic development.

Short-rotation Forest management (SRF)
Short Rotation Coppice (SRC), subdivided into SRF – plantation with a short cutting frequency (1 or 2 years) and in MRF – plantation with a medium cutting time (5 years), takes up about 7,000 hectares, mainly in Lombardy and Veneto Regions (Fiala and Bacenetti, 2010). Some SRF plantations developed in the 90s have been abandoned or managed more extensively for economic and environmental reasons (Alessandro et al., 2024). In Italy, SRC is based on the use of fast-growing species, high planting density, and short harvesting cycles. Fast growing broadleaved tree species with high sprouting ability are used in short rotation coppice (SRC) plantations to produce woody biomass as part of the bioenergy solution (Sabatti et al., 2014).

2.4 **Balkans:** Bulgaria, Serbia, Bosnia and Herzegovina, Romania, Slovenia

Bulgaria

Forest cover and characteristics
In Bulgaria, forest covers about 35.9% of the total land area (Forest Europe, 2020). Forests are managed according to 10-year forestry plans, which regulate the economic activities and utilisation of forests and set the maximum level of use of forest resources (Stoyanov et al., 2017). The Forestry Act classifies forest areas into three functional categories (Article 5): 1) Protective Forests: Managed to safeguard soil, water, infrastructure, and prevent erosion. 2) Special Forests: These include protected areas and Natura 2000 sites, managed to conserve biodiversity. 3) Timber-Extraction Forests: Intensively managed forests aimed at wood production (FSC, 2017). All forest areas outside national parks and nature reserves are managed under the Forestry Act (2011) and are subject to silviculture activities. The management of forests on agricultural land is more restricted, governed by both the Forestry Act and the Act for Protection of Agricultural Property.

Multi-objective forest management
In national parks (), forestry activities are limited and regulated under the Protected Areas Act (FSC, 2017). Less than 2% of all forests are strictly protected. Logging is fully prohibited in nature reserves and core zones of national parks. However, in forests with special or protective functions, logging is allowed but subject to restrictions (FSC, 2017). The felling is carried out with cutting-from-above bias. Regeneration felling is carried out in mature forest stands (Stiptzov and Kostov, 2001). The following final cuts are carried out: regeneration felling with preliminary natural regeneration, regeneration felling to combine natural with artificial regeneration, regeneration felling with subsequent regeneration. Clear felling in large areas (up to 5 – 10 hectares) has stopped in 2005 and allowed only in hunting reserve areas with an area of up to 5 hectares and with the objective of creating game foraging fields and game logging grounds (Ministry of Environment and Water, 2020). Most private forest owners do not have the specific knowledge and experience in forest management. Their interest is limited to single use

of wood resources for personal purposes, construction, heating, or income generation. Small-scale forest owners have difficulties to manage their forest holdings (Zivojinovic et al., 2015). The state-owned forested areas are managed by six state forest companies (SFC) which include 164 state forest enterprises (SFE) and state hunting reserves (SHR) (Ministry of Environment and Water, 2020). Moreover, the application of these silvicultural practices is supported by national policies aimed at sustainable forest management, as outlined in Bulgaria's National Forest Policy (Filchev and Roumenina, 2012).

Short-rotation Forest management (SRF)

Bulgarian coppice forests cover an area of almost 2,000,000 ha, or 48% of the total forest area. There are no plans for their protection; however, an large percentage of these coppices is protected under the Natura 2000 network, a network which covers 60% of Bulgarian forests. Most coppice is state-owned (ca. 70%) or municipal (15%); privately owned coppice is characterised by very small plots belonging to millions of owners (Markoff et al., 2018).

Serbia

Forest cover and characteristics

In Serbia, forests cover 31.1% of the territory (Forest Europe, 2020). The most common trees are oak (*Quercus petrea, Q. robur, Q.cerris, Q. frainetto*), beech (*Fagus sylvatica*), pines and firs[2]. The National Forest Inventory divides forests into three categories, namely forests without human intervention (virgin forests), semi-natural forests and artificially raised stands and plantations of softwoods. The largest part is occupied by semi-natural forests with over 90%, followed by artificially raised stands and plantations, while the virgin forests occupy less than 1%[3]. Stands of high origin[4] are represented by 27.5%, coppiced stands with 64.7%, and artificially grown stands with 6.1% and plantations (poplar and willow clones) with 1.7%[5]. Most State forests are managed by two public forest companies, Srbijašume and Vojvodinašume (Malovrh et al., 2019). The restitution of forests triggered new management approaches and the emergence of independent forest companies dedicated to forest management, without the involvement or influence of public enterprises. In these newly formed private companies, the business management concept has shifted towards generating profit for owners in alignment with the Forest Law (Nonić et al., 2015). Forest activities (cutting, production and transport) became undertaken by legal entities and forestry service contractors. However, these are not well equipped, both professionally and technically, for performing the forestry work[6]. Forest management in Serbia faces several challenges, namely poor condition of forests - large proportion of forest of coppice origin, a low annual increment, unfavourable age structure - uneven distribution of forest cover, poor road infrastructure, essential for the use and protection of forests, and organizational problems in management related to the large number of private forest owners[7].

[2] https://www.china-ceecforestry.org/about/
[3] https://www.china-ceecforestry.org/about/
[4] 'High forest' describes stands grown mainly from seedlings rather than coppice shoots.
[5] https://www.china-ceecforestry.org/about/
[6] https://www.china-ceecforestry.org/about/
[7] https://www.china-ceecforestry.org/about/

Unmanaged forest

Some private forests remain unmanaged, and some are primarily managed to fulfil the owners' firewood needs. Apart from few experimental fields, the production of wood biomass from short rotation energy crops plantations in Serbia is practically non-existent, in terms of practical and commercially relevant information for consideration (Stajić, 2016). The Forestry Development Strategy of Serbia (2006) focuses on biodiversity conservation and enhancement, and the sustainable use of forest resources[8].

Short-rotation Forest management (SRF)

Short rotation coppice (SRC) is permitted exclusively on agricultural land in Serbia. The primary species utilized for SRC are Salix spp. and Poplar (Krstić and Petrović, 2018). Currently, the total area dedicated to short rotation forestry (SRF) poplar plantations is approximately 48.0 hectares, accounting for about 2.1% of the country's forested areas (Morkovina and Keča, 2019; Krstić and Petrović, 2018). The high costs associated with the establishment phase pose a significant barrier to the broader adoption of SRF poplar plantations in Serbia (Morkovina and Keča, 2019). The silvicultural practices employed are designed to be close to nature, focusing on sustainable and economically viable methods that are guided by natural processes (Krstić and Petrović, 2018).

Bosnia and Herzegovina (BiH)

Forest cover and/or characteristics

BiH has the highest forest coverage (42.7%) (Forest Europe, 2020), and forest diversity of the Western Balkans countries (UNECE, 2019). European beech (*Fagus sylvatica* L.) is the dominating tree species and provides 53% of the growing stock, fir (*Abies alba* Mill.) 21%, spruce (*Picea abies* (L.) H.Karst.) 15%, oak (*Quercus petraea* (Matt.) Liebl.) 6% and pine (*Pinus* spp.) 4% (FAO cited by Cilas et al., 2023). There are three main forest types, from north to south, namely temperate continental forests, temperate mountain forests, and subtropical dry forests[9]. The most important forest community consists of mixed uneven-aged beech-fir and spruce stands (Abieti-fagetum), which cover 702,270 ha or 43% of the high forest area (Ivojevic et al., cited by Cilas et al., 2023). In 2019, approximately 1.79 million hectares of forests in the country were FSC certified, with no certification under the Programme for the Endorsement of Forest Certification (PEFC). Forests in BiH face, however, several challenges namely, forest fires, plant diseases and pests, unplanned and illegal logging, exploitation of mineral resources, hydro-accumulation, landslides, and contamination from mines. Fire risk has considerably increased over the past few decades due to the rise in average and extreme air temperatures, especially in the mountainous areas[10]. Bosnia and Herzegovina are developing its Environmental Strategy and Action Plan (the BiH ESAP 2030+ project), with the goal to improve the environment in BiH and help the progress of BiH on its path to EU membership[11].

Multi-objective forest management

[8] https://www.euforgen.org/
[9] https://www.climatechangepost.com/countries/bosnia/forestry-and-peatlands/
[10] https://esap.ba/how-can-we-sustainably-manage-forests-in-bosnia-and-herzegovina/
[11] https://esap.ba/how-can-we-sustainably-manage-forests-in-bosnia-and-herzegovina/

Traditionally, the typical forest management practices was "Plenter" forest management (Cabaravdic et al.; Matic; Pintaric et al.; cited by Cilas et al., 2023). The management system has been optimized to preserve as well as to enhance stand structure, floristic composition, and biodiversity (Cilas et al., 2023). Close-to-nature-forestry involving natural regeneration, selective cutting to manage tree species composition and keeping a diverse stand structure, as well as keeping the stocking volume and volume increment within a certain range, has been practiced in BiH for decades (Cilas et al., 2023). Thus, more than 90% of the total high forest area in BiH can be considered an uneven-aged "Plenter" forest system (Cabaravdic et al.; cited by Cilas et al., 2023). Only 5% of the high forested area is planted (Visnjic et al., cited by Cilas et al., 2023). Single tree selection forests (plenter forests) are a particular type of uneven-aged forest composed of many size or age classes with a negative exponential shaped diameter distribution[12]. Plenter forest management is a selection cutting system, semi synonymous with continuous cover forests, "Dauerwald", multi-aged or uneven-aged forests (Pommerening and Murphy, cited by Cilas et al., 2023). The selective cutting process results in a multilayered, uneven-aged forest structure (Cilas et al., 2023). Even though, Plenter forest management is common in BiH, it is uncommon throughout Europe (Cilas et al., 2023).

Nature reserve

Only 1% of the country's territory is designated as legally protected forests (Zivojinovic et al., 2015). BiH is the Western Balkan country with the most developed Forest Stewardship Council (FSC) Standard (WWF, 2023). All certified forests in BiH are state-owned and certified by the FSC (Malovrh et al., 2019).

Short-rotation Forest management (SRF)

In Bosnia and Herzegovina (BiH), the discussion around short rotation forestry (SRF) is closely linked to broader policy goals related to clean and renewable energy. This often involves cultivating fast-growing willow plantations on former coal mine sites with rotation periods of 1 to 5 years. Elektroprivreda BiH (EPBiH) is exploring the possibility of converting some coal plant units to biomass, utilizing short rotation coppicing (SRC). However, EPBiH estimates that less than 7,800 hectares of suitable former coal mine sites are available, which is insufficient to produce enough willow to sustain even one 50 MWe plant. Additionally, a trial by EPBiH to cultivate SRC willow on a former open-pit mining site has reportedly failed due to low yields (Biofuel Watch, 2023).

Romania

Forest cover and characteristics

In Romania, forestland covers approximately 30.1% of the country (Forest Europe, 2020) mostly concentrated in the mountainous areas (59%) and hills (34%) and less in the low plains (7%, where agriculture removed the forest cover in the past). Approximately 73.5% of Romania's forests consist of broadleaved species, primarily beech and oak, while coniferous forests, dominated by spruce, cover the remaining 26.5%. About 57.3% of Romanian forests fall under the protective functional category, with the other 42.7% designated as productive. (Forest-Based Sector Technology Platform, 2024). The main factor influencing forest management in

[12] https://sites.google.com/site/davidforresterssite/home/projects/single-tree-selection-forests-plenter-forests

the last 30 years is the transition from the centralised socialist system prior to 1990 to a market-based economy, which involved privatisation of the forest industry and the restitution of forests to the descendants of former (pre-1948) forest owners (Abrudan et al., 2009). The post-communist period has also seen a gradual shift in forest management paradigms, with an increasing recognition of the need to balance economic objectives with environmental sustainability. This approach enhances the ecological integrity of forest ecosystems and supports the provision of various ecosystem services, such as carbon sequestration, water regulation, and recreational opportunities (Albulescu et al., 2022). Management is still tightly regulated by the State regardless of ownership type and size, following a single strict set of rules (technical norms) (Nichiforel et al., 2021). The Forestry Code sets the principles which define the sustainable forest management of all forests giving priority to ecological objectives in forest management. As a result, forests designated as having special protection functions (soil, waters, biodiversity, etc.) constitute 57.3% of Romania's wooded regions, while the remaining 42.7% is classified as production and protection forest (never production alone).

Multi-objective forest management
Romania’s highly regulated forest management planning (FMPs) has a long tradition in implementing the forest multi-functionality. The multi-functionality principle had secured the provision of forest ecosystem services not only from the perspective of the sustained-yield principle, but also from the view of regulatory functions, recreational values, and biological diversity, making Romanian forests the largest remaining intact areas of continuous naturally regenerated forests in Europe (World Bank, cited by Nichiforel et al., 2021).

Closer-to-nature forest management
The long-term implementation of compulsory forest management plans (FMPs) has supported the conservation of closer-to-nature forests for decades, both inside protected areas and across the entire forested landscapes (Stancioiu et al., cited by Nichiforel et al., 2021).

Nature reserve
The Romanian Network of Protected Areas, encompassing nature reserves, national and natural parks, and Natura 2000 sites, covers approximately 26% of the country's total land area (Ciceu et al., 2019). Romania has a FSC National Standard since 2019 and roughly 2.8 million ha are certified. PEFC system covers around 600.000 ha (some of which are also FSC certified). Management is carried out only by specialized entities (forest districts) and only according to management plans valid for 10 years. Such plans are developed by forest management planning companies (authorized by the ministry) and are approved by the national forest authority before implementation. They follow the national technical norms with very little flexibility in terms of owner’s objectives. Their implementation is obligatory (Ciceu et al., 2019) and is checked by the state control agency (Forest Guard). Biodiversity is actively promoted through these forest management plans, which support natural forest types by regulating the composition during regeneration, as outlined in the National Forest Regulations. For regeneration diverse silvicultural treatments (imposed by national norms) are used, in most cases using natural regeneration under shelter (group or uniform shelterwood, selection cuttings). The principle of sustained yield (balanced proportion of age classes) is also imposed to all owners ensuring not only a continuous flow of timber but also a permanent presence of all habitat types (stages of development). As the rotation age (imposed by national norms) is

usually over 100-120 year (and old-growth forests are protected), the landscape mosaic contains forests from freshly harvested/regenerated to old and very old stands.

Short rotation forest management (SRF)

In Romania, SRC is practised on a small scale, only for willows and hybrid poplars (Nicolescu and Hernea, 2018). Romania's environmental policies promote the cultivation of hybrid poplar for biomass production as a renewable energy source through short rotation coppicing (SRC). The typical rotation period for these crops is between 2 to 4 years. Over 800 hectares of these poplar plantations are found in Suceava County, located in the Northeast (NE) of Romania (Dănilă et al., 2022). A study by Werner et al. (2012) indicated that poplar SRC plantations could significantly enhance the national energy supply. However, achieving this potential will require the establishment of substantial areas for SRC, as expected yields range from approximately 10 to 13 tons per hectare per year.

Slovenia

Forest cover and characteristics

In Slovenia, forests cover more than a half of the country (61.5%) (Forest Europe, 2020). About 79% of forests are privately owned and 21% are owned by the state or municipalities. Large, uninterrupted state-owned forest holdings allow for effective sustainable management, while private forest holdings are very fragmented[13]. Forest work in private forests is guided by district foresters in their direct contacts with forest owners, but forest owners are not interested in long-term investments in forests such as tending the young forest work[14].

Multi-objective forest management

Irregular shelterwood system, a forest management technique that involves a series of regeneration fellings to produce a stand of trees with varying ages, is the predominant system in Slovenia[15]. Around 99.5 % of forests are regenerated naturally, which is a guarantee of the ecological stability of the forest. Only exceptionally forest regeneration is carried out by planting seedlings or sowing seeds, in addition to natural regeneration and when ground growth needs to be accelerated. When forest regeneration occurs by planting seedlings of sowing seeds of tree species, those suited to individual sites are chosen, and half of seedlings are of deciduous trees (beech, oak, ash, maple, cherry) and a half are of coniferous trees (spruce, larch), including more than twenty different species of trees. To ensure a continuous supply of suitable seeding material, the Slovenia Forest Service manages a seed bank[16]. Forest tending is based on the principle of selecting trees according to the criteria of vitality, adaptability to the site, role in the ecosystem, health condition and quality. Using the same criteria, trees in adult forests are selected for cut by district foresters in all forests regardless of their ownership, in co-operation with forest owners and guided by FMPs[17].

[13] https://www.gov.si/en/policies/agriculture-forestry-and-food/forestry/
[14] http://www.zgs.si/eng/areas_of_work/silviculture/index.html
[15] https://adria-balkan.fsc.org/en/forest-ecosystems/forests-in-slovenia#forest-area
[16] http://www.zgs.si/eng/areas_of_work/silviculture/index.html
[17] http://www.zgs.si/eng/areas_of_work/silviculture/index.html

Closer-to-nature forest management

The Forests Act (from 1993), one of the first laws passed in independent Slovenia, requested a change in the forest management methods employed in the country, including making the inexperienced and poorly equipped forest owners in charge of forest management. The Act limits the possibility of more intensive management and, therefore, low intensity forest management prevails in private forests. Biodiversity was included in forest management plans as instructed by the Decree on special protection areas (Natura 2000 areas) from 2004. Rules on forest protection from 2009 include preserving at least 3% of the growing stock for dead wood. The implementation of concrete measures to preserve species and habitat types was enhanced in 2016 with the adoption of the Management of State Forests Act (2016). Under Article 7 of the Act, one of the seven management objectives in State owned forests is to achieve nature conservation goals, particularly in Natura 2000 sites. In 2016 a company for managing state-owned forests and a budgetary fund for forests – the Forest Fund – were established for the purpose of fostering model forest management[18]. Silvicultural plans are prepared at the forest compartment level (on average 30 hectares). These plans are based on Forest Management Plans (FMPS) and contain prescribed silviculture measures to guide implementation. Environmental protection is considered in the plans for all forests, independently of ownership, as productive forests are not managed as commercial plantations with only limited biodiversity value but promote biodiversity in accordance with the Habitats Directive and the EU Biodiversity Strategy. The realization of the allowable cut is increasing in private forests, but still below planned. Forest operations have been modernised, and the forest road density has been improved (Poljanec et al., 2019). Closer-to-nature forestry in Slovenia combines different silvicultural tools that can be broadly classified into three silvicultural systems, namely irregular shelterwood, selection, and free-style silviculture[19]. All three silvicultural systems used are based on leading principle of forest tending, which represents gradual continuous improvement of individual crop trees, forest stands and sites, they also advocate a holistic approach to complex forest ecosystems[20]. Special attention is given to forest regeneration when life of a tree begins that may last for decades or even centuries. Slovenian forestry is outstanding in the preservation of this forest type structure.

Short-rotation Forest management (SRF)

Short rotation coppice is allowed only on agricultural land (Forest law, 2016). Distinctively short rotation, felling age is between 12-30 years (Krainc et al., 2018). Trial plots of short rotation coppice (SRC) willow were established in areas impacted by mining activities. The mining company set up 4 hectares of test plantations to assess the production potential of two willow clones (Salix sp., Tordis and Inger) as alternative energy sources. Measurements were conducted annually over four years. For the Tordis clone, the biomass production was recorded at 0.88 dry tons per hectare in the first year, 4.58 dry tons per hectare in the second year, and 27.29 dry tons per hectare in the third year (Krajnc et al., 2018).

[18] https://www.gov.si/en/policies/agriculture-forestry-and-food/forestry/
[19] https://adria-balkan.fsc.org/en/forest-ecosystems/forests-in-slovenia#forest-area
[20] https://adria-balkan.fsc.org/en/forest-ecosystems/forests-in-slovenia#forest-area

2.5 **West Europe:** United Kingdom, Ireland, Belgium, The Netherlands, Germany, France, Austria, Switzerland

United Kingdom (UK)

Forest cover and characteristics

The UK is one of the least forested countries in Europe with 13.2% of the land area covered with forests larger than 2 hectares in size (Forest Europe, 2020). Within the UK, Scotland has 18% forest cover, Wales has 15% forest cover, England has 10% forest cover, and Northern Ireland has about 8% forest cover (Zivojinovic et al., 2015).

Even-aged Forest management

In the UK, EFM is typically based on clear-cutting primarily with Sitka spruce, as well as some hardwoods. There is emphasis on sustainable forestry practices, including certification schemes like the UK Woodland Assurance Standard (UKWAS).

Multi-objective forest management

All forests are managed to follow the principles of sustainable forest management and multi-purpose objectives (McIntosh, 1995). In the UK, coppicing has been recently adopted as a retro-innovation and a return to traditional modes of management in broadleaved forests, with the objective to improve management, particularly to produce firewood for own consumption (Zivojinovic et al., 2015). The UK Forestry Standard specifies good forest management including criteria covering sustainable yield, conservation of biodiversity and natural resources such as water and carbon stocks. This Standard, referring to countries' biodiversity strategies, and its supporting assurance scheme (UKWAS) have been in place before 2000. All felling of more than 5 m^3 in any calendar quarter (2 m^3 if sold) requires a licence under the terms of the Felling Licence Regulations (BEIS, 2020). Multi-objective forestry is particularly relevant in the UK, where diverse forest ecosystems provide critical resources and services to local communities while facing pressures from economic development and environmental degradation (Garrod et al., 2009).

Unmanaged forest

About 20% of private woodland in England and 23% in Wales have 'no obvious management' or "passive forest management" (Lawrence & Dandy 2014) and about 71% of private woodlands in England did not receive government grants or applied for felling licences, this indicating they may not be managed for timber or agri-environmental objectives (Yeomans & Hemery, 2010). Wood production has been declining in broadleaved forests in Great Britain, since the 1970s, with these being mostly unmanaged (BEIS, 2020). This neglecting condition is common in many small woodlands throughout the UK (Zivojinovic et al., 2015). Currently, commercial hardwood production is very low (less than 1 million cubic metres per year over bark standing). Northern Ireland private forests cover about 28,600 hectares of old, unproductive, and unmanaged woodlands. In Scotland, around 530,000 hectares of the forest area is composed by planted, fast growing Sitka spruce (*Picea sitchensis*) forests with an average productivity of 14 m^3 ha^{-1} yr^{-1} (BEIS, 2020). Stands are generally managed so that pulpwood and small roundwood is produced in early thinning while sawtimber is provided by later thinning and final felling (Duncker et al., 2012).

Table 3 presents a summary of forest areas according to management types.

Table 3 Summary of forest areas in the UK showing assignment of high-level management types (BEIS, 2020)

Ownership	Tree groups	No harvesting (% of total area)	No thinning with clearcutting (% of total area)	Thinning and clearcutting (% of total area)	Continuous cover (% of total area)
Public	Conifers	38.7	28.8	20.9	11.5
	Broadleaved	58.8	0.1	0.1	41.0
	Total	41.4	24.9	18.1	15.5
Private	Conifers	53.5	31.6	14.8	0.0
	Broadleaved	93.3	0.0	6.6	0.0
	Total	80.1	10.5	9.4	0.0
All	**Conifers**	**47.4**	**30.5**	**17.4**	**4.8**
	Broadleaved	**91.5**	**0.0**	**6.3**	**2.2**
	Total	**71.8**	**13.6**	**11.2**	**3.3**

Short rotation forest management

Short rotation coppicing (SRC) is practiced as an agricultural alternative to traditional farm crops. While it is not a significant part of the UK's woodland management heritage—aside from hazel coppice harvested on a 7–9-year rotation (Bartlett et al., 2018)—the primary species used for SRC in the UK are willow and poplar. Willow (Salix spp.) is planted in spring as rods or cuttings using specialized equipment, at a density of 15,000 plants per hectare. In contrast, the planting density for poplar is typically lower, ranging from 10,000 to 12,000 per hectare. Coppicing occurs late in the following winter (Forest Research, 2023).

Ireland

Forest cover and characteristics

In Ireland, forest land covers about 11.4% of the total land area (Forest Europe, 2020). In 2022, 49.1% of forests were in State ownership (reduced from 50.8% in 2017). The expansion of the private sector forest cover is a result of afforestation and natural expansion of semi-natural forests. Of all the EU member states, Ireland has had the highest rate of increase in forest expansion as a percentage of total forest cover since 1990 [21]. Most forests (~70%) consist of trees with 30 years old or less (Department of Agriculture, Food, and the Marine, 2022). Around 50% of Irish forests are covered by sustainable forest management certification either from FSC and/or PEFC (Department of Agriculture, Food & the Marine Department of Agriculture, Food, and the Maritime, 2019). Ireland is committed to Sustainable Forest Management [22].

Even-aged Forest management

According to the NFAP for Ireland (Department of Agriculture, Food, and the Marine, 2019), most forests are managed using EFM, intensive clear-fell, forest management approach. Afforestation, since the 1800s, has been dominated by the planting of coniferous on former

[21] https://www.gov.ie/en/publication/57d2a-forestry-facts-and-news/
[22] https://www.askaboutireland.ie/enfo/irelands-environment/forestry/forest-management/

agricultural lands, or on peat and heavy mineral soils. Forest stands with the objective of producing timber, pulp and energy-related biomass are under clear-fell systems (European Commission, 2023). Broadleaved forests are generally managed less intensively than coniferous forests. In Ireland, public forests are managed a commercially by a forestry business named *Coillte*, which is owned by the State.

Multi-objective forest management

A survey of forest owners undertaken by Ní Dhubháin et al. (2010) found that 75% were farmers and that only 7% of the forest stands visited had been previously thinned, all thinning performed was for merchantable purpose, including firewood production. The survey also found that the primary objective of most forest owners was to produce timber from their woods, landscape enhancement was an objective for 20% of respondents, and that 45% of forest owners had multiple objectives. They also found that most forest owners were undertaking forest management themselves and planned to continue to do so in the future, almost a 75% of all forest owners surveyed planned to thin their forests in the future, and almost half of those who were planning to thin, did not know how many thinning operations they would be carried out.

Nature reserve

About 100,000 hectares consisting of mixed conifer and non-native broadleaf forest are natural or semi-natural forest areas. Of these, approximately 20,000 hectares are designated native ancient forest, dating from before the 1600s (Perrin and Daly, 2010).

Short-rotation Forest management (SRF)

Short rotation coppicing (SRC) in Ireland is mostly based on willow cultivation for biomass (Short, 2018). Energy from biomass is one of the most promising renewable energy technologies which could be used in Ireland. One tonne of willow has an energy content of 13.2 Giga Joules (GJ) (at 20% moisture), so one hectare produces 172 GJ of energy per year (Teagasc, 2015). Coppicing is not widely practiced in Ireland. Anecdotal evidence suggests that a few landowners maintain small-coppiced areas for household fuelwood or for crafting and other minor products. Some coppicing is also being done with biodiversity and conservation goals in mind (Short, 2018). In the bioenergy sector, several companies are offering contracts to farmers to cultivate short rotation coppice willow, often spanning multiple years (Kofman, 2012). This willow can be coppiced six to eight times, giving the plantation a lifespan of 19 to 25 years, including the establishment year. Harvest cycles can vary, with shorter (2 years) and longer (4 or 5 years) options considered based on-site productivity and other end-use factors (Teagasc, 2015).

Belgium

Forest cover and characteristics

In Belgium, forest covers about 21% of the territory (Brussels, Wallonia, Flanders), with 53% being owned privately and 47% publicly. Five main tree species represents 76% of the total growing stock of 157,4 million cubic meters in 2000 (i.e., 120 Mm^3), namely Norway spruce, native oaks (*Quercus petraea and Quercus robur*), common beech (*Fagus sylvatica*), Scots pine (*Pinus sylvestris*) and hybrid poplar (*Populus* hybrid) (Jérôme et al., 2018). Forest management plans are compulsory in Brussels but only partially in Flanders and Wallonia. About 47% of forests in Flanders and Brussels are under a management plan. Most private forest owners do not use a management plan due to small size of their holdings (~2.5 hectares per forest owner) or lack of knowledge (Zivojinovic et al., 2015). The percentage of forest area currently undergoing transformation to CCF is significant (~45% of the total forest cover) (Mason et al., 2022).

Multi-objective forest management

Multifunctional forest management has become popular amongst those forest owners interested in other forest values than timber production. Many large forest owners are becoming more favourable to open their forests for recreational activities and to preserve and enhance biodiversity even without economic returns (Zivojinovic et al., 2015). Deforestation is forbidden. In Wallonia, the Forest Code (Decree of 15 July 2008) has introduced a several constraints to favour forest conservation and the maintenance of wood materials and carbon as for example, the restriction of clear-cutting, the obligation to plant species suited to the site, or the limitation on drainage. Three measures have been recently adopted for the management of public forest, namely thinning standard in 2009 even-aged spruce stands to produce timber in stable, healthy stands, with higher biodiversity and a shorter life cycle, higher mix of species to increase biodiversity and resilience, and permanent forest cover management (continuous cover forestry) aiming at increasing biodiversity and resilience and reduce windstorm disturbances. In the Brussels Capital Region, the Sonian Forest is protected (no deforestation allowed) and FSC certified. In Flanders, Forest Decree introduced on 13 June 1990 aims at regulating the preservation, protection, management, restoration of forests and their natural environment and afforestation, as well as maintaining the societal functions of the forest ecosystem, and it covers both public forests and private forests (Jérôme et al., 2018).

Short-rotation Forest management

In Belgium, SRC, known locally as ‘korte omloop hout’ (KOH), is classified as an agricultural crop and is not subject to forest legislation. The primary species grown for SRC in Belgium are willow (Salix sp.) and poplar (Populus sp.) (Vandekerkhove et al., 2018). These trees are planted at high densities, ranging from 5,000 to 30,000 per hectare. Harvest cycles typically last between 2 to 5 years, although they can extend to 8 to 10 years depending on growth conditions and management practices. Despite considerable research on SRC, it has not been widely implemented in Belgium. In 2021, around 83 hectares of SRC were established on agricultural land, with 31 hectares in Wallonia and 52 hectares in Flanders. A significant barrier in Flanders is the unclear and complex legislation surrounding SRC. Regulations in place often hinder ecologically beneficial SRC practices. Sites that could most benefit from SRC for nature conservation—such as areas near forests or in agricultural landscapes with high ecological value—are often the least likely to be converted due to the stringent requirements of the Flemish Forest Decree (Vlaams Bosdecreet) (Desair et al., 2022). Integrating SRC into agricultural landscapes can enhance biodiversity and improve ecosystem services. In areas lacking natural features, SRC can boost biodiversity, agricultural productivity, and protect watercourses from nutrient leaching. These benefits are maximized when SRC is implemented on a small scale in ecologically fewer valuable lands, particularly when it connects with existing natural elements (Desair et al., 2022).

The Netherlands

Forest cover and/or characteristics

In the Netherlands, most of the forest area is managed according to sustainable forest management principles. The Netherlands contains 363,800 ha of forested land, which accounts for 11% of the total land-use (Forest Europe, 2020). In the forested area, 44.5% are broadleaves and 44.3% are conifers. Most common tree species are Scots pine (*Pinus sylvestris*- 28.0%), native oak (*Quercus spp*.- 17.9%), and Birch (*Betula spp*.- 6.3%). In terms of mixture, 28.2% are unmixed broadleaves (<20%), 16.6% is mixed broadleaves, 20.5% is a mixture between conifers and broadleaves, 15.8% are unmixed conifers, 3.7% are a mixture of conifers (Schelhaas et al., 2022).

Even-aged Forest management

Most forests were planted using regular spacing and only one or two species in EFM stands, with wood production as the main objective. Due to concerns about soil fertility extraction of felling residues is limited. The majority (95%) of harvesting is done using harvesters and forwarders, but occasionally, individual trees with large diameters are manually harvested.

Multi-objective forest management

The proportion of even-aged stands has declined from 61% (in NBI-6) to 52% currently, while uneven-aged stands have increased from 15% in NBI-6 to 22% (Schelhaas et al., 2017). Natural regeneration is key in the transformation from the even-aged, pure stands to more irregular tree stands, with more species and more age classes. The percentage of forest area currently undergoing transformation to CCF in the Netherlands is relevant (~31%) (Mason et al., 2022) and increasing over time (European Commission, 2023). A change towards multifunctional forests for multiple purposes (e.g., nature conservation, recreation, and wood production) started in the 1970s, and has impacted the management and appearance of EFM stands. Harvesting mainly targets stem wood and larger branches of broadleaved species may be removed as fuel wood.

Nature reserve

In protected forests, harvesting activities are limited to 20% of the increment with these aim at removing exotic species or improving forest structure. Production usually integrates wood production and other functions such as nature conservation and recreation. Harvesting in these forests therefore is usually limited to thinning and small group felling (<0.5 ha). All forest area in the Netherlands is protected by the Forest Act to prevent deforestation and land use change (Arets and Schelhaas, 2019).

Short-rotation Forest management (SRF)

In the Netherlands, willow short rotation coppice (SRC) is cultivated in limited areas for energy purposes (Jansen et al., 2018). However, traditional willow coppice is well-regarded for its ecological and landscape contributions. Historically, traditional willow coppice has been utilized for various applications, including baskets, barrel hoops, and bean poles (Jansen et al., 2018; Londo et al., 2004; Faaij et al., 1998). These markets have declined due to material substitution, leading to the conversion of most coppice plots into other types of land use. Currently, much of the remaining traditional coppice is preserved by governmental and private nature management organizations for landscape and conservation purposes (Londo et al., 2004; Faaij et al., 1998). However, the declining market for willow twigs and the costs associated with traditional management have placed this land use under significant pressure. As traditional outlets diminish, wood for energy presents a new opportunity that could support the conservation of specific ecological qualities (Londo et al., 2004; Faaij et al., 1998). A key aspect of current Dutch nature policy is the establishment of a National Ecological Network, which includes nature conservation areas and ecological corridors. These corridors facilitate species migration between core reserve areas. For willow SRC, ecological corridors may offer promising opportunities, as they can be relatively easily integrated with other land uses (Londo et al., 2004; Faaij et al., 1998).

Germany

Forest cover and characteristics

In Germany forests cover about 32.7% of the total area (Forest Europe, 2020). In regional terms, the proportion of woodland cover varies widely, ranging from 11% in Schleswig-Holstein to over 42 % in Rhineland-Palatinate and Hesse, the most thickly wooded Länder (federal states). Forests increased by more than 1 million hectares in Germany over the past five decades[23]. Approximately, 73% of German forests nowadays consist of mixed stands. Spruce accounts for the largest share among the tree species (28%), followed by pine (23%), beech trees (15%) and oak trees (10%)[24]. All forests are considered managed and current forest management is considered sustainable and in line with EU and national forest and natural resource-related policies (Rock et al., 2019). The tree species proportions vary and depend on the specific natural features and site conditions as well as on different historic developments. Large-scale forest zones can be found in Germany with pine trees abounding in the north of Germany, deciduous trees prevailing in the lower mountain ranges and coastal areas and southern Germany is rich in spruce trees[25]. Norway spruce (*Picea abies*) is the most common and important tree species, accounting for 25% of the forest cover, 30% of the timber stock and more than 50% of the timber use (European Commission, 2023).

Multi-objective forest management

Since the mid-1980s, and in response to widespread forest dieback, the Germany's Federal Government and the *Länder* State Government launched funding programmes for the conversion of conifers forests to mixed forests. Recent forest inventory confirms the decrease in the share of Norway spruce and the increase in the share of mixed and deciduous forests (European Commission, 2023). About 52% of the forest area is owned by the Federal Government and 48% is owned by private owners or companies. The private forest in Germany is predominantly small structured and fragmented and about 50% of the privately owned forest area has less than 20 hectares[26]. All public and privately owned forest estates larger than 50 hectares are required to have forest inventories and management plans, which are monitored for compliance with the forest- and land use-related laws by the forest authorities of the *Länder* (Rock et al., 2019). More than 75% of the forest area is mixed forest (two or more species in the

[23] https://www.forstwirtschaft-in-deutschland.de/german-forestry/forest-facts/?L=1
[24] https://www.forstwirtschaft-in-deutschland.de/german-forestry/forest-facts/?L=1
[25] https://www.forstwirtschaft-in-deutschland.de/german-forestry/forest-facts/?L=1
[26] https://www.forstwirtschaft-in-deutschland.de/german-forestry/forest-facts/?L=1

main canopy layer), and more than two thirds have two or more canopy layers or are selection forests.

Closer-to-nature forest management
Forest management practices and approaches include shelterwood cuttings and partially closer-to-nature deciduous forest management and does not include the use of pesticides and fertilizers and clear cuttings. Closer-to-nature forest management uses natural processes to develop both ecologically and economically valuable forests, and similar species diversity has been found in mixed forest management and unmanaged natural forests[27]. The implementation of continuous cover forestry (CCF) is significant (~30%) and interest in the application of CCF has increased over time *(*European Commission, 2023*).* High forest management (stands grown from seedlings) is the main silvicultural system in Germany. The stands are either naturally or artificially regenerated at the end of a long production period (80 to 300 years depending on the tree species). “Plenter” forests (multi-aged forests), a type of forest that is closer to nature has had an inspiring effect on many other silvicultural methods over many decades. In these forests, trees of different age classes stand side by side, regeneration occurs on a continuous basis and selective cutting use or group-selection cutting in undertaken.

Short-rotation Forest management
Coppice forests and coppice-with-standards forests are rare today. They are, among other things, based on a regeneration of stands at intervals of a few decades by means of coppice shoots and root suckers. In terms of forest structure, these coppice stands, and coppice-with-standards stands clearly differ from high forests.[28].

France

Forest cover and characteristics
In mainland France**,** forests cover 31.5% of the area of the total land area (Forest Europe, 2020). About 25% of the forest area belongs to more than 3 million private owners, with 2.2 million of them owning less than one hectare, and approximately 380,000 owning more than 4 hectares, these accounting for 76% of the privately owned forest land. The State and municipalities own 25% of forest land with public forests playing a key role in the delivery of societal benefits, including visitor access, as well as biodiversity and habitat conservation (Robert et al., 2019; Tissot and Kohler, 2013).

Even-aged Forest management
Coniferous forests are primarily managed as even-aged stands, except in mountainous regions, and serve as an important source of raw materials for the timber industry (Ols and Bontemps, 2021). These even-aged (EFM) conifer forests are found across diverse climatic zones—oceanic, continental, and Mediterranean—accounting for 25% of the forest area and 40% of the growing stock (Ols and Bontemps, 2021).

Multi-objective forest management

[27] https://www.forstwirtschaft-in-deutschland.de/german-forestry/forest-facts/?L=1
[28] https://www.forstwirtschaft-in-deutschland.de/german-forestry/forest-facts/?L=1

All public forests are managed according to the principle of multifunctionality, and their management regime is aligned with the French forestry regime. CCF is a common forest management approach in eastern France and covers 25% of the forested area (Mason et al., 2022). Forest owners owning more than 25 hectares are also obliged by law to develop a legal forest management plan (*Plan Simple de Gestion* - PSG), which needs to be approved by the regional centres for forestry property (CRPFs). This plan is outlined in the forestry code and forms an integral part of the sustainable management framework for French forests (Tissot and Kohler, 2013). Small forest owners have the option to either adhere to a code of good forestry practices (CBPS) or to submit a management model regulation (RTG). The RTG outlines recommended forestry measures, optimal rotation periods and species selection, and key environmental considerations (Tissot and Kohler, 2013). Restoration by afforestation of degraded sites is encouraged and the protection of particularly sensitive forest ecosystems is reinforced by forest policy (Robert et al., 2019).

Short rotation forest management

Coppice structures are still widely present in French forests. Simple coppice structures cover 11% of the total forest area, while coppice with standards cover 30% (Ruch et al., 2018).

Austria

Forest cover and characteristics

In Austria, forests cover 47.2% of the territory (Forest Europe, 2020). Forests are mainly composed by coniferous trees (>70 %), mainly spruce (*Picea spp.*). Broadleaved trees cover about 25% of the forests. Sustainable forest management has been the guiding principle of forest management policy for more than 100 years (Federal Ministry of Agriculture, Forestry, Regions, and Water Management, 2023).

Closer-to-nature forest management

Forest management mainly focuses on biodiversity maintenance, productivity, regeneration capacity and vitality of forests, and on climate change adaptation (Federal Ministry Republic of Austria, 2019). The diverse conditions of the Alpine landscape have led to diversification of management and harvest conditions in technical and economic sense. Principles of forest management are determined in the Forest Act (adopted in 1975) and include general bans on forest clearcuts and deforestation and on forest destruction, requirements for reforestation after felling, sustaining forest soil productivity, specific protection and management measures against pests and other disturbances, restrictions on forest litter removal, provisions on harvest, haulage, and forest protection (Federal Ministry Republic of Austria, 2019). Closer-to-nature forestry practices are already being implemented in some areas. The combination of different closer-to-nature forestry measures has led to a greater distribution area of beech (*Fagus* spp.) forests and to the promotion of natural composition of tree species, namely replacing monocultures of Norway spruce (*Pice abies*) at lower altitudes with native broadleaved tree species (European Commission, 2023).

coppice forests presently cover an area of about 100,000 ha or 2.3% of the total forested area. Approximately 75,000 ha belong to the "land-coppice system" and 25,000 ha are part of coppice forests in the alluvial plains.

Short-rotation Forest management (SRF)
Coppice forests presently cover an area of about 100,000 ha or 2.3% of the total forested area. Around 75,000 ha belong to the "land-coppice system" and 25,000 hectares are part of coppice forests in the alluvial plains. Coppice (15–30-year rotation); coppice with reserves (underwood 20–30-year rotation; reserves 40-60 years) and coppice-with-standards management (underwood 20-30 years; overwood 100-120 years) have been a widespread silvicultural practice in the eastern part of Austria for many years (Kühmaier et al., 2018).

Switzerland

Forest cover and/or characteristics
In Switzerland, 32.1% of the land area is covered with forest (Forest Europe, 2020). Forest area at higher altitudes and on the southern side of the Alps has increased marginally over the past decade but has remained constant in lower-lying areas. About 73% of the total forest area are publicly owned (Zivojinovic et al., 2015). Twenty-seven percent of the forest area (about 340,000 ha) is privately owned by approximately 240,000 different owners and private forests are highly fragmented. Private actors own small forest areas, and public actors own larger forest areas (Landolt et al., 2015).

Multi-objective forest management
There is increasing trend in the diversity of domestic tree species and structured forests, and volumes of dead wood are rising[29]. All forests are subjected to forest management. Forest management and conservation are decentralised with governance/management shared by the national (federal) level in Berne, the regional (cantonal) level and the local (commune and community) level (Landolt et al., 2015). Although approximately 95% of the total forest area in Switzerland is available for timber production, strong incentives for efficient wood production are generally lacking. About 17% of the forest area is certified by PEFC, while 49% are certified by FSC (Zivojinovic et al., 2015). The main objective of the Swiss National Forest Plan is to guarantee sustainable forest management, and to create favourable framework conditions for an efficient and innovative forest and wood sector. It also aims at ensuring the provision of societal services in a cost-effective way (SAEFL, 2004). The discourse surrounding nature reserves and forest conservation in Switzerland is characterized by a strong commitment to sustainable management practices that prioritize ecological integrity, biodiversity, and the provision of ecosystem services (Angst, 2012).

Short-rotation Forest management (SRF)
Short rotation coppice is not relevant in Switzerland (Cueni et al., 2018).

2.6 **Central Europe:** Slovakia, Czechia, Croatia, Hungary, Poland

[29] https://www.bafu.admin.ch/bafu/en/home/topics/forest/in-brief.html

Slovakia

Forest cover and characteristics

In Slovakia, forest covers about 40.1% of the total land area of the country and is steadily expanding (Forest Europe, 2020). The most prevalent forest types are broadleaved and mixed forests (Ministry of Agriculture and Rural Development of the Slovak Republic, 2020). Slovak forests are very diverse in tree species composition. The most abundant tree species include beech (33.2%), spruce (23.4%), and oaks (10.6%). The percentage of conifers has steadily decreased, which is most apparent in the case of spruce, which has declined by 2.9% in last 10 years (MPSR 2016 cited by Repáč et al., 2017). In 1950 almost 60% and in 1990 already around 92% of the forests belonged to the State ownership. After the restitution, forests of the Slovak Republic (state enterprise) own 43% The remaining forest land is owned by nonstate entities, include which forest under private (the average size of private holding is only 2.8 hectares), community, church, agricultural cooperative, and municipal ownership. About 15% of forest areas are forests of unidentified ownership. State enterprises manages 55.5% of the forest, which include forests owned by the State, forests leased from non-state owners and unclaimed forests[30].

Nature reserve

Slovakia has significant sources of biodiversity and the proportion of forest areas included in the Natura 2000 is 46.5% (APA 2015 cited by Repáč et al., 2017). About 70% of forests is created by indigenous ecosystems (Repáč et al., 2017). Broadleaved species are dominant and comprise 62.2% of Slovak forests and the percentage of conifers has been steadily decreasing (Barka et al., 2018). According to FAO (cited by WWF[31]), 1.13 million hectares of forests are located within protected areas, corresponding to approximately 58% of the total surface of forests. Forest management is based on management plans, which include logging plans. There are six regional forest offices in Slovakia, that supervise compliance with legal regulations, approve forest management plans and declare protection and special purpose forests[32].

Closer-to-nature forest management

Currently, forest management is more focused on closer-to-nature forest management and establishment of forest stands with better structural and species diversity and higher ecological stability. All forest area is managed, and forest management is guided by a forest management plan renewed every 10 years, covering regeneration and afforestation, clearing, regular thinning, logging (timber felling, skidding, and hauling) and forest protection (Barka et al., 2018).

Short-rotation Forest management (SRF)

The total area of short rotation coppice (SRC) on Slovakian forest land is about 520 hectares, while the potential area is estimated at 15,000 hectares. Anticipated annual production is

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[30] https://www.wwf.de/fileadmin/fm-wwf/Publikationen-PDF/EU-Forest-Crime-Initiative-Slovakia-GAP-Analysis.pdf

[31] https://www.wwf.de/fileadmin/fm-wwf/Publikationen-PDF/EU-Forest-Crime-Initiative-Slovakia-GAP-Analysis.pdf

[32]https://www.eurosaiwgea.org/documents/meetings/Training%20Forests/Forestry%20in%20Slovakia%20(introduction).pdf

around 10 tons of dry matter per hectare. According to the National Forest Centre, the theoretical potential for SRC on agricultural land is 45,000 hectares, though only about 150 hectares are currently cultivated. The primary species used for SRC are willow and poplar. Rotation times range from three years for willow to up to twenty years for poplar, with expected annual yields of 12 to 18 tons of fresh biomass per hectare (or 6 to 10 tons of dry matter under optimal conditions and management) (Fehér, 2018).

Czechia

Forest cover and characteristics

In Czechia, forests cover about 34.7 % of the total land area (Forest Europe, 2020). The principles of sustainable forest management practice are derived from the Czech Forest Act, which is one of the strictest in Europe. Natural forests are reported to account for 1.1% of the forest area (Czech Ministry of Agriculture 2021). Approximately 60% of the current forest stands are mainly coniferous, 11% are formed mainly by deciduous species with the remaining 29% being mixed species (Czech Ministry of Agriculture cited by Kjučukov et al., 2022). Coniferous monocultures dominate Czech forestry, but the proportion of deciduous stands has gradually increased by around 6% between 2000 and 2020 (Czech Ministry of Agriculture cited by Kjučukov et al., 2022). Nearly 75% of the forests are designated for commercial use, with the remainder serving non-productive purposes. Ownership is primarily state-held, accounting for almost 54% of forests, followed by 19% owned by private individuals, 17% by municipalities, 5% by churches, 3% by private companies, and 2% by cooperatives or other entities (Kjučukov et al., 2022). Every forest owner with more than 50 hectares is obliged to have a forest management plan (FMP), where the maximum amount of wood removals is prescribed and cannot be exceeded (Ministry of the Environment of the Czech Republic, 2019).

Even-aged Forest management

Even-aged silvicultural systems especially the clearcutting and the shelterwood system dominate the Czech forestry. A high level of salvage loggings whose volume exceeded the annual increment has taken place in the recent years (Kjučukov et al., 2022).

Closer-to-nature forest management

The practice of closer-to-nature silviculture in the Czechia has evolved significantly, reflecting broader trends in ecological awareness and sustainable forest management. Its origins can be traced back to the late 19th century, when advocates like Liebich and Tichý promoted diverse, natural forest management and rejected monocultures and clear-cutting. In the mid-20th century, however, these practices declined under centralized planning, which prioritized large-scale clear-cutting and even-aged monocultures for timber production efficiency. After the political changes of 1989, there was a resurgence of interest in closer-to-nature silviculture as part of a broader movement towards sustainability and biodiversity conservation. Organizations such as PRO SILVA EUROPE played a key role in promoting these practices across Europe. Closer-to-nature is progressively being established as an alternative to the forest management system based on clear cutting and management of even-aged coniferous monocultures (Remeš, 2018). The transition to closer-to-nature forestry in the Czechia was initially motivated by the need to manage large areas of monoculture, even-aged forest stands planted on acidic and nutrient-poor soils as these conditions had led to unstable forests, increasingly vulnerable to various calamities (Remeš, 2018).

Short-rotation Forest management (SRF)

Coppicing was a widespread management system in the Czech lands (Bohemia, Moravia and Silesia) at least since the Late Middle Ages. Forest has always been relatively scarce in the lowlands of t Czechia and coppicing for fuelwood production has prevailed in the lowlands (Hédl, 2018). The interest in the coppice forests has been increasing in the Czechia to protect endangered species, enhance biodiversity, and obtain a sustainable source of energy (Štochlová and Hédl, 2018). Seven sites (some of them with several sub-sites) have so far been restored to traditional coppicing. Around 9,310 ha (0.36 %) of simple coppice forest and 2,393 ha (0.09 %) of coppice with standards can now be found in the Czechia (ÚHUL cited by Štochlová and Hédl, 2018) and most of these stands are found in protected areas, including natural reserves and national parks (Hédl, 2018). Coppice forests are mainly composed by softwood trees (e.g., willow, black locust) (Štochlová and Hédl, 2018).

Croatia

Forest cover and characteristics

In Croatia, forests cover about 34.7% of the country (Forest Europe, 2020). The Croatian Law on Forests (Zakon o šumama) classifies forests into productive (52%), protective (30%) and special purpose forests (18%), which roughly defines the primary goal of forest management. The forest stands classified according to cultivation form, namely high forest stands (56%), coppice forests (14%) and degraded stands of scrubland, thickets, maquis, garrigues (27%), forest plantations and forest cultures. About 97% of forests in Croatia are semi-natural forests (self-regenerated or planted or sown) and 3% are plantation forests[33]. Forests are managed according to 10-year management plans (Zivojinovic et al., 2015). The wood stock harvest plan is prepared in accordance with the provisions of the Law on Forests and the Ordinance on Forest Management and the principles of sustainable forest management. In the planned area for harvest, the main tree species are common beech (36%), sessile oak (11%), common hornbeam (10%), common oak (9%), common fir (7%), field ash (4%), while other types of trees are represented by 23%[34]. About 76% of forests are owned by the Republic of Croatia and private forest owners own about 24% of forests, most of these private forests are smaller than 1 hectare. Forest management methods implemented in Croatia are EFM (52%), selective forests (18%) and uneven-aged (30%). Private forests are facing numerous difficulties to ensure SFM[35]. In Croatia, publicly owned forests are managed by Croatian Forests Ltd. (98%) and other public institutions (2%) (Zivojinovic et al., 2015). Forest management in Croatia faces several challenges, including unclear ownership, forest property fragmentation, small size of parcels, restrictive forest regulations, lack of forest management plans, illegal logging, unfinished process of forest restitution[36], and new challenges such increasing frequency of climate change-related disturbances such as wildfires and storms (Posavec et al., 2023).

[33] https://www.cepf-eu.org/about-us/members/croatia
[34] https://adria-balkan.fsc.org/en/forests-in-croatia
[35] https://www.sumins.hr/wp-content/uploads/2016/11/Bro%C5%A1ura_FACESMAP_Forests-in-Croatia.pdf
[36] https://www.sumins.hr/wp-content/uploads/2016/11/Bro%C5%A1ura_FACESMAP_Forests-in-Croatia.pdf

Even-aged Forest management

Even-aged stands with a high growth form are rejuvenated naturally, by "rejuvenation" felling. In this type of felling, rejuvenation occurs under the cover of the old tree crowns, and the trees of the old stand are progressively removed by "rejuvenation" felling, with the appearing a new generation of plants, i.e., a new stand. Thus, at one moment, during the rejuvenation period, two generations of forest stands grow simultaneously on the rejuvenated surface (an old stand and a new stand in the development stages). "Rejuvenation" felling includes the implementation of preparatory cuts, rejuvenation cuts and final cuts[37]. Selection forests represent an area where regeneration is a permanent process that occurs simultaneously with other management activities.

Multi-objective forest management

Uneven-aged management in private-owned forests is considered as a transitory stage between the first two modes of management. Detailed forest management practices applied per type of forest management approach (even-aged, uneven-aged) and per tree species (e.g., oak, beech, fir) and in strictly protected areas are described in the NFAP for the Republic of Croatia (Ministry of Environment and Energy & Ministry of Agriculture, 2018).

Closer-to-nature forest management

Biodiversity is considered highly important in Croatian legislation and in the management of forest resources. About 36% of the Natura 2000 network in Croatia are forests and forests land (broadleaves 25.58%, coniferous 2,57% and mixed 7.65%) and about 95% of forests are closer-to-nature managed forests[38]. The principles of sustainable management (SFM) implemented in Croatia are based on the scientific knowledge of the Zagreb School of Forestry are intertwined into Croatian forest management, with natural forest regeneration and preservation of climatogenic forest communities[39].

Short-rotation Forest management (SRF)

The area of coppice forests in Croatia amounts to 359,610 hectares (14.4 % of forests in Croatia), while 192,986 ha (53.7 %) are managed by the state-owned company „Hrvatske šume“Ltd., 5,832 ha (1.6 %) of state-owned coppices are managed by other legal entities and 160,792 ha (44.7 %) are privately owned. Coppice forests in Croatia represent a significant source of wood products and provide a variety of forest services and functions (e.g., soil and water protection, biodiversity). Coppicing is the most convenient form of management for owners of small deciduous forests, from which they extract firewood, poles, small-sized industrial wood fallen leaves, as well as grazing (Dubravac et al., 2018).

Hungary

Forest cover and characteristics

In Hungary, forest land cover 22.7% of the country’s territory (Forest Europe, 2020). Forest composition is 90.5% deciduous tree species and are typically mixed forest communities (Kiraly,

[37] https://adria-balkan.fsc.org/en/forests-in-croatia

[38] https://www.sumins.hr/wp-content/uploads/2016/11/Bro%C5%A1ura_FACESMAP_Forests-in-Croatia.pdf

[39] https://www.exportdrvo.hr/company/forests-of-croatia

cited by Kiraly and Borovics, 2024). Conifers are mainly considered as introduced species and high proportion of the broadleaved forests also consists of introduced species, such as black locust and improved poplars. The Hungarian Forest Act (2023) considers four forest management systems, namely rotation forest management, continuous cover management, non-production forest management, and transitional forest management (Kiraly and Borovics, 2024).

Even-aged Forest management

Almost all forests in Hungary are considered as even aged and established artificially and stands of coppice origin represent 40% of the area. After felling, the natural regeneration process is favoured. The proportion of naturally regenerated stands (coppice and regeneration cuts) consists of about 50%. The age structure of Hungarian forests has been improving because of regulations to achieve sustained yield. In the case of the rotation forest management system the cultivation of nearly same-aged trees is undertaken in the forest stand, and stands are felled and regenerated following a temporal and spatial cycle.

Multi-objective forest management

Hungarian forests have a large variety of mixed, often multi-storied stands of broadleaved species[40]. Forests designated for protection purposes (37.3%) encompass soil protection, water protection, settlement protection, and nature conservation (Levente, 2018). About 55 % of the Hungarian forests is state-owned and managed by 21 state forestry companies, while private forests are owned by 450,000 private persons and managed by nearly 32,000 private forest managers, who typically manage small, fragmented areas (Borovics et al., cited by Kiraly and Borovics, 2024). The State Forest Administration oversees, approves, and formulates the forest management plans for both State and private forest owners and managers. Therefore, forest managers do not have much autonomy, and have their activities under strict regulation and supervision, having to comply with traditional practices (Zivojinovic et al., 2015). In the case of the continuous cover forest management system no final cutting resulting in regeneration obligation occurs. The main objective of transitional forest management is the transition from rotation forest management to continuous cover forest management, and the more continuous maintenance of forest cover as compared to the rotation forest management system. To extend the period of forest regeneration the final harvest and regeneration activities are undertaken in many different phases, separated in space and time according to the forest transformation and regeneration plan. Contiguous final cut areas cannot exceed 1.5 hectares by law; and during the implementation of harvesting activities, an important aspect is the continuous provision of forest regeneration and renewal.

Unmanaged forest

Forest owners do not have much knowledge about their forests and about forest management, sometimes not even knowing where their forests are located (Zivojinovic et al., 2015).

Nature reserve

Less than half of the forest area consists of natural, “real forests”, mainly oak and beech forests. These almost disappeared after the deforestation of the plains for agricultural reasons in the previous centuries and were replaced in the 20th century by plantations of pine, black locust,

[40] https://www.fao.org/4/w3722e/w3722e20.htm

and poplar. In the mountains, forests consist of native, young trees. There are only a few old-growth forests left on mountainsides and in ravines that are difficult to access [41]. In the case of the non-production forest management system there is no timber management, and logging activities are only allowed for experimental purposes or because of forest protection, nature conservation, public welfare, forest regeneration or other public interest.

Closer-to-nature forest management

In Hungary, the area of alternative forest management systems (i.e., continuous cover management, non-production forest management, and transitional forest management) has been increasing. Nevertheless, in 2021, the forest area under alternative management only accounted for the 9.2 % of the total forest area of the country. In Hungary, 62% of the forest land is under some type of nature conservation, either under national protection or Natura 2000, or both. It is possible to undertake harvesting activities in nature conservation and in only a small proportion of nature conservation areas are under complete harvesting restrictions. In protected forest lands under rotation forest management Nature Protection Authority prescribes retention of living single trees or tree patches when final harvesting takes place. The retention of standing and lying dead trees is also prescribed when thinning or final harvest is undertaken (Kiraly and Borovics, 2024).

Short rotation Forest management (SRF)

Field experiments with poplar short rotation coppices (SRC) in Hungary began in the 1980s and broader utilization started in 2007 after the introduction of an SRC subsidy scheme. This financial support covered establishment costs, including site preparation, soil fertilization, the purchase and storage of reproductive materials, planting, and initial maintenance, as well as expenses for pavement construction and fencing. However, many poplar SRCs became unprofitable despite this support, primarily because the yields from the plantations did not meet expectations. Additionally, harvesting services were hard to access and costly due to the small scale of the plantations. Optimistic forecasts regarding wood chip demand and transportation costs further contributed to the challenges faced (Schiberna et al., 2021).

Poland

Forest cover and characteristics

In Poland, forests cover about 31% of the country area (Forest Europe, 2020). Forest ecosystems are an essential part of the national system of protected areas, with forested land accounting for 61% of the area within National Parks, 66% in Nature Reserves, 53% in Landscape Parks and 39% in Areas of Protected Landscape. Most forests are public forests (~80.8%) and 77% of the management is overseen by the State Forests National Forest Holding (Kruk and Kornatowska, 2014; Ministry of the Environment 2018). Forest management in forests constituting nature reserves or in national parks is based on regulations of the Act on Protection of Nature[42]. While the State Forests National Forest Holding manages 7.6 million hectares, the remaining 1.6 million hectares are distributed among approximately 1.5 to 2 million forest owners, averaging about 1 hectare per owner (Kruk and Kornatowska, 2014). All State-

[41] https://wwf.panda.org/wwf_news/?269991/Old-growth-forests-in-Hungary-in-danger
[42] https://www.fao.org/4/ad744e/AD744E10.htm

owned forests are certified by the Programme for the Endorsement of Forest Certification (PEFC). The forest habitat composition in Poland is notably defined by pinewood habitats, covering 50.5% of the total forest area, and habitats dominated by broadleaved trees, encompassing 49.5% (Kruk and Kornatowska, 2014; Ministry of the Environment, 2018)

Nature reserve
About 40% of Polish forests are classed as protection forests[43]. Forest management is guided by legal regulations, including the Forest Act and its implementing acts, as well as arrangements included in 10-year plans. All forests managed by the State Forests are covered by Forest Management Plans (FMP). These documents are prepared for each forest district for a period of 10 years. Forest management objectives and functions of forests in the managed forest district are considered in the actions planned for implementation[44].

Multi-objective forest management
Forest policy goals aim at ensuring the sustainability of forests together with their multifunctionality (Ministry of the Environment, 2018). While timber production remains a significant aspect of forestry, there is a growing recognition that sustainable practices can lead to long-term economic benefits by enhancing the health and productivity of forest ecosystems (Banaś et al., 2021).

Short-rotation Forest management (SRF)
Currently, in response to the growing demand for renewable energy sources, short-rotation plantations of fast-growing trees like willow and poplar are being established. These plantations represent a notable expansion of coppice utilization for energy purposes in Poland, alongside a variety of other coppice species (Mederski et al., 2018).

3 Forest managers' typologies

Forest management approaches and practices are implemented by public and private forest owners and managers, and these depend on several conditions such as biogeographically determined site factors, exposure to major disturbances, as well as societal demands which are external factors outside the control of forest owners and managers, and by internal factors to forest owners such as their attitudes, values, norms or perceived behavioural control. All these factors influence forest management approaches and practices implemented, such as species selection, site preparation, planting, tending, or thinning, can be altered by management. The management implemented indicates different types of private and public forest owners and managers. Additionally, private ownership of forests is characterized by a significant degree of fragmentation, with approximately 60% of these forests being less than one hectare in size (Weiss et al., 2019; Blanco et al., 2015). This small size poses numerous challenges in terms of management, resulting in a lack of proper management practices across most of these forests (Matilainen and Lahdesmaki, 2023).

[43] https://www.fao.org/4/ad744e/AD744E10.htm
[44] https://www.un.org/esa/forests/wp-content/uploads/2022/05/VNC_Poland_May2022.pdf

In Europe, the increasing diversity of non-industrial private forest owners (NIPFOs) has been widely recognized (Živojinović et al., 2015; Ficko et al., 2019). Typologies of forest managers have been developed to help research, policy, and practice to better understand forest owners' decision-making processes by considering the diversity of their attitudes, values, beliefs, management objectives and behaviour. A typology helps to segment forest owners in categories. Examples of factors used to categorise private forest owner in types include actual or expected management behaviour, forest ownership objectives, forest owner's goals, significance of various benefits provided by the forest, motivations for ownership, decision-making modes, perceptions, and attitudes to multifunctional woodland management among others (Ficko et al., 2019). **In this report, there is special interest in forest management approaches per type of forest manager.**

Several forest owner typologies can be found in the literature and Ficko et al. (2019) reviewed European PFO (Private Forest Owners) typologies published in international peer-reviewed journals from 1985 to 2015. Even though typologies listed by Ficko et al. (2019) are only defined as PFO typologies, in some of the studies reviewed (e.g., Hugosson and Ingemarson, 2004; Van Herzele and Van Gossum, 2008) **typologies are constructed from a sample composed by private forest owners and professional foresters/managers**. In Hugosson and Ingemarson (2004) professional foresters, defined as those with a formal education in forestry and with wide-ranging experience of small-scale forest owners and forest management working with forest owners, were interviewed to collect their knowledge about forest owners' motivations and objectives. Van Herzele and Van Gossum (2008) interviewed a group of forest coordinators of small pine plantations in Flanders (the northern part of Belgium) to assess how they would distinguish the various types of owners based on their knowledge of forest owners they worked with.

Understanding which key factors influence forest owners' decision making, and how the different types of owners respond to the different drivers (global and national environmental policy targets, climate change, wood prices, global demand for wood and wood products etc.) is crucial to understand how future forest management might change. Even though forest owners' typologies can help in predicting owner's behaviour or target advice and incentives, its usefulness and effectiveness can be questioned as these are not usually context specific. For example, in many cases older owners are found to be less likely to manage their forest or harvest timber, and more likely to outsource forest work, while in other cases, older owners are more likely to harvest (Conway et al.; Favada et al.; Novais and Canadas; Rodríguez-Vicente and Marey-Pérez *In* Lawrence et al., 2020).

The most recent review of typology studies is Ficko et al. (2019) who analysed 66 publications published in the period 1985–2015. The publications represented forest owners from 16 European countries. The most represented groups were forest owners from Northern European (i.e., Denmark, Finland, Sweden). Table 4 provides a concrete breakdown of the number of publications per country—this breakdown highlights the historical lacuna in forest typology research, as forest owners from most regions are vastly underrepresented. Southeastern Europe (e.g., Albania, Bulgaria, Croatia), Central Europe (e.g., Poland, Slovakia, Slovenia), and Eastern Europe (e.g., Czechia, Latvia) are especially underrepresented, as no publications were sourced from most countries in these regions.

Table 4 Number of forest typology articles published between 1985-2015 on a per country basis (Source: Ficko et al, 2019).

Countries by regions[45]	**Articles (n)**
North Europe	
Denmark	*5*
Finland	*9*
Sweden	*3*
Estonia	*1*
Lithuania	*1*
Total	**19**
Central-West Europe	
Belgium	*2*
Ireland	*2*
Netherlands	*1*
The United Kingdom	*2*
Total	**7**
Central-East Europe	
Hungary	*1*
Austria	*3*
Germany	*3*
Total	**7**
South-East Europe	
Greece	*1*
Romania	*1*
Total	**2**
South-West Europe	
Portugal	1
Spain	1
Total	**2**

3.1 Private forest owner typologies in Europe

3.1.1 Main typologies identified in the literature.

The most common types of forest owners found by **Ficko et al. (2019)** review is: the **multi-objective owners (**mentioned 7 times); the **recreationists**, **investors, and farmers** (mentioned 6 times), the **indifferent owners** (mentioned 5 times) and the **conservationists**,

[45] Regions are classified as presented in State of Europe Forest (SoEF) reports.

multifunctional owners, and **self-employed owners** (mentioned 4 times). A further review of studies undertaken within ForestPaths complemented the review undertaken by Ficko et al. (2019) and established the following **5 most common types of forest owners/managers**:

- **Economic-oriented Forest Managers, this covering the following types:** materialists (Austria), economically interested forest owners (Germany), materialistic profit seeking forest owners (Belgium), economist (Sweden), businessmen (Lithuania), Forest entrepreneurs (France, Sweden), Large-scale Forest owners (Germany), and Forest farmers (Ireland).
- **Tradition-oriented Forest Managers, this covering the following types:** custodians (United Kingdom), classic forest owner (Denmark), traditionalist and family forest owners (Sweden), traditionalist forest owner (France), Forest family owner and household forest owner (Lithuania) and traditionalists (Italy).
- **Environment-oriented Forest Managers, this covering the following types:** forest conservationist (Austria), idealist (Germany), non-materialist (Slovenia), forest environmentalists (France), forest lovers (Lithuania), green values forest owners, (Sweden), no management forest owner (Germany), recreationists (Finland).
- **Passive Forest Managers, this covering the following types:** hobby owners (Austria and Denmark), uninterested forest owners (Germany), urban forest owners (Germany), passive outsiders (France), ad hoc owners (Lithuania), disinterested forest owner (Italy).
- **Multi-objective Forest Managers, this covering the following types:** public forest managers (Bulgaria and Germany), multi-objective owner (Finland), municipalities forest managers (Bulgaria and France).

In the reviews undertaken by Ficko et al. (2019) and within ForestPaths, forest manager types are mainly classified according to **ownership objectives rather than to forest management approaches undertaken per type of forest manager.** In the studies reviewed, the main **factors differentiating owner types are**:

- the contribution of forest earnings to household income.
- the perceived importance of economic, environmental, and recreational benefits from the forest.
- the perceived importance of the forest as a legacy.
- the perceived importance of the forest as a place to do forest work, for self-employment and/or as a hobby.

Even though the “forest management approach” has not been one of the main factors used to define forest manager types, there are scattered information in the studies reviewed about forest management per forest manager type as well as about the role of networks and knowledge on their management decisions and this information is summarised in **Table 5** below.

Table 5 Forest managers' typologies according to owners' characteristics and management style

Forest managers' typologies	Forest owners' characteristics and the role of networks and knowledge on their decisions	Management style
Economic-oriented Forest Managers	Large-scale private forest owners (France, Germany, Lithuania, and Sweden) with forest properties >100ha Representatives of forest cooperatives (Sweden) with forest properties >100ha Regard professional knowledge as a vital factor in decision making (Germany, France, Sweden). The role of science, expertise, advisory systems, and economic calculation prevail over traditional know-how.	Active management Technologically advanced. Use the latest technological innovations (e.g., genetically selected plants, fertilisation, GIS, and mechanized harvesting). Forest certification schemes (e.g., PEFC, FSC) for pragmatic and commercial reasons. Accept subsidies for pre-commercial thinning in Sweden, afforestation in Ireland and Portugal, timber stand improvement (Finland).
Tradition-oriented Forest Managers	Small to medium-sized forest owners. Cooperative. Emphasis on traditional knowledge. Formal advisory networks have a limited impact. Forest management that is close to nature and less intensive.	Commercial thinning in SE and IE and longer tree rotations (maintain their trees long after they have reached their maximum economic worth). Avoid cutting down family woods.
Environment-oriented Forest Managers	Knowledge: Pay a lot of attention to advances in ecological sciences.	Non-intervention, extensive (close-to-nature) or restoration-oriented forest management. Let nature run its course and not interfere with it. Implement activities that are less intensive and destructive to the environment (i.e., adopting technologies with less impact on the environment).
Passive Forest Managers	Small-scaled non-industrial private forest owners.	Not active forest management.

	Lifestyle: highly educated and have urban values and lifestyle, typically lives relatively far away from their forest property and are often residents of larger towns or cities. Members of local forest owners' groups.	Limited maintenance and thinning are conducted some years later, some forest owners in this group admit to "closing the gate" once the forest is established and never stepping inside. Difficult to persuade these forest owners to mobilize more timber, as wood production has never been their primary priority. Rarely take action to implement ecologically friendly forest management practices.
Multi-objective Forest Managers	Public forest managers dominated by State and municipal forest services and other large-scale public forest management organizations.	Sustainable forest management. Respect of environmental standards, and satisfaction of social demands, among others.

More recent published typology studies include **Sotirov et al. (2019)**, who developed an agent-based framework of the interplay between forest owner behaviours and structural factors as a tool to study the provision of forest Ecosystem Services at the landscape level in Europe; **Malovrh et al. (2015),** covering **Slovenia and Serbia**, which are countries not usually included in typology studies; **Kumer and Štrumbelj (2017)** who covered small-scale farmers in **Slovenia; Danley (2019),** who investigated the relationship between private forest owners' ownership objectives and their opinions on forest conservation policy instruments in **Sweden;** and **Matilainen and Lähdesmäki (2023),** who created a qualitative typology for passive non-industrial private forest owners (NFPI) in **Finland**. **These studies also provide some information about forest manager's types and their forest management approaches**:

Sotirov et al. (2019) considered three behavioural models from social science theories and analysed how forest management would change according to the strength (weak, strong, or no behavioural impact) of the influence of each model on the management behaviour (Table 6).

- ***Homo economicus*** - Individual actors will change their behaviour in response to policy and socio-economic changes only if they can capture material benefits or avoid substantial costs.
- ***Homo sociologicus*** - People follow certain rules of the game, and often they do so unconsciously, because they have internalized these rules. Behavioural changes conforming to new rules and norms is likely to be facilitated by long-term exposure to legally-binding regulations, moral arguments and/or socialization.
- ***Homo psychologicus*** - Forest owners will adapt their forest management to and/or follow policy and socioeconomic changes only when these resonate with their core beliefs and values.

Table 6 Management according to forest owners' typologies (Sotirov et al., 2019) and responsiveness to key structural factors (adapted from Deuffic et al., 2018)

Forest owners' typologies	Homo economics	Homo sociologicus	Homo psychologicus	Forest management behaviour	Main influencing structural factors (Weak – to Strong ++)
Optimisers	High	Low (social norms)	Low	Intensive profit-oriented **even-aged forestry while respecting (minimal) rules**	Policy + Market ++ Environment −/+ Knowledge +/− Norms −/+
Traditionalists	Low	High (social norms)	Low	**Low intensive, close-to-nature forestry based on family tradition, local knowledge, and sporadic needs**	Policy +/− Market +/− Environment - Knowledge ++ Norms ++
Maximisers	High	No	Low	**Highly intensive (short-rotation) profit-oriented forestry; Sometimes without respecting rules (e.g."illegal loggers")**	N.a.
Passives	No	Low	High	**Passive/little management due to lack of interest in forestry according to urban values and lifestyle**	Policy – Market - Environment + Knowledge - Norms -
Multi-functionalists	Low	High (legal norms)	Low	**Medium intensive, mixed-objective forestry in respect of professional forestry rules and norms**	Policy ++ Market + Environment +/− Knowledge ++ Norms ++
Environmentalists	Low (if "right", social control)	Low, High (if "right")	High	**Passive non-intervention and/or extensive forest management due**	Policy + Market - Environment ++

				to environmental core beliefs and values	Knowledge ++ Norms +

Malovrh et al. (2015) (not included in the review by Ficko et al., 2019) covers **Slovenia and Serbia**, which are countries not usually included in typology studies. These authors identified and described private forest owner types in Slovenia and Serbia based on several criteria, namely forest management objectives, participation in private forest owner associations, cooperation with other private forest owners and the public forest administration, **performing forest and harvesting activities**. Surveys were conducted in Slovenia (n = 322) and Serbia (n = 248) on random samples of private forest owners and the percentage of forest managers' type was assessed. **Active Forest Managers** accounted for 26.1% in Slovenia and for 32.6% in Serbia, **Passive-Forest Managers** accounted for 33.2% in Slovenia**, Multi-objective Forest Managers** accounted for 18.6 % in Slovenia and 67.4% in Serbia and **Uninterested Forest Managers** accounted for 22% in Slovenia.

Kumer and Štrumbelj (2017) conducted a questionnaire-based survey (n=387) on small-scale private forest owners (SPFO) in **Slovenia** and constructed a typology based on three values (environmental, social and production) and four management objectives, namely **production**, **preservation**, **economic**, **efficiency** and **amenity** objectives. These authors found only two types of forest owners and related these with their lifestyle (urban) and their willingness to harvest.

- **Detached owners –** Forest owners who are less active and live in more urbanised areas of Slovenia. They show a lower likelihood to manage forest in the future.
- **Engaged owners –** Forest owners who are more willing to harvest. Are often reluctant to cooperate (farm owners prefer to work on their own as they have enough knowledge and their own machinery) the most effective type of cooperation would be informal cooperation.

Danley (2019) investigated the relationship between private forest owners' ownership objectives and their opinions on forest conservation policy instruments in **Sweden** with a survey disseminated among non-industrial private forest owners with a registered Swedish address (N= 1231). This author found out that forest owners' objectives are not aligned with policy instruments, namely the Sweden's command and control green tree retention measures, participation in voluntary forest stewardship certification, acceptance of a hypothetical financial incentive, and **overall interest in taking more environmentally beneficial forest management measures**. In the study, 3 significant clusters of forest types were found, namely **multi-objective** (family and recreation), **recreation**, **multi-objective** (family, recreation, and income). The 17 forest owners' objectives considered to select the 3 clusters were income (consumption), finance investments, financial security old age, forest work, investment future, firewood provision, next generation, berry & mushroom, time on property, hunt & fish, meaningful work, recreation, relation, environmental protection, enjoyable experience, contact with origin, tradition.

Matilainen and Lähdesmäki (2023) created a qualitative typology for passive non-industrial private forest owners (NFPI) in **Finland** (n=273). Their findings challenge old ideas of passive forest management. **Passive owners were defined as those who have not put in a forest usage notification in the last 15 years (i.e., have not sold timber or applied for state support for forest management work).** The passive owner can be typified into six groups (Table 7), with passive activities classified according to "timber sales" or "management activities". Notably, this study **challenges views that passive owners are simply disinterested in their forest** (c.f. Weiss et al., 2019, Sotirov et al., 2019, Urquhart and Courtney, 2011), **having found that passive management does not mean the owner is unknowledgeable or uncaring**. In some cases, **they are simply downshifting their activities in preparation for future generations**. Authors also argue that **passive owners are disinterested in subsidies** that support the contracting out of forest management services because they prefer to control their own forest rather than contract work out.

Table 7 Summary of passive forest owners' typologies from Finland (Source: Matilainen and Lähdesmäki, 2023)

Passive forest owner typologies	Forest management behaviour	Management Activities	Timber Sales
Domestic User	• Timber for private personal use • No subsidy paperwork (limited time / holding too small) • Live close to their forest • **Value doing forest management personally** • Interested in forestry • Have extensive knowledge of own forest • Moral obligation to be "proper forest owner" • Want control over forest holding • Small forest holding	ACTIVE (3)	PASSIVE (1)
Leisure lumberjack	• Light forestry work primarily done by owner • **Don't own heavy machinery so heavy work contracted out** • Moral obligation to be "proper forest owner" • Timber used in family • Have extensive knowledge of own forest • Want control over forest holding • Unwilling to sell land • Older men • Small forest holding	ACTIVE (2)	PASSIVE (1)
Downshifter	• Elderly forest owners • Giving up forest in near future (to family) • **Disinterested in management decisions believe management's choice of future generations** • Previously active; knowledgeable of forest	PASSIVE (1)	PASSIVE (1)

	• Forest work done in family, not contracted • No data on forest holding size in article		
Recreational User	• **Used for recreation (not forest work) or conservation** • Value aesthetics • Holdings near summer cottage • Small forest holdings • Prefer to keep decision in own hands	PASSIVE (1)	PASSIVE (1)
Heritage Upholder	• Forest valued for family/regional history • **Passive but unwilling to cede control** • No moral obligation of "proper forest owner" • Some absentee owners • Sometimes holding seen as burden	PASSIVE (1)	PASSIVE (1)
Indifferent	• Inherited forest but meaningless to them • No interest or knowledge of forest • More willing to sell forest land	PASSIVE (1)	PASSIVE (1)

3.1.2 Other potential forest owner/manager types

From the wider review of the literature other **potential forest owner types** have emerged and these should be further investigated to understand if they can be considered as a separate type of owner or if their characteristics would place them in any of the five forest owner types identified. The potential new types are **female forest owners, new forest owners**, and **maximisers**. The evidence collected explores **how forest management is undertaken by these potential new forest owner types.**

3.1.2.1 Female forest owners

Follo et al. (2017) have estimated that ~30% of forests owners across 15 countries are female. Ficko and Bončina (2013) found that gender differences affect economy-oriented management behaviours and that female owners are more likely to behave as "materialists" than as "non-materialists". **Several authors consider that female forest owners undertake less active forest management and undertake less forest operations themselves** (Lidestav AND Wästerlund, 1999, Follo et al., 2017). Lidestav and Ekström (2000) argued that gender disparities in forest management activities are associated to differences in value orientations resulting in distinct rationales as women may accumulate larger responsibilities because of their social function in society.

In **Finland**, the harvesting frequency or **probability of harvest was found to be lower among female forest owners** (Ripatti 1999 *in* Lidestav and Ekstrom 2000). Kuuluvainen et al. (2014) found that **women were selling on average 1 m^3/ha/year less than men**, and that women were selling less frequently and in larger quantities per sale than men. Korhonen et al. (2012)

found that Finnish female owners relied more strongly on local Forest Management Associations that deal with timber sales than male forest owners (22% and 14%, respectively).

In **Sweden** and **Norway,** female forest owners organise themselves in networks and challenge the traditional understanding of forestry as a competence for men and of men (Lidestav & Andersson, 2011; Brandth et al., 2015). In the **Norwegian** counties of Trøndelag, female owners were found to visit their forests 10 days per year on average, while their male counterparts would visit 6 days more (16 days) on average (Blekesaune, 2005 *in* Follo et al., 2017).

In **Lithuania**, 75% of male owners and 59% of female owners were found to carry out forest-related activities in their forests, with male owners undertaking a wider range of activities (Follo et al., 2017). In **Latvia**, Vilkriste (2008) found that the use of service providers for forest management activities are less focused on female owned forests.

3.1.2.2 New forest owners

There has been a growing number of “new forest owners” in many European regions. These are characterised by holding only small parcels, having no agricultural or forestry knowledge and no capacity or interest to manage their forests. **However, in some countries there is evidence this new community of private owners is also bringing fresh interest and new objectives to forest management** (Živojinović et al., 2015), **so they can be differentiated from passive or absent forest owners**. Deuffic et al. (2018) noticed the emergence of **“new forest owners”, who may assume different roles and change forestry norms rather than just following the current rules**. According to these authors “new forest owners” do not place so much importance on social values norms, as they are not systematically aware of the locally applicable norms in the field of forestry and may be less sensitive to the social control undertaken by traditional forest owners. The term **“new forest owners” has been mostly characterised in relation to changes in attitudes, values and/or behaviour of the forest owner** (e.g., Hogl et al., 2005, Matilainen et al., 2019), where **‘new’ refers more specifically to a type of forest owner**. According to Živojinović et al. (2015), “new forest owners” may include those that obtained ownership of land through:

- Transformed public ownership categories (e.g., through privatisation, contracting out forest management, transfer to municipalities, etc.)
- New legal forms of ownership in the countries (e.g., new common property regimes, community ownership), both for private and State land.
- Individuals or organisations that previously have not owned forest land
- Traditional forest owner categories who have changed motives or introduced new goals and/or management practices for their forests.

The studies reviewed mainly focused on the objectives of new forest owners rather on their actual management. However, there are some management-related observations that can be noticed. In Sweden, new forest owners were found to (jointly) own sub-divided, small-scale forests and are believed to not manage their forests, **to reside outside of their forest property, with little or no involvement in forest management** (Lidestav and Nordfiell., 2005).

In **Austria**, “new forest owners” **are not actively participating in the market**, they have interest in forestry for several reasons, **which do not necessarily align with timber production**. In **Spain**, for example, these are new, urban forest owners (descendants of forest owners but no longer connected to the property). The category of “new forest owners” can include “**involuntary forest owners**” who acquired land through the acquisition of a house with attached forest land. These owners were mainly interested in the houses and **its recreational use and without knowledge about forest management or agriculture** (Dominguez and Shannon, 2007).

Companies that buy or rent out land for carbon offsetting purposes may also be included in the new forest owner/manager category. For example, in **Scotland**[46], the government, businesses and landowners are establishing partnerships for carbon offset purposes. Businesses will buy or rent the land themselves to plant trees and “offset” their carbon emissions.

The map published by Lawrence et al. (2020) below shows the predominance of 3 types of forest managers in 10 countries in Europe (Portugal, France, Romania, Poland, Latvia, Estonia, Belgium, Finland, Sweden, United Kingdom), namely traditional forest owners, owners/managers with a changing lifestyle and new forest owners (Figure 2).

[46] https://forestryandland.gov.scot/business-and-services/carbon-offset-partnerships#:~:text=The%20Scottish%20Government%20has%20committed,CO2%20from%20the%20atmosphere.

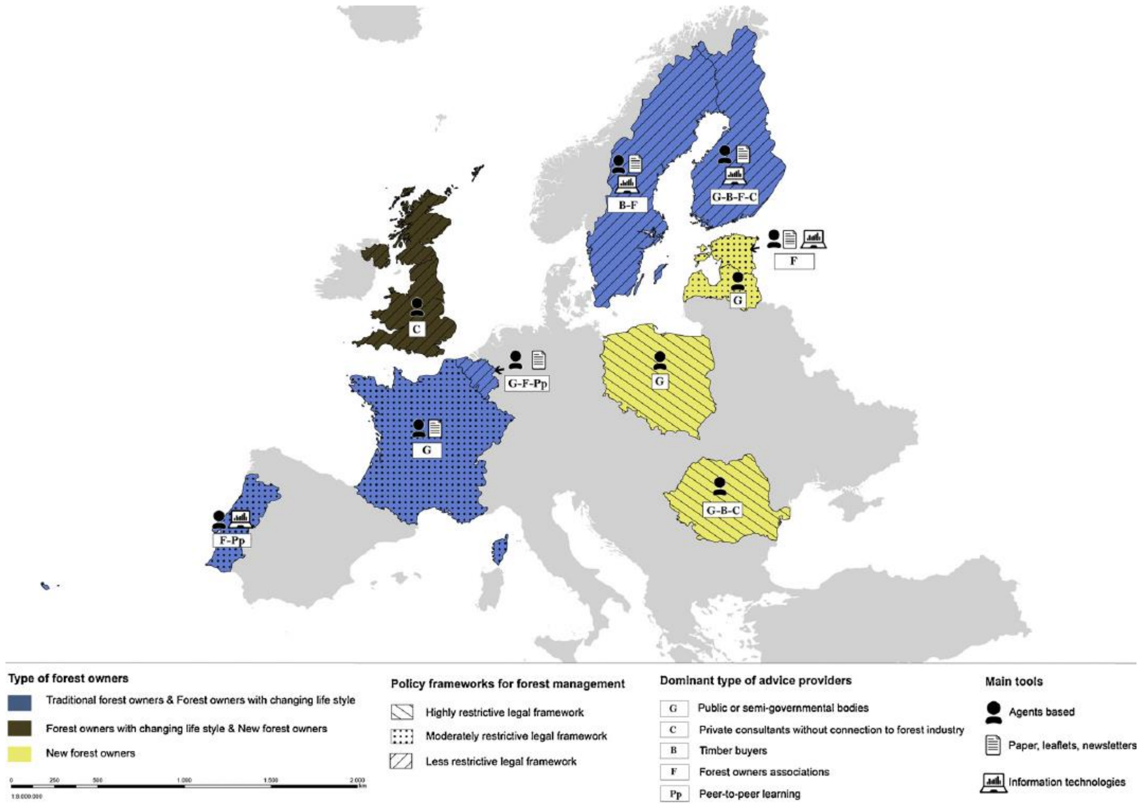


Figure 2: Forest Advisory Systems and types of forest owners in European countries

3.1.2.3 Illegal loggers/Users/maximisers

“Maximisers engaging in illegal logging” are a type of forest manager identified by Sotirov et al. (2019) based on the previous typification by Angelova et al. (2009), but not considered in the 5 types of forest owners/managers based on the review undertaken within ForestPaths as there is lack of information on its relevance in many European countries. Maximisation objectives lead to highly intensive (short-rotation), profit-oriented forest management, often without respect for rules (e.g., “illegal loggers”). This type of forest owners is found in **Eastern Europe** and represent some private forest owners that implement clear cutting in their forests for profit at the edge or beyond the rules that regulate property rights and/or economic sustainability. They refuse rules constraining short term gains from intensive forestry.

3.2 Synthesis: Integration of forest management characteristics and type of forest owner

Five types of forest owners are the most mentioned in the literature: **Passive/Non-active/Absent**, **economic/profit-oriented**, **tradition-oriented, environment-oriented, multi-objective.** Based in Duncker et al. (2012), Lawrence et al. (2020), Ficko et al. (2019) and the review of studies undertaken within ForestPaths and mentioned in the previous sections, **each**

forest manager type has been associated to forest management approaches and management characteristics as described below.

3.2.1 Passive/Non-Active/Absent Forest Managers

- **Forest Management Approach:** Uneven-aged forestry.
- **Size:** Small-scale private forest owners (0-10 hectares).
- **Practices:** Natural regeneration/natural succession. No machine operation, no soil operation, no fertilisation nor liming, no tree removals, no final harvest, no intervention.
- **Management preferences:** Absentee Forest Managers may have limited involvement in day-to-day forest management. They may hire professionals or lease their land to others for management. Their preferences can vary widely based on the management decisions made by their hired agents. Do not use the forest for at least 15 years.
- **Tree improvement:** No tree improvement.
- **Tree species:** Only species characteristic of the potential natural vegetation (PNV).
- **Integration of nature protection:** High integration of nature protection.
- **Ownership type:** Private.
- **Activity:** Off-farm jobs. Most of them rely on other sources of income rather than their forest.
- **Resistance to change:** Not concerned with forest policies. Not accessed by advisory services. Do not engage in agri-environment schemes.
- **Sources of information:** Socially isolated, they often ignore innovations or are dubious about them. They rarely engaged in communicative actions with their peers.

3.2.2 Economic/profit-oriented Forest Managers

- **Forest Management Approaches:** Intensive even-aged forestry/ High-Intensive/ Shorter-rotation forestry.
- **Size:** Large-scale private forest owners. Can own extensive forested lands ranging from thousands to millions of acres.
- **Practices:** Planting, seeding, intensive machinery, soil cultivation, fertilisation, liming whole tree and residues removed, coppice, clearcut and shorter rotation or clearcut with long-rotation preferably used.
- **Tree improvement:** Planting material can be derived from tree breeding.
- **Tree species:** Any species (not invasive). *Eucalyptus spp*. (PT, SP), *Quercus suber* (PT), *Picea sitchensis* (UK), *Picea abies* (FI), Pinus sylvestris (FI), *Pinus radiata* (SP), *Pinus pinaster* (SP, FR), *Quercus spp*. (FR)
- **Integration of nature protection:** Low-medium. Certification.
- **Ownership type:** private, industry, cooperatives
- **Activity:** Full-time forest managers and forestry is their main source of income.
- **Resistance to change:** Less prone to take for granted constraining norms that are imposed by external sources of authority (e.g., EU policies). Market fluctuations and professional knowledge used to make decisions.

- **Source of information:** active in global, regional, and national science/policy/information network. Hence draws information from scientific advisory systems, and policy guidelines.

3.2.3 Traditional Forest Managers

- **Forest Management Approaches:** Combined objectives. Low intensive, close-to-nature forestry based on family tradition.
- **Size:** Small or medium scale property. Typically own small, forested properties ranging from a few acres to a few hundred acres.
- **Practices:** Happy to increase biodiversity (deadwood conservation, diversification of tree species) in some dedicated and often less fertile or profitable places (riverbanks, peat bogs, rocky areas); Non intensive machine operations; no fertilisation, no soil cultivation.
- **Tree improvement:** Not genetically modified or derived from tree breeding programmes.
- **Tree species:** Tree species suitable for the site.
- **Integration of nature protection:** High.
- **Ownership type:** Private.
- **Activity:** Part-time forest owners. Main source of income does not come from forest products, but from other professions.
- **Resistance to change:** The implementation of forest operations is based on empirical knowledge, observations in the field, traditional experiences, and “trial and error methods”. Rely more on personal communication to make their decision.
- **Sources of information:** Peers, relatives, social networks. They trust scientists with whom they have personal contact.

3.2.4 Environmental Forest Managers

- **Forest Management Approaches:** Low intensity, close-to-nature forestry, continuous cover forestry, stimulating biodiversity in the forest ecosystem. Passive non-intervention and/or extensive forest management due to environmental core beliefs and values.
- **Size:** Small-scale private forest owners. Range from small nature reserves to extensive conservation easements covering large-forested areas.
- **Practices:** Natural regeneration/natural succession, planting for enrichment or change in tree species composition. Extensive machine operation, no soil operation, no fertilisation nor liming, no tree removals, mimics natural disturbances, irregular shelterwood, single stem selection, group selection.
- **Tree improvement:** No tree improvement.
- **Tree species:** Native or site-adapted species.
- **Integration of nature protection:** High integration.
- **Ownership type:** Private
- **Resistance to change:** Not prone to ask for public supports.
- **Sources of information:** Active in global, regional, and nation science/policy/information network. Hence draws information from scientific advisory systems, and policy guidelines.

3.2.5 Multi-objective Forest Managers

- **Forest Management Approaches:** Sustainable forest management. Medium intensive, mixed-objective forestry in respect of professional forestry rules and norms.
- **Size:** Large-scale forest managers, state municipalities property.
- **Practices:** Are willing to adjust their management strategies based on changing circumstances and new information. They regularly monitor forest health and adapt their plans to address issues like pest outbreaks or climate change. They may be early adopters of sustainable practices, such as agroforestry or carbon sequestration projects.
- **Tree species:** open to using Mixed species, multi-specie stand.
- **Integration of nature protection:** High integration of nature protection
- **Ownership type:** Both public and private but largely public
- **Activity:** Full time workers in state forest enterprises and municipalities.
- **Resistance to change:** More perceptive to forest policy change: less “command and control” and mandatory rules, more voluntary agreement as certification, more public debate.
- **Sources of information:** formal international and national forest information network, scientific organisations.

3.2.6 Percentage (assumed) of forest owner types per country.

Based on available literature and expert knowledge, Table 8 gives an overview of assumed shares of forest owner types per country. Published literature on forest owners’ typologies in Europe allows for a low confidence estimative of the percentage of forest owner types per country and further research and data collection is essential to improving these estimates.

Table 8 Percentage of types of forest owners per country (low to medium confidence)

Country	Economic / profit-oriented (%)	Traditionalists (%)	Environmentalists (%)	Passive / Absent / Non-active (%)	Multi-objective (%)
Austria	36	32	23	9	0
Belgium	42	10	0	0	44
Bosnia and Herzegovina	0	34	36	29	0
Bulgaria	42	10	0	10	39
Croatia	82	2	3	4	9
Cyprus	25	10	3	6	56
Czechia	1	23	15	0	61
Denmark	52	0	30	18	0
Estonia	36	28	23	1	12
Finland	16	20	24	10	30
France	16	34	16	19	15

Germany	23	0	10	18	45
Greece	10	8	12	4	65
Hungary	13	28	1	0	58
Italy	34	6	21	21	18
Ireland	75	0	0	0	25
Latvia	16	35	0	0	49
Lithuania	10	25	13	0	50
Netherland	27	0	13	0	50
Norway	8	69	2	0	21
Poland	1	16	1	0	82
Portugal	40	20	10	10	20
Romania	10	11	12	1	66
Serbia	33	0	0	0	67
Slovakia	42	13	16	0	30
Slovenia	26	0	22	33	19
Spain	20	20	12	2	46
Sweden	17	13	34	17	19
Switzerland	40	5	8	7	40
United Kingdom	18	23	14	8	37

The percentages were extracted, assumed, or derived from the sources below:

- **Ireland, Belgium, Sweden, Portugal, Bulgaria, France, The Netherlands, Italy, Slovakia, Germany:** extracted from Deuffic et al. (2018), which in turn was adapted from Sotirov and Deuffic (2015).
- **Latvia:** extracted from Zivojinovic et al. (2015) (pp349, Table 1).
- **Finland and Lithuania:** derived from Hänninen et al. (2010) and Zivojinovic et al. (2015) (pp206).
- **Greece:** adapted from Zivojinovic et al. (2015).
- **Denmark:** extracted from Boon et al. (2004).
- **Bosnia and Herzegovina:** derived from Čabaravdić et al. (2011).
- **Austria:** extracted from Hogl et al. (2005).
- **Serbia and Slovenia:** extracted from Malovrh et al. (2015).
- **Estonia:** derived from Põllumäe et al. (2014).
- **Hungary, Romania, Norway, Poland, Czechia:** adapted from Schmithüsen and Hirsch (2010). The forest types used by these authors were reclassified as follow: State ownership as multi-objective, forest industries/private institutions as economists, individuals/families as traditional, communal/commons as environmentalists and provincial as passive/non-active/absent.
- **United Kingdom:** derived from Urquhart & Courtney (2011).

- **Spain, Cyprus, Croatia, Switzerland**: the percentage of forest under each function type (productive, protective, conservation, social services, multiple use, unknown function) as classified by each country under the Global Forest Resources Assessment (FRA 2005) was used. Forest functions were combined with forest owner's types as follow: productive as economists, protective and conservation as environmentalists, traditional as social services, multiple use as multi-objective, passive as unknown. The percentages of forest under each function are provided by Mongabay[47].

4 Baseline maps of forest management in Europe

4.1 Background and aim

Within the ForestPaths framework, forest resource development will be modelled by EFISCEN-Space and LPJ-GUESS in WP 3 and 5. EFISCEN-Space is applied at the NFI plot level, while LPJ-GUESS is applied at gridded level, which encompasses multiple NFI plots. For both applications, it is important to capture the current management structure as good as possible, allowing accurate simulations both under current management as well as under different CBS options. For both models, it is important to be able to estimate the management style as was most likely applied to each NFI plot in the (recent) past. This assigned management style will be used in two different ways:

- During the simulation, each plot will be assigned a management style, which steers the management actions that can be carried out on that plot. Under a business-as-usual scenario, this management style should reflect as close as possible the management style that was applied in the past.
- Each management style should be parameterized in the models, with parameters like thinning frequency and intensity, target diameters, etc. Such parameters can be estimated from plots where repeated censuses are available. Each plot must be assigned a past management style to group the plot, so the parameters can be estimated on the group as a whole.

Management style is defined here quite loosely, by purpose. It is not fixed to any of the existing concepts, and it is up front not entirely clear how many styles will be distinguished, and how they are ordered/related to each other. In the model implementation step, it will be decided what exact styles will be implemented.

Our aim was to analyze the available repeated NFI plot data using a variety of (European-scale) predictors to find groups of plots that are managed (more specifically: harvested) using a similar management style. These groups should be as generic as possible, allowing application of similar styles across borders, but capture sufficient variation. At the same time, groups should

[47] https://rainforests.mongabay.com/deforestation/2000/

be of sufficient size (enough plots) to allow to estimate the required management parameters (harvesting intensity, frequency, target diameter etc.).

4.2 Approach

The assignment of the management style is based on two pillars:

- **Plot-based observations:** Management was assumed to leave a clear imprint at the forest in terms of species composition, forest structure, amount of deadwood etc, which should be detectable at the plot level. Here, the focus was on observed forest structure and identity of the dominant species.
- **External factors (also known as location factors):** Management was assumed to be partly determined by external factors, such as climate conditions, terrain conditions, policies, distance to markets, etc. The influence of these factors was explored using a set of European maps representing these factors.

A management style is characterized by a range of activities, such as regeneration method, tree species choice, soil preparation, fertilization, rate of mechanization and harvest frequency and intensity (Duncker et al. 2012). Although all of these are important, many of them are difficult to observe using NFI plot-level data. Harvest activities are the easiest to observe directly, which is why the analysis is focused on harvest activities. Specifically, differences in management style were assumed to translate into differences in the observed annual harvest rate. The observed annual harvest rate is computed as:

$$z = 1 - (1 - \frac{\sum M_h}{\sum M})^{(\frac{1}{X})}$$

where *z* is the annual rate with which a tree of a certain population is harvested, M the number of live trees of that population in the first measurement, and *Mh* the number of trees of that population that have been harvested between the first and the second measurement (Schelhaas et al. 2018). The measurement interval *X* is computed as the weighted mean of that population.

First, the average harvest rate per 1-degree grid cell over Europe was computed and the result mapped. This map shows the real pattern over Europe, since no assumptions are made about the possible influence of country borders or any other data layer. We aggregated to 1-degree grid cells to have a sufficient number of observations to be able to compute the average. Next, the average harvest rate was computed per country, and within each country for each class present in each of the map layers. After mapping these outputs, the results were visually compared to the 1-degree grid harvest rate map for similarities in patterns, to assess the potential predictive value of this map layer. Finally, we discussed per country the patterns visible and tried to link these patterns to the external factors and plot observations. A minimum class size of 100 plot observations was used in a country, to have enough observations to make a reliable estimate and to have reasonably sized (potential) classes for the final selection of classes.

4.2.1 Data

For this analysis, NFI data with repeated measurements of permanent plots are required. Table 9 gives an overview of the data available to the project, which consists of over 230 thousand plots. This set is based on the TreeMort data collection, extended with Ireland and Denmark. Other countries decided not to share their raw NFI data as needed for this analysis, have no NFI, do not have repeated sample plots in their NFI, or implemented so far only a single census. All data were processed using the formats and quality check procedures as developed in that project. A threshold of 10 cm to all NFI data was applied to make the observations more comparable between the countries. This threshold was chosen to strike a balance between comparability between countries and the loss of data when increasing the threshold too much. Only Switzerland is an exception with a threshold of 12 cm. Especially the lower dbh classes can have a high harvest rate, which leads to large differences between countries if they are included or not. Usually, random noise of up to 500 m has been added to the plot coordinates to not reveal the exact coordinates.

Table 9 Overview of repeated NFI data available to the project

Country	Inventory years	Mean interval	No. censuses	No. plots	Plot radius (m)	Minimum DBH (cm)	Reference
Denmark	2002-2021	5.36	4	2415	15	0.2	Nord-Larsen & Johannsen 2016
Belgium-Flanders	1997-2019	16.74	2	689	4.5/9/18	0/7/39	Govaere 2020
Belgium-Wallonia	1985-2011	9.63	2	1238	4.5/9/18	6.4/22/38	Alderweireld et al. 2015
Ireland	2004-2022	4.74	4	1741	3/7/12.62	7/10/20	Government of Ireland 2023
Germany	1986-2013	10.96	3	45901	Angle count sampling	10	BMEL, 2018
France	2010-2019	5	2	72336	15	7.5	Bontemps et al. 2020
Netherlands	2001-2020	7.5	3	1459	variable (8-15 m)	5	Schelhaas et al., 2022
Norway	2007-2021	5	3	12047	8.92	5	Breidenbach et al., 2020
Poland	2005-2019	5	3	24898	variable (7.98, 11.28 or 12.62)	7	Anonymous 2015; Talarczyk 2014
Switzerland	1983-2017	9.56	4	4516	8/12.6 (in flat terrain)	12/36	Fischer & Traub, 2019

Spain	1981-2017	11.31	3	49252	5/10/15/25	7.5/12.5/22.5/42.5	Alberdi et al., 2017
Sweden	2003-2017	5	3	14734	3.5/10	4/10	Fridman et al., 2014

To analyze patterns in harvest rate, the following maps were used, based on the work by Nabuurs et al. (2019):

- Biogeographic region (Metzger et al. 2005)
- Elevation, obtained from EEA (2013), aggregated to 250 m classes.
- Ruggedness, obtained from EEA (2013), aggregated to classes according to Riley et al. (1999).
- Slope, obtained from EEA (2013), aggregated to classes of 5 degrees.
- IUCN management classes (IUCN 2017)
- Soil wetness JRC (2006)
- Distance to population centres of at least 50 thousand inhabitants (Nelson 2019)
- Distance to population centres of at least 1 million inhabitants (Nelson 2019)
- Distance to the nearest port of any size (Nelson 2019)

4.2.2 Determining forest structure

Plots were classified as monocultures if the basal area share of the dominant species was more than 80%, otherwise they were classified as a mixture. We adopted the Gini coefficient as a measure of how regular the diameter class distribution is. A Gini below 0.5 was classified as a forest with a regular structure (a narrow diameter distribution), and above 0.5 it was classified as irregular (wide distribution). The Gini was calculated for the stand as a whole, as well as on the dominant species. Based on these indicators, we distinguished six forest structures classes (Table 10, Figure 3). The class “multiple species layered” was interpreted as the first stage of conversion of regular forests to irregular multi-species forest, and was thus interpreted as “irregular”. The class “single species admixture” was considered as one of the forms of a regular mono-species forest, where a small share of other species is (temporarily) tolerated. Based on this forest structure classification, we can classify the management style into the classes “regular” and “irregular”.

Table 10 Conceptual classification scheme. Classes highlighted in green are considered as irregular forests, classes highlighted in blue as regular forests.

dbh distribution	Gini of whole stand	Gini of dominant species	species mixture	
			single	multiple
			BA share dominant species >=80%	BA share dominant species <80%
wide	>=0.5	>=0.5	single species irregular	multiple species irregular
		<0.5	single species admixture	multiple species layered
narrow	<0.5		single species regular	multiple species regular

Figure 3 Visualisation of the six structure classes

4.3 Results

The observed harvest rate in Europe at 1-degree grid level ranges between 0 and 7 % per year (Figure 2), with substantial variation within and among countries.

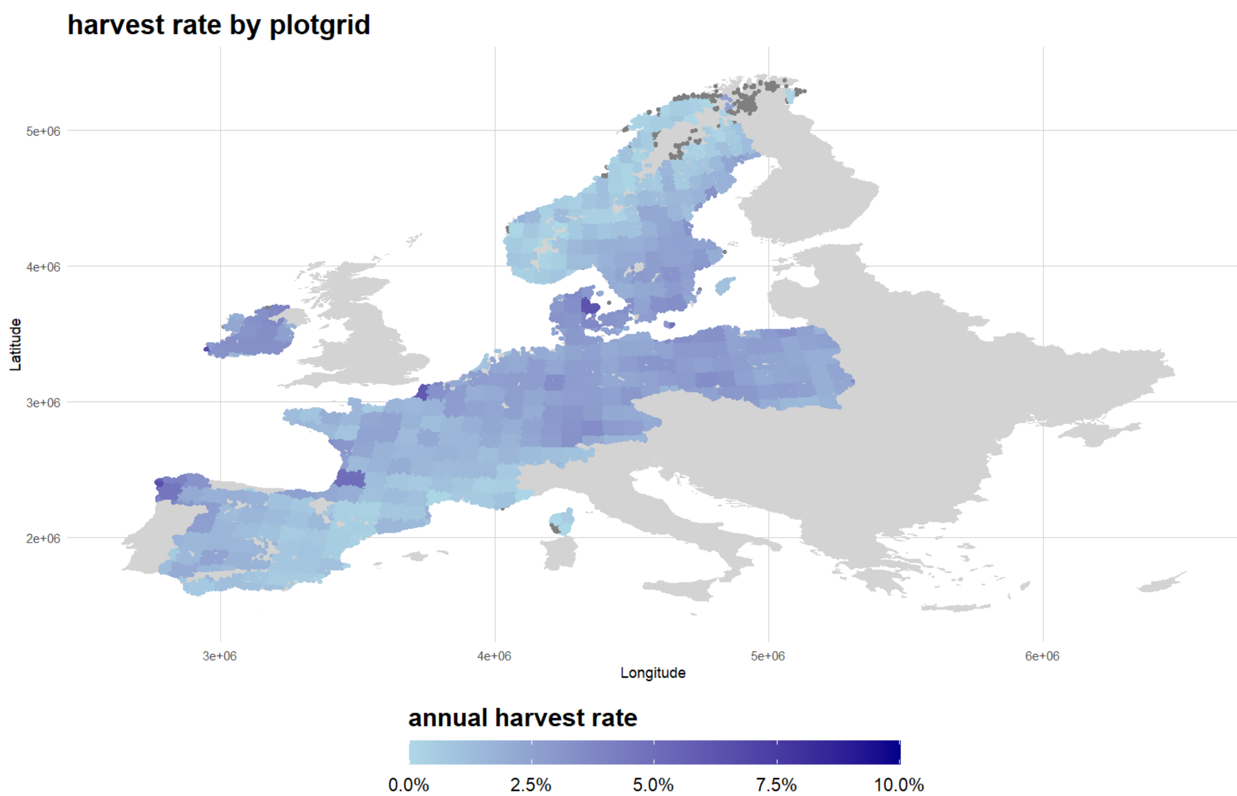


Figure 4 Observed harvest rate (proportion of stems harvested) over Europe at a 1-degree grid

The biogeographic region seems to have an important influence on the observed harvest rate, with overall high rates for the Atlantic and Continental zone and lower rates for Boreal, Alpine and Mediterranean regions (Figure 5, Table 11).

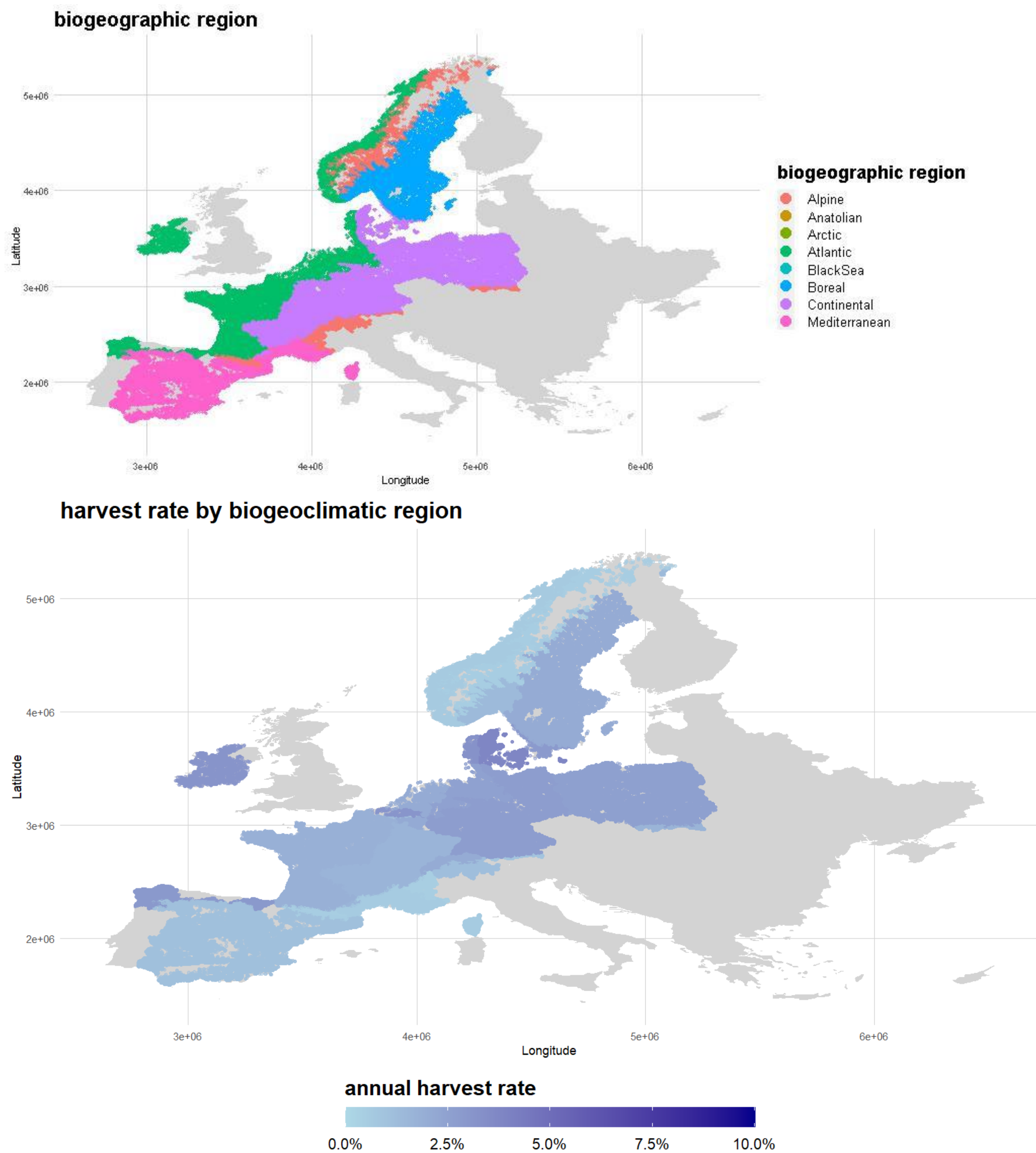


Figure 5 Distribution of biogeoclimatic regions in Europe (top) and annual harvest rates(proportion of stems harvested) per combination of country and biogeoclimatic region (bottom)

Table 11 Annual harvest rate (proportion of stems harvested) per combination of country and biogeoclimatic region

	Country average	Boreal	Continental	Atlantic	Alpine	Mediterranean
Denmark	3.7%		3.8%	3.2%		
Belgium-Flanders	3.1%			3.1%		
Belgium-Wallonia	2.0%		2.1%			
Ireland	3.1%			3.1%		
Germany	2.6%		2.7%	2.5%	0.9%	
France	1.5%		1.6%	1.8%	0.4%	0.6%
Netherlands	2.0%			2.0%		
Norway	0.9%	1.4%		0.6%	0.5%	
Poland	2.5%		2.6%		1.7%	
Switzerland	1.6%		2.0%		1.2%	
Spain	1.3%			2.9%	0.5%	1.1%
Sweden	2.0%	2.1%	2.9%		0.6%	

Also, elevation shows a clear pattern within the countries (Figure 6, Table 12). While most countries show a decreasing trend in harvest rate with increasing elevation, some countries (Germany, Ireland, Belgium-Wallonia) show an increasing trend with increasing elevation, but only in the elevation range up to 750 m.

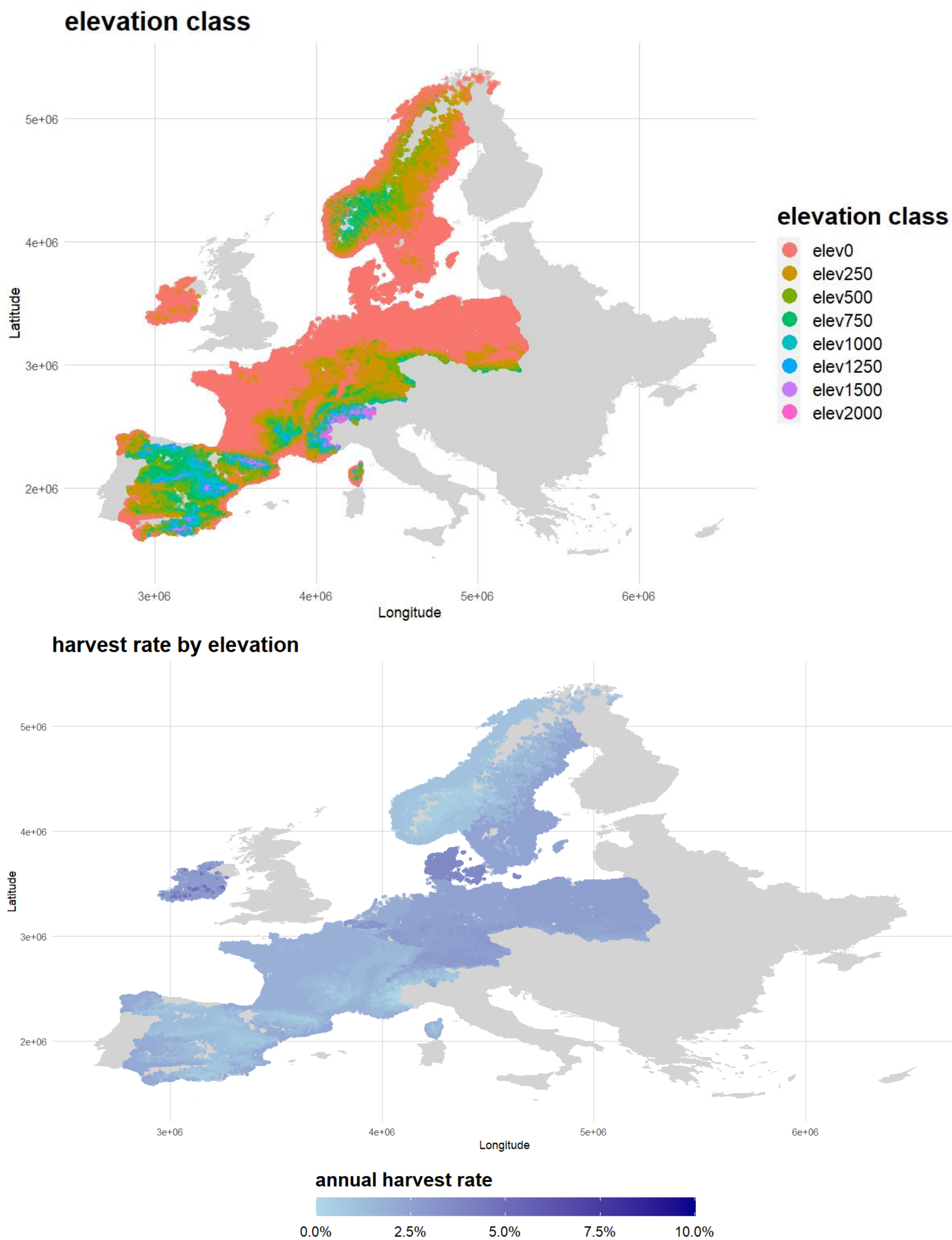
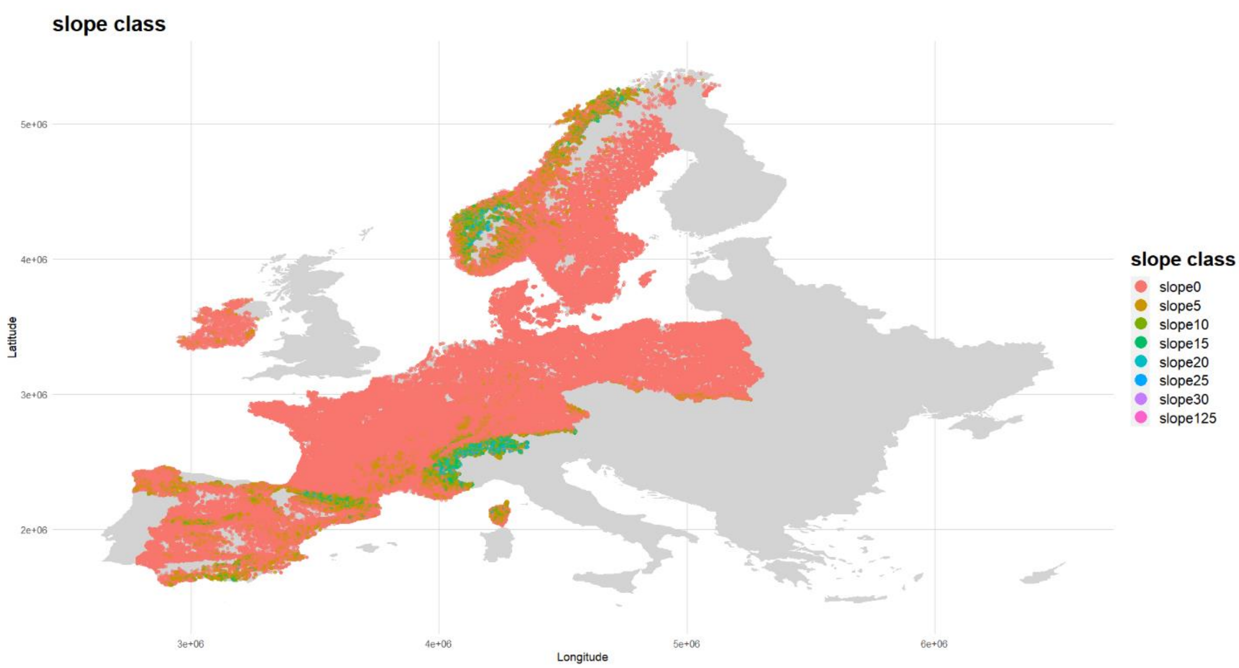


Figure 6 Distribution of elevational classes in Europe (top) and annual harvest rates (proportion of stems harvested) per combination of country and elevation class (bottom)

Table 12 Annual harvest rate (proportion of stems harvested) per combination of country and elevation class (m)

	Country average	0-250	250-500	500-750	750-1000	1000-1250	1250-1500	1500-2000	>2000
Denmark	3.7%	3.7%							
Belgium-Flanders	3.1%	3.1%							
Belgium-Wallonia	2.0%	1.3%	2.2%	2.8%					
Ireland	3.1%	2.8%	5.0%						
Germany	2.6%	2.5%	2.6%	3.0%	2.5%	1.9%	0.8%		
France	1.5%	1.8%	1.5%	1.3%	1.1%	0.9%	0.5%	0.2%	0.1%
Netherlands	2.0%	2.0%							
Norway	0.9%	1.1%	1.1%	0.6%	0.4%	0.2%			
Poland	2.5%	2.6%	2.3%	2.0%	2.0%				
Switzerland	1.6%		2.5%	2.1%	1.6%	1.3%	1.2%	0.9%	0.6%
Spain	1.3%	2.2%	1.9%	1.4%	1.2%	0.9%	0.7%	0.7%	0.3%
Sweden	2.0%	2.4%	1.5%	0.8%					

Not surprisingly, slope shows very similar patterns to that of elevation (Figure 5, Table 5). However, the slope classes seem less distinctive. Overall, the decrease of harvest rate with increasing slope is less pronounced than with increasing.



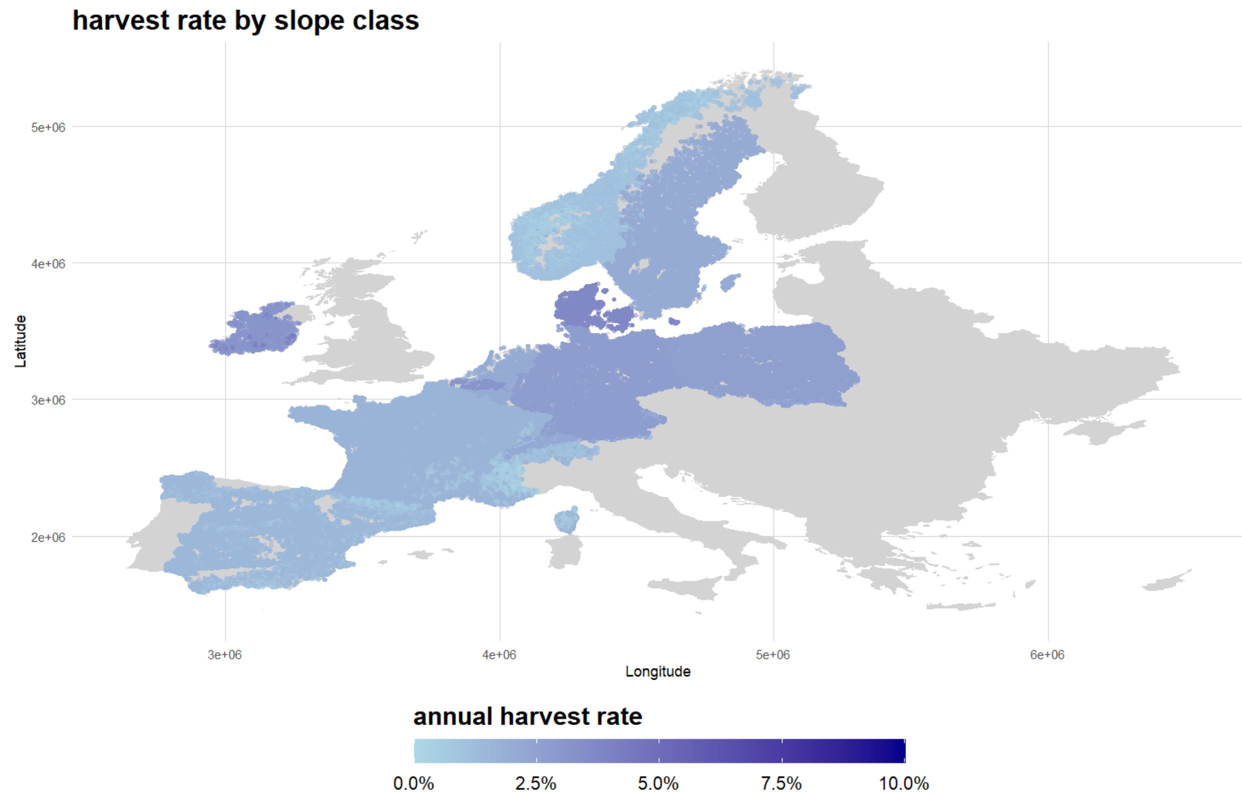


Figure 7 Distribution of slope classes in Europe (top) and annual harvest rates (proportion of stems harvested) per combination of country and slope class (bottom)

Table 13 Annual harvest rate (proportion of stems harvested) per combination of country and slope class

	Country average	0-5%	5-10%	10-15%	15-20%	20-25%	25-30%	30-35%	>35%
Denmark	3.7%	3.7%							
Belgium-Flanders	3.1%	3.1%							
Belgium-Wallonia	2.0%	2.0%							
Ireland	3.1%	3.1%	4.3%						
Germany	2.6%	2.7%	2.1%	1.8%					
France	1.5%	1.6%	0.8%	0.5%	0.2%	0.5%			
Netherlands	2.0%	2.0%							
Norway	0.9%	1.1%	0.8%	0.5%	0.3%	0.4%			
Poland	2.5%	2.5%	1.8%						
Switzerland	1.6%	2.2%	1.6%	1.1%	1.1%	1.1%	0.8%		
Spain	1.3%	1.5%	1.1%	0.8%	0.6%	0.3%			
Sweden	2.0%	2.0%	1.2%						

Also, ruggedness shows patterns very similar to that of elevation, with overall a decrease in harvest rate with increasing ruggedness (Figure 8, Table ***14***). Again, Belgium-Wallonia and Germany show the opposite pattern for the lower range of ruggedness classes.

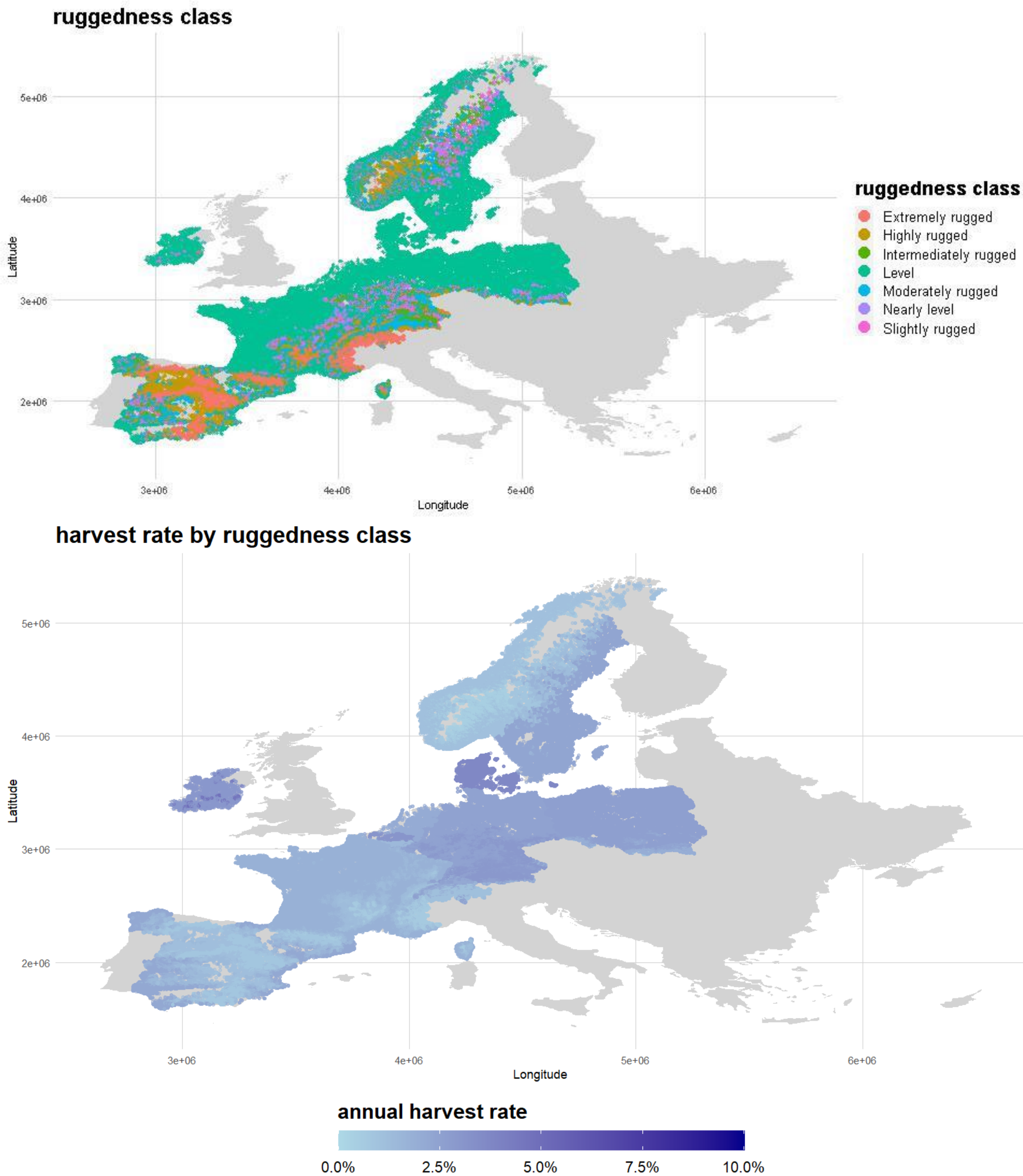


Figure 8 Distribution of ruggedness classes in Europe (top) and annual harvest rates (proportion of stems harvested) per combination of country and slope class (bottom)

Table 14 Annual harvest rate (proportion of stems harvested) per combination of country and ruggedness class

	Country average	Level	Nearly level	Slightly rugged	Intermediately rugged	Moderately rugged	Highly rugged	Extremely rugged
Denmark	3.7%	3.7%						
Belgium-Flanders	3.1%	3.1%						
Belgium-Wallonia	2.0%	1.4%	2.2%	2.4%	2.4%	2.7%		
Ireland	3.1%	3.0%						
Germany	2.6%	2.5%	2.5%	2.6%	2.8%	3.0%	2.5%	1.7%
France	1.5%	1.8%	1.5%	1.7%	1.4%	1.2%	1.1%	0.6%
Netherlands	2.0%	2.0%						
Norway	0.9%	1.1%	1.0%	0.8%	1.1%	0.7%	0.4%	
Poland	2.5%	2.6%	2.4%	2.2%	1.8%	2.0%	1.9%	1.0%
Switzerland	1.6%				2.5%	2.1%	1.6%	1.1%
Spain	1.3%	2.2%	2.2%	1.9%	1.7%	1.4%	1.2%	0.8%
Sweden	2.0%	2.3%	1.7%	1.3%	1.2%	0.8%		

The protection status as derived from the IUCN map shows a mixed pattern (**Figure *9***). Smaller countries tend to have enough observations only in one class (Belgium-Flanders, Belgium-Wallonia, Switzerland), two classes (Denmark, Netherlands) or no classes at all (Ireland). For the classes Ia (strict nature reserve), Ib (wilderness area) and II (national park), the harvest rates are always lower than the country average (except Belgium-Wallonia). For the classes III (natural monument or feature) and IV (habitat species management), harvest rates are in some cases higher than average (III Netherlands, III Spain, IV Denmark), while this is always the case for V (protected landscape).

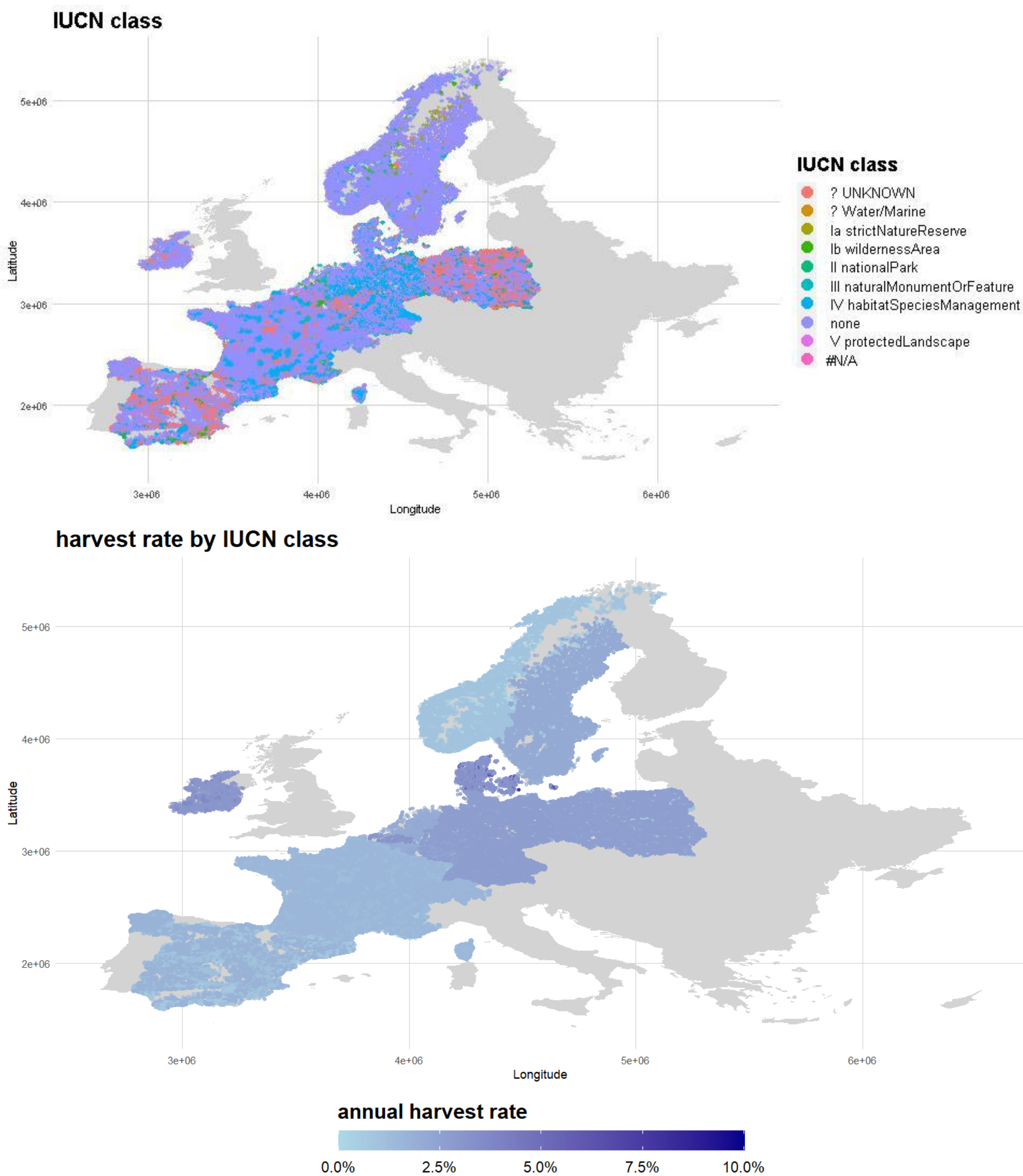


Figure 9 Distribution of IUCN classes in Europe (top) and annual harvest rates (proportion of stems harvested) per combination of country and IUCN class (bottom)

Table 15 Annual harvest rate (proportion of stems harvested) per combination of country and IUCN class

	Country average	Ia Strict Nature Reserve	Ib Wilderness Area	II National Park	III Natural Monument Or Feature	IV Habitat Species Management	V Protected Landscape	Unknown	none
Denmark	3.7%				2.7%	2.6%		6.2%	3.3%
Belgium-Flanders	3.1%						3.2%	3.3%	3.0%
Belgium-Wallonia	2.0%		2.2%					2.0%	2.0%
Ireland	3.1%							3.7%	3.0%
Germany	2.6%		1.8%		2.3%	2.7%		2.4%	2.7%
France	1.5%		0.0%		1.3%	1.4%		1.2%	1.5%
Netherlands	2.0%		1.9%		2.2%				2.0%
Norway	0.9%	0.1%	0.0%			0.2%			1.0%
Poland	2.5%		0.8%		0.9%	2.4%		2.6%	2.6%
Switzerland	1.6%				1.4%				1.6%
Spain	1.3%		0.8%	0.9%	1.4%	0.7%	1.5%	1.1%	1.7%
Sweden	2.0%	0.5%				1.4%		1.5%	2.1%

Overall, harvest rates seem to be higher in locations with dry soils than in locations with wet soils, but without a clear gradient (Figure 8, Table 8). In most countries the harvest rates start to be lower in the class “medium” and higher. Smaller countries tend to show less of a pattern or no pattern at all (Denmark, Ireland, Netherlands, Belgium-Flanders), while Belgium-Wallonia shows a reversed pattern. Also Spain does not show a clear pattern, probably due it its southern location and a general absence of wet soil types like clay and peat.

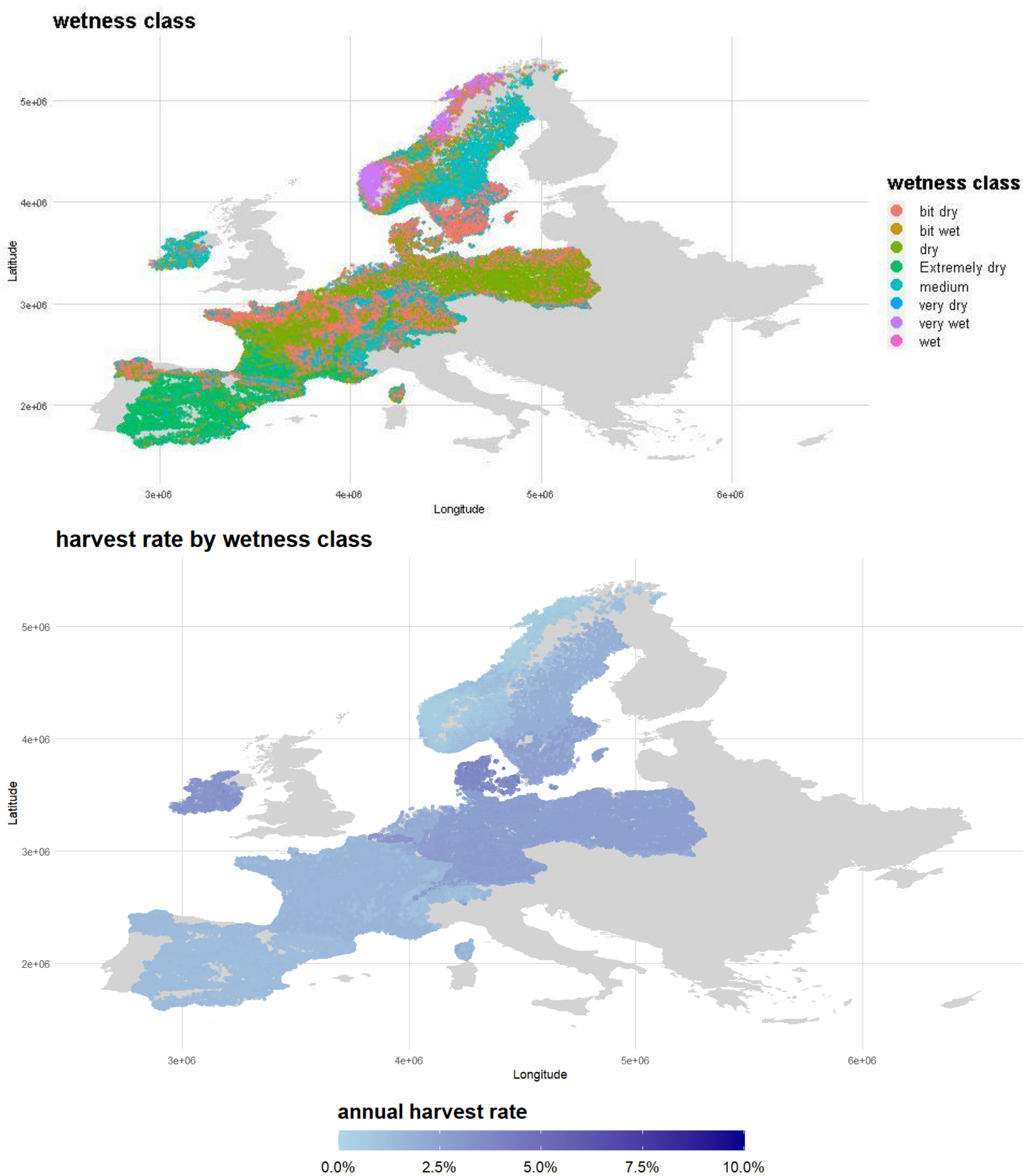


Figure 10 Distribution of soil wetness classes in Europe (top) and annual harvest rates (proportion of stems harvested) per combination of country and IUCN class (bottom)

Table 16 Annual harvest rate (proportion of stems harvested) per combination of country and soil wetness class

	Country average	Extremely dry	Very dry	Dry	Bit dry	Medium	Bit wet	Wet	Very wet
Denmark	3.7%			3.5%	3.8%	2.9%			
Belgium-Flanders	3.1%			3.1%	2.9%				
Belgium-Wallonia	2.0%				1.8%	2.4%			
Ireland	3.1%					3.3%	2.8%		
Germany	2.6%	2.5%		2.6%	2.8%	2.5%	1.5%		
France	1.5%	1.7%	1.3%	1.5%	1.6%	1.1%	0.6%		
Netherlands	2.0%			1.9%	2.2%	1.9%			
Norway	0.9%				1.8%	1.3%	0.8%	0.5%	0.5%
Poland	2.5%			2.6%	2.6%	1.9%			
Switzerland	1.6%			2.8%	2.5%	1.4%	1.2%	0.9%	1.1%
Spain	1.3%	1.3%	1.4%	1.3%	1.4%	1.3%			
Sweden	2.0%				2.6%	1.9%	1.1%		

In most countries, harvest rates show a negative correlation with the travel time to population centers with more than 50 thousand inhabitants (Figure 11, Table 17). Within these countries, there are large differences, with Switzerland having a lower harvest rate than average already if the travel time is larger than 30 minutes, while in Sweden this happens only at 150 minutes. Densely populated areas like Netherlands and Belgium-Flanders only have a single class, while Belgium-Wallonia and Ireland show a positive correlation.

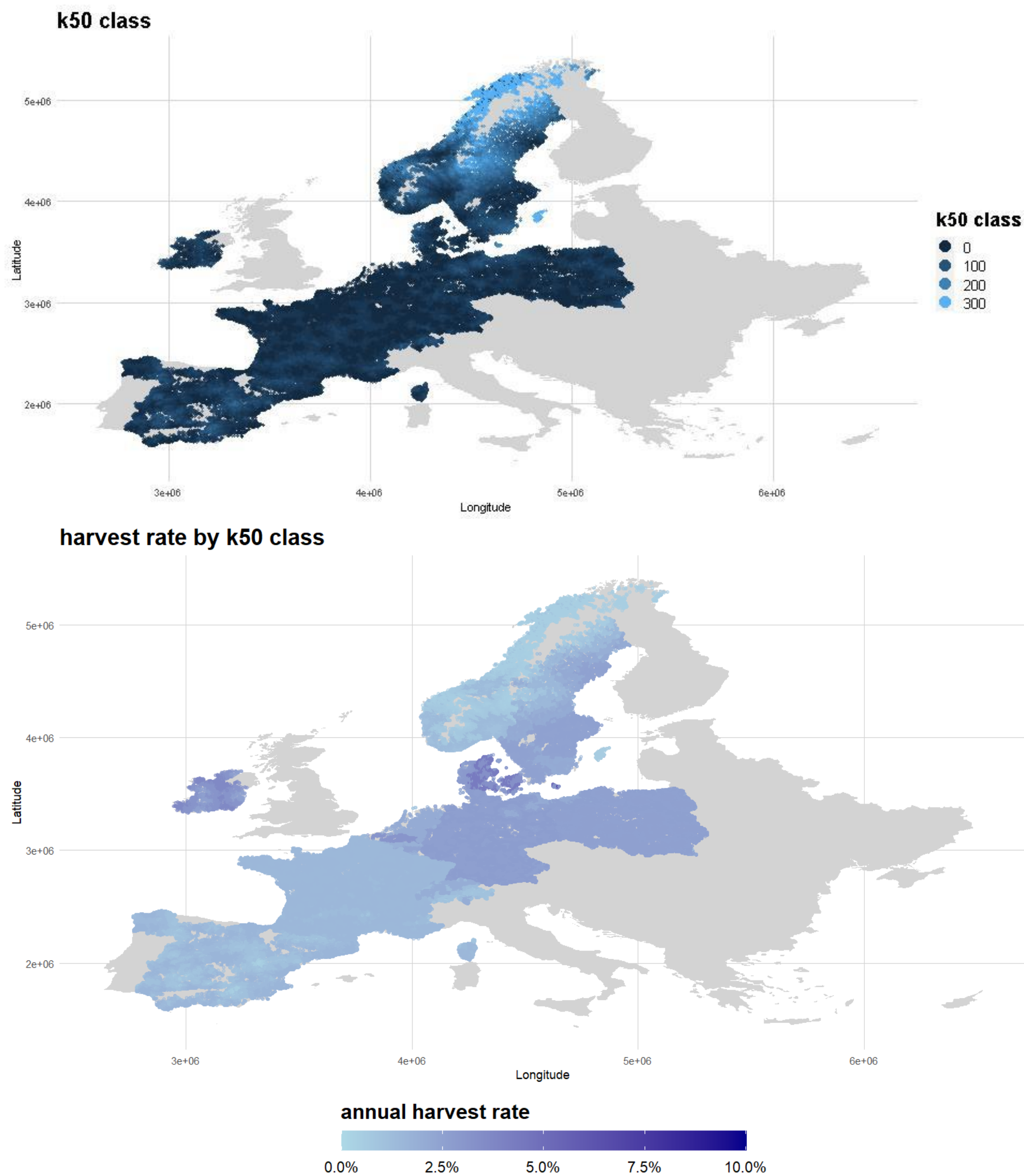


Figure 11 Distribution of 50k access classes in Europe (top) and annual harvest rates (proportion of stems harvested) per combination of country and 50k access class (bottom)

Table 17 Annual harvest rate (proportion of stems harvested) per combination of country and 50k access class (minutes)

	Country average	0-30	30-60	60-90	90-120	120-150	150-180	180-210	210-240	240-270	270-300	>300
Denmark	3.7%	3.3%	4.3%	2.9%	2.8%	2.5%						
Belgium-Flanders	3.1%	3.1%										
Belgium-Wallonia	2.0%	1.8%	2.4%									
Ireland	3.1%	2.6%	3.1%	3.7%								
Germany	2.6%	2.6%	2.7%	2.5%	2.0%							
France	1.5%	1.5%	1.5%	1.3%	0.8%							
Netherlands	2.0%	2.1%										
Norway	0.9%	1.1%	1.3%	1.4%	0.8%	0.7%	0.5%	0.5%	0.5%	0.4%	0.4%	0.5%
Poland	2.5%	2.6%	2.5%	2.6%	2.1%							
Switzerland	1.6%	2.0%	1.3%	1.0%	1.0%							
Spain	1.3%	1.6%	1.4%	1.1%	1.0%	0.5%	0.4%					0.6%
Sweden	2.0%	2.5%	2.5%	2.5%	2.1%	2.2%	1.9%	1.5%	1.5%	1.0%	0.8%	0.5%

There is hardly a pattern in relation to the travel time to population centers with more than 1 million inhabitants (Table 8, Table 18). Only for the most extreme values in the larger countries, harvest rates are clearly lower (Germany, Spain, Sweden).

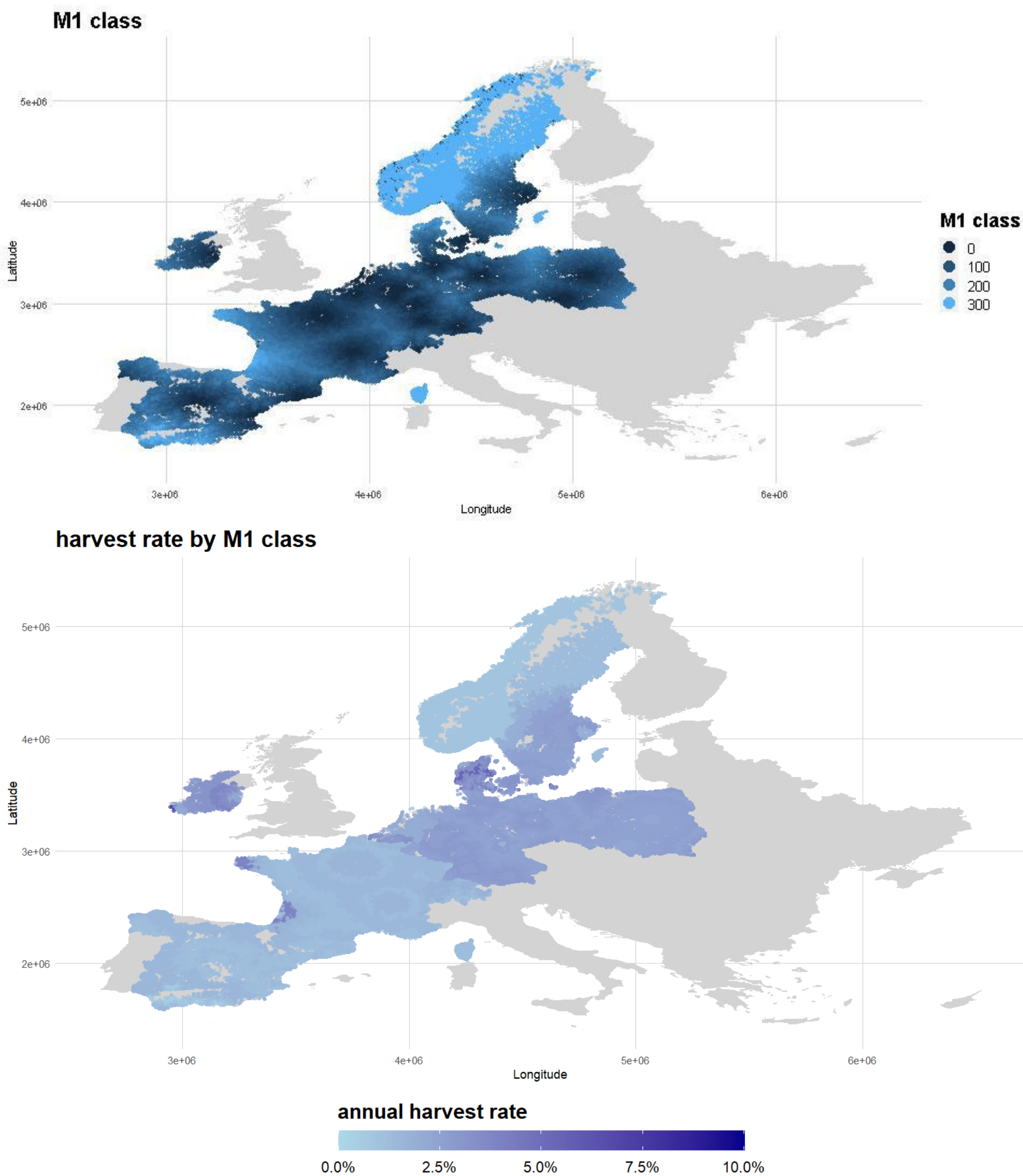


Figure 12 Distribution of 1M access classes in Europe (top) and annual harvest rates (proportion of stems harvested) per combination of country and 1M access class (bottom)

Table 18 Annual harvest rate (proportion of stems harvested) per combination of country and 1M access class (minutes)

	Country average	0-30	30-60	60-90	90-120	120-150	150-180	180-210	210-240	240-270	270-300	>300
Denmark	3.7%	3.2%	3.0%	2.6%	3.8%	2.9%	3.4%	5.4%	3.2%	3.6%	2.1%	
Belgium-Flanders	3.1%	2.9%	3.1%									
Belgium-Wallonia	2.0%		1.4%	2.4%	2.2%							
Ireland	3.1%		3.4%	3.8%	3.1%	3.1%	3.0%	2.2%				
Germany	2.6%	2.6%	2.8%	2.7%	2.5%	2.4%	2.7%	1.7%				
France	1.5%	1.6%	1.6%	1.3%	1.5%	1.5%	1.3%	1.3%	1.4%	1.6%	3.9%	1.3%
Netherlands	2.0%	2.0%	2.0%	2.1%	2.3%							
Norway	0.9%	0.8%										0.9%
Poland	2.5%	2.3%	2.5%	2.5%	2.5%	2.6%	2.4%	2.7%	2.9%	3.0%		
Switzerland	1.6%		1.1%	1.2%	1.4%	1.7%	1.8%	1.5%				
Spain	1.3%	1.1%	1.4%	1.1%	1.2%	1.3%	1.5%	1.4%	1.5%	1.3%	0.9%	0.5%
Sweden	2.0%	1.9%	2.8%	2.6%	2.5%	2.7%	2.5%	2.5%	2.0%	1.9%	1.8%	1.3%

Also, the travel time to the nearest port of any size does not give a very clear pattern (Figure 13, Table ***19***). For some of the smaller and more densely populated countries (Denmark, Belgium-Wallonia, Ireland), a positive relation seems to exist, with lower harvest rates close to ports. A similar relationship seems to be visible in Switzerland. Norway and Sweden show the opposite pattern, with higher harvest rates close to ports than further away. No clear patterns are visible in Germany, France, and Spain.

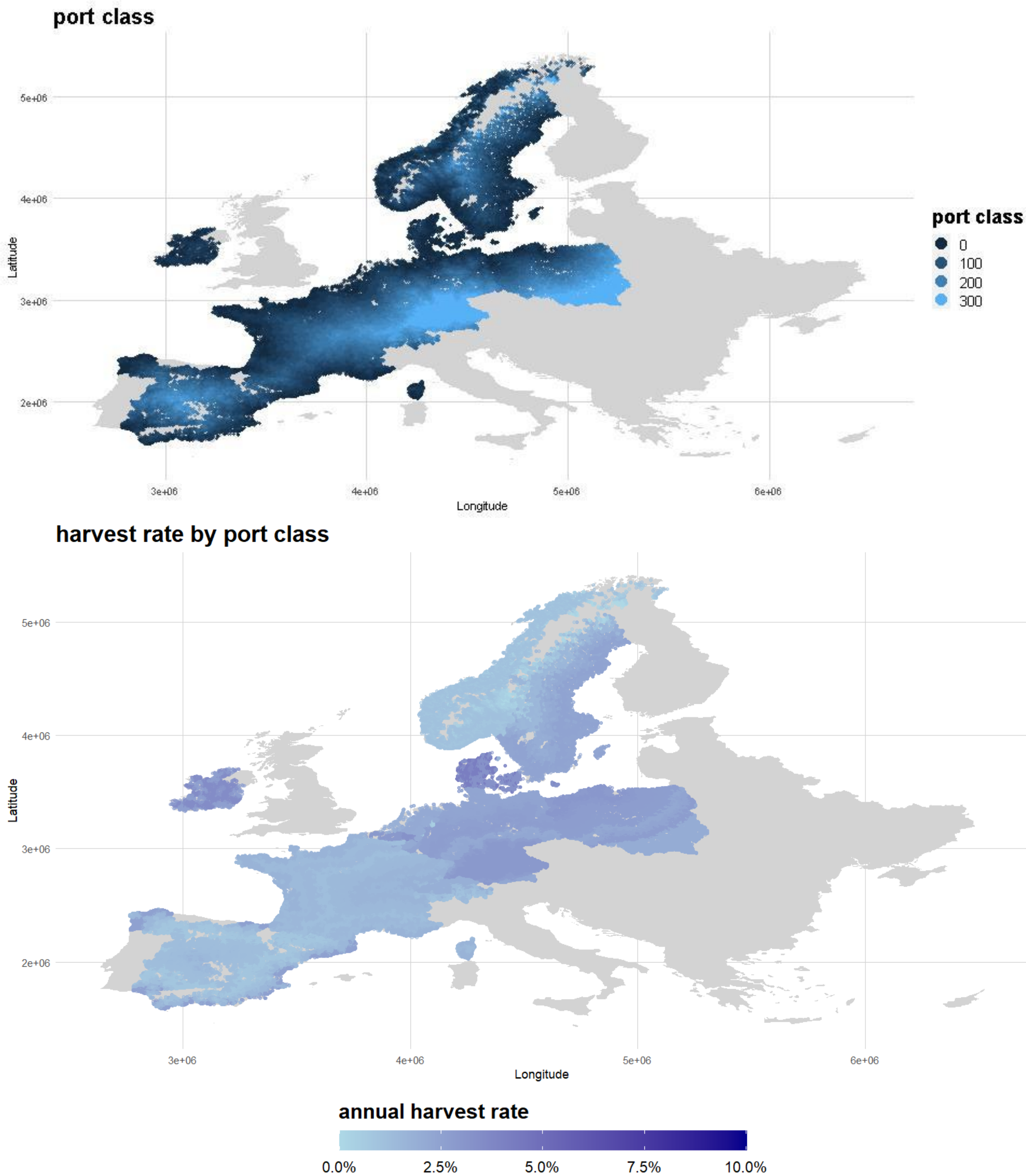
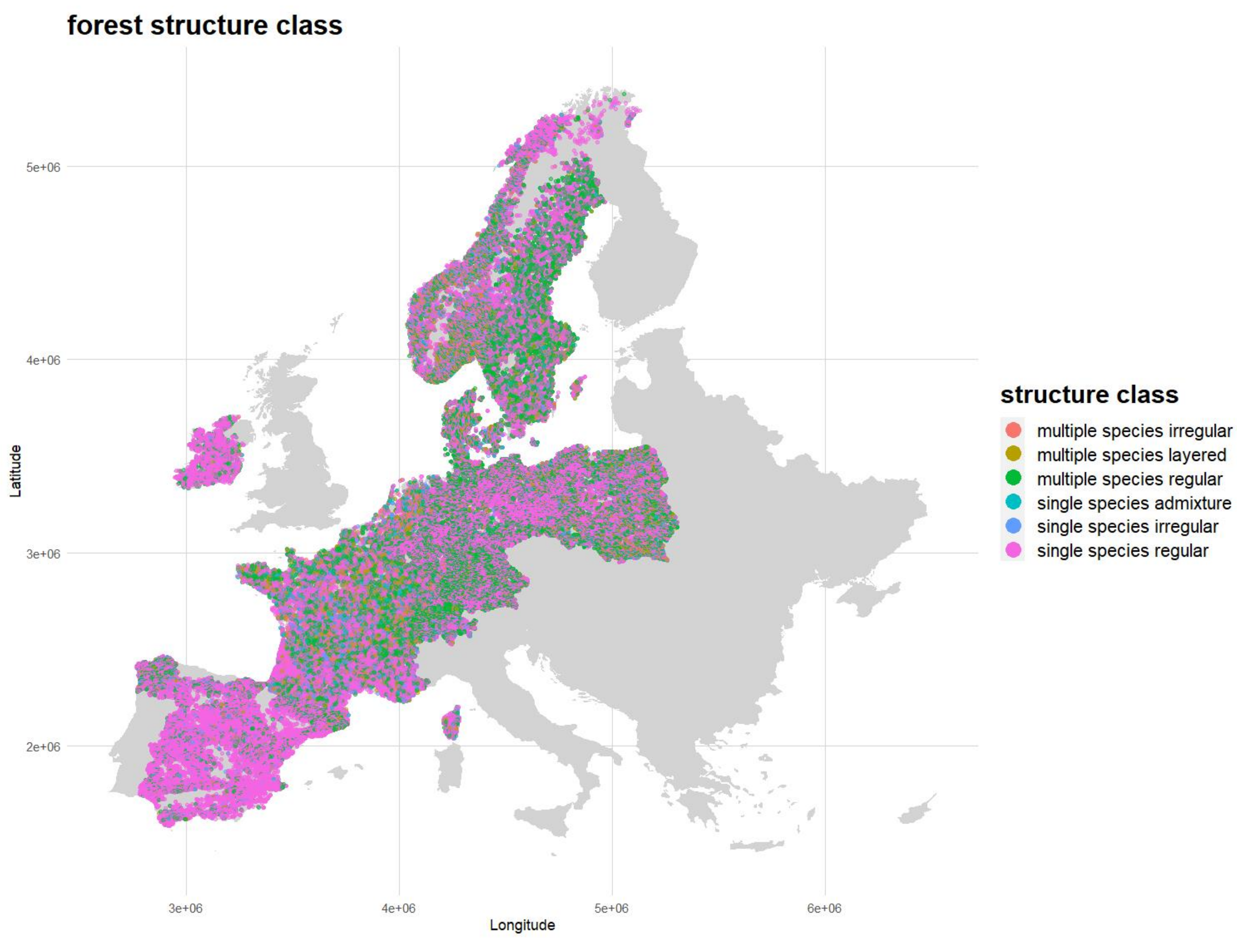


Figure 13 Distribution of port access classes in Europe (top) and annual harvest rates (proportion of stems harvested) per combination of country and port access class (bottom)

Table 19 Annual harvest rate (proportion of stems harvested) per combination of country and port access class (minutes)

	Country average	0-30	30-60	60-90	90-120	120-150	150-180	180-210	210-240	240-270	270-300	>300
Denmark	3.7%	3.2%	4.2%	3.7%								
Belgium-Flanders	3.1%	2.9%	3.2%									
Belgium-Wallonia	2.0%		1.2%	2.1%	2.4%							
Ireland	3.1%	2.6%	3.5%									
Germany	2.6%	2.3%	2.4%	2.4%	2.6%	2.6%	2.7%	2.6%	2.1%	2.2%	2.7%	2.9%
France	1.5%	1.7%	1.4%	1.5%	1.2%	1.4%	1.5%	1.6%	1.5%	1.8%	1.3%	
Netherlands	2.0%	1.8%	2.1%	2.1%								
Norway	0.9%	1.0%	0.9%	1.1%	1.0%	0.7%	0.4%	0.4%	0.0%			
Poland	2.5%	2.8%	3.0%	2.8%	2.7%	2.7%	2.7%	2.7%	2.2%	2.4%	2.7%	2.0%
Switzerland	1.6%					1.4%	1.0%	1.0%	1.3%	1.9%	1.9%	
Spain	1.3%	2.5%	1.5%	1.1%	0.9%	0.8%	1.2%	1.2%	1.3%	1.4%	1.6%	
Sweden	2.0%	2.3%	2.4%	2.2%	2.0%	1.5%	1.5%	0.9%	0.5%			

The forest structure in all countries is dominated by regular forests, either with single or multiple species (Figure 14, Table 20). Forests that are more irregular have lower harvest rates in some countries (Germany, France, Netherlands, Poland, Spain) but equal or higher rates in others. Belgium-Wallonia and Ireland don't have enough plots in irregular forests to calculate a harvest rate (Table ***19***).


forest structure class
5e+06
4e+06
3e+06
2e+06
Latitude
3e+06
4e+06
5e+06
6e+06
Longitude
structure class
multiple species irregular
multiple species layered
multiple species regular
single species admixture
single species irregular
single species regular

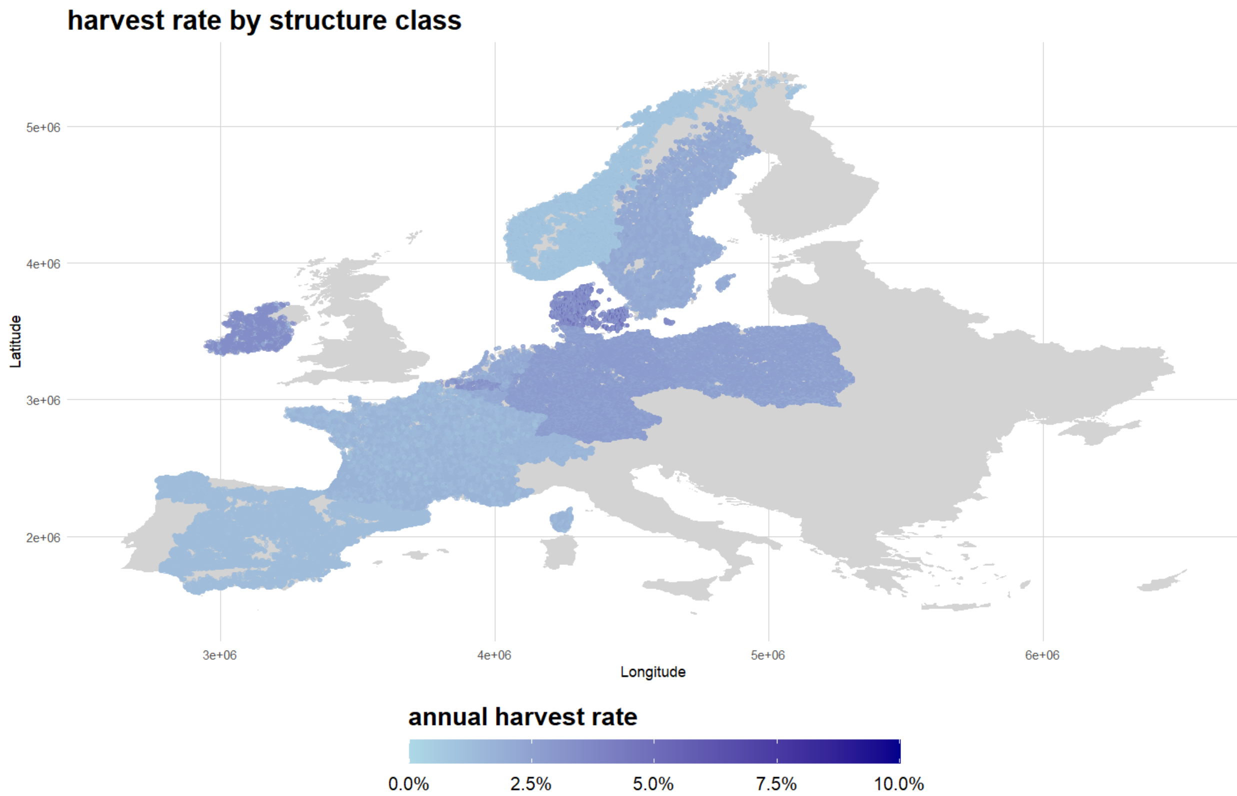


Figure 14 Distribution of forest structure classes in Europe (top) and annual harvest rates (proportion of stems harvested) per combination of country and forest structure class (bottom)

Table 20 Annual harvest rate (proportion of stems harvested) per combination of country and forest structure class

	Country average	single species regular	single species admixture	single species irregular	multiple species regular	multiple species layered	multiple species irregular
Denmark	3.7%	3.6%		3.2%	3.1%	2.5%	5.2%
Belgium-Flanders	3.1%	3.3%			2.6%		
Belgium-Wallonia	2.0%	2.2%			1.8%		
Ireland	3.1%	3.5%			2.2%		
Germany	2.6%	2.8%	2.7%	2.5%	2.4%	2.4%	2.2%
France	1.5%	1.7%	1.3%	1.0%	1.3%	1.4%	1.0%
Netherlands	2.0%	2.2%	2.0%		2.0%	1.5%	2.3%
Norway	0.9%	0.9%	1.0%	1.3%	0.9%	0.8%	0.9%
Poland	2.5%	2.6%	2.3%	1.9%	2.4%	2.1%	1.9%
Switzerland	1.6%	1.5%		1.4%	1.6%	1.7%	1.8%
Spain	1.3%	1.2%	1.2%	1.0%	1.2%	1.2%	1.1%

Sweden	2.0%	2.2%	2.6%	2.3%	1.9%	1.9%	2.1%

Table 21 Annual harvest rate (proportion of stems harvested) per combination of country and forest structure class, aggregated to regular and irregular forest structure; total share of irregular forests per country and total share of monocultures.

	Country average	Harvest rate regular	Harvest rate irregular	Share irregular	Share of monocultures
Denmark	3.7%	3.4%	4.3%	27.5%	52%
Belgium-Flanders	3.1%	3.1%	3.1%	19.3%	62%
Belgium-Wallonia	2.0%	2.0%		2.6%	63%
Ireland	3.1%	3.2%		3.3%	74%
Germany	2.6%	2.7%	2.4%	3.9%	60%
France	1.5%	1.5%	1.2%	16.6%	24%
Netherlands	2.0%	2.1%	1.9%	35.1%	50%
Norway	0.9%	0.9%	0.9%	23.5%	59%
Poland	2.5%	2.6%	2.0%	12.9%	64%
Switzerland	1.6%	1.6%	1.7%	11.2%	44%
Spain	1.3%	1.2%	1.1%	5.4%	79%
Sweden	2.0%	2.0%	2.0%	6.8%	52%

Species identity shows important correlations with the annual harvest rates (Figure 15, Table ***22***, Table ***23***). Especially the conifers tend to have higher harvest rates than average, with the exception of *Pinus sylvestris*, *Pinus nigra and mugo* and other conifers in most countries. From the broadleaves, Populus tends to have higher harvest rates than average in most countries, while *Quercus robur* and *petraea* sometimes has higher and sometimes lower rates than average. Eucalypt also has a clearly higher harvest rate. Countries show clear differences in their distribution of the dominant species (Table ***24***). Conifers are more common than broadleaves, only France and Belgium-Wallonia have a conifer share lower than 50%. Dominance of long-lived broadleaved species is more common than dominance of short-lived broadleaves.

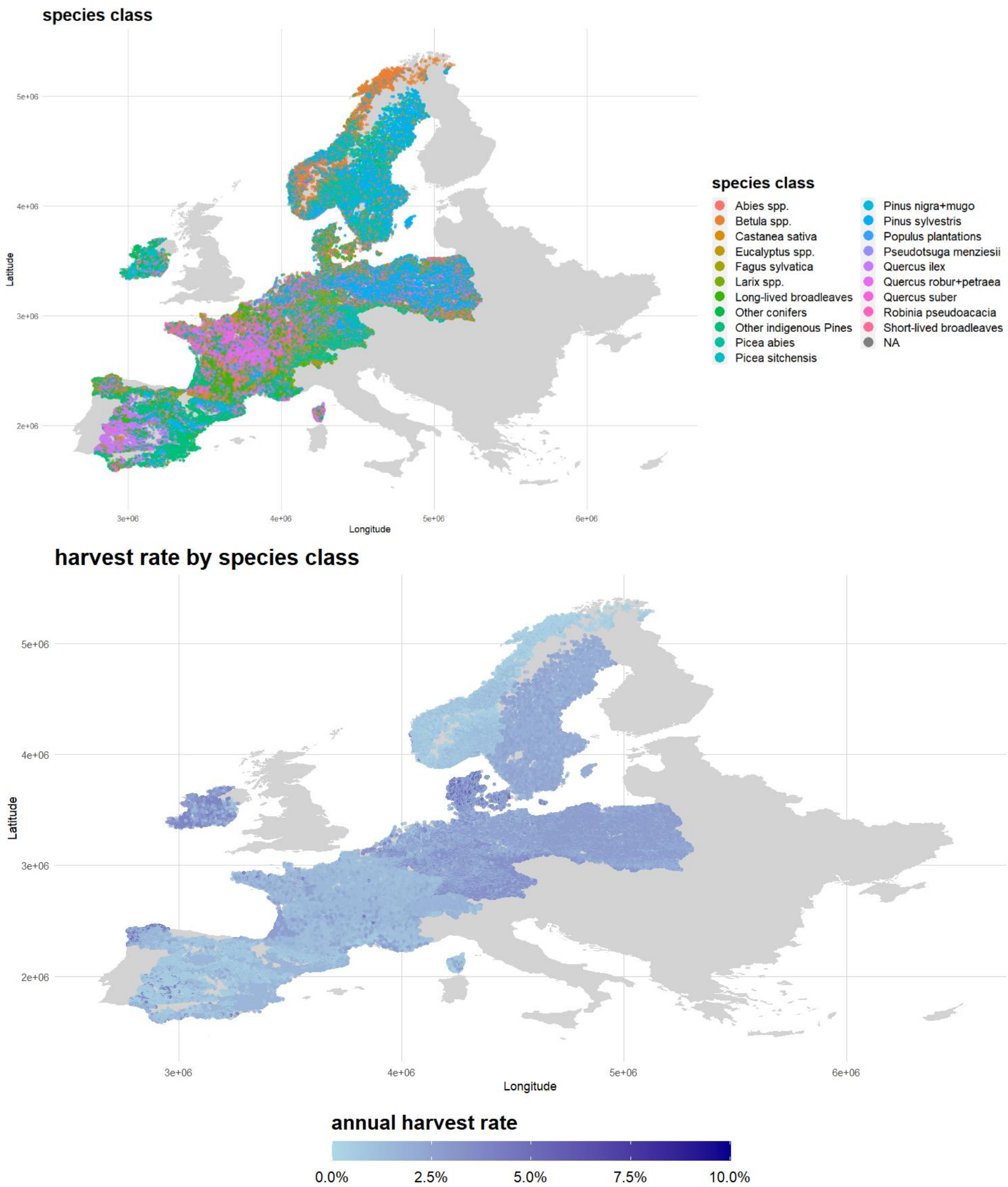


Figure 15 Distribution of species classes in Europe (top) and annual harvest rates (proportion of stems harvested) per combination of country and species class (bottom)

Table 22 Annual harvest rate v per combination of country and species class (conifers)

	Country average	Abies spp.	Larix spp.	Picea abies	Picea sitchensis	Pseudotsuga menziesii	Pinus sylvestris	Pinus nigra+mugo	Other indigenous Pinus	Other conifers
Denmark	3.7%	6.2%	3.2%	4.1%	3.8%		2.7%	2.6%		3.3%
Belgium-Flanders	3.1%						2.9%			
Belgium-Wallonia	2.0%			2.7%						
Ireland	3.1%				3.8%					2.6%
Germany	2.6%	2.3%	3.0%	3.3%	3.3%	3.3%	2.5%			
France	1.5%	1.6%	1.2%	2.3%		2.6%	0.9%	1.2%	2.6%	1.5%
Netherlands	2.0%						2.4%			
Norway	0.9%			1.3%			0.8%			
Poland	2.5%	1.5%	2.7%	3.0%			2.7%			
Switzerland	1.6%	1.5%	0.9%	1.7%			1.6%			
Spain	1.3%	0.5%					1.0%	0.8%	1.6%	0.4%
Sweden	2.0%			2.4%			1.9%			1.2%

Table 23 Annual harvest rate (proportion of stems harvested) per combination of country and species class (broadleaves)

	Betula spp.	Castanea sativa	Eucalyptus spp.	Fagus sylvatica	Robinia pseudoacacia	Populus plantations	Quercus robur&petraea	Quercus ilex	Quercus suber	long-lived broadleaves	short-lived broadleaves
Denmark	1.9%			2.2%			2.4%			2.7%	2.8%
Belgium-Flanders							2.5%				
Belgium-Wallonia				2.0%			1.3%				

Ireland	0.8%										1.6%
Germany	1.4%			2.2%	1.5%	2.1%	1.7%			2.0%	1.2%
France	1.8%	1.8%		1.1%	1.7%	1.6%	1.4%	0.4%	0.7%	1.1%	1.1%
Netherlands							1.3%			2.1%	
Norway	0.4%					0.5%					1.2%
Poland	2.2%			2.1%		2.6%	2.2%			1.9%	1.9%
Switzerland				1.4%						1.6%	
Spain		2.0%	4.6%	0.6%		2.5%	1.5%	0.6%	1.0%	0.8%	1.2%
Sweden	1.4%					2.4%	2.2%				1.5%

Table 24 Share of forests by dominant species by country. Shade-tolerant conifers includes *Abies, Picea, Pseudotsuga* and other conifers, long-lived broadleaves include *Castanea, Fagus, Robinia, Quercus*, and long-lived broadleaves.

	Shade-tolerant conifers	Light-demanding conifers	Long-lived broadleaves	Short-lived broadleaves
Denmark	37%	14%	35%	14%
Belgium-Flanders	3%	50%	34%	14%
Belgium-Wallonia	28%	6%	61%	4%
Ireland	72%	5%	10%	13%
Germany	37%	26%	32%	5%
France	13%	16%	64%	7%
Netherlands	10%	41%	34%	15%
Norway	34%	32%	1%	33%
Poland	9%	62%	15%	14%
Switzerland	60%	11%	27%	2%
Spain	5%	54%	37%	4%
Sweden	40%	46%	2%	12%

Country analysis

All countries differ in their average annual harvest rate and have distinct patterns inside their borders. Here we discuss country by country the patterns we find and potential groupings for the management parameterization.

Sweden clearly features a gradient from the south to the north and from the coast in the east to the mountains in the west, with the highest harvest rates in the southeastern region. This pattern is best reflected by the elevation classes, although the dry soils also seem to correlate with the area with high harvest rates.

Norway shows low harvest rates throughout the country compared to Sweden, with slightly higher rates in the region around Oslo and perhaps some regions along the coastline. The country has a very rugged topography and a low population density moving inland and northward. Harvesting is concentrated in the easily accessible regions. Many map layers reflect this pattern, like the elevation, slope, ruggedness, and all access layers. Also, the boreal region coincides well with the region around Oslo. IUCN protection classes show nearly no harvests, but are not sufficient by itself to explain the spatial pattern throughout the country.

Denmark is a rather flat country with easily accessible forests. The harvest rate is high compared to other countries, with no clear differentiation within the country.

Also, for the Netherlands, no clear patterns can be derived from the map layers. Only soil wetness seems to have some correlation with harvest intensity.

Also, for Belgium-Flanders no patterns can be derived from this analysis, which is partly related to the low number of plots available.

Ireland seems to show some tendency for higher harvest rates at higher elevations and steeper slope, also reflected in the 50k access classes. The reason for this gradient is unclear and the pattern is not very strong.

Within Belgium-Wallonia there is a gradient with increasing harvest rates moving from the west to the east. This is reflected in the elevation, ruggedness, and all access layers. Probably this is connected to rather intensive forestry practices in the region of the Ardennes.

Germany features a medium harvest rate, evenly spread across the country but with lower harvest rates in the southern part approaching the Alps. This is reflected in the biogeographic zone, with a clearly lower harvest rate in the Alpine zone compared to the Atlantic and Continental zone. The same pattern is visible in the elevation, with lower rates in the highest elevation classes (above 1000 m), also reflected but less clearly in relation to slope and ruggedness.

Also, Poland has a medium harvest rate and shows a lower harvest rate in the Alpine zone as compared to the Continental zone, but less pronounced than in Germany. This may be partly caused by a more limited elevation range. The influence of ruggedness seems more pronounced than in Germany. Some IUCN classes have a lower harvest rate, but this may be overlapping with the higher elevation areas.

France shows higher harvest rates in the west and northeast part of the country and lower rates in the south and southeast. This is well reflected by the biogeographical zones, with higher harvest rates in the Atlantic and Continental zones and lower rates in the Alpine and Mediterranean zones. Elevation zones follow the same pattern but fail to identify lower harvest rates along the Mediterranean coastline. The increased harvest rate in the region around Bordeaux is reflected in the species effect, owing to the intensive plantations of Pinus pinaster in this region.

Switzerland is a mountainous country. The more intensive forestry is located on the northern side where conditions are more favorable, while large parts in the mid and the south are in difficult terrain, where avalanche protection is usually more important than wood production.

This is reflected in higher harvest rates in the Continental zone as compared to the Alpine zone, as well as in clearly declining gradients with increasing elevation, slope and ruggedness.

Spain features higher harvest rates in Galicia and some border regions with Portugal, with low rates inland. This is partly reflected by the biogeographical zones, with higher rates in the Atlantic region and particularly low rates in the Alpine zone. However, the species effect seems to reproduce the pattern even better, with the elevated harvest rates corresponding to locations where Eucalypt occurs.

4.4 Summary of the results

Conceptually, we assumed that forest management is constrained by external factors such as soil, climate, topography, distance to markets and availability of workforce. Within these constraints, there is manoeuvring space for the owner or manager to emphasize different goals and applying different management techniques. We assume such differences should become visible in the species composition and forest structure.

Overall, we see a clear influence of topography, climate, and accessibility, expressed as lower harvest rates at higher elevations, steeper slopes, more rugged terrain, harsher climate conditions and longer travel distances to population centres of different size. However, no single map layer stands out in explaining harvest rate patterns across Europe. This may partly be explained by the fact that many of these factors are related. Population and road densities for example tend to be lower at higher elevations and harsher climate conditions. Also, there are important differences in the effect of these gradients within the countries. Poland and Germany have similar climate conditions and cover a range of elevations. Although the average harvest rate is comparable, the decline of harvest rate with elevation seems to be faster within Poland. This may be related to the fact that the absolute elevation range is lower in Poland. Perhaps in both countries the highest elevation zones are the least interesting for management and more interesting for protection purposes.

In contrast, increasing harvest rates with increasing elevations are found in Belgium-Wallonia and Ireland. Low-altitude zones in these countries are probably densely populated and/or very suitable for agriculture. Forest cover is probably low, and forest management may be more oriented towards recreation and biodiversity conservation. Areas at mid-altitude range will have higher forest cover and a stronger focus on wood production. In these cases, a forest cover layer may offer an alternative explanation of the harvest rate pattern.

Countries and regions sharing similar climate and topographical conditions still show important differences in overall harvest rates. Such differences are probably related to a range of factors, such as forest culture and traditions, importance of the forest sector, history, tree species and ownership. Such a difference is for example visible within Belgium, where Wallonia has an average harvest rate of 2.0% and Flanders an average rate of 3.1%. At the same time, the share of irregular forest is much higher in Flanders (19.3%) than in Wallonia (2.6%), but the share of monocultures is almost the same (62% and 63% respectively). The higher share of irregular forest in Flanders may be related to high share of light demanding species (Scots pine and oak), while Wallonia has a high share of shade-tolerant species (Norway spruce and beech), but such differences may also be caused by a difference in goals in management and the way management is implemented.

Interestingly, the IUCN protection classes did not show a very strong signal with regard to the harvest rate. Only in specific classes in specific countries an effect was visible. First of all, there may be a difference among the countries how they translate the actual situation in the country towards the common IUCN classes. Furthermore, the size of the protected areas may differ per country. When protected areas are small, it is more likely that the NFI plots are not properly allocated to be inside or outside the area due to noise added to the coordinates.

All countries included in our analysis have an NFI based on a statistical design with circular plots that are measured regularly. However, there are important differences between the countries with regards to measurement interval, dbh threshold and plot size. Partly these differences have been mitigated by harmonizing the data for the same interval (annual) and using a common dbh threshold (10 cm, only Switzerland has a 12 cm threshold). However, longer intervals may still lead to somewhat higher harvest rates, because there is a higher probability that trees that died naturally are taken out of the forest and thus will be labelled as being harvested. Furthermore, some countries (Spain, Belgium-Flanders) do not distinguish between lying dead trees and harvested, which would lead to an overestimation of the harvest rate. Plot size is difficult to harmonise but will have an effect only on the plot structure and species composition and not on the harvest rate. It is unclear how much of the country effect is caused by differences in the NFI designs.

We used the observed annual harvest rate as an indication for differences in forest management. However, the same harvest rate may be obtained by different ways of implementing harvesting. Suvanto et al. (submitted) for example showed a clear difference between Poland and Germany, with Poland featuring many harvest events of low intensity, while Germany showed a lower frequency but higher intensity, where we found a very similar harvest rate, based on the same data. Conversely, the same management may lead to different harvest rates. Observed differences within a country along an elevational gradient may simply be caused by lower productivity at higher elevations, leading to longer rotation times to obtain the same size of trees. For the specific parameterization of management in LPJ-GUESS and EFISCEN-Space, we will investigate harvest parameters in more detail. This will give more insight in the actual harvest events that are recorded in the data to extract information on frequency, intensity and type of thinning (from above or from below). More information on these parameters will allow a better judgement on what groupings make sense with regards to the modelling, and how this grouping could be combined with the information on ownership and management as collected in the previous chapter. Management encompasses much more than just the harvesting activities, such as regeneration method, soil preparation, fertilization, and tree species choice (Chapter 2). Many of these actions are difficult or impossible to obtain from NFI observations. Information on these aspects will be added from the literature review, the survey and the interviews.

In conclusion, we found a clear effect of constraining external factors on the harvest rate that works in a similar way all over Europe. However, within these constraints, we also found very clear differences between countries. This is very much in line with earlier work by Levers et al. (2014) and parallel work by Suvanto et al (submitted). These country effects seem so strong that it will be hardly possible to distinguish similar groups across borders. Also, our analysis does not allow to allocate plots to any of the common ownership groups as defined in Chapter 3 from observed forest structure at the NFI plot level. Information on ownership within the country, preferably at the NFI plot level, may help to further differentiate management styles and align better with the objectives of the model framework and scenario analysis, specifically with regards to the agent-based modelling.

5 Climate and Biodiversity Smart (CBS) forestry

Since the early 1990s, sustainable forest management (SFM) policy aims to deliver multiple forest benefits and services that are socially just, ecologically sound, and economically viable MCPFE, 1993). Recent evidence on continuing climate change with extreme climatic events (Buras, 2020) and increasing forest disturbance impacts (Patacca, 2023) underlined the importance of adapting SFM to these new challenges. In this context, Climate Smart Forestry (CSF) has been proposed as a concept that integrates climate change mitigation and adaptation (Nabuurs et al. 2017). The CSF concept has quickly gained popularity and is applied in different regions (Jandl et al., 2018; Nabuurs et al., 2018; Yousefpour et al., 2018). However, the concept was approached in different ways (e.g., Bowditch et al., 2020; Verkerk et al., 2020). Some authors claim that adaptation, mitigation, and social dimensions are the core focus, recognizing the need to integrate and avoid the development of these aspects in isolation (Bowditch et al., 2020). Others emphasize sustainability and the sustainable use of wood for climate change mitigation (Verkerk et al., 2020) or stressed the importance to also consider unmanaged forests and restoration of degraded land (Cooper & MacFarlane, 2023). We carried out a literature review on CSF and found diverse definitions and explanations of what CSF is. The most cited definitions (as of August 2023) are:
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Nabuurs et al. (2017): "*CSF is a more specific (climate-oriented) form of the Sustainable Forest Management paradigm. The idea behind CSF is that it considers the whole value chain from forest to wood products and energy, and illustrates that a wide range of measures can be* *applied to provide positive incentives for more firmly integrating climate objectives into the forest and forest sector framework.[…] It builds upon three main objectives; (i) reducing and/or removing greenhouse gas emissions; (ii) adapting and building forest resilience to climate change: and (iii) sustainably increasing forest productivity and incomes."*

Bowditch et al. (2020): *"Climate-Smart Forestry is sustainable adaptive forest management and governance to protect and enhance the potential of forests to adapt to and mitigate climate change. The aim is to sustain ecosystem integrity and functions and to ensure the continuous delivery of ecosystem goods and services while minimizing the impact of climate-induced changes on mountain forests on well-being and nature's contribution to people. In summary, CSF should enable both forests and society to transform, adapt to, and mitigate climate-induced changes".*

Verkerk et al. (2020): "CSF aims to connect mitigation with adaption measures, enhance the resilience of forest resources and ecosystem services, and meet the needs of a growing population and expanding middle class. CSF has been introduced as a holistic approach to guide forest management [...]. *CSF builds on the concepts of sustainable forest management, with a strong focus on climate and ecosystem services. It builds on three mutually reinforcing components:*
•*Increasing carbon storage in forests and wood products, in conjunction with the provisioning of other ecosystem services*
•*Enhancing health and resilience through adaptive forest management*
•*Using wood resources sustainably to substitute non-renewable, carbon-intensive materials*."

All three definitions prominently refer to SFM as a starting point. They also share the key elements of climate change mitigation, adaptation to climate change, and provisioning of ecosystem services. However, these statements mostly describe the concept and lack a simple and concise definition (Bowditch et al., 2022; Cooper & MacFarlane, 2023), which is a prerequisite to applying the concept in practice.

This chapter is structured into three main sections. In chapter 5.1 we present a literature review which aimed to provide a better understanding of the differences in existing definitions of CSF. To respond to a common critique that biodiversity aspects are insufficiently considered in widely used CSF definitions, we also review scientific literature on biodiversity management in forests. Based on our reviews we propose a wider comprehensive definition of CSF that we define as Climate and Biodiversity-Smart (CBS) Forestry and reviewed existing efforts on how to assess CSF/CBS in decision-making, with a focus on forest management. Chapter 5.2 reviews and categorizes forest management practices based on existing forest management typologies, and then evaluates them based on literature, in accordance with the pillars of our CBS definitions. As CBS measures are strongly context-dependent, we show in Chapter 5.3 how CBS measures vary regionally and how they are influenced by e.g., forest management types and disturbance regimes. Finally, in Chapter 5.4 we provide an outlook on further steps needed to implement CBS in decision-making practice.

5.1 Defining and assessing Climate and Biodiversity-Smart Forestry

5.1.1 Literature review and proposed CBS definition

In April 2023, we conducted a systematic literature review of studies referring to Climate-Smart Forestry (CSF) and Biodiversity. We firstly reviewed CSF related papers, and secondly, biodiversity management related papers, to better integrate biodiversity into the CSF definition, as requested by several authors (e.g., Cooper and MacFarlane, 2023). To identify the state of the art of defining CSF, we performed a literature search using the keywords shown in Table 25. The oldest reference to climate-smart and forest was found in Nitschke & Innes (2008), for this reason, we set our literature review from 2005 to 2023. The results (19100 articles) were sorted by relevance (from highest to lowest), and we found that most articles were related to climate-smart agriculture with some reference in the text to forest. Among 698 papers that used the terms climate-smart/climate smart forestry we screened for articles that defined or explained what CSF is. We selected 36 items.

Table 25 Keywords used in Advance Google Search to find papers on CSF.

Keyword	Findings
“Climate Smart” AND “forest”	19100
“Climate-Smart Forestry” OR “Climate Smart Forestry” AND “Forest Management”	698

Biodiversity management aspects are more widely studied. To identify terms for expanding the CSF concept with biodiversity aspects, we searched keywords related to the interaction between forest management regimes (e.g., integrative forest management, retention forestry, forest zoning, salvage logging, etc.) and biodiversity. The keyword search included: “Forest management” AND “biodiversity” AND “adaptation” OR “resilience” OR “carbon” OR “mitigation” OR “Climate” (**Table *26***). A total of 117,000 hits were found. The final selection of papers was limited to papers with the keywords in the title and/or the abstract of the articles, which resulted in 45 papers.

Table 26 Keywords used in Advance Google Search to find papers on Biodiversity topics.

	Keyword	Findings within the text	Findings within the title/abstract
1.	“Forest Biodiversity Management”	268	13
2.	Biodiversity AND manage* AND preservation AND Forest	19400	0
3.	Biodiversity AND manage* AND conservation AND Forest	18600	0
4.	“Forest management” AND “biodiversity” AND “adaptation” OR “resilience” OR “carbon” OR “mitigation” OR “Climate”	117000	41
5.	“Nature Conservation” AND Manage* AND Forest	23800	0
6.	“Integrative Forest Management” AND Biodiversity	135	0
7.	“Reversing biodiversity decline” AND Forest	91	0
8.	“Halting the loss of biodiversity” AND Forest	1650	0

TOTAL	180944	54*

* Includes duplicates; there were 45 distinct papers

To visualize which 25 words were most frequently repeated within the extracted information, we used TagCrowd, a web application for visualizing word frequencies (**Figure *16*** and **Figure 17**). The words “CSF”, “climate-smart” and “Climate Smart Forestry” and “biodiversity” were left out on purpose from the respective TagCrowds. The varying frequency of identified keywords indicates how homogenous CSF is perceived in the literature. We then utilized the most emphasized words to extract a comprehensive definition for CSF including biodiversity management.

Figure *16* shows the 25 most repeated words out of the 36 papers reviewed defining or understanding CSF. The variable understanding of CSF is reflected by the fact that few words besides adaptation and mitigation are commonly used in the literature.

Figure 16 Most repeated 25 words to define Climate-Smart Forestry by different authors within the literature searched.

Error! Reference source not found.Figure *17* shows the 25 most repeated words in the literature review on 45 papers defining biodiversity management including maintenance, protection, and increase of biodiversity. The most predominant terms we found were “Conservation”, “Habitat”, “management”, “retention”, “species”, “trees”, and “integrative”.

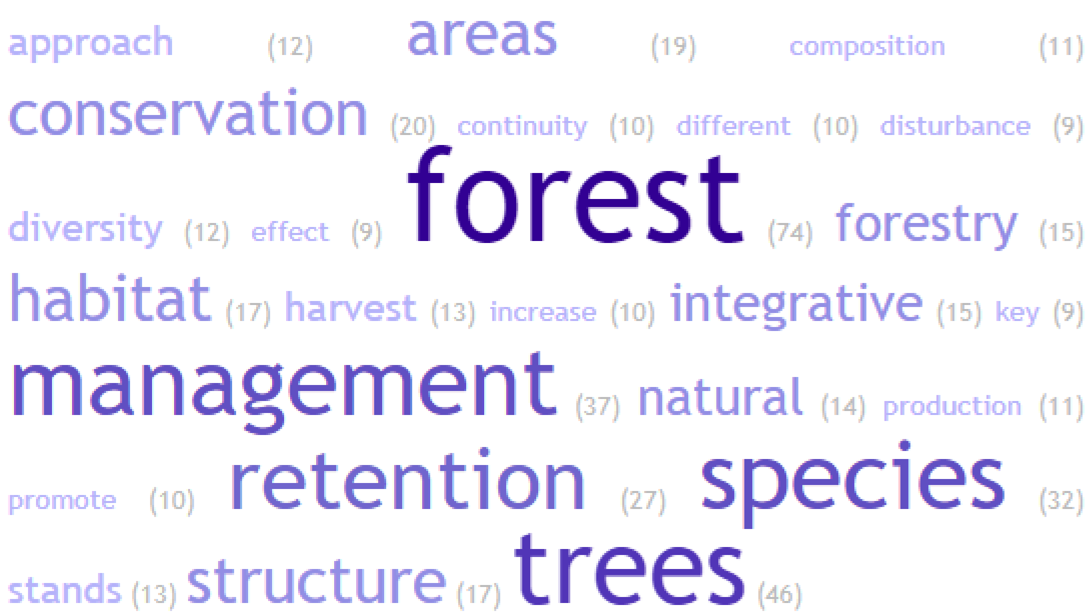

Figure 17 Most repeated 25 words to define "Biodiversity-smart" management within the 45 retained articles from the literature search.

Following our literature review and word *TagCrowd* analysis, we propose the following definition for CBS. The **coloured text** was added to incorporate biodiversity management into CSF:

Climate and Biodiversity Smart Forestry is a comprehensive approach that aims to enhance the resilience and productivity of forest ecosystems and related forest value chains, seeking to integrate adaptation and mitigation strategies to cope with climate change and improve biodiversity status while maintaining forest systems that sustainably provide ecosystem services and contribute to a circular bioeconomy. It is a holistic concept that considers and needs to be adapted to regional differences and country-specific challenges.

CBS targets climate change mitigation effects in forest ecosystems, value chains, and forest product usage, including the substitution of fossil fuels and carbon intensive materials.
Improving biodiversity status implies promoting retention of key habitat elements, increasing structural and species diversity, and sustaining continuity in forested areas, considering natural disturbance regimes.

CBS implementation needs flexible pathways for decision-makers to support the implementation of CBS approaches toward achieving climate neutrality, adapting to climate change, reversing biodiversity loss, and mitigating disturbance impacts.
This will require a robust methodology how to assess CBS practices.

5.1.2 Assessment of CBS forestry

Existing efforts to establish methods for CBS forestry assessment focussed on assessing CSF. Nabuurs et al. (2017) argue that CSF assessment should find synergies and minimize trade-offs between climate and forest policy goals like (1) reducing and/or removing greenhouse gas emissions; (2) adapting and building forest resilience; and (3) sustainably increasing forest productivity and incomes. Bowditch et al. (2022), Santopuoli et al. (2020) and Temperli et al. (2022) developed a list of CSF indicators based on the pan-European set of criteria and indicators for sustainable forest management. Santopuoli et al. (2020), listed 10 out of 34 indicators to assess CSF mitigation and adaptation effects and Temperli et al. (2022) listed 17 indicators to assess adaptation and 18 indicators for mitigation, both based on the most cited SFM indicators within the literature. Bowditch et al. (2022) listed 29 SFM indicators as a result of a survey targeting forest managers from 15 European countries. Bowditch et al. (2022) differentiated between State forests, Private forests and National parks. The top five rankings were similar except for two indicators: (1) “Accessibility for recreation” was mentioned as most important for the private forests and National parks and (2) “Naturalness” was an important indicator only for National parks. Across the three CSF indicator lists, “Forest damage” and “Carbon Stock” were common CSF indicators, and “Tree Species composition” and “Management plan” were listed twice. An overview of the most important CSF indicators is shown in **Table *27***.

Table 27 Most important SFM indicators for CSF according to Santopuoli et al (2020), Bowditch et al. (2022), and Temperli et al. (2022).

Indicator selected	Resource	Managers	Author
Forest damage	Most cited/ Mentioned by forest managers	state, private, national park	Bowditch et al., 2022; Santopuoli et al., 2020; Temperli et al., 2022
Carbon Stock	Most cited/mentioned by forest managers	state, private, national park	Bowditch et al., 2022; Santopuoli et al., 2020; Temperli et al., 2022
Tree Species composition	Most cited		Santopuoli et al., 2020; Temperli et al., 2022
Roundwood	Most cited		Temperli et al., 2022
Deadwood	Most cited		Temperli et al., 2022
Energy from wood resources	Most cited		Santopuoli et al., 2020
Natural Regeneration	Most mentioned by forest managers	state, private, national park	Bowditch et al., 2022
Protective Forest-soil, water and other ES	Most mentioned by forest managers	state, private, national park	Bowditch et al., 2022
Forest Structure and/or diameter distribution	Most mentioned by Forest managers	state, private, national park	Bowditch et al., 2022
Management Plans	Most mentioned by Forest managers	state, private, national park	Bowditch et al., 2022; Temperli et al., 2022

Accessibility for recreation	Most mentioned by Forest managers	private, national park	Bowditch et al., 2022
Naturalness	Most mentioned by Forest managers	national park	Bowditch et al., 2022

We observed that the indicators shown in **Table *27*** mostly focus on the forest conditions, but indicators for the forest value chain and dependent sectors (e.g., Harvested Wood Products and substitution effects) are not covered.

Nabuurs et al. (2017) proposed to estimate all carbon pools and flows relevant to forests and forest value chains (forest biomass, forest soil, HWP, substitution). A valuable data source for such CSF indicators are metrics and indicators in the Monitoring, Reporting, and Verification (MRV) used for greenhouse gas emission reporting (Cooper & MacFarlane, 2023). MRV practices are well-established according to national commitments and receive immense efforts by nation-states and increasingly also from sub-state actors to claim carbon dioxide removal (CDR) credits. Jandl et al. (2018) adopted indicators proposed by Nabuurs et al. (2017) to assess CSF measures in a simulation in Austrian forests under different sustainable management scenarios. They compared the development of standing stock and carbon pool of the stem biomass and the soil carbon pool in scenario simulations until 2100 and concluded that the production of long-living wood products is the preferred implementation of CSF in Austria. Yousefpour et al. (2018) applied a coupled ecological-economic framework incorporating economic factors along with ecological potentials to optimize CSF for European forests. They used a multi-objective optimization approach to compute the trade-off between carbon sequestration and commercial wood production using a forest simulation model.

Our proposed wider definition of CBS practices calls for further criteria for assessing biodiversity impacts in addition to those included already in **Table *27***, e.g., to cover other key habitats or habitat connectivity. Moreover, not only indicators but a criterion to assess forest practices as “biodiversity smart” is needed. Establishing minimum requirements or thresholds to link a forest management activity on biodiversity with the international goal for halting biodiversity loss is important to identify practices as CBS or not.

Existing efforts on assessing CSF are very relevant and can be used as CBS indicators. However, strategies to weigh these indicators together with biodiversity indicators need to be developed. A minor change in managements that improves only one element (climate change mitigation or biodiversity) does not necessarily deserve the label CBS. A harmonized methodology would be desirable to objectively identify whether any forest management activity qualifies as CBS or not.

5.2 CBS forestry practices in the literature

Many authors have proposed forest management approaches that could qualify as CBS. Based on a literature review, we categorised CBS forestry approaches following forest management approaches reviewed in chapter 2 (**Table 28**). The categories were divided into concrete management practices that are widely implemented in forestry and are relevant for CBS (e.g., den Ouden et al., 2010; Mayer et al., 2020; Muys et al., 2022). The relevance of these practices for CBS was determined according to the definition stated earlier in chapter 5.1. Practices studied in the literature were listed and assessed according to the pillars of climate change mitigation, adaptation, biodiversity, and ecosystem services. For each listed practice, literature was evaluated and checked whether the practice had a positive (↑) or negative (↓) effect on each pillar. The resulting database consisted of 383 literature sources[48], which were summarized in **Table 28** and further described below by management category.

Table 28 Typology of CBS approaches based on a literature review. Practices were assessed according to the pillars of CBS, i.e. mitigation, adaptation, biodiversity, and ecosystem services provisioning. Effects were defined as (↑) = Positive, (↓) = Negative, NA = Not Assessed.

Category	Practice		Mitigation	Adaptation	Biodiversity	Ecosystem services
Tree species selection	Type	Adapted provenances	↑	↑ ↓	↑ ↓	↑ ↓
		Native and non-native tree species	↑	↑ ↓	↑ ↓	↑
		Broadleaves	↑	↑	↑	↑↓
	Diversity	Genetic and species variation	↑	↑	↑	↑
Thinning	Thinning method		↑ ↓	↑	↑ ↓	NA
	Intensity and density		↑ ↓	↑ ↓	↑ ↓	NA
Harvest regime	Partial harvest		↑ ↓	↑ ↓	↑ ↓	NA
	Rotation length		↑ ↓	↑ ↓	↑ ↓	↑ ↓
	Silvicultural systems		↑ ↓	↑ ↓	↑ ↓	↑ ↓
Measures for biodiversity	Set-aside/non-management		↑ ↓	↑ ↓	↑ ↓	↑↓

[4]The database is available upon request

The forestry practices show a diverse range of effects for each pillar of CBS, highlighting the complexity and context dependency of these practices (Table 27). The table includes many contradicting arrows per pillar, which means that the same practice can have contrasting effects depending on specific site conditions, species involved, and broader environmental and management contexts. The following sections provide a detailed explanation of these practices and their potential impacts.

Tree species selection

Tree species selection is divided into tree species type and diversity. Tree species type consists of adapted provenances and species, broadleaves and conifers, fast-growing species, native and non-native tree species. Tree species diversity consists of genetic and species variation.

As for tree species type, adapted provenances and species or trees with selected genotypes for fast-growing characteristics have improved growth rates, which in turn increases the C sequestration potential (Perry, 1998, Noormets et al., 2015; Ameray et al., 2021). Soil C stocks in the forest floor are generally greater under conifers than under broadleaved species (Augusto et al., 2003; Vesterdal et al., 2013; Boča et al., 2014; Augusto et al., 2015), while larger mineral soil C have been reported under broadleaved species. The effect of tree species type is context-dependent, relating to the site conditions (Vesterdal et al., 2008; Vesterdal et al., 2013; Mayer et al., 2020). As for adaptation, introducing adapted provenances from the same species or introducing tree species that are more adapted towards, for example, droughts, may favour drought resistance of trees (Brang et al., 2014; Larsen et al., 2022). Additionally, increasing the share of broadleaves in forest stands reduces vulnerability to wind and drought damage (SCCV, 2007; Gerger Swartling et al., 2012; Wallstedt, 2013). Native tree species and current rare species that are well adapted to warmer and drier conditions in Europe could be another viable option for adaptation (Harrison et al., 2000; Felton et al., 2016), while also providing valuable habitat and directly benefiting biodiversity and thereby increasing the overall resilience (Bauhus et al. 2017).

There are possible trade-offs between mitigation (e.g., high carbon storage) and adaptation (e.g., high fitness) of the selected provenance (Verkerk et al., 2022). Additionally, introducing closely related tree species may cause uncontrolled gene flow into the present population, consequently, hybridization could induce lower adaptation of this species to the natural ecosystem. As for ecosystem services, introduced tree species can improve the delivery/provisioning of ecosystem services (e.g., timber products, erosion control) (Krumm and Vítková, 2016), but they can be also considered as potential threats to biodiversity (Sahoo and Wani, 2020). Semi-natural forests, consisting of a mixture of native and non-native tree species can reconcile biodiversity with timber harvesting objectives or assist in restoring degraded soils (Lõhmus et al. 2016; Desie et al., 2020).

Carbon sequestration can be optimised by increasing forest species richness (Augusto and Boča, 2022). The aboveground biomass production increases with a higher number of tree species mixed (Pacquette and Messier 2011; Gamfeldt et al., 2013), it is also more likely that more tree species contribute to a diverse set of ecosystem services (Hector et al. 2011; Hulvey et al. 2013; Shanin et al., 2014; Poorter et al. 2015). Mixed stands have shown to be more productive and sequester more carbon than single species stands because they use resources more efficiently and in a complementary way (Shanin et al. 2014; Verkerk et al., 2022). The effect of mixture is context dependent, i.e., influenced by differences in climate, soil type, or species identity (Dawud et al., 2017; Ratcliffe et al., 2017). Tree species diversity is considered as a strong driver for the adaptive capacity of forests (Brang et al., 2014), mixed stands are slightly more resistant and more resilient towards disturbances (von Lüpke and Spellmann, 1999; Brang, 2001; Schütz et al., 2006; Knoke et al., 2008; Jactel et al., 2009; Lebourgeois et al., 2013). There is a positive relationship between tree species diversity and the diversity of other forest-dwelling species, which also promotes adaptation (Ampoorter et al. 2020; Barbaro et al. 2019; Muys et al., 2022). A variety of tree species spread the risk towards disturbances, sustain various ecosystem functions, and promote the use of various ecological niches (Gamfeldt et al. 2013; Brang et al., 2014; Mori et al 2016).

Thinning

Thinning is divided into thinning methods (e.g., thinning from above and below, precommercial, and future crop tree thinning), intensity and density. The type of thinning method has various effects on CBS attributes. Thinning from above can result in a better carbon balance (i.e., forest and value chain) compared to thinning from below (Zubizarreta-Gerendiain et al., 2016). Although, thinning from below is also evaluated as a positive strategy for carbon sequestration (Ameray et al., 2021). As for adaptation, thinning develops long-crowned trees, which stabilizes the stand, especially in case of thinning from above (Brang et al., 2014). In terms of biodiversity, future crop tree thinning can promote biodiversity, since it increases deadwood quantities (Lombardi et al., 2018). Thinning can also negatively affect biodiversity, since thinning from below reduces the diversity of tree microhabitats (Courbaud et al., 2022).

Early thinning can stimulate growth, which in turn leads to higher rates of carbon sequestration in biomass (De las Heras et al., 2013). Reducing stand density with thinning reduces the risk of fire damage and therefore reduces carbon losses related to fire, (and related C-losses) (Hurteau et al., 2008). As a caveat, thinning can temporarily decrease the forest carbon stock (Strengbom et al. 2017). For adaptation, as earlier stated, thinning can increase stability, which positively affects adaptive capabilities. As higher stand density is linked with susceptibility to disturbances that are combined with high growing stocks, thinnings can be used as a tool to reduce density and therefore reduce risks (Waring and O'Hara, 2005; Hurteau et al., 2008; D'Amato et al., 2013; Brang et al., 2014). The opposite is also true when thinning too intensively, which also leads to stand instability, this negatively affects adaptation and conflicts with carbon sequestration in forest systems (Verkerk et al., 2022). After a thinning is conducted, the resistance may initially drop, which makes the stands prone to disturbances during this phase (Maringer et al. 2021). On the long-term when the density is kept low, the level of resistance and resilience lowers. This is attributed to significantly greater tree sizes attained within the lower-density stands through stand development, which in turn increases tree-level water demand during later droughts (D'Amato et al., 2013), this in turn negatively affects adaptation. As for biodiversity, thinnings can help to promote or maintain (rare) species with low competitiveness which otherwise could disappear (Brang et al., 2008). Consequently, thinning operations promote the redistribution of light and soil resources, which affects the growth of tree regeneration and other ground vegetation (Griffis et al. 2001; Burton et al. 2013; Strengbom et al. 2017 Muys et al., 2022). Depending on the density and intensity, when looking in a long-term perspective, thinning has varying effects on biodiversity (Økland et al. 2003). On the negative spectrum, intense thinnings have a negative impact on shade-demanding understory species and the ectomycorrhizal community (Buée et al. 2005).

Harvest regime

In high forest systems, partial harvesting, such as selective cutting, can positively affect climate change mitigation (Pötzelsberger and Hasenauer, 2015). Though there are caveats with partial harvest systems, studies found little or no difference between the effects of partial, selection, shelterwood, and clearcut harvesting on soil C stocks (Hoover, 2011; Christophel et al., 2015; Puhlick et al., 2016). Harvesting in general has negative effects on soil C stocks, due to C losses, but promote carbon storage in HWP (Pilli et al., 2015; Mayer et al., 2020). In terms of adaptation, selective harvesting increases resistance of individual trees to biotic and abiotic stressors. Additionally, it increases structural diversity and genetic variation (Brang et al., 2014). There is a caveat that single-tree selection does not allow a radical replacement of high-risk stands. However, single-tree selection rarely produces the uniform and short-crowned trees characteristic of high-risk stands (Brang et al., 2014). As a negative effect, strictly applied selection cuttings only promote a certain group of tree species, mainly shade-tolerant species. In contrast, group cutting tends to promote light-demanding species. This hampers adaptive capacities, in terms of tree species diversity and genetic variation (Brang et al., 2014; Schall et al., 2018; Muys et al., 2022). Therefore, a mix of methods between selection and group cutting is beneficial, since it can promote the regeneration of both light and shade-demanding species (Muys et al., 2022).

Partial harvests are often part of silvicultural systems, such as continuous cover forestry, close(r)-to-nature forestry, and integrative forest management. These systems encompass various management activities, such as regeneration, retention, thinning, and harvesting. Systems, such as continuous cover forestry are evaluated to be fit for mitigation (Felton et al., 2016). As for adaptation, promoting the principles of closer-to-nature forest management would contribute to improved resistance and resilience and thereby to an increased adaptive capability (Larsen et al., 2022). However, these systems are not free of risk, as uneven-aged stands under continuous cover forestry have potentially an increased risk of Heterobasidion root rot (Piri and Valkonen, 2013). These management approaches often seek multifunctionality, aiming to maintain conservation elements, such as tree species and structurally diverse forest stands, a preference for site-adapted native tree species, a reliance on natural processes, such as natural regeneration as well as using long production cycles, which promotes biodiversity and ecosystem service provisioning (Bauhus et al. 2013; Pukkala, 2016). There lies both a caveat and a negative effect in balancing conservation with societal needs, namely trade-offs at the level of forest management units, which are context-dependent (Deuffic et al., 2018; Maier and Winkel, 2017; Sotirov et al., 2019). At the landscape level, Triad management encourages flexibility to find a compromise between the conservation of biodiversity and other societal demands. Triad can optimise predetermined wood production goals and conservation targets (Muys et al., 2022).

In harvesting regimes, rotation length has various influences on the different pillars. Longer rotation lengths can increase carbon storage within production forests (Jandl et al., 2007; Pawson et al., 2013). Longer rotation stimulates both mitigation and biodiversity through increased habitat availability (Verkerk et al., 2022). However, stands with high growing stocks and larger tree heights are more prone to disturbances (Spiecker, 2004; Mayer et al., 2005; Jactel et al., 2012). Thus, lowering the rotation length is expected to decrease disturbance risks, which results in smaller economic risks (Roberge et al., 2016). Reduction of rotation length is not seen as sufficient to improve adaptive capabilities (Zimová et al., 2020). Additionally, reduced rotation lengths are not always favourable, since it may deplete soil nutrients and diminish biodiversity, especially, biodiversity linked to old growth structures and individual older trees (Noss 2001, Felton et al., 2016). Absence of older trees affect recreation values (Curtis, 1997), shortening rotations can negatively affect provisioning services (e.g., production of wood, bilberries, reindeer (Roberge et al., 2016), although reducing rotation length can result in a temporal surplus of timber, bioenergy and wood fiber (Millar et al., 2007).

Measures for biodiversity

Measures for biodiversity focus in this section on either set-aside from harvest or retention of elements (e.g., deadwood, individual or patches of trees). Setting-aside areas from active management, protecting carbon-rich forests from deforestation and soil degradation adds to climate change mitigation in forest systems (Pörtner et al., 2021; Verkerk et al., 2022; Nagel et al., 2023). Set-aside increases average forest carbon stock at the stand scale (Finer et al. 2003; Mäkipää et al. 2011) and synergizes with higher biodiversity in conserved and unmanaged forests compared to managed forests. Set-aside supports natural adaptation, which synergizes with mitigation in forest systems (Verkerk et al., 2022). Reduced harvesting in forests that are currently under active management may lead to an increase in carbon storage in forest ecosystems at one location but may lead to a decrease in carbon storage in the value chain (Nabuurs et al., 2018; Verkerk et al., 2022). Retention supports forest biodiversity, and thus could lead to a positive effect on ecosystem functioning (Yachi and Loreau 1999; Messier et al.2013). Retaining such legacies can enhance the restoration capacities post-disturbance (Larsen et al., 2022), as these legacies provide structural diversity, nutrient translocation, and water storage in the recovery phase of an ecosystem after disturbance (Bauhus et al. 2009; Drever et al. 2006; Seidl et al. 2014; Johnstone et al. 2016; Jõgiste et al. 2017; Spathelf et al. 2018). Additionally, these elements are indicators which can be used to reconcile habitat and economic values. Forest management can actively enhance the conservation of biodiversity in forests, evidencing and valuing the multi-functional role of forests, which require optimization with production goals (Seibold et al., 2016; Santopuoli et al., 2019).

5.3 Regional implementation of CBS in Europe

Our definition of CBS underlines the importance of the regional context for CBS. There are few measures that would qualify as CBS regardless of the circumstances they are embedded in. In the next section we present key factors that affect the suitability of CBS measures. A short characterization of the demo regions of ForestPaths is given in Annex 1 to illustrate how the context differs between regions across Europe. We conclude the section with a selection of CBS measures that were suggested in the demo regions.

5.3.1 Regional context – factors affecting CBS implementation

Several factors affect forest management in Europe, these include natural and socio-economic factors (cf. chapter 3). We are describing below four main factors that affect the regional implementation of CBS. Ownership types and socio-economic aspects such as the forest sector activities are not separated as independent factors, but they are considered mostly under the management regimes.

Biogeographical conditions (climate and soil conditions)

The main forested biogeographical regions in Europe are: Alpine, Atlantic, Boreal, Continental, Mediterranean, and Pannonian, which all have specific climatic conditions (EEA). As the projected climate change impacts differ between these regions, CBS needs to recognize the contrasting requirements for climate change adaptation. In addition to differences in climate, biogeographical regions also vary in soil characteristics. For example, peatlands of the Boreal region are very different from mountainous areas of the Alpine region with similar temperature regimes. The different conditions strongly affect potential forest management strategies and measures. Also projected changing climate impacts vary per biogeographical regions, e.g. Boreal region will have an initial increase of growth rate (Bergh et al., 2003), whereas forest growth in the Mediterranean and Continental regions may be particularly impaired by drought and heat (Bolte et al., 2009).

Forest types

Affected by biogeographical influences, forest types vary across Europe, each type containing varied vegetation compositions and demands in terms of site conditions (Barbati et al., 2007). Forest types in Europe include pure and mixed conifers and broadleaved stands. Pure conifers stands naturally occur often on extreme sites (e.g. Scots pine stands on nutrient-poor sandy soils or Stone pine and larch forests in high mountain elevations). Forest types are dynamic and develop to other types according to natural succession. Beech is a late successional species that due to its shade tolerance can naturally form homogenous mono-specific stands in large parts of the temperate zone. Forest types may respond differently to climate change induced alterations in site conditions. Moreover, forests with less dense canopies maintain microclimatic conditions differently than forests with denser canopies, which affects their responses to drought. All these differences need to be considered in the selection of CBS measures.

Management regimes

Historically, forests in Europe have a legacy of human use, which in turn influences the composition, structure, and functioning (Krumm et al., 2020). Around three-quarters of forests in Europe are managed (FOREST EUROPE, 2020). Objectives of forest management vary along with societal demand, which affects forest functioning. Forest management can either be passive or active. Passive forest management entails unmanaged forests, which can act as a nature reserve, where natural processes and natural disturbance regimes can develop without management intervention and ecological and societal goals are given primacy. Active management involves silvicultural interventions adapted to management objectives. Managing forest actively can vary along an intensity scale: low (i.e. close-to-nature forestry), medium (combined objective forestry), high (intense even-aged), and intense (short rotation forestry) (Duncker et al., 2012; Larsen et al., 2022). Depending on management objectives, similar forest types can be managed in very different ways, which affect the suitability of CSF measures.

Disturbance regimes

Natural disturbances are an integral part of forest ecosystems and influence their dynamics. Disturbances can enhance the structural heterogeneity of forests, affect tree species composition, create habitats of high conservation value, and affect the long-term resilience of forests to future stressors (Franklin et al., 2002; Swanson et al., 2011). Disturbance regimes can be divided into abiotic (e.g. fire, windthrow, and drought) and biotic (e.g. bark beetles, defoliators and pathogens) agents. These agents can have a direct, indirect or interaction effect with other disturbance agents (Seidl et al., 2017). Under a changing climate, disturbances are expected to increase in severity and frequency, consequently, this affects forests and ecosystem provisioning (Lindner et al., 2010; Seidl et al., 2011), with possible negative effects on carbon-sequestration of forests, as forests may change from carbon sinks to carbon sources. Disturbance regimes vary regionally across Europe, additionally their occurrence and severity are influenced by past and future management practices.

5.3.2 CBS measures in Demo Regions

In February 2023, together with experts of the four ForestPaths' demo regions, a view on CBS was developed for each region. These insights were categorized according to the types of practices found in the literature and presented in chapter 5.2 and synthesized in Table 32. Following a more detailed description of what their perception is on CBS for each region.

Table 29 Selected CBS measures proposed in the four Demo regions in ForestPaths (indicated with Letters: FI (Finland) IT (Italy), NL (The Netherlands), RO (Romania). (*) is used to indicate if the demo case representative mentioned if the respective practice is in function of climate in general, then the practice was categorized for both mitigation and adaptation.

Category	Sub-category	Climate			Biodiversity	Ecosystem services
		Mitigation: Carbon Sequestration		Adaptation		
		in soils and trees	in value chain			
Tree species selection	Type	IT, NL (*)		FI, IT, NL (*), RO	IT, NL, RO	
	Diversity	I, NL (*)		FI, IT, NL (*), RO	FI, IT, NL, RO	
Regeneration	Natural regeneration	IT, NL (*)		I, NL(*), R	IT, NL,RO	

	Artificial regeneration	NL	FI	FI, NL		
Thinning and tending		FI		FI, RO		
Harvest Cutting regimes	Long rotation length	FI, RO	FI, RO		RO	
	Silvicultural systems	IT, NL (*)		IT	FI, IT, RO	
	Less impactful harvesting	FI, NL (*), RO		NL (*)	FI, NL, RO	
Measures for biodiversity	Old-growth protection/ Protected areas	RO				
	Special habitats	RO			FI, RO	
	Deadwood	FI, RO			FI, NL, RO	
	Habitat tree(s)	FI			FI	
	Connectivity				RO	
	Structure	FI (*)	FI (*)	FI (*), RO	FI, NL, RO	
Forest condition	Nutrient management	FI			FI	
	Soil protection		NL, IT	FI	FI	IT
Afforestation		FI(*)	FI(*)	FI(*)		
Product usage	Wood products		RO, IT			
Measuring, inventory, planning and mapping		FI (*)	FI (*)	FI(*), IT	IT	IT

FINLAND

The Finnish demo case noted there is no silver bullet. The listed CBS need to be applied on appropriate soils and conditions. Areal age/species structures of forest composition, and time frames also affect what can be considered climate smart. All trade-offs cannot likely be avoided.

Climate smart is defined with various practices, such as harvest regimes, tree species selection, and fertilization. A first practice contains the extension of the rotation period to extend sink period of forest stand, and to accumulate larger C stocks, additionally this will stouter wood that serves the manufacturing of long-term wood products more. Reduce thinning density also, earlier and less intensive seedling forest cleaning can be expected to accumulate more C to forests. Improved seedling material**.** Nitrogen fertilization on mineral soils (recommendations exist for timings, and site types). Mixed species forests when soils conditions allow to improve resilience to disturbances. Note, soils matter a lot, so e.g., avoid regenerating with spruce on dry soils. Also prefer diversity in forest structures and management strategies. Increasing quantities of decayed wood C storage (through retention trees)**.** Avoid steep forest edges to reduce wind (and bark beetle) damage. Fast regeneration after clear-cut and ensuring the growth of the seedling stands with the needed measures/Taking better care of the good quality of tillage, forest cultivation and material. This reduces the risk of rust damage to small seedlings, which is increased by climate change. Afforestation, avoiding deforestation.

Specifically for **Peatland forests** practices are defined with fertilization with ash, here recommendations exist for timings, and site types. In terms of harvest regimes clear cutting is to be avoided in terms of large follow-up emissions. Consequently, as a protective measure, deep drainage is to be avoided and ditches are maintained, if the water balance allows it. Deforestation of peatland forests to agricultural use is to be avoided. As management system, continuous cover forestry is implemented without maintenance of the diching networks to keep the ground water level high enough to prevent the decomposing of the peat but ensuring the tree growth.

Biodiversity smart practices are defined with the avoidance of intensive forest management practices. For tree species selection, it is to prefer diversity in tree species, forest structures and management strategies when possible. To improve biodiversity further, increase the amount of retention trees, more specifically retain big and old trees as well as deciduous trees. Increasing amount of decayed wood, this can be done artificially. Leaving deciduous trees in conifers tree stands**.** Leaving untouched buffer zones along water bodies, and valuable patches for biodiversity**.** Restoration of fertile but unproductive peatland forests.

ITALY

In Italy, the recently issued Natural Forest Strategy (Jan 2022) aims at creating extensive and resilient forests, rich in biodiversity, capable of contributing to climate change mitigation and adaptation, delivering ecological, social and economic benefits, especially for rural and mountain communities, as well for citizens and future generations. The Forest Strategy identifies, as Italian forests' strength, the presence of a "consolidated national and local silvicultural tradition, based on naturalistic bases (natural renewal, continuous forest cover in managed high forest stands, prevalence of mixed formations with native species and limited presence of exotic species) and sustainability", crucial elements towards the new paradigm "closer to nature forest management" (Ministero delle Politiche Agricole Alimentari e Forestali, 2022).

Climate-smart forestry measures were identified for Mountainous forests (Tognetti et al. 2022). These regions are vulnerable to climate change impacts (see Annex 1), which threatens future ecosystem service provisioning. Adaptive forest management is therefore crucial and can address these impacts, containing strategies that focus on enhancing resistance and resilience, and conserving biodiversity. Thus, silvicultural measures should focus on increasing stand features, that is, making the forest stand more capable of adapting to and mitigating climate

change (e.g., diverse stand structure, mixed species composition, deadwood) (Pach et al., 2022). Recent work underlined the importance of tree species composition, forest damage, and regeneration for assessing CSF in Italy (Alfieri et al. 2024). Due to the high wildfire risk in mediterranean forests, climate smart forestry in Italy includes also integrated forest management measures to prevent wildfires (Corona et al. 2015). Moreover, adaptive forest management requires implementation of locally tailored rules to safeguard prominent forest functions (Fabbio et al. 2003).
Biodiversity smart management in Italy focusses for example on the conversion of pure coniferous stands toward mixed stands with a complex structure and increasing structural diversity in Natura2000 stands at different space and time scales (Ciancio and Nocentini 2011; Nocentini et al. 2022; Testolin et al. 2023). Considerations should also include managing biodiversity in economically marginal forest areas (Fabbio et al. 2003).

THE NETHERLANDS

For the Netherlands, **Climate Smart Forestry** would entail avoiding large clear-fells (max 0.5 ha) to maintain forest microclimate and avoid loss of carbon from the soil, increase species diversity for adaptation, and active planting of new tree species or climate-adapted provenances of the same species for better adaptation, and possibly better growth, and in turn increase carbon sequestration in the future. Climate-Smart Forestry in this region focussed so far mostly on storing carbon in the forest with less attention on what assortments to produce or increasing wood use in the construction sector. However, the State Forest Service recently stopped selling firewood because of climate reasons.

For **Biodiversity Smart Forestry** it is important to increase the species diversity (but only if it doesn't conflict current conservation goals, like maintaining old beech or oak forest), increase share of broadleaves, improve the forest structure (more shrubs; more layers; diversity in diameter classes), use natural processes (natural regeneration, disturbances), get more light on the soil (not 100%sure about that one), decrease wood harvest (which would conflict the previous). Recommendations for biodiversity management can be rather extreme, including not to harvest at all, actively killing trees to get more deadwood, or removing forest to create other types of nature. Usually, climate smart and biodiversity smart would not *per se* lead to the same management, but there are many similarities. In practice, for some decades there was already a focus on increasing species diversity, conversion to broadleaves, improving forest structure, using natural processes and less clear-felling. Moreover, more attention was given to introducing climate-adapted species and provenances.

ROMANIA

Conditions to meet these two goals (Climate change and biodiversity) overlap to a large extent. CBS forestry would entail all these requirements together and at large scale (national if possible).

Climate smart practices are categorized as the use native site adapted species to produce stands of natural compositions (obtained as much as possible by natural regeneration; maintain natural mixtures, avoid simplified compositions). Plantations with site adapted species and as much as possible with native species. Produce various stand structures (more uniform but also diversified) and a landscape mosaic of stands with different ages (various stages of development), which results in higher resilience at stand and landscape level. Tending operations implemented in a timely manner and with proper intensity to ensure vigorous (resistant to abiotic and biotic disturbing agents) trees and stands. Conservation of carbon rich ecosystems in the forest: true old-growth forests, bog woodlands, swamps. Regeneration harvesting methods with reduced impact on the carbon pool (maintain stumps and roots and harvesting waste – branches, treetops; avoid/reduce soil erosion, damage to residual stand and undergrowth). Long rotations (high forest system) and high efficiency in timber use (long-living products).

Biodiversity smart practices are categorized as to maintain and restore natural composition of stands. Additionally, the connectivity of forested land needs to be maintained and restored (i.e., max. 1 km distance between forest patches). Long rotations (high forest system, at least 100-120 years for most species, to ensure presence of large trees in enough numbers) = ensure habitat for some specialized species (needing habitat in big size trees – birds, bats, small mammals, insects). Mosaic of structures at landscape level (a shifting steady state mosaic – Kimmins, 2004) maintained by using the principles of sustained yield (aiming at balancing the proportion of all age classes in a landscape) = ensure habitat (at present but also continuously in time) for both generalist (=needing the mosaic) and specialized species (needing a certain stage of development). Use of different treatments (from selection cuttings to even aged systems - various forms of shelterwood but also small area clearcutting) which produce a high variety of stand structures and emulate all disturbance types/intensities, i.e., ensure habitats for all types of species (shade tolerant and light demanding plants; feeding and hiding habitats for mammals, bates and birds etc.). Conservation of deadwood in certain quantities (no “clean” forest), according to the stand development stage and forest condition. Conservation of rare ecosystems in the forest (marginal habitats): riparian forest vegetation strips along rivers, ponds, swamps, bogs woodlands, screes, small meadows inside forested landscapes, scrublands, sparse woodlands (=all these ensure habitat to various species not found in closed canopy forest; provides resources to forest fauna = water, food, winter feeding places etc.).

5.4 CBS forestry – synthesis and outlook

The literature on CSF has grown rapidly over the last few years. While most studies referred to the work of Nabuurs et al. (2017), Bowditch et al. (2020) and Verkerk et al. (2020) for definitions of the concept, there remains ambiguity on the precise meaning of CSF. Several authors proposed amendments to the original definitions (e.g., Cooper and MacFarlane, 2023). We carried out an analysis of the CSF definitions used in the current literature and proposed a comprehensive new definition on CBS that also incorporates biodiversity management aspects, as this was a major innovation proposed within ForestPaths.

To make the CBS forestry concept operational there is a need to assess whether a practice is CBS or not. For this purpose, we studied the existing efforts in making CSF operational but only limited guidance on how to apply the concept in practical decision-making (Bowditch et al., 2022; Nabuurs et al., 2017) were found. In the absence of a defined framework, the utilization of certain Pan-European SFM indicators have shown to be good indicators for mitigation and adaptation effects (Bowditch et al., 2022; Santopuoli et al., 2020), but these indicators do not cover the forest value chain and product use aspects of CSF. Consequently, there is further work needed to establish criteria and indicators for assessing the broader concept of CBS as proposed in this report. In addition, an implementation strategy linking the interests of the forest sector actors and the policy framework is also needed (Nabuurs et al., 2017). Moreover, Hermoso et al. (2022) stressed the need to carefully plan a strategy to minimize potential conflicts between biodiversity conservation and other sectoral interests that must be taken into account when defining an operational CBS framework.

A promising opportunity for effective CBS evaluation lies in the continuous MRV protocols that are mandatory under the UNFCCC emission reporting. Monitoring of damages in forest ecosystems is crucial to identify the best adaptive management strategies to prevent and reduce the negative impacts caused by climate change on forest health (Santopuoli et al., 2020. National forest inventories (NFI) are a robust source of data (Santopuoli et al., 2020). We found some examples at a regional level to assess the implementation of CSF utilizing NFI data (e.g., (Jandl et al., 2018; Temperli et al., 2022). However, common goals need common efforts (Hermoso et al., 2022), and thus researchers should facilitate harmonized methods for data collection and analysis (Santopuoli et al., 2020; Temperli et al., 2022) to make them comparable across regions (Cooper & MacFarlane, 2023; Jandl et al., 2018; Santopuoli et al., 2020). Forest inventories and reporting schemes should be synchronized to operationalize their application in policy and practice (Temperli et al., 2022). Without these, future implementation of EU environmental policies will be prone to fall into past mistakes and failures (Hermoso et al., 2022). Forest inventories and reporting schemes should be synchronized to operationalize their application in policy and practice (Temperli et al., 2022). Without these, future implementation of EU environmental policies will be prone to fall into past mistakes and failures (Hermoso et al., 2022).

We found existing efforts to specify indicators to evaluate CSF that can be used for CBS forestry assessment. However, these indicators are only focused on forest conditions, and they are lacking a way to quantify biodiversity thresholds or harvest intensity. The broader scope of CBS forestry should include suitable indicators to also quantify and assess the impacts on the forest value chain and biodiversity. Future efforts are needed to develop a comprehensive assessment framework with criteria, indicators and desired target ranges to guide decision making in policy and practice.

The review on CBS practices (chapter 5.2) and the evaluation of measures proposed for the demo cases (chapter 5.3) shows that there is not a “one fits all” management approach that would completely fit all the pillars of CBS in all regions. Instead, a combination of management practices is needed to fit to the pillars of CBS. The combination depends on the context and management goals. The effectiveness also depends on the regional context, as drivers for CBS vary across regions and thus have different requirements for CBS. A further recommendation would be to make the literature-based table more comprehensive. The table serves as an initial starting point for classifying forest management practices that are considered as CBS. For further steps, practices need to be evaluated for the 4 pillars simultaneously in order to identify trade-offs and synergies. Lastly, as CBS goes beyond forest management, more research is needed on the coherence of forest management practices and their influence on both the forest ecosystem and the value chain with its associated product use and substitution effects in other sectors.

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Annex 1 Characteristics of ForestPaths Demo regions

Previous defined factors that affect the regional implementation of CBS are described in the following sections per demo region, i.e., Finland, Italy, the Netherlands, and Romania.

Finland

Finland is located in the Boreal biogeographic region with contrasting site conditions including large share of peatland forests (EEA). Finland's current climate translates to an intermediate between maritime and continental climate. Growing seasons are strongly limited by low winter temperatures and daylight hours, particularly in the Northern part of Finland. Forest types are dominated by Norway spruce (*Picea abies*), Scots pine (*Pinus sylvestris*), Downy (*Betula pubescens*) and Silver birch (*Betula pendula*), with limited shares of other broadleaved species including Aspen (*Populus spp.*) and Willow (*Salix spp.*) (MMM.fi).

Key ecosystem services are wood provisioning, recreational use and berry and mushroom collection (MMM.fi). Management systems are divided into even-aged and uneven-aged systems. Most forest in Finland are managed by even-aged forest management, implemented by usually 1-3 thinnings and clear cuts (M. Peltoniemi, personal communication). Practices are carried out highly mechanized. Finnish forestry implements various strategies. There are certain requirements in the Finnish law, such as; stand re-establishment after clearcut , minimum basal area and even distribution of remaining trees after thinnings, preserving natural features of small-sized valuable habitats, and allowing mainly native tree species. There are also other requirements e.g. for special forest environments. Additionally, Finnish forestry does implement PEFC and FSC certification standards widely, which have hold requirements such as tree retention strategies (M. Peltoniemi, personal communication; MMM.fi).

In the light of climate change, warming will be larger at high latitudes in northern Europe compared to regions close to the equator. It is also larger in winter than in summer. The precipitation is also projected to increase in the boreal zone, especially during cold seasons

(Ruosteenoja et al., 2016). With increasing temperatures soil frost depth will decrease (Jylhä et al., 2012). Several disturbances are expected to increase in Finland, including risks of wind and snow-induced damage (Lehtonen et al., 2019), occurrence of droughts and forest fires, and occurrence of pest and diseases. For example, Norway spruce as the most dominant tree species in Finland is expected to be affected by more bark beetle infestations (*Ips typographus*) (Garbelotto and Gonthier, 2013).

Italy

Italy is situated in three biogeographical regions, Alpine, Continental, and Mediterranean (EEA). The total wooded area covers 36.7%, divided into forested area (30.2%) and other wooded land (6.5%). At the national level, broadleaved woods dominate both in Forest (68.5%) and in Other wooded land (53.9%). Conifers forest accounts for 12.8%, occurring mostly in the Alpine regions, due to coastal pine forests and to the presence of some mountain-Mediterranean conifer species. The class mixed conifers and broadleaves accounts for 10.1% of Forest area and 6.1% of Other wooded land area; it is more common in some northern regions. The most dominant forest types in Italy are Temperate oaks, Other deciduous broadleaved, Mediterranean oaks and Beech forests, followed by Hornbeam and Hophornbeam, Chestnut, Holm oak and Norway spruce (Gasparini et al., 2022). Forest dynamics have changed over-time, many coppices have been converted into high forests (Regione Toscana, 2003), additionally, abandonment of forest management and rural landscapes has also led to a widespread ageing of all Apennine forests (Florenzano, 2004). Land abandonment and decreased forest harvesting has raised interest in old-growth forests characteristics with improved habitat and biodiversity conditions (Marchetti and Blasi, 2010; Chirici and Nocentini, 2010; Schulz et al., 2014). Under climatic change, temperatures are expected to further increase, whereas yearly precipitation is projected to decrease. Potential consequences of the northward extension of the Mediterranean subtropical climatic region in Italy include a decline in soil organic carbon and reduced snow cover. In turn, a shallower, ephemeral snowpack will promote soil freezing, with important consequences on soil nutrient dynamics. As for natural disturbances, fire is the most common disturbance agent in peninsular Italy. The percentage of wooded area burned is amongst the highest in Mediterranean Europe, vulnerability to fires is increasing (Vacchiano et al., 2017: FAO, 2020). In mountainous areas, landslides are a common form of disturbance (Triglia and Iadanza, 2014). As pure conifers forest accounts for 12.8%, especially situated in mountainous regions, elevation plays an important role on the occurrence of insect outbreaks. The forest inventory demonstrates that at the national level, the main disturbances are pests and diseases (33.8% of the assessed Forest area), followed by extreme climate events (26.5%) and forest fires on crowns (20.7%). The mountainous regions show a lower vulnerability to fire but have an increase in vulnerability to windthrows, triggered by land abandonment and altering land cover patterns and vegetation communities (Vacchiano et al., 2017; Gasparini et al., 2022).

The Netherlands

The Netherlands is located in the Atlantic biogeographical region (EEA). The Netherlands contains 363.800 ha of forested land, which is 11% of the total land-use. In the forested area, 44.5% are broadleaves and 44.3% are conifer tree species, the remaining area are forests in an open phase or were not visited/deforested during the inventory. Most occurring tree species are

Scots pine (*Pinus sylvestris- 28.0%),* native oak (*Quercus spp.- 17.9%*), and Birch (*Betula spp.-* 6.3%). In terms of mixture, 28.2% are unmixed broadleaves (<20%), 16.6% is mixed broadleaves, 20.5% is a mixture between conifers and broadleaves, 15.8% are unmixed conifers, 3.7% are a mixture of conifers (Schelhaas et al., 2022).

Decreased observed forest vitality affects significantly more deciduous tree species (14.3%) than forest with a conifer as main tree species (6.5%). Among deciduous tree species, ash stands out, with reduced vitality at 70.2% of the sample points due to ash dieback. 20.0% of Norway spruce suffered by drought and Bark beetle infestations. The Scots pine shows the smallest proportion of points with reduced vitality (3.7%) (Schelhaas et al., 2022).

As for types of disturbances, damage caused by ungulates was reported most frequently (7.0%), followed by wind (5.5%) and drought (5.2%), fire was not reported. The patterns vary by tree species. On three quarters of the sample points with ash trees, disturbances were reported, the majority of which were ash dieback at 63.8% of the total number of points. This was willow, where on 44.4% of the plots there was natural disturbance, mostly caused by wind (33.3%). In third place is Norway spruce with 40.0% of the plots, caused by a combination of wind, drought and insects (Schelhaas et al., 2022).

The annual increment is averaged at 6.6 (m^3 ha^{-1} yr^{-1}). On average 3.2 m^3/ha/year is cut. Deadwood is divided into standing, lying deadwood. and living stem wood is estimated at 224 m^3/ha. As for biomass has an increment of 2.5 tonnes per ha per year, this translates to an average carbon content in biomass of 50%, means an increase of 1.25 tonnes of carbon per ha per year (Schelhaas et al., 2022).

Romania

Romania has five different biogeographical regions: Pannonian, Steppic, Alpine, Continental, and the Black Sea (EEA). Romania has a total forested area of 7.038 million ha, which is 29.56 percent of the total land cover (http://roifn.ro/site/rezultate-ifn-2/). The main tree species type is broadleaves, which covers 74 percent of the forested land cover. The two dominant broadleaves species are European beech (*Fagus sylvatica* L.- 31.51%), and various oak species (*Quercus spp.*- 16.72%). Consequently, conifers cover 26 percent of the total forested area. The most dominant conifers are Norway spruce (*Picea abies* (L.) Karst.-19.95%), followed by Silver fir (*Abies alba* Mill.-4.36%), European larch (Larix decidua Mill.) and pines (Pinus spp.) cover 2.18% (MAP 2018). The current annual increment of Romanian forests is 58.6 mil.m^3 (8.46 m^3 $ha^{-1}yr^{-1}$) (Giurcă and Dima, 2022).

Forests in Romania are assigned to one of the following main functional categories: Forests with special protection functions (66% of the forested area) and Forests with production and protection functions (34% of the forested area) (MMAP 2021). For the first category, depending on the special protection function assigned, management ranges from non-intervention in some areas to low intensity interventions (selection cuttings and irregular shelterwood) in others. In the second category besides selection cuttings, classic even-aged systems (shelterwood, clearcutting) are allowed. The protected area network covers roughly 24% of the country and is largely represented by forested land. It is represented by Natura 2000 sites overlapping with national parks and natural parks, Biosphere reserves as well as other smaller natural reserves.

Romania hosts important areas of old-growth forests (primary and secondary virgin and quasi-virgin forests) zones strictly protected integrally protected as national parks and natural parks, as well as zones strictly protected as Biosphere reserves and some of which were designated as UNESCO sites (P. Stancioiu, personal communication; Giurcă and Dima, 2022).

Romania follows the approaches of close-to-nature forest management aiming to perpetuate the natural forest types (i.e., native species in stand composition) by using natural regeneration (generally obtained under shelter). Rules also impose long rotations of usually over 100 years while also striving to reach a balanced proportion of age classes at production unit level (i.e. principle of sustained yield).The main silvicultural systems consist of group and uniform shelterwood cuttings (60% of annual logging area), single-tree and group selection cuttings (ca. 5-7% of annual logging area), and clear-felling ca. 4-5 % of annual logging area and used only in even-aged stands of Norway spruce, pines, hybrid poplars, and willows. Marginally, coppice systems (both low and high) are also applied to ca. 4-5% of the annual cutting area. Next to the area where intense silvicultural systems are allowed, there are also zones of non-management (with and without conservation cuttings). Next to the applied silvicultural systems, Romania has challenges in combating illegal logging activities (P. Stancioiu, personal communication; Giurcă and Dima, 2022).

As for climate change, mountainous regions, such as the Carpathians are vulnerable to windthrows (Forzieri et al., 2021). The main disturbance factors in mountainous areas are most likely wind, with bark beetles as a secondary agent in spruce-dominated forests (Kameniar et al., 2023). Next to spruce-dominated forests, beech dominated forests were lately more affected by thunderstorms and windthrows, particularly in the summer when foliage is still present (P. Stancioiu, personal communication; Frankovič et al., 2021).