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Mapping forest management regimes in Europe

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ABSTRACT

Forests provide a multitude of ecosystem services, such as wood provisioning, carbon sequestration, biodiversity conservation, and cultural value. Numerous European Union (EU) policies introduce diverse goals for forests, leading to inherent trade-offs when balancing different forest functions and targets. Effective planning is crucial for optimizing such trade-offs across Europe. This requires an understanding of the current spatial distribution of forest management regimes. However, the mapping of European forest management regimes is challenging due to the limited availability of comprehensive, harmonized data. This study aimed to produce a high-resolution forest management map for Europe by integrating the most recent spatial forest datasets from multiple sources available in the literature. Our integrated map depicts the spatial distribution of five forest management classes with different objectives, highlighting distinct regional patterns across the continent. Western Europe predominantly features *close-to-nature forestry* and *combined objective forestry*, whereas Northern Europe is characterized primarily by *intensive forestry*. Southern and Eastern Europe exhibit a more varied distribution, with *combined objective forestry* emerging as the most prevalent forest management class. *Unmanaged forests* are mostly found in Northern Europe and *very intensive forestry* in Portugal, Galicia, and Gascony. Comparison with National Forest Inventory data provides insight into the overlaps between European scale patterns from the mapping exercise and plot-level observations. This comprehensive map offers a valuable basis for policy decisions, supporting the EU's climate mitigation objectives and improving the understanding of forest management regimes across Europe.

1. Introduction

European forests play a pivotal role in climate change mitigation, acting as crucial carbon sinks, preserving biodiversity, and delivering ecological services such as water and temperature regulation (Erb et al., 2018; FAO, 2024; Jenkins and Schaap, 2018; Reek et al., 2024). Beyond their environmental significance, forests also hold profound social and cultural value, shaping landscapes and communities across the continent and providing raw materials from wood products to biomass for bioenergy (FAO, 2024; Jenkins and Schaap, 2018; Tieskens et al., 2017).

Acknowledging the vital role of forests for a sustainable future, the European Union (EU) has set policy targets on climate, the bioeconomy, and biodiversity that will likely significantly influence forest management regimes (Di Marzo et al., 2023). One of the most ambitious examples is the EU Green Deal, aimed at achieving climate neutrality by 2050 while recognizing the essential role of forests as carbon sinks and preserving ecosystems (European Commission, 2019). Another example is the New EU Forestry Strategy for 2030, which emphasizes the significance of sustainable forest management, aiming to enhance the bioeconomy while safeguarding primary and old-growth forests to improve climate adaptation and resilience (European Commission, 2021). Legally binding policies have also been introduced at the European level, such as the Land Use, Land Use Change and Forestry (LULUCF) Regulation, which delineates targets for carbon removal (European Parliament and Council of the European Union., 2023). These policies are expected to collectively reshape current and future forest management regimes across the continent.

Forest management encompasses all activities undertaken by forest managers, serving a set of different objectives. Effective forest management is essential to meet the targets set by EU policies, but it also

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presents significant challenges due to the inherent trade-offs (Duncker et al., 2012b; Luyssaert et al., 2018). For instance, biodiversity conservation necessitates the protection of natural forests, whereas enhancing the bioeconomy demands increased wood production from forest plantations (Biber et al., 2020; Chaudhary et al., 2016; Eyvindson et al., 2018; Morán-Ordóñez et al., 2020; Rybar and Bosela, 2023). Understanding and mapping forest management regimes across Europe is essential to assess EU-level policies and navigate the trade-offs they entail.

Definitions of forest management classes are not consistently aligned across Europe, and comprehensive European data on forest ownership and management regimes are limited. This knowledge gap leaves forest management at a European scale relatively poorly identified. To address this, Aszalós et al. (2022) conducted an expert-based survey that categorized diverse silvicultural systems and their regional variations, including distinctions specific to boreal and temperate forest practices. Their work provided valuable insights into management methods, harvest characteristics, and the challenges of harmonizing definitions; yet, it did not result in a spatially explicit map of European forest management.

While efforts have been made to map specific forest management regimes, they have not encompassed the full range of objectives set by the EU. For instance, Verkerk et al. (2015) developed a wood production map that offers insights into regional wood production levels across Europe, but it does not provide information on biodiversity conservation and climate mitigation efforts. Similarly, Levers et al. (2014) focused solely on mapping harvesting intensity and its drivers, while Suvanto et al. (2025) investigated various harvesting regimes across Europe, assessing the frequency and intensity of harvesting events and examining their potential drivers using plot-level data. In addition, various forest characteristics have been mapped independently. Sabatini et al. (2021) mapped primary forests in Europe, identifying areas of high conservation value, while Brus et al. (2012) and de Rigo et al. (2016) focused on the distribution of tree species across the continent. Besnard et al. (2021) developed a forest age map, and Viana-Soto and Senf (2024) mapped forest disturbances across Europe. Dou et al. (2021) focused on mapping forest management intensity classes based on the volume of wood production, which offers limited insights into the various functions and services provided by the forests. In contrast, while Duncker et al. (2012a) adopted a more detailed classification of forest management regimes based on multiple forest characteristics, their work presents a framework rather than a detailed map of Europe. Despite the contributions to the literature, these studies were insufficient in developing a comprehensive and integrated Europe-wide forest management map.

Additional efforts have been made to capture various forest management regimes on a global scale (Lesiv et al., 2022; Schulze et al., 2019), as well as on a regional scale within Europe (Hengeveld et al., 2012; Nabuurs et al., 2019). However, these maps also present several limitations, such as insufficient data availability, and possible overestimation of mixed-use classes, and may have become outdated as newer, more relevant datasets have become available in the past few years.

This study aims to overcome the limitations of existing European forest management maps by integrating the latest harvesting disturbance data with other relevant spatial datasets on forest age and species distribution. Our primary goals are (1) to gain a better understanding of the geographic distribution of distinct forest management regimes in Europe; (2) to construct an up-to-date, integrated forest management map utilizing the most recent data available, allowing for future enhancements; and (3) to provide a baseline map that can be used for future studies involving forest management and LULUCF scenarios.

2. Materials and methods

2.1. Forest management classes

Five forest management classes were distinguished along a gradient of management intensity, ranging from no management to very intensive management regimes (Table 1). We adopted exhaustive definitions to classify the management classes, ensuring the inclusion of all different regimes, while attempting to minimize overlap between classes. The forest management definitions were aligned with existing studies and the Food and Agriculture Organization's Global Forest Resources Assessment (FAO-FRA) standards (Duncker et al., 2012a; FAO, 2018). To facilitate the practical implementation of the management map, the classification was designed based on publicly available datasets (Table S1), with each management class associated with a specific set of characteristics (Table 1).

2.2. Forest mask

A forest mask was used to delineate the forest areas in our integrated map. The mask selection requires careful consideration because clear-cuts might appear as non-forest areas in tree or land cover maps, such as the Copernicus' Tree Cover Density map (Copernicus, 2018). Clear-cuts must be considered while defining a forest mask as they fall within FAO's forest definition of "temporally non-wooded lands" (FAO, 2018), and often indicate the presence of intensive or very intensive management regimes (Duncker et al., 2012a).

Several European forest maps exist; however, they are usually restricted to the current tree cover at the time of mapping, ignoring clear-cut management dynamics. To overcome this limitation, we derived our forest mask from Viana-Soto and Senf (2024). The country-level forest cover maps constructed by the former authors are based on 30-m satellite imagery spanning 1985–2023, making it less prone to misclassifications due to clear-cuts. In their maps, each pixel is classified as either "forest" or "non-forest," following the FAO's forest definition (2018).

We combined and resampled the country-level maps from Viana-Soto and Senf (2024) into a European map at 1-km resolution, with each pixel indicating a forest cover percentage. Pixels with $\geq$ 50 % cover were classified as forest and assigned to a forest management class. The 50 % cut-off was chosen to best visualize all pixels where forest is the dominant land cover.

Table 1
Forest management classes and definitions.

Forest management class	Definition
Unmanaged forest	Forest systems with limited or no anthropogenic disturbance, with its ecological functions largely intact and little-to-no management in place
Close-to-nature forestry	Forest systems with limited anthropogenic disturbance, characterized by uneven-aged and mature stand structures, where management activities mostly aim to support biodiversity, resilience, and climate adaptation
Combined objective forestry	Forest systems where multiple functions are promoted and no single objective dominates. Functions may include protection, recreation, wood production, among others
Intensive forestry	Forest systems managed for wood production. Management activities include frequent and/or large-scale felling
Very intensive forestry	Forest systems intensely used for wood production, including short-rotation forestry. Management activities include very frequent and/or large-scale felling, often with even-aged management, and may consist of fast-growing tree species

2.3. Input data

Five datasets from the literature serve as the main inputs for our integrated forest management map (Table S1). These datasets were selected because they depict various forest characteristics that can be attributed to differences in management regimes, as well as based on their suitable spatial resolutions allowing detailed mapping. Our final map has a 1-km resolution, suitable to depict forest management regimes, which typically occur at broader scales than the forest stand level.

The size and frequency of anthropogenic disturbances are key indicators for mapping forest management regimes because of their direct correlation with harvesting intensity (Duncker et al., 2012a; FAO, 2018). We derived such information from the disturbance data of Viana-Soto and Senf (2024). Their map indicates whether a 30-m resolution pixel was disturbed and specifies the disturbance agent, distinguishing between human and natural origin. The former authors identified disturbances using a random forest model applied to annual spectral data from the Landsat imagery archive, where significant spectral changes indicated a disturbance. For our integrated mapping, we computed two variables from Viana-Soto and Senf (2024): (1) disturbed area, expressed as the percentage of a 1-km pixel that was harvested at least once throughout 1985–2023 (each 30-m harvested pixel contributed its area once, regardless of multiple disturbance events within that 30-m pixel); and (2) disturbance frequency, which represents the cumulative number of anthropogenic disturbance events within a 1-km pixel during the same timeframe, calculated by summing individual harvesting events observed for each 30-m pixel. Both computed disturbance frequency and area were divided by the percentage of forest cover within each 1-km pixel. Disturbance frequency is particularly insightful for identifying areas of *very intensive forestry*, as its definition is based on short-rotation forestry practices (Duncker et al., 2012a; Table 1). Similarly, disturbed area is useful for analyzing forest stands with long rotation cycles characterized by infrequent, large-scale interventions (e.g., clearcuts), as these stands inherently exhibit a lower disturbance frequency.

Tree species data were used as proxies to assist in the mapping of the most intensive forest management class. Those were based on the relative probability of presence maps for *Picea abies*, *Pinus pinaster*, *Pinus sylvestris*, *Populus nigra*, *Populus tremula*, and *Robinia pseudoacacia* by de Rigo et al. (2016), in addition to the European distribution of *Eucalyptus sp*., derived from the tree species distribution maps by Brus et al. (2012), at 1-km resolution. These species are among the most commonly cultivated in intensive wood production systems in Europe (Freer-Smith et al., 2019; Levers et al., 2014; Liu et al., 2018; Nabuurs et al., 2019; Verkerk et al., 2015).

Forest age data from Besnard et al. (2021) were also used as an indicator, with young, even-aged forests indicating intensive forestry practices, and mature, uneven-aged forests suggesting less intensively managed forest classes. This age data was derived from a robust machine learning approach that integrated forest inventory, biomass, climate, and remote sensing data, demonstrating strong predictive capacity for classifying young versus mature forests. The original data were resampled to 1-km resolution using the median to reflect whether the forest cover in a given pixel is majorly composed of young or mature trees. Age evenness was determined by first grouping the original age data into 20-year intervals. For each 1-km pixel, we then calculated the proportion of its forest area falling into each of these 20-year age intervals.

Finally, the European Primary Forests Database (EPFD) by Sabatini et al. (2021) was used to map *unmanaged forests*. To our knowledge, this is the most comprehensive dataset on European primary forests to date. The forest definition adopted by the former authors aligns with the FAO-FRA definition, thus facilitating its integration into our forest management class framework. According to the previous study, primary forests are defined as "naturally regenerated forest of native tree species, where there are no clearly visible indications of human activities and the ecological processes are not significantly disturbed." Sabatini et al. (2021) classified forest areas without human intervention (or strongly blurred signs of human intervention that took place nearly 60–80 years ago) as primary forests. The original data, provided in vector format, was rasterized into a 1-km resolution.

2.4. Decision tree

We adopted a rule-based approach to construct the integrated forest management map (Fig. 1), a common practice for the classification of land systems (e.g., Dou et al., 2021; van Asselen and Verburg, 2012). Data-driven classification systems can lead to classes that do not align with definitions or the perceptions of stakeholders, and may result in unrealistic spatial patterns. Therefore, our classification rules were designed to align the forest management class definitions (Table 1) with the information available from the different data sources. The mapping relied on the use of thresholds set to differentiate the forest classes included in our study based on human-induced disturbance area and frequency, forest age class and evenness, tree species distributions, proportion of forest cover, and the presence or absence of primary forest (Fig. 1).

2.4.1. Disturbance data thresholds

The decision tree employs two distinct rules based on disturbed area (high and low) and one on disturbance frequency. The thresholds adopted by these rules were based on the definitions of Duncker et al. (2012a) and FAO (2018), and calibrated using Forest Europe (2020), Mason et al. (2022), and the Swedish Forestry Agency (2014). The Forest Europe (2020) data consist of country-level statistical indicators derived from national reporting. Mason et al. (2022) provide continuous cover forestry (CCF) data at the country level, and data from Swedish Forestry Agency (2014) state the amount of productive forest area in Sweden. Collectively, this data served as a general reference to ensure that the overall distribution of forest classes in our map and its regional patterns are consistent with officially reported figures and existing literature.

According to Forest Europe (2020), 76.6 % of Europe's forests are categorized as "forest available for wood supply" (FAWS), leaving 23.4 % designated as non-production forests. The distinction between *close-to-nature forestry* and *combined objective forestry* is partly defined by differences in wood production objectives, with the former prioritizing ecological processes in wood extraction while the latter explicitly pursues it as an objective. The threshold for low-disturbed areas was calibrated using the proportion of FAWS in Europe (Forest Europe, 2020), as this directly influences the European share of *unmanaged forest* and *close-to-nature forestry* in the decision tree (Fig. 1). For *close-to-nature forestry* calibration, we also referenced country-specific estimates of CCF from Mason et al. (2022), reporting approximately 22 % of total European forests under CCF. Given that CCF constitutes a significant component of close-to-nature practices (Larsen et al., 2022), the regional patterns derived from their work served as a key reference for the calibration of the thresholds adopted in our map. Forest pixels with less than 10 % of forest area disturbed were considered low-disturbed areas, while those with 25 % or more were classified as high-disturbed. The 25 % threshold aligns with the definition of *combined objective forestry* and FAO's definition of multiple-use forestry (FAO, 2018), indicating that no single forest function is dominant. This threshold notably influences the distribution of *combined objective forestry* and *intensive forestry*, with the classification of Swedish forests particularly sensitive around that value. Given this sensitivity, Sweden served as an instrumental case for setting the high-disturbed area threshold, which in turn was used to classify forest pixels under *intensive forestry*.

Data from the Swedish Forestry Agency (2014) indicate that Swedish forests encompass 23.2 million hectares of productive forest land, defined as areas with wood production exceeding 1 m^3 ha^{-1} $year^{-1}$. By adopting a threshold of 25 % for the high-disturbed areas, 1.85 million hectares of Swedish forests were classified as *very intensive forestry*,

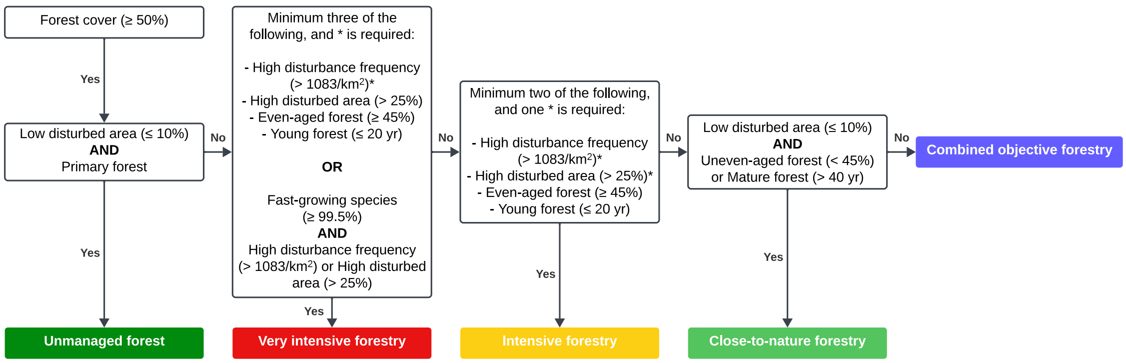

Fig. 1. Decision tree used to classify forest management based on forest cover, anthropogenic forest disturbances, forest age, tree species distributions, and the presence or absence of primary forest. Threshold values are indicated in brackets, with percentages representing cover within 1-km pixels. (See Section 2.4.1 for the justification of the adopted threshold values in the decision tree.)

14.99 million hectares as *intensive forestry*, and another 10.20 million hectares as *combined objective forestry*.

The threshold for high disturbance frequency was aligned with the definition of *very intensive forestry*. Forest pixels were classified as exposed to high disturbance frequency when experiencing a minimum of 1083 disturbances per km^2 over the 1985–2023 period (see the Supplementary Material for details). This threshold was calculated based on the definition of "intensive-short rotation forestry" by Duncker et al. (2012a), which is characterized by rotation lengths of 20 years or less.

2.4.2. Forest age and evenness thresholds

Forest age data from Besnard et al. (2021) were used to identify young and mature forest pixels, which determine the proportion of *close-to-nature forestry* and *combined objective forestry*. However, there is no universally accepted definition for what constitutes young or mature forests, as forest age thresholds vary by stand characteristics and across regions (Martin et al., 2016; O'Brien et al., 2021; Barredo et al., 2021). To harmonize our integrated map, the decision tree employs two age thresholds. The first is a minimum of 40 years to identify mature forests. This threshold is low enough to include mature forests composed of shorter-lived species, while still distinguishing stands that are very unlikely to be mature. In our classification, the category young forests serves to identify short-rotation forestry, which is commonly defined as forest stands with a maximum age of 20 years (Duncker et al., 2012a; FAO, 2018; Lindegaard et al., 2016). Accordingly, our threshold for young forests was set at 20 years. The chosen thresholds resulted in comparable proportions of *unmanaged forests* (0.53 %) and *close-to-nature forestry* (22.60 %) to the share of forest not available for wood supply (23.4 %) in Europe (Forest Europe, 2020).

Given the ambiguity about forest age thresholds, they were applied in combination with the classification of even-aged and uneven-aged forests (Fig. 1). A pixel was considered even-aged if at least 45 % of its forest area fell within the same 20-year age interval. Applying this threshold resulted in 74.4 % of the total European forest being characterized as even-aged, while according to Forest Europe (2020), approximately 75 % of Europe's forest is even-aged.

2.4.3. Fast-growing species thresholds

The distributions of the selected tree species assisted in mapping areas under *very intensive forestry*. Given that plantations represent 3.8 % of Europe's forest according to Forest Europe (2020), we identified the top 0.5 % quantile pixels from the distribution maps, representing the locations with the highest number of fast-growing species, to be classified as *very intensive forestry*.

2.5. Comparison with National Forest Inventory data

As a way to validate our integrated forest management map it was compared with National Forest Inventory (NFI) plot-level volume data from Austria, Belgium, Czechia, Germany, Ireland, Norway, Poland, Slovenia, Spain, and Sweden. This comparison is only a partial validation as it concerns only the harvesting intensity aspect of our classification. Challenges associated with working with NFI data are the variability in the time intervals between measurements and the number of plots per forest management class across countries (Table S2). To ensure comparability, we calculated the annual occurrence of volume reductions for each forest management class and country. We first assigned the corresponding forest management class to each plot based on our map, then determined the relative volume change per plot and categorized the results into volume change quintiles. The number of plots in each quintile was used to calculate the percentage distribution across all quintiles relative to the total for each class. The final distribution of the quintiles indicating a volume decrease was divided by the average time span between measurement dates, in years, to facilitate comparison across all countries. This "standard" comparison was conducted for each country and is referred to as the standard analysis hereafter.

A second comparison was conducted for Austria, Belgium, Czechia, Germany, Ireland, Norway, and Sweden, based on a so-called "intervention variable." This variable indicates whether harvesting was observed on a plot during a given time interval, allowing us to exclude volume reductions caused by natural factors. Our intervention analysis follows the standard analysis, except that volume reductions were counted only for plots that fell within reducing quintiles with a recorded intervention according to national NFI data.

Both standard and intervention comparison analyses were conducted for each country individually and for the combined dataset of all countries (Figure S2 and Tables S3-S13). Only quintiles with volume reductions ≥ 20 % are presented, as smaller reductions are common across all forest management classes, except *unmanaged forest*, and are therefore less informative.

3. Results

3.1. Forest management map

The distribution of forest management classes differs substantially per region (Fig. 2 and Table 2). Northern Europe exhibits the highest proportion of *unmanaged forest* (1.18 %) and *intensive forestry* (50.96 %), showing large, undisturbed forest areas in Northern Finland and Norway, alongside productive forest management across large areas of Sweden and Finland. Eastern and Southern Europe display similar trends (46.98 % and 47.36 %, respectively), with *combined objective forestry* being the dominant management type, reflecting a balanced approach to wood production and the provisioning of ecosystem services. The Baltics and northwestern Poland show more *intensive forestry* and *very intensive*

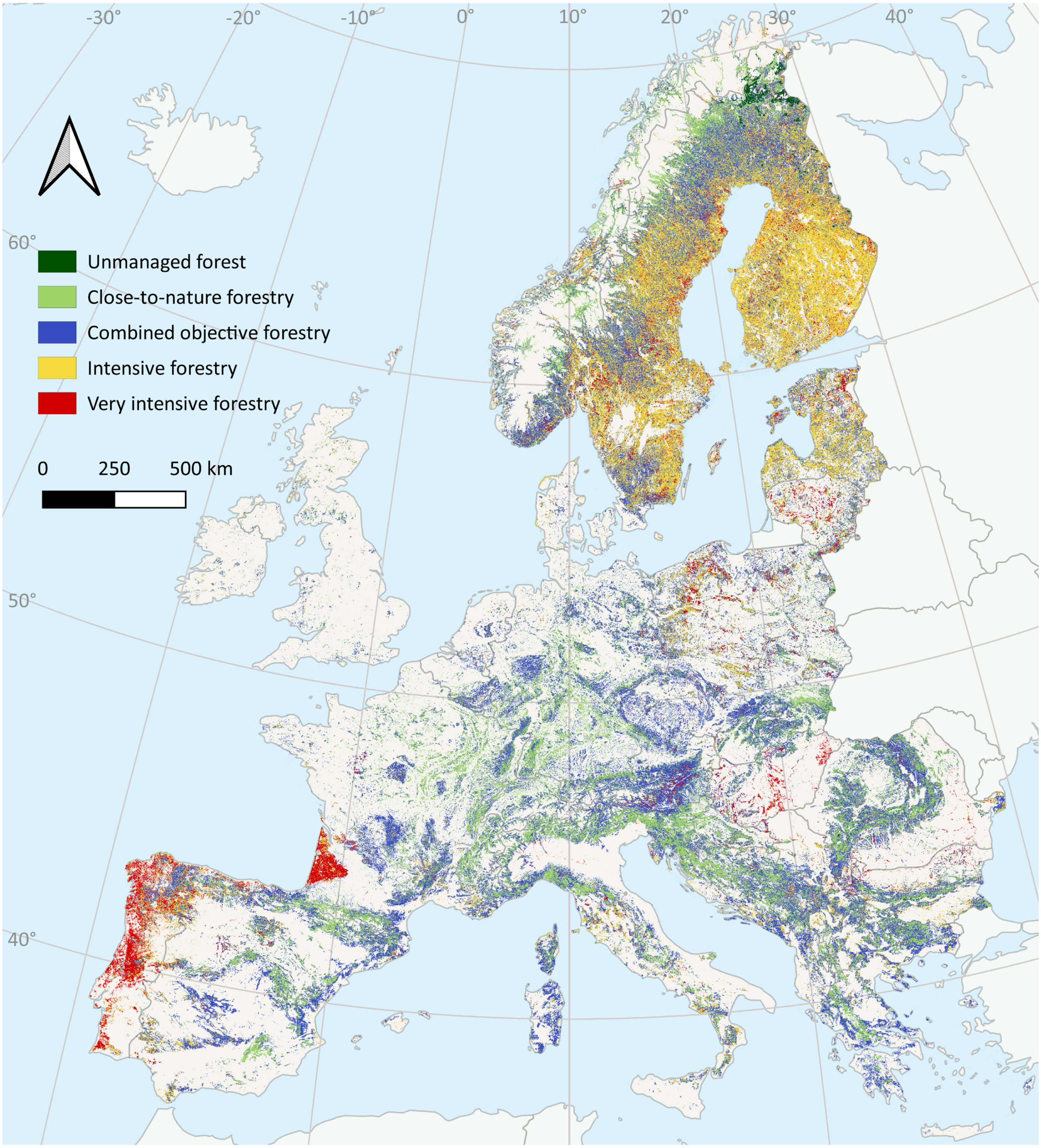

Fig. 2. Forest management map of Europe.

forestry compared to the Southern countries of Eastern Europe, where *close-to-nature forestry* is more prevalent. Hungary stands out due to its significant proportion of *very intensive forestry* (25.67 %), while maintaining close-to-average proportions of *close-to-nature forestry* (22.92 %) and *combined objective forestry* (41.47 %). Southern Europe has the highest share of *very intensive forestry* (10.88 %); however, these forests are primarily located in Portugal and Galicia, Spain. Italy and Greece show opposite patterns, emphasizing *close-to-nature forestry* and *combined objective forestry*. Western Europe is primarily dominated by *close-to-nature forestry* (38.53 %) and *combined objective forestry* (50.02 %), reflecting sustainable forest management. Furthermore, *close-to-nature forestry* is more prevalent in mountainous regions, while *intensive forestry* and *very intensive forestry* are generally found in lower, less steep locations.

3.2. Comparison with National Forest Inventory data

The standard NFI comparison indicates that more intensive forest

Table 2
Distribution of the forest management classes per region (%), average slope (degrees), and elevation (m) per forest management class.

	Forest management class distribution per region (%)					Terrain attributes	
Forest management class	Europe	Northern Europe	Eastern Europe	Southern Europe	Western Europe	Slope (degrees)	Elevation (m)
Unmanaged forest	0.53	1.18	0.28	0.02	0.02	4.7	407
Close-to-nature forestry	22.60	10.98	26.23	24.59	38.53	11.3	641
Combined objective forestry	41.71	31.08	46.98	47.36	50.02	8.0	488
Intensive forestry	29.21	50.96	21.55	17.15	7.87	3.1	274
Very intensive forestry	5.96	5.79	4.97	10.88	3.55	4.1	274

Note: Northern Europe = Denmark, Norway, Sweden, and Finland. Eastern Europe = Albania, Bosnia and Herzegovina, Bulgaria, Croatia, Czechia, Estonia, Hungary, Kosovo, Latvia, Lithuania, Montenegro, North Macedonia, Poland, Romania, Serbia, Slovakia, and Slovenia. Southern Europe = Andorra, Greece, Italy, Portugal, Spain, and Vatican City. Western Europe = Austria, Belgium, France, Germany, Ireland, Liechtenstein, Luxembourg, Monaco, the Netherlands, Switzerland, and the United Kingdom.

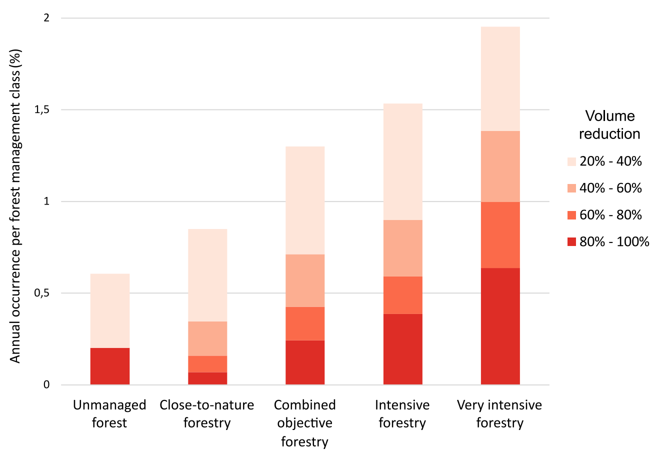

Fig. 3. National Forest Inventory comparison results of the standard analysis, based on the dataset comprising all countries. The figure presents the annual occurrence of volume reductions ≥ 20 %, divided into four 20 %-intervals, per forest management class.

management classes are associated with a higher annual relative occurrence of volume reduction of 20 % or more (Fig. 3). These classes also tend to exhibit greater volume reductions. The intervention analysis shows similar results (Figure S2). Overall, results for all countries reveal a correlation between the forest management classes and volume change in the NFI data. Nevertheless, some deviations are present (Figure S2 and Tables S3-S13).

Spain, Poland, Sweden, and Norway have a high number of observations across all forest management classes (excluding *unmanaged forest*), making them the most reliable case studies. Spain and Sweden show a higher annual relative occurrence of volume reductions in more intensive management classes, with Sweden's intervention analysis reinforcing this pattern. Results from the standard analysis for Norway indicate a similar trend, though relatively fewer *very intensive forestry* (1.50 %) plots exhibit volume losses compared to *intensive forestry* (1.74 %) (Table S9). However, in the intervention analysis, *very intensive forestry* (1.21 %) had a slightly higher annual relative occurrence of volume reductions than *intensive forestry* (1.18 %) (Table S9). Poland shows a comparable pattern, although differences among management classes are smaller, and *intensive forestry* (1.65 %) has a lower annual relative occurrence of volume reductions than *combined objective forestry* (1.76 %) (Table S11).

Austria, Belgium, Germany, and Slovenia have a substantial number of observations for *close-to-nature forestry* and *combined objective forestry*. In all four countries, the annual relative occurrence of volume reductions is higher in *combined objective forestry* compared to *close-to-nature forestry* in the standard analysis: 2.13 % vs. 2.35 % in Austria (Table S4); 1.31 % vs. 1.50 % in Belgium (Table S5); 2.17 % vs. 2.59 % in Germany (Table S7); and 2.34 % vs. 3.74 % in Slovenia (Table S12).

Despite the smaller sample size, the results for Belgium (n = 127; Table S2) and Germany (n = 164; Table S2) in *intensive forestry* (Belgium: 0.90 %; Table S5; and Germany: 1.94 %; Table S7) are noteworthy, as both countries exhibit a significantly lower-than-expected annual relative occurrence of volume reductions, a pattern also observed in the intervention analysis.

Czechia has a significant number of observations for *close-to-nature forestry*, *combined objective forestry*, *intensive forestry* revealing an upward trend in annual relative occurrence of volume reductions with increasing management intensity for both the standard (respectively 1.46 %, 2.78 %, and 2.99 %) and the intervention analysis (1.30 %, 2.62 %, and 2.86 %, respectively; Table S6). Although the v*ery intensive forestry* class has a limited number of observations (n = 119; Table S2), it confirms this pattern, with 3.69 % in the standard analysis and 3.35 % in the intervention analysis (Table S6). Ireland exhibits a similar trend, though the low number of observations limits interpretation (Table S2).

4. Discussion

The distribution of forest management classes across Europe follows similar patterns reported in previous studies. Northern Europe is dominated by *intensive forestry*, in agreement with existing literature and national statistics (FAO, 2023; Forest Europe, 2020; Schelhaas et al., 2018). Following World War II, forest management in Northern Europe shifted towards industrial practices, focusing on clear-cutting and even-aged stand cultivation (Kuuluvainen, 2009). Additionally, Aszalós et al. (2022) found that even-aged clearcutting systems dominate European boreal forests (86.7 %), and maps from Suvanto et al. (2025) show a relatively low frequency of harvest events but high intensities in Northern Europe, collectively aligning with our integrated map.

Similar forest management regimes are found in the Baltic countries, characterized by even-aged stands and clear-cutting (Girdziušas et al., 2021). This is evident in our integrated map, as those countries are dominated by *intensive forestry*. Poland shows a high frequency of harvesting events, indicating more intensive forestry practices (Suvanto et al., 2025). Additionally, Potapov et al. (2015) indicate a higher forest area loss in the Baltics, Western Poland, Czechia, and Hungary, suggesting more intensive forestry in these regions compared to the Balkans. These patterns can also be observed in the integrated map.

Portugal and Galicia, Spain, have a relatively high share of *very intensive forestry*, largely due to the extensive use of *Eucalyptus globulus* for wood production. This species is characterized by rapid growth and a substantially higher annual harvesting probability due to shorter rotation lengths than other tree species (Cerasoli et al., 2016; Schelhaas et al., 2018). In contrast, 87 % of Italian forests are protected, while Greek forests are fully protected under Greek Constitution Law (No. 998/1979), leading to less intensively managed stands, particularly in mountainous regions (Agnoletti, 2013; Christopoulou, 2011; Forest Europe, 2020; Vizzarri et al., 2015).

The results for Western Europe align with national policies promoting multifunctional forestry. Countries such as Germany, Austria, and the Netherlands emphasize a balance between high wood production, biodiversity conservation, and other ecosystem services (Bäck et al., 2017; Borrass et al., 2017; Di Marzo et al., 2023; Forest Europe, 2020). Finally, higher harvesting rates are associated with lower elevation and slope values, aligning with our findings (Levers et al., 2014; Suvanto et al., 2025).

The forest management map was compared with NFI data, revealing a clear relationship between plot-level volume changes and forest management classes, particularly for larger volume reductions. Nevertheless, these patterns are not always homogeneous. This is partially explained by the unequal representation of forest management classes across the countries and the difference in scale between NFI data and the management map. Therefore, it is crucial to consider the number of observations available while interpreting country-level results (see Table S2 for sample sizes, and Figure S2 and Tables S3-S13 for country-level results). Another possible explanation relates to the distinction between the intensity and frequency of volume reductions. Northern Europe is characterized by clear-cutting practices with a lower frequency, particularly evident in Norway. In contrast, Western European countries exhibit a relatively higher frequency of smaller volume reductions, resulting in a less pronounced relationship between forest management intensity and the annual occurrence of volume reductions, as *close-to-nature forestry* and *combined objective forestry* could have small volume reductions. Overall, this comparison indicates that our forest management map effectively captures differences in harvesting intensities, with higher management intensity classes revealing a greater annual relative occurrence of volume decreases.

The harvesting maps developed by Suvanto et al. (2025) are comparable to our integrated map, as regions with a high presence of *intensive forestry* and *very intensive forestry* were associated with higher harvest rates. For example, their total harvest rate map follows similar patterns to our forest management map, with a high harvesting rate observed in Gascony, Galicia, Southern Finland, and most of Sweden. However, discrepancies were observed for Germany: while Suvanto et al. (2025)'s map displays an average to high harvest rate, our map predominantly indicates *close-to-nature forestry* and *combined objective forestry*. This difference may be due to variations in the timeframes, as Suvanto et al. (2025) use data from 2000–2013, whereas our map includes indicators that span 1985–2023. German roundwood production data from FAO (2023) indicates that average production was 14 % higher during the period analyzed by Suvanto et al. (2025) compared to the timeframe of our forest management map, giving a possible explanation for the observed difference.

A comparison with the global forest management maps developed by Lesiv et al. (2022) and Schulze et al. (2019) is challenging due to differences in the management classes used and the methodologies applied. The results for Northern and Western Europe, as well as for Spain and Portugal, align closely with the patterns observed in Schulze et al. (2019). However, Eastern Europe demonstrates a greater extent of productive forests in Schulze et al. (2019) compared to our forest management map. Comparing our map with Lesiv et al. (2022) presents inherent challenges due to their primary focus on regeneration type and differences in definitions. Nevertheless, some similarities exist: our *unmanaged forest* class aligns with "naturally regenerating forests without any signs of management, including primary forests," notably prevalent in Northern Scandinavia in both maps.

The existing forest management maps of Europe by Nabuurs et al. (2019) and Hengeveld et al. (2012) align more closely with our integrated map, allowing for easier comparison, as their definitions are also based on Duncker et al. (2012a). Compared to our integrated map, the forest management map of Hengeveld et al. (2012) displays similar patterns across Europe, but the proportions of the classes differ from our results with "nature reserves" (similar to our *unmanaged forest* class) having 8.2 % of total forest cover, "close-to-nature forestry" 18.3 %, "combined objective management" 64.7 %, "even-aged forestry" 5.7 %, and "short rotation forestry" 3.1 %. The proportions of the management classes used by Nabuurs et al. (2019) more closely reflect our results, with similar spatial patterns observed across Europe. However, Nabuurs et al. (2019) map slightly more "multifunctional management" (equivalent to the *combined objective forestry* class in our map) in Northern Europe than our forest management map, while Central and Western Europe are more intensively managed in comparison to our forest management map. The observed differences can be attributed to variations in the methodology and data used, which were often constrained, representing one of the main limitations of the existing forest management maps.

The aforementioned comparisons confirm the overall consistency of patterns between our map and the other sources from the literature, but also emphasize the limitations of our work. Our NFI comparison included a vast number of observations from forest plots (78,885; Table S2), successfully revealing broad patterns across forest management classes. However, it does not serve as a direct validation, as the data lacked sufficient detail to align with our forest management classes or to fully replicate our decision tree. While some national-level ground-truth data are available (e.g., Vrška and Adam, 2009; Naturvårdsverket 2020), differing forest management classes and definitions significantly limits its usefulness for the validation of our map. Developing a Europe-wide forest management map poses challenges in harmonizing forest definitions and thresholds due to regional variations in forest practices. For example, boreal forests exhibit a higher prevalence of clearcutting systems compared to temperate forests, where smaller interventions are more common (Aszalós et al., 2022), a pattern also confirmed by our NFI comparison (Figure S2). Defining quantitative thresholds further highlights these challenges. The thresholds for young and mature forests are highly dependent on the tree species considered; while *Quercus robur* can live for over 1000 years, *Salix alba* typically survives only 20–30 years (Eaton et al., 2016; Houston Durrant et al., 2016). Similarly, harvesting rotation cycles differ across Europe, with *Eucalyptus globulus* plantations in Southern Europe associated with rotation periods of 8–12 years, whereas *Picea abies* plantations in Northern Europe have rotation periods of approximately a 100 years, depending on site productivity (Bergh et al., 2005; Cerasoli et al., 2016; Kuuluvainen, 2009). To minimize subjectivity, we attempted to align our definitions and thresholds with well-established forestry standards in the literature and national statistics; however, standardized definitions across Europe remain lacking (e.g., Duncker et al., 2012a; FAO, 2018; Forest Europe, 2020; Swedish Forestry Agency, 2014).

An additional limitation concerns the integration of the underlying Viana-Soto and Senf (2024)'s disturbance data. Those data primarily suffer from omission errors for low-severity disturbances, which can lead to an underestimation of management intensity, particularly in Central and Southern Europe where such disturbances are widespread (Viana-Soto and Senf, 2024). Conversely, higher commission errors in Northern Europe, attributed to factors like missing data and noise, may locally influence classification accuracy (Viana-Soto and Senf, 2024). The complex interactions between natural and anthropogenic disturbances pose another challenge for our classification (Seidl and Senf, 2024). Remote sensing primarily detects change events, making it difficult to disentangle the root cause when natural disturbances are followed by management interventions such as salvage logging, potentially overemphasizing anthropogenic disturbances (Seidl and Senf, 2024; Viana-Soto and Senf, 2024). At the same time, comprehensive data on fast-growing, native, and introduced tree species are lacking. This affects the precise interpretation of *very intensive forestry*, as some fast-growing species indicative of intensive forestry are not necessarily captured, while native fast-growing species are not necessarily indicative of that management class. Consequently, the interpretation of the management classes is inherently limited by the characteristics of the input data. It is particularly challenging to differentiate between various close-to-nature practices due to the higher omission errors for low-severity disturbances. Similarly, distinctions between specific silviculture systems within *intensive forestry* and *very intensive forestry* are difficult to make with the available data. Additionally, the broad scope of *combined objective forestry*, which encompasses a wide range of forest ecosystem services, inherently restricts its detailed interpretation. While our map integrates the most up-to-date information from the literature, additional data would allow for finer distinctions between and within the existing forest management classes.

This research demonstrates that while harmonizing forestry definitions across Europe is challenging, it is also feasible and crucial for developing novel European forestry maps. Increased availability of forest data and standardization would reduce the subjectivity of the definitions and thresholds applied in this study. This would enable the development of a more detailed decision tree that more effectively captures differences in forest practices and characteristics across countries. Future analyses should focus on enhancing data inputs and potentially expanding the range of forest management classes. For instance, with broader availability of data on various forest services and characteristics, the *combined objective forestry* class could be further subdivided to represent specific management objectives, such as recreation, preservation of cultural heritage, or tourism. These advancements would allow for more detailed management classes, enhancing the map's applicability for forest research and policy decisions.

5. Conclusion

We developed a European forest management map using a rule-based classification approach, integrating the most recent data on harvesting disturbances, forest age, tree species distributions, and the European primary forest database. Five forest management classes were delineated along a gradient of management intensity, namely *unmanaged forest*, *close-to-nature forestry*, *combined objective forestry*, *intensive forestry*, and *very intensive forestry*. The resulting map was compared against NFI plot-level volume data. The distribution of forest management classes varies substantially across Europe. *Intensive forestry* and *unmanaged forests* are predominantly found in Northern Europe, where *intensive forestry* is the dominant class. The prevailing forest management class in Eastern, Southern, and Western Europe is *combined objective forestry*. *Close-to-nature forestry* is mostly found in Western Europe and mountainous areas, while *very intensive forestry* is most prominently found in Portugal, Galicia, and Gascony. The comparison with NFI plot-level volume data reveal that our map effectively captures differences in harvesting intensities between the forest management classes. However, some observed discrepancies may be attributed to the heterogeneity of harvesting regimes across Europe, suggesting the potential for improvements. With the increasing availability of comprehensive forest datasets, potential improvements could focus on additional ways of distinguishing forest management classes and refining our rule-based classification. This research can help policymakers identify regions for targeted conservation efforts or climate mitigation strategies, and monitor the effectiveness of sustainable forest management practices across the continent. Despite its limitations, our integrated map serves as a valuable resource for forest policy and research, enhancing the understanding of the spatial distribution and diversity of forest management regimes across Europe.

CRediT authorship contribution statement

Patricia Adame: Writing – review & editing. **Rasmus Astrup:** Writing – review & editing. **Niels Debonne:** Supervision, Methodology, Conceptualization. **Saskia Oostdijk:** Methodology, Investigation, Formal analysis, Conceptualization. **Verburg Peter:** Writing – review & editing, Writing – original draft, Supervision, Methodology, Conceptualization. **Niek Scherpenhuijzen:** Writing – review & editing, Writing – original draft, Methodology, Investigation, Formal analysis, Conceptualization. **West Thales:** Writing – review & editing, Writing – original draft, Supervision, Methodology, Conceptualization.

Declaration of Competing Interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Niek Scherpenhuijzen reports financial support was provided by European Union Horizon Europe (HORIZON) Research & Innovation programme. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.foreco.2025.122940.

Data availability

The forest management map, the input data, and codes can be accessed through the DataverseNL repository (Scherpenhuijzen et al., 2025). The NFI data cannot be shared due to contractual agreements.

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