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A gridded dataset of European Forest Types to support forest monitoring, modelling and reporting

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Abstract. A standardized system of nomenclature for forest types is essential for effectively monitoring and understanding the impacts of climate change on diverse ecosystems in Europe and beyond. A comprehensive classification system, such as the European Forest Types (EFTs) scheme, is essential for assessing baseline conditions, tracking changes, and guiding conservation decisions. A unified forest type nomenclature supports international collaboration, enables researchers and policymakers to accurately compare data across regions and time periods, and enhances the development of targeted conservation strategies and adaptive management practices aimed at preserving biodiversity and ecosystem services. This classification breaks down forested areas in Europe into a handful of ecologically homogeneous units, thus facilitating the analysis of data related to forest conditions and management practices across a wide range of climatic and edaphic conditions. The current lack of an EFTs map for Europe prompted its processing, using a shared rule-based expert system algorithm. Utilizing a dataset featuring 39 "relative probability of presence (RPP) maps" of tree species and various forest masks, the algorithm identified 14 EFT categories. This initiative filled a critical gap in spatial monitoring, providing the first consistent pan-European EFT maps gridded dataset. The availability of standardized and comprehensive spatial data on forest types enhances our capacity to understand, manage, and conserve forest ecosystems effectively. Such data support biodiversity conservation and ensure the sustained provision of essential ecosystem services, highlighting the critical role of forest types in maintaining ecological balance and supporting human well-being.

1. Introduction

The growing impacts of climate change on forest ecosystems, in Europe in particular, has led to an acceleration in the development of comprehensive classification systems, able to depict the actual distribution of forest vegetation using dominant tree species composition, in correlation with large-scale biogeographic, climatic and edaphic gradients (EEA, 2006;

Giannetti et al., 2018; Ivanova et al., 2022; Jenssen et al., 2021; Kusbach et al., 2023). These classification systems are recognized to play a pivotal role in understanding, assessing, modelling, monitoring, reporting and managing ecological communities, contributing to a deeper insight into ecosystem dynamics (Dahdouh-Guebas et al., 1998; Grondin et al., 2023; Ivanova et al., 2022; Kusbach et al., 2023; Schick et al., 2019). These systems allow to derive details about natural habitats and ecosystems, such as the biophysical/ecological attributes and their historical variations across diverse spatial scales (i.e. global, national, regional, local) (Barbati et al., 2014; De Cáceres et al., 2019; Giannetti et al., 2018; Grondin et al., 2023; Jacquemoud and Ustin, 2019).

On the variety of habitats and ecosystems classifications those linked with vegetation are considered mandatory for articulating, synthesizing and depicting the association of diverse vegetation communities (Dahdouh-Guebas et al., 1998; Williamson et al., 2016). These data are indispensable for guiding strategies in vegetation management, aiming to ensure the sustained functionality of ecosystems over time (Barbati et al., 2014; De Cáceres et al., 2019).

In this context, from the onset of forestry science, foresters have developed forest typologies or forest types of classification schemes (FTCS) as tools for characterizing forest sites and stands (De Cáceres et al., 2019; Cajander, 1949) in terms of dominant association of vegetation communities (i.e. dominant plant species) and site factors (e.g. climate, altitude, edaphic conditions). Although historically these classification schemes were used in the forest sector to support conventional forest management activities (Cajander, 1949; Giannetti et al., 2018), today FTCS are considered essential for the comprehensive assessment and monitoring of changes in forest ecosystems, encompassing all associated ecosystem service indicators rather than focusing solely on timber production (Barbati et al., 2014; Bergeron et al., 2012; Corona, 2016). Moreover, FTCS are becoming increasingly important for the initialization and calibration of forest, more broadly, vegetation, models, particularly those used to compare alternative forest management strategies under climate change scenarios (Dalmonech et al., 2022; Grünig et al., 2026; Santini et al., 2014; Saponaro et al., 2025), and at assessing ecosystem services prevision (Morichetti et al., 2024; Vangi et al., 2026).

In detail, the FTCS are essential, on the one hand, to further break down data on forest monitoring indicators to a higher level of information to support decision-making in forest conservation and resource management (Barbati et al., 2007). On the other hand, they are crucial for understanding the impact of environmental and climate changes on diverse forest ecosystems (Maes et al., 2023; Nemani and Running, 1996). Moreover, FTCS serve multiple purposes, including the evaluation of habitat quality, the assessment of susceptibility to disturbances, the analysis of forest dynamics also through models, and the cartography of forest resources, all of which are essential for the development of sustainable forest management strategies (Barbati et al., 2014; Corona, 2016; EEA, 2006; Grondin et al., 2023).

The development of FTCS involves breaking down large regions covered by forests into ecologically homogeneous units (Barbati et al., 2014; De Cáceres et al., 2019; Cajander, 1949). This process translates in the search of discontinuities in the tree species composition of the forest canopy, to differentiate the main classes of the FTCS using the dominant species and biogeographical, altitudinal zonation or site-specific factors as diagnostic criteria. This breakdown significantly enhances the analysis, interpretation, and communication of forest-related data (Barbati et al., 2014). The availability of FTCS can improve the data collection, interpretation, and reporting of forest data, especially those linked with Sustainable Forest Management (SFM) and biodiversity (Barbati et al., 2014). Typically, a basic classification system consisting of three main categories (broadleaved forest, coniferous forest, mixed broadleaved forests) is used for reporting Sustainable Forest Management (SFM) indicators (Barbati et al., 2014; FAO and UEP, 2020; FOREST EUROPE, 2015b). This simplistic approach fails to adequately capture the ecological and biodiversity characteristics of forests (Barbati et al., 2014; Giannetti et al., 2017), particularly in countries with significant environmental and forest variability and heterogeneity, such as for example in France, Spain, or Italy (EEA, 2006).

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Many FTCS exist around Europe differing among countries, and even among regions of the same country (D'amico et al., 2021). Currently, there are three existing FTCS that allow for the systematic identification of distinct forest communities in the whole Europe as reported in Giannetti et al. (2018): the "EUNIS Habitat Classification" (Davies et al., 2004), the "Overview of Phytosociological Alliances" presented by Rodwell & Mucina (2002) and the "European Forest Types - EFTs"(EEA, 2006). The first two classifications schemes are scientifically robust and widely accepted; however, both schemes, as pointed out in the report of the European Environment Agency (EEA, 2006) and the works of Barbati et al. (2007, 2014) and Giannetti et al. (2018), do have limitations when it comes to their potential usability for reporting the pan-European indicators for sustainable forest management of the FOREST EUROPE process (FOREST EUROPE, UNECE and FAO, 2011). One notable limitation is that both systems (e.g. EUNIS and Overview of Phytosociological Alliances) have too many classes, which makes their use impractical for feasible reporting purposes (EEA, 2006). In the context of international framework, reporting a FTCS should adequately capture just the primary factors that contribute to the variations (EEA, 2006), such as: (i) the changes in ecological forest zones that impact the natural composition of tree species, (ii) the length of the growing seasons that reflect the growing stock capacity, (iii) the rate of deadwood decomposition and the occurrence of natural disturbances that have impact for example on the types and quantities of deadwood. Additionally, FTCS should account for changes in management practices that affect the age and density structure, growing stock, and the presence of dead and dying wood left in the forest.

In response to this need, the European Environment Agency (EEA) promoted the development of the European Forest Types classification to be adopted as reference for European-level reporting within the FOREST EUROPE process (Forest Europe UNECE and FAO, 2011). The classification of EFTs was developed through an expert review process with the initial goal of optimizing the monitoring of forest biodiversity in the EU countries (European Environmental Agency, 2006), and to reflect the ecological diversity of pan-European forests (Barbati et al., 2014; European Environmental Agency, 2006; Giannetti et al., 2018; Pividori et al., 2016). The EFTs are categorized using a hierarchical classification system that consists of 14 first-level classes (categories) and 75 second-level classes (types). The 14 categories of the EFTs represent extensively distributed zonal and azonal forest communities with characteristic tree species combinations. The spatial distribution of the categories in the European region is largely driven by biogeographical, latitudinal/altitudinal gradients or site-factors (e.g. soil water-nutrient conditions). The "type" level is mainly intended to further distinguish the variety and the characteristics of forest ecosystems covered by each category. The classification specifically pertains to forest land as defined by FAO and UNEP, (2020) and applied for the FOREST EUROPE national reporting (FOREST EUROPE and FAO, 2020), but the EFTs do not include other wooded lands within its scope (European Environmental Agency, 2006). The EFTs have proven instrumental in facilitating the comparison, interpretation, and dissemination of data pertaining to European forests' conditions. A pilot reporting by EFTs was tested in the State of Europe's Forests 2011 report (FOREST EUROPE, UNECE and FAO, 2011) for a selection of quantitative indicators, primarily forest area and growing stock and some key-biodiversity related indicators (e.g. share of old stands (>140 yrs) out of total area of even aged forest by EFTs, share of single species stands out of total area of forest by EFTs and volume of deadwood per hectare of forest by EFTs). This initiative required an individual effort from European countries to reclassify National Forest Inventories ground plots by EFTs categories, so that data on the pan-European indicators for sustainable forest management (FOREST EUROPE, 2015a; MCPFE, 2003) could be aggregated by EFTs throughout the pan-European region. Though the comparison of data on indicators by ecologically sound units, proved useful to better interpret the values taken by the indicators, explicitly considering ecological differences between EFTs (Barbati et al., 2014), reporting by EFTs has not been further implemented in the subsequent FOREST EUROPE reports, (FOREST EUROPE, 2015; FOREST EUROPE, 2020).

Despite the existence of several forest typology frameworks and Pan-European classification systems, a spatially explicit, harmonized, and operational map of forest types – such as those based on EUNIS and EFTs – covering the entire European territory is still lacking. At present, the only forest-type map consistently available across all European Union Member States is the product developed within the Copernicus Land Monitoring Services under the High-Resolution Layers called "*Forest Type*" (Langanke, 2017). This gridded dataset provides a simplified classification with only two categories - coniferous and broadleaved forests - at a spatial resolution of 10 meters. A coarse version at 100 meters resolution included and additional mixed forest category, distinguish among coniferous, broadleaved forests and mixed forest types (Copernicus Land Monitoring Service, 2021).

However, although the Copernicus High Resolution Layer of *Forest Types* ensures spatial consistency across Europe, its ecological resolution remains limited, as it captures only broad forest categories (i.e. coniferous, broadleaves, and mixed forests). This level of generalization constrains the disaggregation of forest indicators into ecologically meaningful units across countries, thereby limiting cross-country comparability, biodiversity assessments, and the ecological interpretation of forest monitoring data at the continental scale. More detailed classification systems, such as EUNIS or phytosociological alliances, are conceptually robust but often too complex for operational use in pan-European reporting frameworks (Giannetti et al., 2018). In this context, the EFTs classifications, developed by EEA – supported by the experiment of FOREST EUROPE (Forest Europe UNECE and FAO, 2011) – represents a suitable compromise, balancing ecological relevance with applicability for large-scale forest monitoring and reporting of sustainable forest management indicators.

It is important to highlighted that, to date, no formal reporting requirements established by the EEA regarding the use of the EFTs (European Environment Agency, 2008; Xanthopoulos et al., 2012). However, this situation may evolve in the near future, as the EFTs have been included in the Draft EC Forest Monitoring Regulation (European Commission, 2023). Although it is not yet defined which indicators will be reported by EFTs, it is likely that Member States will be required to provide the information, similarly to the pilot reporting by EFTs in the State of Europe's Forests 2011 report (Forest Europe UNECE and FAO, 2011).

Significant progress has been made to facilitate the classification of National Forest Inventory (NFI) plots according to the EFT system. Giannetti et al., (2018) developed the first methodology for the automatic classification of inventory plots into EFTs, based on a rule-based algorithm integrating spatially explicit environmental variables with the tree species composition derived from field data (i.e., percentage of basal area per each one of the tree species). This approch enabled the accurate classification of approximately 6000 ICP BIOSOIL plots into the 14 EFTs categories.

However, as noted above, spatially consistent, wall-to-wall gridded datasets of EFTs covering the entire European territory are still lacking, thereby limiting the operational applicability of this classification framework for large-scale monitoring and reporting of sustainable forest management including biodiversity indicators. This gap also constrains the application of certain forest models at broader spatial scales, as their calibration requires detailed wall-to-wall information on tree species composition or group of species (Chirici et al., 2022; Dalmonech et al., 2024).

The dataset presented in this study directly addresses this gap by providing the first harmonised, wall-to-wall, spatially explicit gridded dataset map of the 14 EFT categories at 100 m spatial resolution. The dataset is generated through a reproducible rule-based expert system that integrates "relative probability of presence (RPP) maps" of 39 forest tree species provided by the EC Joint Research Centre (Caudullo et al., 2017; De Rigo et al., 2016), together with forest masks representing major environment domines that facilitated the accurate identification of distinct EFT categories. The rule-based expert system algorithm originally developed by Giannetti et al. (2018) was adapted and extended for this purpose. This effort resulted in a georeferenced raster map at a 100-meter resolution, representing the first consistent EFT map across

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Europe. By translating the EFT conceptual framework into a coherent geospatial product, this work operationalises a classification scheme specifically designed to support pan-European forest monitoring, reporting and modelling.

In this context, the terms "*monitoring, modelling and reporting*" refer to the use of ecologically stratified forest information derived from the dataset within several complementary frameworks. Specifically, monitoring refers to the derivation of indicators such as forest area by forest type, modelling to the use of this information in ecological and management-oriented applications (e.g. scenario analysis and forest planning) and reporting to its use in policy and assessment contexts.

These applications include: (i) National Forest Inventory-based indicator assessments, (ii) pan-European Sustainable Forest Management (SFM) reporting frameworks such as FOREST EUROPE indicators, (iii) emerging European policy instruments based on the Green Deal, and (iv) ecological and climate-impact modelling applications requiring stratification by forest types.

The dataset is not intended for greenhouse gas MRV (monitoring, reporting and verification) systems, where verification represents a formal component of emissions accounting. Rather, it is designed to support ecological, structural, and biodiversity-oriented forest monitoring, modelling, and reporting.

2. Material and Methods

2.1. EFTs classification scheme

In this section a brief description of the EFTs is provided, since detailed descriptions are already published in different scientific papers (Barbati et al., 2014; Giannetti et al., 2018), report (European Environmental Agency, 2006) and in the EU atlas of forest tree species (Pividori et al., 2016). While the EFTs are a hierarchical classification system with 14 first-level categories and 75 second-level classes (types), this paper focuses on the level of categories. Annex 1 presents the 14 classes and the main characteristics summarized on the basis of the report of the European Environment Agency (EEA, 2006) and the work of Barbati et al. (2014). The forest tree species that characterize each category as dominant species, present co-dominant or present in either categories, are derived by the forest tree species matrix developed by Pividori et al. (2016) and summarized in Table 2. EFTs classification proposed in this study is not only based on species composition but it also reflects environmental, biological, and anthropogenic diversity of forest types (Barbati et al., 2014; EEA, 2006; Giannetti et al., 2018). The access to data that captures the environmental diversity of the system is essential to classify each EFT category. The EFTs classes include environmental and biological diversity of forest types. Each category is distinguished on a latitudinal/altitudinal and climatological basis in the categories 1-10 and 13, while categories 11-12 are considered azonal communities, and category 14 identifies forests dominated by alien tree species in Europe.

2.2. Study Site

This study spans over the pan-European forest region (shown in red in Fig. 1), which includes the EU-28 countries plus Switzerland, San Marino, Liechtenstein, Montenegro, Bosnia and Herzegovina, Serbia, Albania, North Macedonia, and Andorra. The countries were selected based on the availability of all the datasets needed for the classification described in the following sections.

In Europe, forests cover an area of approximately 227 million hectares, accounting for more than a third of the continent's total land. Over the last 30 years, there has been a 9% increase in forested areas (FOREST EUROPE and FAO, 2020). Approximately 46% of forests are primarily composed of coniferous trees, while 37% consist of broadleaved trees. Mixed stands make up around 17% of this area. Conifers dominate in Northern Europe in particular (66.9%), while a higher proportion of broadleaved trees can be found in other parts of Europe. In particular, Southwest Europe has the highest share

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of broadleaved forests, accounting for 61.4%. Around two-thirds of European forests are dominated by two or more tree species. Specifically, 4.6% of European forest stands are estimated to be composed of more than 6 species, while 13.1% consist of 4-5 species. Nearly half, 49.5%, are composed of 2-3 species, and the remaining 33% of a single tree species. In Southeast Europe, 62.3% of forests are single-species forests. Contrarily, in Southwest Europe, the forest tree species composition is more diverse, with stands featuring more than six species representing 19.9% of the total forested areas. Most European forests are estimated to be composed of native species (96.9%), with introduced tree species covering 3.1% of the forest area. Moreover, 66% of the forests in Europe are naturally regenerated, while only 2.2% are considered undisturbed by human activities, exhibiting a high level of naturalness (FOREST EUROPE and FAO, 2018, 2020).

Based on the data of the State of Europe's Forests 2011 report (FOREST EUROPE, UNECE and FAO, 2011), which utilized EFTs for a pilot test on reporting indicators using data gathered from 28 countries for 2010 (Switzerland referred to 2005 and UK to 2000), the forest area in Europe is assigned as following: 21.9% 1- Boreal forests; 21.4% 2- Hemiboreal and nemoral coniferous and mixed broadleaved-coniferous forests; 7.3% 4- Acidophilous oak and oak-birch forests; 6.6% 11- Mire and swamp forests; 6.1% 7- Mountainous beech forests; 5.4% 9- Broadleaved evergreen forests; 5.2% 13- Non-riverine alder, birch or aspen forests; 4.5% 12- Floodplain forests; 4.2% 14- Introduced tree species forests; 3.6%; 10-Coniferous forests of the Mediterranean, Anatolian and Macaronesian regions; 3.6% 3- Alpine forests; 3.0% 8-Thermophilous deciduous forests; 2% 5- Mesophytic deciduous forests, and 1.2% 6- Beech forests. The details for each country are reported in Table 1.

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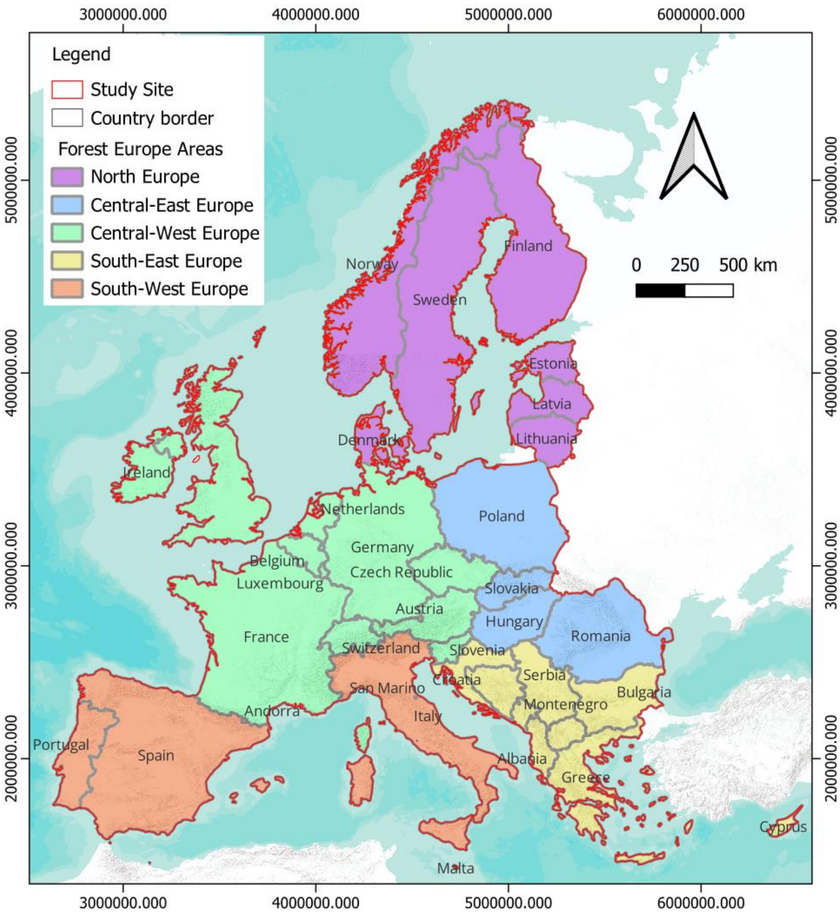

Figure 1. Study site, including country borders and geographic regions as defined by FOREST EUROPE, UNECE, and FAO (2011). The background map is powered by ESRI Source: "World Terrain Base".

Table 1. Percentage of forest area reported for each EFTs category in State of Europe's Forests 2011 (FOREST EUROPE, UNECE, and FAO 2011).

	Percentage of forest area reported for each EFTs category in the State of Europe's Forests 2011													
Country	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**
Austria	0.0	31.9	28.5	0.2	5.3	7.6	10.4	0.1	0.0	0.0	0.1	1.6	1.1	0.9
Belgium	0.0	0.0	0.0	14.7	21.1	11.4	0.0	0.0	0.0	0.0	1.3	2.1	0.0	42.2
Bulgaria	0.0	8.3	20.8	0.0	9.0	10.5	2.9	43.0	0.0	0.2	0.0	0.0	0.0	5.3
Croatia	0.0	1.3	1.8	3.1	21.6	9.4	29.4	11.7	4.2	2.8	0.0	10.5	0.0	4.3
Cyprus	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.6	0.0	98.8	0.0	0.0	0.0	0.6
Czech Republic	0.0	61.2	15.0	0.3	5.9	7.0	3.0	0.0	0.0	0.0	2.5	1.5	1.8	1.5

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Denmark	0.0	4.8	0.0	4.8	16.2	14.1	0.0	0.0	0.0	0.0	0.3	5.8	0.0	48.7
Estonia	43.1	1.8	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	13.8	0.0	41.3	0.0
Finland	70.0	2.0	1.4	0.0	0.0	0.0	0.0	0.0	0.0	0.0	19.7	0.0	6.6	0.2
France	0.0	11.9	2.8	14.7	20.4	3.9	12.6	13.3	5.5	2.6	0.5	2.5	2.3	4.9
Germany	0.0	56.1	1.2	0.0	14.8	13.3	3.5	0.0	0.0	0.0	2.8	0.0	4.4	4.0
Hungary	0.0	0.0	0.0	7.3	25.5	6.8	0.0	8.2	0.0	0.0	0.2	2.0	2.7	47.4
Ireland	0.0	0.0	0.0	2.6	6.4	0.0	0.0	0.0	0.0	0.0	2.2	0.5	2.8	85.3
Italy	0.0	0.9	13.6	0.0	1.8	0.7	11.1	38.8	10.0	4.3	0.0	1.2	1.4	3.7
Latvia	12.3	36.6	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	8.0	0.0	35.5	0.0
Lithuania	0.0	51.2	0.0	0.0	6.2	0.0	0.0	0.0	0.0	0.0	17.1	1.3	24.1	0.2
Netherlands	0.0	30.4	0.0	10.7	21.9	3.6	0.0	0.0	0.0	0.0	0.0	0.0	7.7	24.9
Norway	52.8	11.2	10.1	0.2	0.0	0.1	0.0	0.0	0.0	0.0	6.4	0.0	16.8	2.3
Poland	0.0	64.0	3.3	1.1	9.3	2.8	4.0	0.5	0.0	0.0	1.2	3.0	9.8	0.5
Slovakia	0.0	7.4	23.1	0.3	16.0	24.5	11.1	1.6	0.0	0.0	0.4	1.5	0.7	2.1
Slovenia	0.0	6.3	2.6	1.5	8.9	39.1	34.4	6.9	0.0	0.0	0.0	0.2	0.0	0.0
Spain	0.0	2.2	2.7	0.8	0.6	0.5	1.5	8.6	30.6	28.7	0.0	1.0	0.1	4.9
Sweden	53.2	22.3	3.8	0.4	0.1	0.3	0.0	0.0	0.0	0.0	10.0	0.1	7.9	1.9
Switzerland	0.0	21.0	40.0	0.2	10.4	13.7	4.8	2.8	0.0	0.0	0.4	0.9	1.8	0.5
U.K. of Great Britain and Northern Ireland	0.0	3.3	0.0	9.7	11.1	1.7	0.0	0.0	0.0	0.0	0.0	2.0	1.7	52.0

2.3. Data

The data needed to construct the EFT raster grid dataset map are multiple and constitute the main inputs of the analysis, which are described in detail in the following sections. Some layers, such as (i) the relative probability of presence (RPP) maps and (ii) the Copernicus forest types maps, are used to determine forest species composition. In addition, a set of geographic layers available at the EU level, described in Section 2.3.2, is used to identify ecological breakpoints that influence the spatial differentiation of EFTs.

2.3.1. Relative probability of presence (RPP) maps

To the best of our knowledge, a consistent European-wide dataset of single forest tree species (e.g. cartographic layer of forest tree species, or automatic classification of forest tree species by remote sensing data) suitable to be converted in EFTs is not available. However, three datasets including the distribution of forest tree species suitable to map EFTs are available and consistent in all the EU-28 and the selected countries (Fig. 1), as follows: (i) the tree species distribution by Bonannella et al. (2022), (ii) the EU Tree Map by Brus et al. (2012), (iii) the relative probability of presence (RPP) maps of Tree Atlas by the JRC (De Rigo et al., 2016). These datasets are provided as raster layers containing the probability to find a given forest tree species within a pixel. These maps are called “relative probability of presence maps” (RPP maps). The most recent dataset was published by Bonannella et al. (2022), who classified forest tree species using satellite and ancillary data to produce distribution maps for 16 tree species at high spatial resolution (30 m). A more extensive list of forest tree species maps comprise 21 species/group distribution was provided by Brus et al. (2012) at low resolution scale of 1 km using NFI

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and ICP Plot Level I data and 10 covariates variables (i.e. biogeographical region, soil class, elevation, slope, annual mean temperature, temperature seasonality, annual precipitation, precipitation of warmest quarter, easting and northing).

The more comprehensive source of forest tree species maps is distributed by the Joint Research Centre (JRC) through the atlas of forest tree species portal (https://forest.jrc.ec.europa.eu/en/european-atlas/atlas-data-and-metadata/).

A dataset called "EU-Forest" is open-source and publicly available, obtained by merging the three highest-quality tree species distribution datasets available by the JRC in 2017 (Caudullo et al., 2017): the tree occurrence data provided by Forest Focus (ICP-Forest database from 2003 to 2009), Biosoil and the National Forest Inventory dataset of the EU Countries. The latter accounts for the brunt of data in EU-Forest, as it includes more than 350 wood species and more than half million of occurrence records spread over 19 EU Member States and two neighboring countries (Norway and Switzerland) (Beck et al., 2020; Caudullo et al., 2017). Similar to the dataset proposed by Brus et al. (2012), also the JRC dataset provides the Relative Probability of Presence (RPP) maps at 1 km spatial resolution. The RPP maps are provided by tree species and represent the average probability (ranging from 0 to 1) of finding the given tree species, at least one individual of the taxon, at 1 km^2 pixel resolution (De Rigo et al., 2016).

The RPP maps are provided for a specific tree taxon, irrespective of the potential co-occurrence of other tree taxa within the measured plots and should not be confused with the absolute abundance or proportion of each taxon in the plots. Consequently, the sum of the RPPs associated with different taxa in the same area can exceed 100%. More details can be found in (Beck et al., 2020).

Considering all the above information, this study uses the JRC tree species RPP maps since they provide data based on a large list of forest tree species compared with the other two available datasets. The data related to the RPP were used to have quantitative data of occurrence of tree species. The complete list of species/groups of species available in the JRC dataset is presented in Table 2. From the complete list, we excluded *Corylus avellana, Prunus avium, and Salix caprea* since they are not identified as dominant or diagnostic species at the category level, nor as present species.

It is important to highlight that, although the RPP maps are provided for individual tree species, their use in this study relies on a combined interpretation. The joint analysis of multiple species distributions enables the identification of forest composition patterns and the derivation of ecologically meaningful forest types, which cannot be inferred from single-species maps alone. This integrated use of species-level information is particularly relevant for monitoring, modelling, and reporting applications, where aggregated forest types provide a more appropriate level of abstraction than individual species, reducing model complexity and associated uncertainty, while ensuring harmonization and comparability of forest indicators.

Table 2. List of RPP maps available in the JRC dataset. "D" identify species that are dominant and diagnostic at category level. "p" are species that are only present.

EFT Category	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**
Abies alba		D	D				D			D				
Abies spp.							D			D				
Acer campestre					D			D						
Acer pseudoplatanus					D		p							
Alnus glutinosa											D	D	D	
Alnus incana											D	D	D	
Betula spp.	D	D	D	D			p				D	D	D	

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Carpinus betulus					D	p	p							
Castanea sativa						p	p	D						
Fagus sylvatica						D	D							
Fraxinus excelsior		D			D	p	p							
Fraxinus ornus								D						
Larix decidua			D											
Picea abies	D	D	D				D				D			
Picea sitchensis														D
Pinus cembra			D											
Pinus halepensis										D				
Pinus mugo			D											
Pinus nigra		D	D							D				
Pinus pinaster		D								D				
Pinus pinea										D				
Pinus sylvestris	D	D								D	D			
Populus nigra												D		
Populus tremula	p												D	
Pseudotsuga menziesii														D
Quercus cerris						p		D						
Quercus frainetto								D						
Quercus ilex									D					
Quercus pubescens								D						
Quercus pyrenaica								D						
Quercus robur		D		D	D	p	p				D			
Quercus petraea				D	D	p	p	D						
Quercus suber									D					
Robinia pseudoacacia														D
Sorbus aucuparia	p	p					p				p			
Tilia spp.		D			D	p	p							

2.3.2. Available layers for EFTs classification

Since EFTs classification is not just based on species composition, as reported in the previous section, but it reflects as well environmental, biological, and anthropogenic diversity of forest types (Barbati et al., 2014; EEA, 2006; Giannetti et al., 2018), to perform an automatic classification, it is necessary to have access to spatial databases reflecting the environmental diversity of the scheme. While some of the spatial data needed to reflect the environmental and biological diversity were already identified by previous work of Giannetti et al., (2018), we included two additional layers in the present work. We have used all the five-raster grid layers proposed by Giannetti et al. (2018) and two additional geographic layers (Table 3).

Table 3. Geographic layer for EFTs classification. The * indicate the two additional layers added in this work, while the other were already included in Giannetti et al. (2018)

Geographic layer name	**Reference**	**Scale/Type of layer**	**Description/Usage**

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The map of biogeographic regions of Europe	(EEA, 2016)	1:10,000,000 Vector layer	contains the official delineations of nine regions. The map was developed for the Habitats Directive (92/43/EEC) including the design of the Natura 2000 and EMERALD networks related to the implementation of the Convention on the Conservation of European Wildlife and Natural Habitats (Bern Convention) (Concil of Europe, 1979).
The Bioclimatic Map of Europe	(Rivas-Martínez et al., 2014)	1:16,000,000 Vector layer	identifies the thermo-climatic belts of Europe in 5 regions, 9 subregions, 34 provinces, and 88 sub-provinces.
The Natural Vegetation map of Europe	(Bohn et al., 2004)	1:10,000,000 Vector layer	was used to map the potential range of distribution of oligotrophic soils where acidophilus oakwood can occur.
Copernicus Land Monitoring Services high-resolution layers of water and wetness Version 5	(EEA, 2018)	10 m spatial resolution Raster Grid	layers of water and wetness area
pan-European Digital Elevation Model (DEM)	https://www.eea.europa.eu/en/datahub/datahubitem-view/d08852bc-7b5f-4835-a776-08362e2fbf4b	30 arc Raster grid	Digital Elevation Model (m)
Copernicus Land Monitoring Services project Forest Types at the nominal year of 2018 *	(EEA geospatial data catalogue, 2020)	100 m Raster grid	provided classification of forest types at pixel level using four categories (0: all non-forested areas, 1: broadleaved forest, 2: coniferous forest, 3: mixed broadleaves and coniferous forests)
the European catchments and rivers network system *	(EEA geospatial data catalogue, 2012) (https://www.eea.europa.eu/data-and-maps/data/european-catchments-and-rivers-network).	Vector layer	European catchments and rivers network system available for whole area considered in this work and downloaded from the EEA Agency geodata catalogue

2.4 Data preparation

2.4.1. Development of breaking-point masks to classify EFTs.

All the layers presented in the previous section were used to create different Boolean masks (1/0) to identify the breaking points necessary to classify the EFTs categories. These breaking points identified the environmental differences between categories and were identified by a literature review following the work done by Giannetti et al. (2018), the report of EEA (2006), and the work of Barbati et al. (2014).

Some of the masks were developed in accordance with the work of Giannetti et al. (2018) (i.e. Wetlands mask, boreal mask, alpine mask, Mediterranean, Micronesian and Anatolian mask, acidophilous mask, mountain mask and inverse mountain mask), while the other masks were created using additional datasets not yet available in 2018 to improve the classification.

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In details, based on the selected geographic layers described in the section 2.3.2, eight environmental masks (Fig. 2) were created to classify the different EFTs categories as reported in Table 4

Table 4. Overview of the datasets and methodological steps used to derive the break-point masks for the EFT classification.

Mask name	EFT category(ies) supported	Input dataset(s)	Mask construction and criteria
WETLANDS MASK	11 – Mire and Swamp Forest	Copernicus High-Resolution Layer (HRL) Water	Categories "permanent wet" and "temporary wet" were extracted to identify wetland areas. Pixels classified as permanent or temporary wet were assigned value 1, all other pixels were assigned value 0.
FLOODPLAIN MASK	12 – Floodplain Forest	Copernicus HRL Water; European Catchments and Rivers Network	Permanent water bodies were extracted from the HRL Water layer and reclassified to 1 (others to 0). In addition, a buffer of 1 km was applied to the river network vector layer and merged with the HRL-derived mask to extend the area suitable for floodplain forests.
HEMIBOREAL AND ATLANTIC MASK	2 – Hemiboreal Forest	Bioclimatic Map of Europe; Biogeographic Regions of Europe	Hemiboreal regions were identified from the Bioclimatic Map of Europe following Giannetti et al. (2018) and merged with the Atlantic biogeographic region extracted from the biogeographic regions map. The resulting area was converted to a raster grid (1 = hemiboreal/Atlantic area; 0 = outside).
HEMIBOREAL CONTINENTAL MASK	2 – Hemiboreal Forest	Biogeographic Regions of Europe	The Continental biogeographic region was extracted from the biogeographic regions map and converted to a raster grid (1 = Continental region; 0 = outside).
BOREAL MASK	1 – Boreal Forest	Biogeographic Regions of Europe; Hemiboreal and Atlantic Mask	Boreal regions were extracted from the biogeographic regions map. Areas classified as hemiboreal were removed using the Hemiboreal and Atlantic Mask. The resulting area was converted to a raster grid (1 = boreal region; 0 = outside).
ALPINE MASK	3 – Alpine Forest	Biogeographic Regions of Europe	Alpine biogeographic regions were extracted and converted to a raster grid (1 = alpine region; 0 = outside).
MEDITERRANEAN, MACARONESIAN AND ANATOLIAN MASK	9 – Broadleaved Evergreen Forest; 10 – Coniferous Forests of	Biogeographic Regions of Europe	Mediterranean, Macaronesian and Anatolian biogeographic regions were extracted and converted to a raster grid (1 = target regions;

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	the Mediterranean, Anatolian and Macaronesian Regions		0 = outside).
ACIDOPHILOUS MASK	4 – Acidophilous Oak and Oak–Birch Forest	Natural Vegetation Map of Europe (Bohn et al., 2004)	Vegetation units representing the potential distribution of oligotrophic soils suitable for acidophilous oakwoods were extracted and converted to a raster grid (1 = suitable area; 0 = outside).
MOUNTAIN MASK	6 – Beech Forest	Pan-European Digital Elevation Model (DEM)	Elevation data were used following Giannetti et al. (2018). Areas below 500 m a.s.l. were classified as suitable for beech forests (1), while higher elevations were classified as 0.
INVERSE MOUNTAIN MASK	7 – Mountain Beech Forest	Pan-European Digital Elevation Model (DEM)	Areas above 500 m a.s.l. were considered suitable for mountainous beech forests and classified as 1, while areas below this threshold were classified as 0.
CONIFEROUS FOREST MASK	Multiple EFT categories	Copernicus Forest Types (100 m)	Areas classified as coniferous forest and mixed forest were extracted and merged to create a binary mask (1 = coniferous or mixed forest; 0 = other land covers).
BROADLEAVED FOREST MASK	Multiple EFT categories	Copernicus Forest Types (100 m)	Areas classified as broadleaved forest and mixed forest were extracted and merged to create a binary mask (1 = broadleaved or mixed forest; 0 = other land covers).

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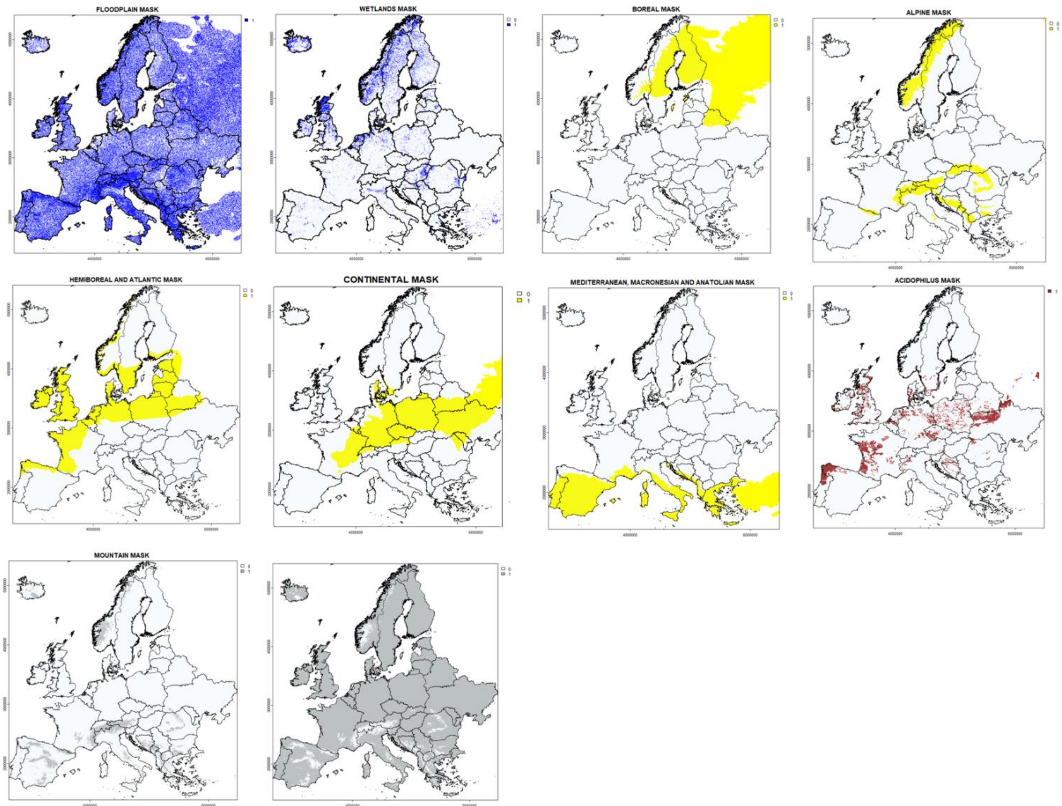

Figure 2. Environmental "Breaking point" forest masks for EFTs classification.

2.4.2 Preparation of the RPP maps for EFTs classification

Prior to their use for EFTs classification, the RPP maps were processed to convey information consistent with the maps provided by *Land Monitoring Services (Copernicus Land Monitoring Service, 2021).* The reclassification was necessary to obtain an EFTs map consistent with the "*Forest Type*" maps of the Copernicus Land Monitoring Service, which currently represent the only harmonized and operational forest type dataset available consistently across all Europe. This alignment ensures interoperability with existing pan-European datasets and facilitates the integration of the EFTs map within forest monitoring and reporting frameworks, enhancing cross-country comparability of forest indicators.

So firstly, the CONIFEROUS and BROADLEAVES FOREST MASKS were used to mask the JRC RPP. The RPP maps were firstly resampled to 100 m resolution, as the HRL Forest, and then masked in accordance with CONIFEROUS FOREST/ BROADLEAVES FORESTS MASKS. In details, the pixels of RPP maps of the broadleaved tree species belonging to coniferous forests in the masks, were forced to be equal to 0 (no probability to find the species); likewise, the pixels of the RPP maps of coniferous tree species belonging to broadleaved forest in the mask, were forced to be equal to 0 (no probability to find the species). The reclassification was necessary to obtain an EFTs map that will be consistent with the Forest Types maps of Copernicus Land Monitoring Services the only available FT maps nowadays. The resampling and masking of the RPP maps were done using R-CRAN with the libraries: *terra*, *rgdal*.

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Secondly, the RPP maps were subjected to a normalization process. Firstly, all available RPP maps by JRC were summed pixel-by-pixel, and we obtained the SUM RPP MAP. Subsequently, each RPP map corresponding to a specific species was divided into pixel-by-pixel by the SUM RPP MAP obtained before. The resulting raster was then multiplied by 100 to complete the normalization. At the end, we obtained a normalized RPP map for each tree species, which was used as input for the rules-based expert system classification algorithm. The flowchart for the preparation of RPP maps is reported in Fig. 3.

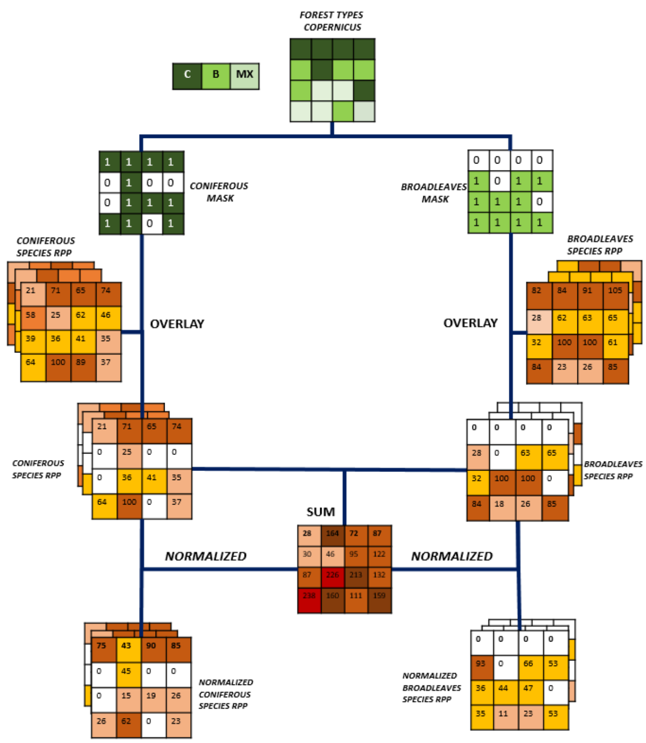

Figure 3. Flowchart of the preparation of RPP maps.

2.4.3 Pixel-level identification of dominant and co-dominant species

For each forest pixel, species-level Relative Presence Probability (RPP) values, derived by the harmonization with the Copernicus forest maps, were analysed and ranked in descending order. The two species with the highest RPP values were extracted and defined as the dominant and co-dominant species, respectively (Fig.4). These two species were selected because they jointly account for a large proportion of the forest composition at the pixel level (Fig.5).

In detail, the normalized value of probability to find a species of the RPP normalized maps was used as "dominant" information, as proposed by Giannetti et al. (2018) for beech forests. Following the previous work done by Giannetti et al., (2018) and Barbati et al. (2014), a species is considered dominant (or group of species are considered dominant) when its basal area per plot represents at least 50% of the total plot basal area. In our case, the cumulative probability of dominant and co-dominant tree species from normalized RPP maps was used as a proxy for basal area. Based on that, we found that at pixel-level statistics of cumulative RPP indicate that, for 87% of the forested area, the combined RPP of the dominant and

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co-dominant species ranges between 40% and 100% of the cumulative RPP raster (Fig.5). Based on this result, the classification strategy was revised comparing to the work done by Giannetti et al., (2018) to rely exclusively on dominant-species and co-dominant species information.

345 Accordingly, the classification rules, described in the next section, were redesigned using the species codes of the dominant and co-dominant species as the primary decision variables.

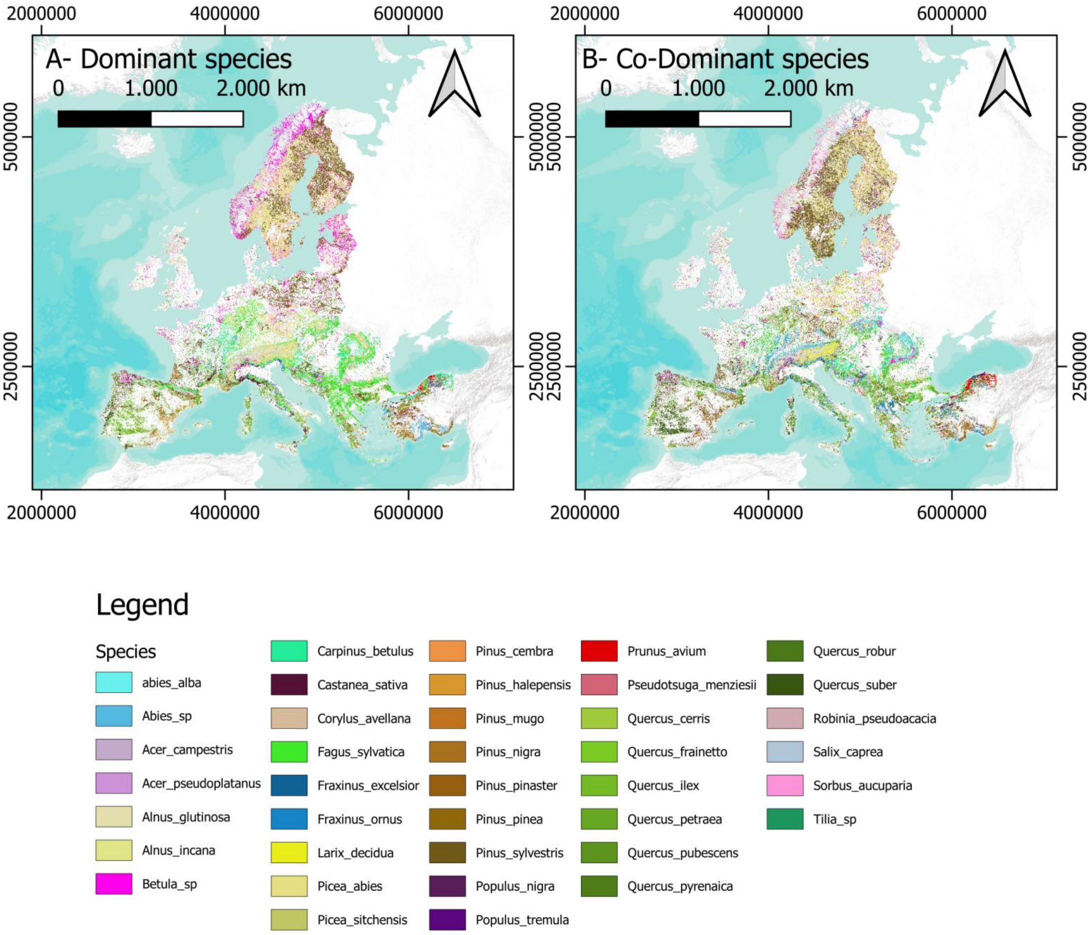

Figure 4. Dominant and co-dominant species in the based on the RPP map. The background map is powered by ESRI Source: "World Terrain Base".

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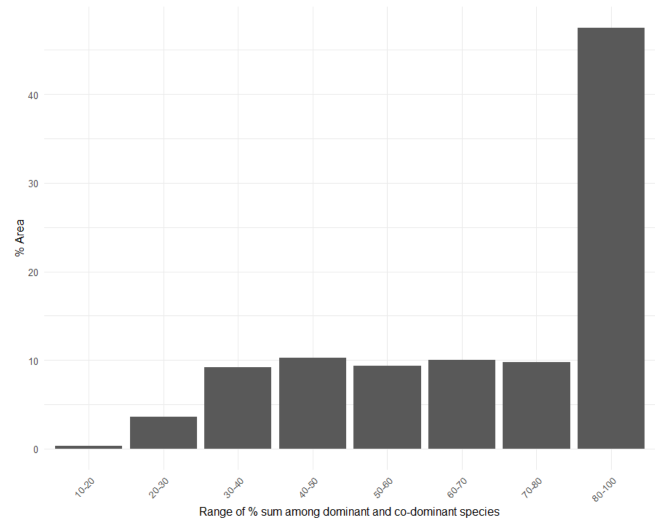

Figure 5. Distribution of forested area (%) across classes of cumulative relative percentage presence (RPP) of dominant and co-dominant species at pixel level. The histogram shows that in the majority of the study area the combined contribution of the two most abundant species exceeds 40%, highlighting a clear dominance structure in forest composition.

2.3. Rule-based algorithm

As presented in the work done by Giannetti et al. (2018), a rule-based expert system, intended as a knowledge-based system (Capelo et al., 2007; Pérez-Ortiz et al., 2016), was developed based on available datasets to create the EFTs raster grid map. This expert system is based on different recursive rules identifying the EFTs categories. The rule-based expert system algorithm uses as input data the RPP dominant and co-dominant species (section 2.4.3) to construct the classification of EFTs categories and is a revision of the one already developed by Giannetti et al. (2018) for plot level classification.

The methodological framework of the rule-based algorithm was explicitly designed to link species composition, environmental variables, and spatial consistency to support forest monitoring, modelling, and reporting applications at the European level. In particular, the development of a wall-to-wall gridded dataset ensures the spatial consistency required for cross-country comparison, as well as for the monitoring and reporting of forest indicators, and the application of forest models at spatial scale.

In details, the EFT classification was implemented through a sequential rule-based approach (Table 5), in which each pixel was evaluated against a predefined set of rules reflecting species composition and ecological context. In a first step, the classification relied on the combination of the dominant and co-dominant tree species, identified as the first and second species according to their relative probability of presence (RPP), and on the application of specific ecological or geographic masks (Fig. 6). This allowed the assignment of EFT categories primarily on the basis of species co-occurrence patterns constrained by biogeographic, bioclimatic, and physiographic conditions.

Rules were applied hierarchically, and pixels not satisfying the condition of a given rule were passed to the subsequent one. The majority of EFT categories were therefore identified using explicit combinations of dominant and co-dominant species, optionally restricted by masks representing wetlands, floodplains, boreal, alpine, Mediterranean, or other ecologically meaningful regions.

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In cases where none of the predefined combinations between dominant and co-dominant species were met (Rules 1–13), a fallback classification strategy was applied to ensure complete spatial coverage of the EFT raster grid. Under this final rule (Rule 14), pixels were classified solely based on the dominant species (i.e. the species with the highest RPP value), in combination with the applicable ecological or geographic masks. This approach allowed all pixels to be consistently assigned to an EFT category, while preserving the ecological coherence of the classification and avoiding the exclusion of valid forest types due to incomplete species combinations.

Table 5. Rule-based expert system classification rules.

Rule No.	**Category Name**	**Involved Species (dominant and co-dominant RPP)**	**Involved Masks**	**Condition**	**Assigned Category**
1	Mire and Swamp Forest	*Picea abies*, *Pinus sylvestris*, *Populus tremula*, *Betula* spp., *Quercus robur*, *Alnus glutinosa*, *Alnus incana*, *Sorbus aucuparia*	WETLANDS MASK	If the **first and second species** belong to the listed taxa **and** the pixel is within the **WETLANDS MASK**, the pixel is classified accordingly; otherwise the classification continues	11
2	Floodplain Forest	*Populus nigra*, *Betula* spp., *Alnus glutinosa*, *Alnus incana*, *Fraxinus excelsior*	FLOODPLAIN MASK	If the **first and second species** belong to the listed taxa **and** the pixel is within the **FLOODPLAIN MASK**, the pixel is classified accordingly; otherwise the classification continues	12
3	Non-Riverine Alder, Birch, or Aspen Forest	*Populus tremula*, *Betula* spp., *Alnus glutinosa*, *Alnus incana*	None	If the **first and second species** belong to the listed taxa, the pixel is classified accordingly; otherwise the classification continues	13
4	Boreal Forest	*Picea abies*, *Pinus sylvestris*, *Populus tremula*, *Betula* spp.	BOREAL MASK	If the **first and second species** belong to the listed taxa **and** the pixel is within the **BOREAL MASK**, the pixel is classified accordingly; otherwise the classification continues	1
5a	Hemiboreal and Nemoral Coniferous and Mixed	*Picea abies*, *Pinus sylvestris*, *Betula* spp., *Fraxinus excelsior*, *Pinus*	HEMIBOREAL MASK	If the **first and second species** belong to the listed taxa **and** the pixel is within the **HEMIBOREAL MASK**,	2

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	Broadleaved–Coniferous Forest	*nigra*, *Pinus pinaster*, *Abies* spp., *Quercus robur*, *Tilia* spp.		the pixel is classified accordingly; otherwise the classification continues	
5b	Hemiboreal and Nemoral Coniferous and Mixed Broadleaved–Coniferous Forest	*Picea abies*, *Pinus sylvestris*, *Pinus nigra*	HEMIBOREAL CONTINENTAL MASK	If the **first and second species** belong to the listed taxa **and** the pixel is within the **HEMIBOREAL CONTINENTAL MASK**, the pixel is classified accordingly; otherwise the classification continues	2
6	Alpine Forest	*Picea abies*, *Larix decidua*, *Betula* spp., *Pinus sylvestris*, *Pinus cembra*, *Pinus nigra*, *Abies alba*, *Pinus mugo*	ALPINE MASK	If the **first and second species** belong to the listed taxa **and** the pixel is within the **ALPINE MASK**, the pixel is classified accordingly; otherwise the classification continues	3
7a	Mountain Beech Forest	**Dominant species:** *Fagus sylvatica*	MOUNTAIN MASK	If the **first species is *Fagus sylvatica*** and the pixel is within the **MOUNTAIN MASK**, the pixel is classified accordingly	7
7b	Beech and Mixed Beech Forest	**Dominant species:** *Fagus sylvatica*; **Second species:** broadleaved taxa listed as "present" or coniferous taxa associated with beech forests	Outside MOUNTAIN MASK	If the **first species is *Fagus sylvatica*** and the pixel is **outside the MOUNTAIN MASK**: pixels are classified as **Category 6** when the second species is a broadleaved "present" taxon, or as **Category 7** when the second species is a coniferous taxon; otherwise the classification continues	6 or 7
8	Acidophilous Oak and Oak–Birch Forest	*Betula* spp., *Quercus robur*, *Quercus petraea*	ACIDOPHILOUS MASK	If the **first and second species** belong to the listed taxa, the pixel is classified accordingly; otherwise the classification continues	4
9	Coniferous	*Abies alba*, *Abies*	MEDITERRANEAN,	If the **first and second**	10

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	Forests of the Mediterranean, Anatolian and Macaronesian Regions	spp., *Pinus nigra*, *Pinus sylvestris*, *Pinus pinea*, *Pinus halepensis*, *Pinus pinaster*	MACARONESIAN AND ANATOLIAN MASK	**species** belong to the listed taxa **and** the pixel is within the **Mediterranean, Macaronesian or Anatolian mask**, the pixel is classified accordingly; otherwise the classification continues	
10	Broadleaved Evergreen Forest	*Quercus ilex*, *Quercus suber*	MEDITERRANEAN, MACARONESIAN AND ANATOLIAN MASK	If the **first and second species** belong to the listed taxa **and** the pixel is within the **Mediterranean, Macaronesian or Anatolian mask**, the pixel is classified accordingly; otherwise the classification continues	9
11	Thermophilous Deciduous Forest	*Quercus cerris*, *Quercus frainetto*, *Quercus pubescens*, *Quercus pyrenaica*, *Tilia* spp., *Acer campestre*, *Fraxinus ornus*, *Castanea sativa*	None	If the **first and second species** belong to the listed taxa, the pixel is classified accordingly; otherwise the classification continues	8
12	Mesophytic Deciduous Forest	*Quercus robur*, *Quercus petraea*, *Carpinus betulus*, *Fraxinus excelsior*, *Tilia* spp., *Acer pseudoplatanus*, *Acer campestre*	None	If the **first and second species** match one of the predefined species combinations (e.g. *Q. robur* + *C. betulus*; *Q. petraea* + *C. betulus*; *F. excelsior* + *Q. robur* with *Acer*/*Tilia*), the pixel is classified accordingly; otherwise the classification continues	5
13	Non-native Forest	*Pseudotsuga menziesii*, *Robinia pseudoacacia*, *Picea sitchensis*	None	If the **first and second species** belong to the listed taxa, the pixel is classified accordingly	14
14	**Dominant-species-based classification (fallback rule)**	**Dominant species only (highest RPP)**	Applicable ecological and geographic masks (biogeographic, bioclimatic, alpine,	If the predefined combination between the first and second species does **not** match any of the taxa combinations	According to dominant species and

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			boreal, Mediterranean)	specified in Rules 1–13, the pixel is classified based on the dominant species in combination with the applicable ecological or geographic masks	mask

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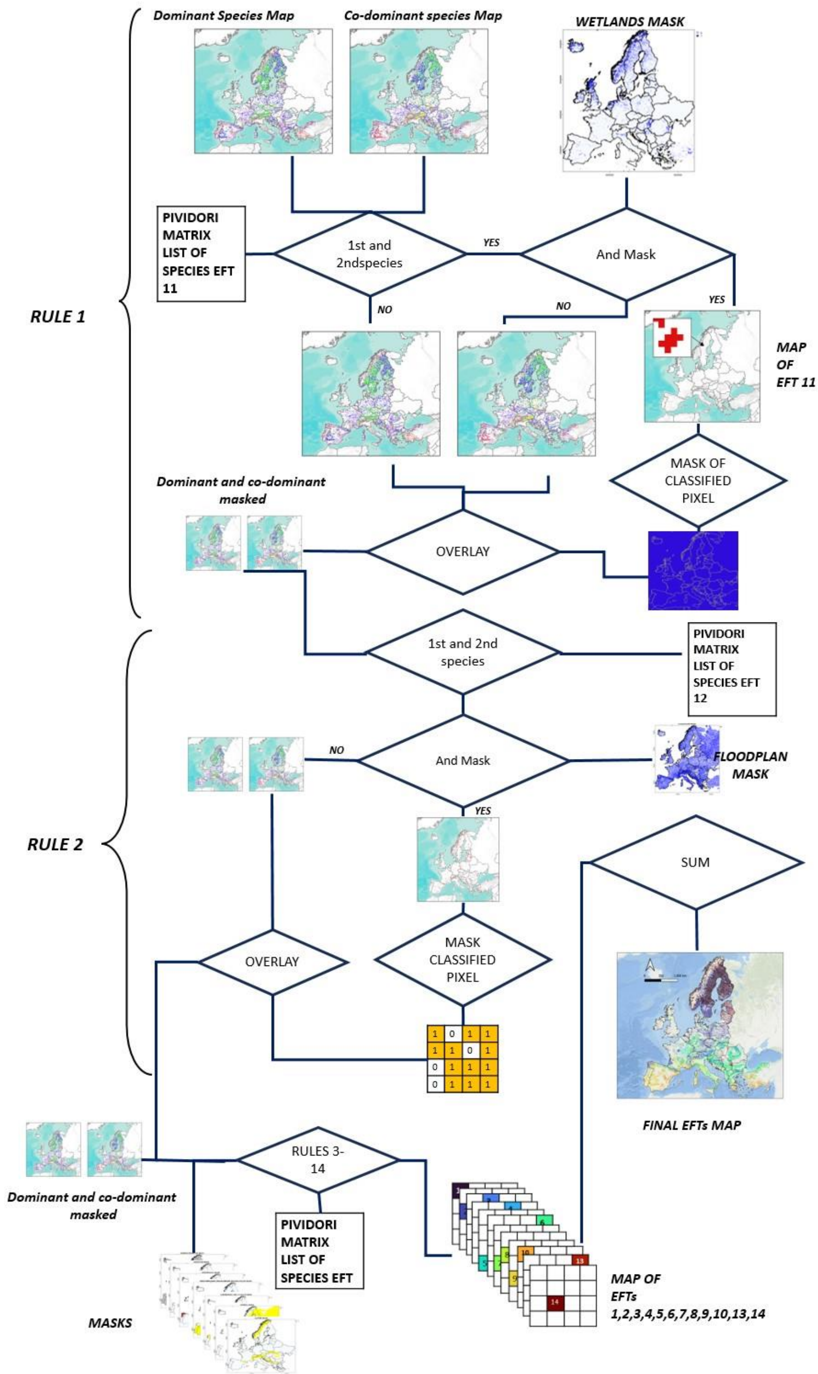

385 **Figure 6.** Overview of the flowchart of the Rule-based algorithm with the details of the geoprocessing of the first two rules. The background map is powered by ESRI Source: "World Terrain Base".

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3. Results

The rule-based expert system enables the classification of all EFTs categories in the forested pixels (Figure 7)

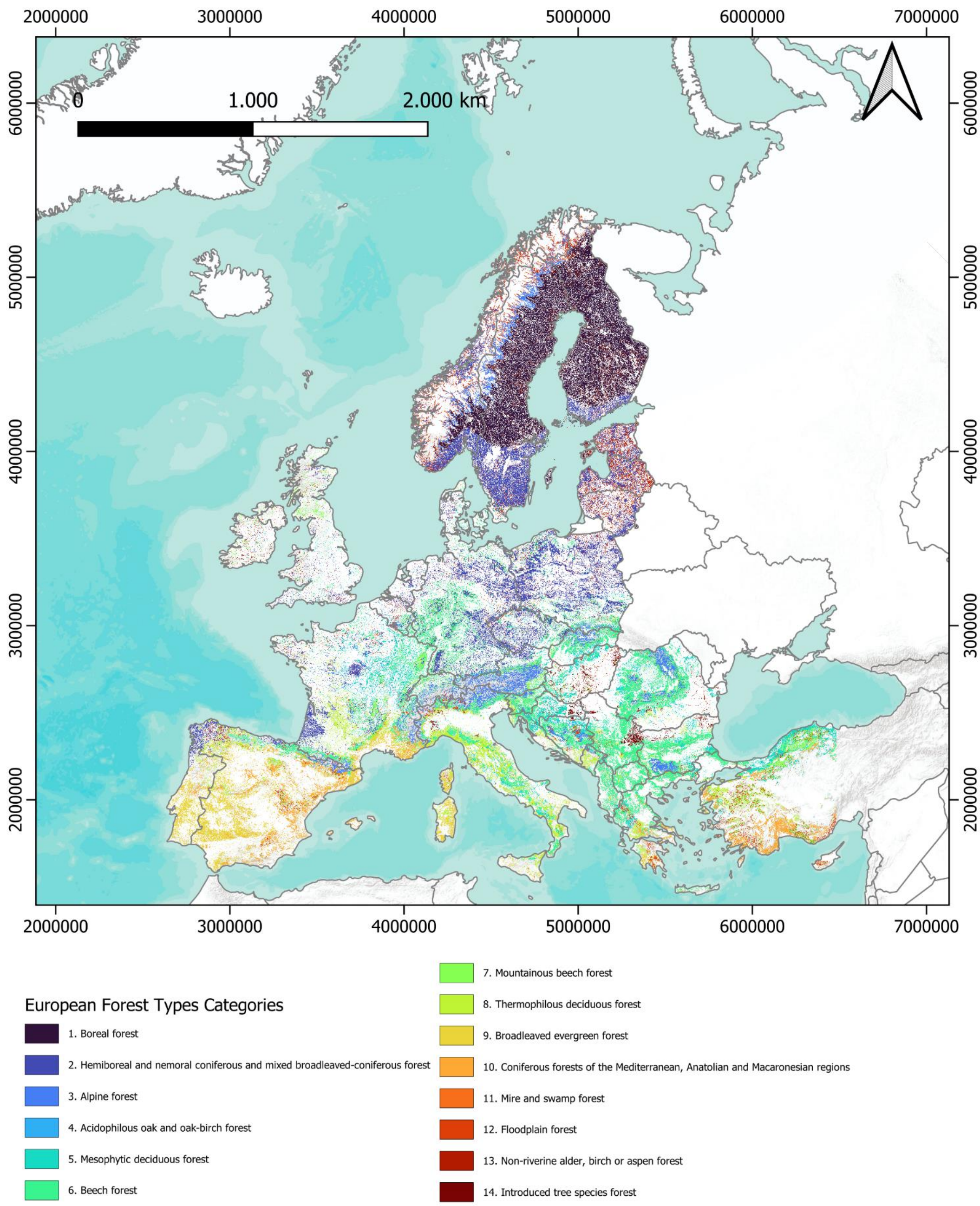

Figure 7: European Forest Types gridded dataset map. The background map is powered by ESRI Source: "World Terrain Base".

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The area and the percentage of forest area covered by each EFT category were extracted based on the pixel level classification. In the total forested area of Europe, category 2 – Hemiboreal and Nemoral Coniferous and Mixed Broadleaved-Coniferous Forest covers the largest area, representing 19.61% of the total forested area, followed closely by 1 – Boreal Forest (19.17%). Other major categories include 6 – Beech Forest (17.95%), 3 Alpine Forest (7.29%), and 12 – Floodplain Forest (7.56%). Smaller contributions are observed for 8 – Thermophilous Deciduous Forest (5.92%), 9 – Broadleaved Evergreen Forest (5.88%), 5 – Mesophytic Deciduous Forest (5.28%), 7 – Mountain Beech Forest (3.74%), 10 – Coniferous Forests of the Mediterranean, Anatolian and Macronesian Regions (3.20%), 13 – Non Riverine Alder, Birch or Aspen Forest (2.26%), 14 – Non-native Forest (1.10%), 11 – Mirne and Swamp Forest (0.38%), and 4 – Acidophilous Oak and Oak-Birch Forest (0.66%) (Fig. 8 and 9).

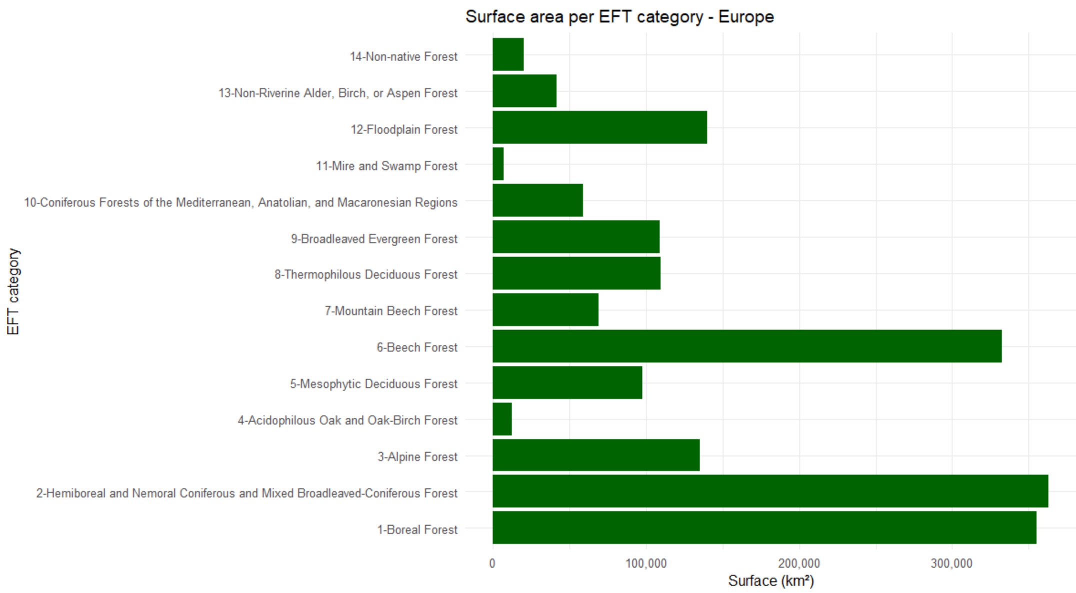

Figure 8: Resulted forested area (km^2) for each EFTs category

In Northern Europe, 1 – Boreal Forest accounted for the largest forested area (52.3%), followed by 2 – Hemiboreal and Nemoral Coniferous and Mixed Broadleaved-Coniferous Forest (21.6%) and 13 – Non-Riverine Alder, Birch, or Aspen Forest (12.5%) (Fig. 9).

In Central-East Europe, the dominant categories were 12 – Floodplain Forest (31.2%), 2 – Hemiboreal and Nemoral Coniferous and Mixed Broadleaved-Coniferous Forest (30.7%), and 3 – Alpine Forest (9.9%). Similarly, in Central-West Europe, the largest forested areas were 2 – Hemiboreal and Nemoral Coniferous and Mixed Broadleaved-Coniferous Forest (30.6%), 12 – Floodplain Forest (23.4%), and 7 – Mountain Beech Forest (10.2%) (Figure 9). Central-West Europe exhibited the highest diversity, with 10 out of 14 EFTs categories present (Fig. 9).

In South-West Europe, 10 – Coniferous Forests of the Mediterranean, Anatolian, and Macaronesian Regions covered the largest area (32.9%), followed by 8 – Thermophilous Deciduous Forest (21.3%), 3 – Alpine Forest (15.4%), and 5 – Mesophytic Deciduous Forest (3.8%) (Fig. 9).

In South-East Europe, 12 – Floodplain Forest dominated the landscape (57.0%), followed by 5 – Mesophytic Deciduous Forest (12.0%), 8 – Thermophilous Deciduous Forest (6.9%), and 3 – Alpine Forest (5.9%) (Fig. 9).

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The comparison between the FOREST EUROPE dataset and the EFTs Map (Fig. 10) highlights some discrepancies in the relative share of forest categories across European regions. Since the variation was calculated as *FOREST EUROPE – EFTs Map*, positive values indicate that FOREST EUROPE reports a higher share of forest area for a given class, while negative values denote a higher share in the EFTs Map (Fig. 10)

In Northern Europe, the strongest positive deviations are observed for 11 – Mire and Swamp Forest (+12.0%) and 13 – Non-Riverine Alder, Birch, or Aspen Forest (+6.8%), suggesting that FOREST EUROPE attributes a larger extent to these categories compared to the EFTs Map. Conversely, 12 – Floodplain Forest (−12.5%) shows a substantial underestimation in the FOREST EUROPE data relative to the EFTs Map, pointing to possible misclassifications between these closely related categories.

In Central-Western Europe, the most notable discrepancies are a sharp underestimation of 6 – Beech Forest (−16.4%) in FOREST EUROPE and strong overestimations in 5 – Mesophytic Deciduous Forest (+8.6%) and 14 – Non-native Forest (+9.3%). This indicates that the two sources diverge, especially in mid-successional or mixed-type forest classes.

In South-Western Europe, differences are more balanced, though still significant. The EFTs Map reports considerably more area for 6 – Beech Forest (−10.0%) and 9 – Broadleaved Evergreen Forest (−8.9%), while the FOREST EUROPE data shows relatively higher proportions for 10 – Coniferous Forests of the Mediterranean, Anatolian, and Macaronesian Regions (+4.6%) and 14 – Non-native Forest (+3.6%).

In South-Eastern Europe, discrepancies reach particularly high values. FOREST EUROPE underestimates 6 – Beech Forest (−42.0%) but largely overestimates 8 – Thermophilous Deciduous Forest (+21.1%) and 7 – Mountain Beech Forest (+11.3%) compared to the EFTs Map. These strong differences suggest systematic issues in the harmonization of forest types in this region.

In Central-Eastern Europe, the most remarkable contrasts include a substantial underestimation of 6 – Beech Forest (−28.2%) in FOREST EUROPE, while 2 – Hemiboreal and Nemoral Coniferous and Mixed Broadleaved-Coniferous Forest (+16.3%) and 13 – Non-Riverine Alder, Birch, or Aspen Forest (+8.0%) are strongly overrepresented. This again highlights potential mismatches in classification schemes between the two datasets.

At the European aggregate level, results confirm these patterns: FOREST EUROPE reports substantially less area for 6 – Beech Forest (−16.7%) and 3 – Alpine Forest (−4.3%), while it assigns more area to 4 – Acidophilous Oak and Oak-Birch Forest (+6.3%), 11 – Mire and Swamp Forest (+6.2%), and 14 – Non-native Forest (+2.5%).

Overall, the analysis shows that discrepancies are not randomly distributed but are instead concentrated in a few specific EFT categories (particularly 6 – Beech Forest, 8 – Thermophilous Deciduous Forest, and 11 – Mire and Swamp Forest).

In supplement materials, the percentage of forest area for each EFTs category in each country is reported (Supplement Tab.S1), while Fig.10 presents the difference between the percentage of forest area from the FOREST EUROPE 2011 report (tab.1) and that derived from the EFTs gridded dataset for each country.
The analysis of percentage differences in forest area between the FOREST EUROPE 2011 report and the EFTs gridded dataset highlights several patterns across European countries (Fig. 11). In Figure 11 Positive values indicate that FOREST EUROPE reported a larger forest area for a category compared to EFTs, while negative values reflect that EFTs estimated a larger forest area compared to the report.

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Austria shows moderate differences, with FOREST EUROPE reporting significantly more area in category 2 (+21%) and less area in category 3 (-29%) relative to EFTs, while other categories remain stable.

Belgium exhibits large differences in category 2 (-38%) and category 12 (-15%), while FOREST EUROPE reports much more area in category 14 (+42%).

Bulgaria has strong underestimation by EFTs in category 6 (-47%), while FOREST EUROPE reports more area in categories 2 and 3 (+8–9%) and especially in category 8 (+41%).

Croatia shows EFTs underestimation in categories 5 (-20%) and 6 (-24%), while FOREST EUROPE reports much more area in category 7 (+28%).

Cyprus presents extreme variation: category 10 shows FOREST EUROPE reporting +94% more area, while EFTs overestimates in category 12 (-80%) and category 7 (-11%).

Czech Republic shows moderate fluctuations, with FOREST EUROPE reporting more area in category 3 (+15%) and EFTs slightly overestimating in categories 2, 4, 6, 7, and 12.

Denmark has notable underestimation by EFTs in category 2 (-31%) and 6 (-18%), while FOREST EUROPE reports significantly more area in category 14 (+47%).

Estonia exhibits large FOREST EUROPE overestimations in category 1 (+37%) and category 13 (+15%), and EFTs overestimations in category 2 (-44%) and category 12 (-21%).

Finland shows minor deviations, with EFTs underestimating in category 1 (-14%) and 12 (-6%) and FOREST EUROPE reporting more in category 11 (+19%).

France shows moderate variations, with FOREST EUROPE reporting more area in category 4 (+10%) and EFTs underestimating in category 6 (-18%).

Germany exhibits minor positive and negative differences, with the largest EFTs underestimation in category 6 (-19%) and slight FOREST EUROPE overestimations in categories 5 (+14%) and 11 (+3%).

Hungary shows large EFTs underestimation in category 5 (-20%) and significant FOREST EUROPE overestimation in category 14 (+26%).

Ireland presents significant EFTs underestimations in category 7 (-37%) and 12 (-20%), but very large FOREST EUROPE overestimation in category 14 (+68%).

Italy has moderate EFTs underestimation in categories 5 (-8%) and 6 (-21%), with FOREST EUROPE reporting more area in categories 7 (+9%) and 10 (+3%).

Latvia shows FOREST EUROPE overestimations in categories 1 (+12%) and 11 (+7%) and EFTs underestimation in category 12 (-24%).

Lithuania exhibits large FOREST EUROPE overestimation in category 11 (+16%) and EFTs underestimation in category 12 (-20%).

Netherlands shows strong EFTs underestimation in category 2 (-43%) and 12 (-9%), with FOREST EUROPE reporting more area in categories 4 (+11%), 5 (+15%), and 14 (+25%).

Norway presents large FOREST EUROPE overestimation in category 1 (+35%), while EFTs underestimates in category 12 (-30%).

Poland has minor deviations, with EFTs underestimation in category 6 (-11%) and slight FOREST EUROPE overestimation in categories 5 and 13 (+8%).

Slovakia shows strong EFTs underestimation in category 6 (-28%) and small FOREST EUROPE overestimations in categories 2 (+7%) and 7 (+4%).

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Slovenia displays EFTs underestimation in categories 3 (-14%) and 6 (-16%), while FOREST EUROPE reports more area in category 7 (+15%).

Spain shows EFTs underestimation in category 9 (-13%), with FOREST EUROPE reporting more area in categories 4, 10, and 14.

Sweden shows minor deviations, with FOREST EUROPE reporting more area in category 11 (+9%) and EFTs underestimating in categories 1 (-6%) and 12 (-7%).

Switzerland has notable EFTs underestimations in categories 6 (-16%) and 7 (-11%), with FOREST EUROPE reporting more in categories 2 (+12%) and 5 (+10%).

U.K. of Great Britain and Northern Ireland shows large EFTs underestimations in categories 2 (-28%) and 7 (-29%), while FOREST EUROPE reports much more area in category 14 (+47%).

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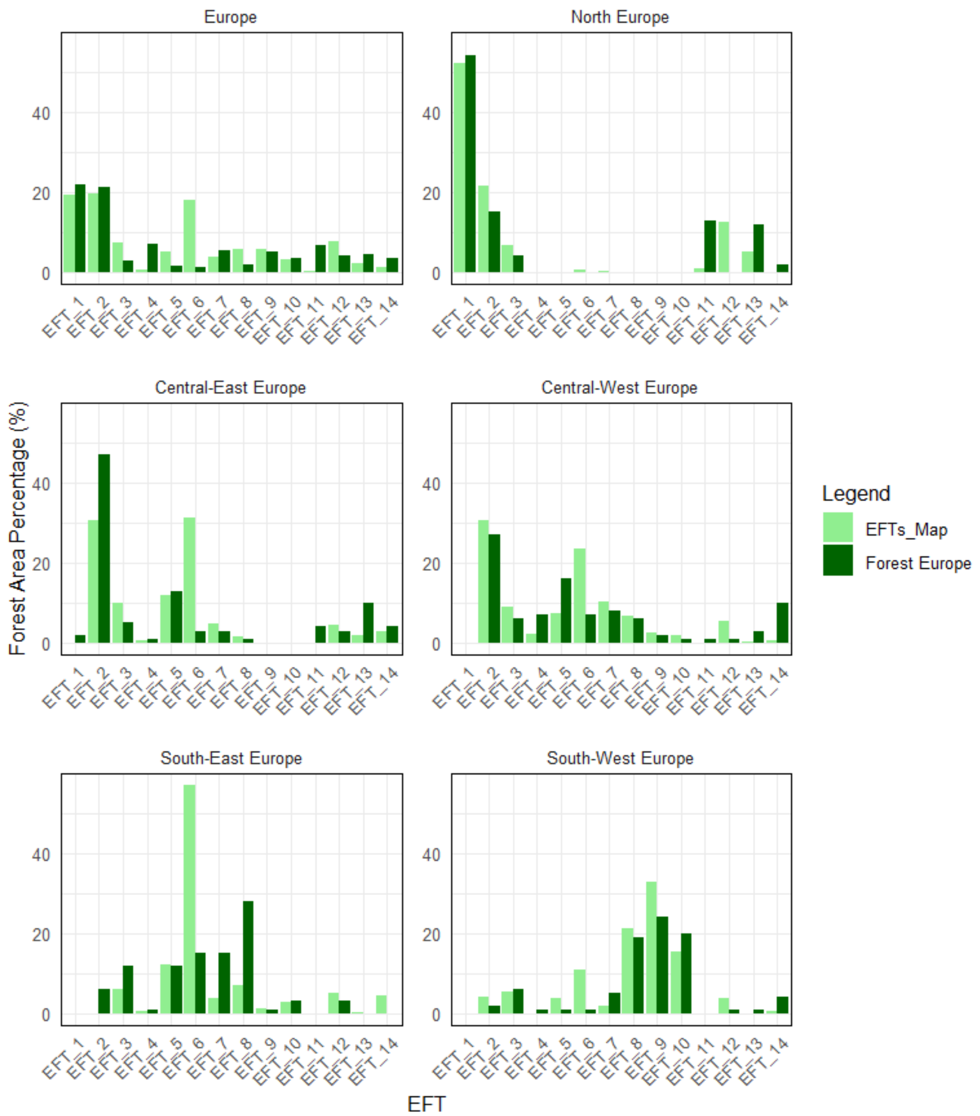

510 **Figure 9: Comparison between the forested area for each EFTs categories based on the State of Europe's Forests 2011 report (dark green) and EFTs map (light green) for all Europe and for the 5 identified geographic area: Central-east Europe, Central-West Europe, North Europe, South-East Europe, South-West Europe.**

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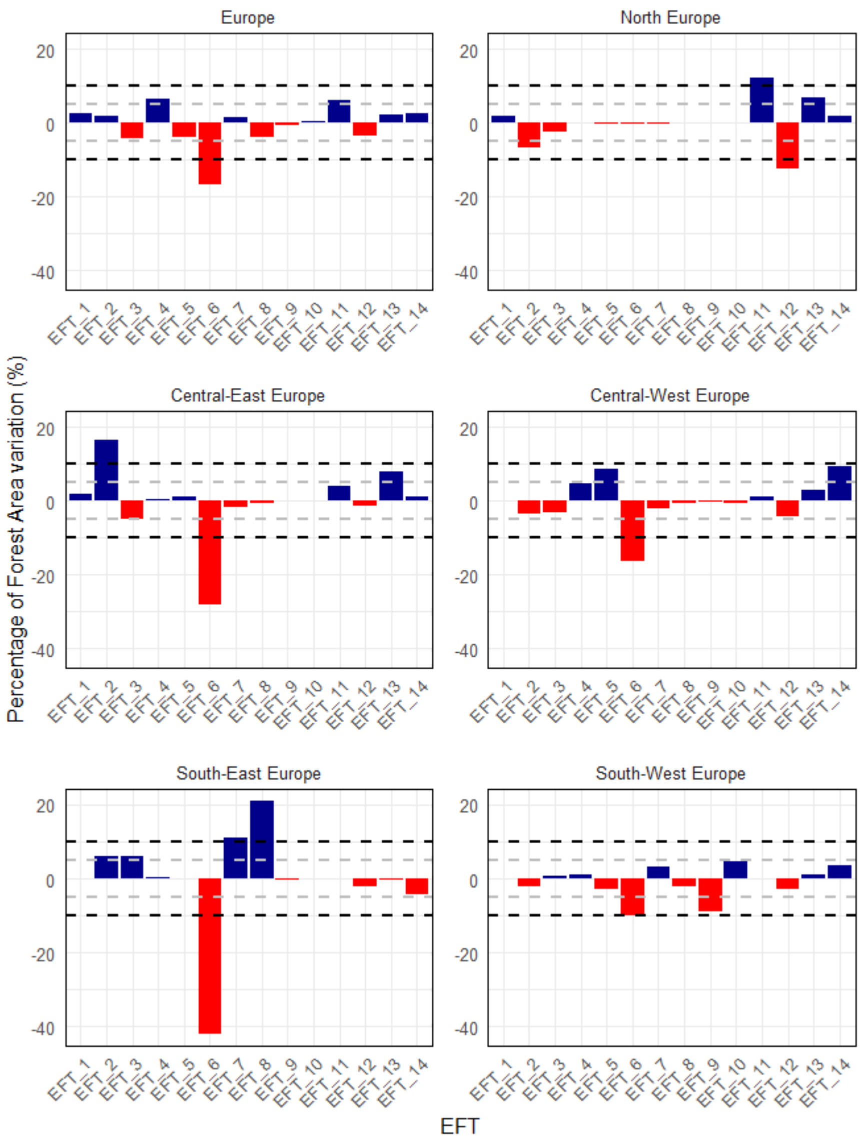

515 **Figure 10: Percentage variation in the forested area for each EFT category, based on the State of Europe's Forests 2011 report and the EFTs map, for Europe as a whole and for the five geographic regions: Central-East Europe, Central-West Europe, Northern Europe, South-Eastern Europe, and South-Western Europe. The grey lines indicate the range between −5% and +5%, while the black lines indicate the range between −10% and +10%. Red bars highlight where the EFTs map reports larger areas compared to FOREST EUROPE data, whereas blue bars indicate where FOREST EUROPE reports larger areas.**

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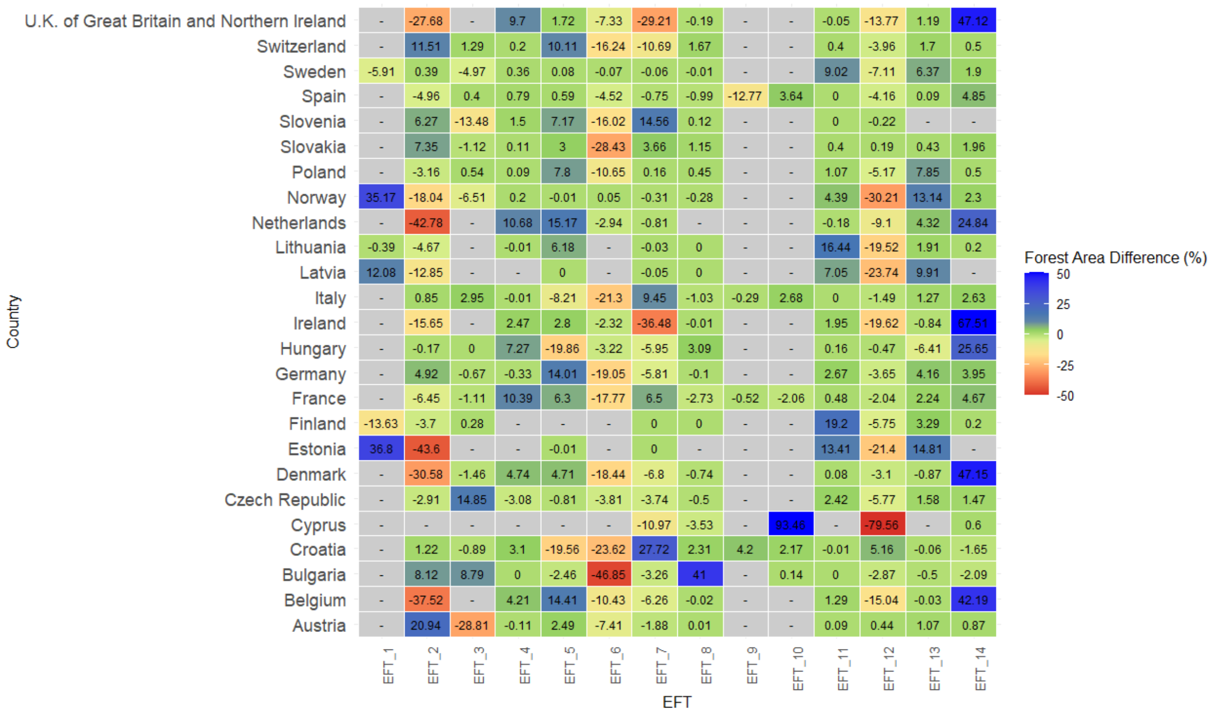

Figure 11: Percentage differences between the forest area reported in State of Europe's Forests 2011 (Table 1) and the EFTs gridded dataset, by country (Annex 2). Negative values indicate that the EFTs gridded dataset overestimates forest area relative to the State of Europe's Forests 2011 report, whereas positive values indicate an underestimation.

4. Discussion

This study shows that through the integration of existing geographic layers with data on species composition, specifically RPP maps, it is feasible to consistently classify EFTs in 14 categories in a spatially explicit manner across pan-European regions, as showed by Giannetti et al. (2018) for plot level data.

The present discussion focuses on two main aspects. The first part compares the data obtained through the developed EFTs map gridded dataset with the ones reported in the State of Europe's Forests 2011 report (Forest EuropeFOREST EUROPE, UNECE and FAO, 2011). The second part concentrates on the usability of this gridded dataset in the context of sustainable forest management reporting, modeling, and forest ecosystem monitoring.

The comparison between FOREST EUROPE data and the EFTs gridded dataset reveals that eight categories (1, 2, 4, 7, 10, 11, 13, and 14) have higher area values in the State of Europe's Forests 2011 report. Conversely, the opposite trend is observed for the remaining categories (3, 5, 6, 8, 9, and 12).

By comparing the percentages of area for each EFT category derived from the developed EFTs gridded dataset maps with the State of Europe's Forests 2011 report, where the corresponding EFT area percentages are available, some differences can be observed between results presented here and those reported in 2011 for pan-Europe level across the different geographic areas (Fig. 9) and countries (Fig. 11) .

Significant discrepancies in the percentage of area for each EFTs are found, however, only in a few instances: Category 6 (Beech forests) shows a notable overestimation of 16.7 %, while Categories 4 (Acidophilous deciduous forest) and 11 (Mire and swamp forest) exhibit underestimations of 6.3% and 6.2% respectively.

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Both the State of Europe's Forests 2011 report and the EFTs gridded dataset map indicate category 1 and 2 cover the largest area at the pan-European level, with the EFTs dataset showing a decrease compared to the State of Europe's Forests 2011 report of 2.72 for category 1 and of 1.79 for category 2 (Fig.10). Considering the category 2 species of composition, it can be presumed that these forests might be reclassified into categories 7 and 6. This inference is supported by the tree species matrix (Pividori et al., 2016), where categories 2, 7, and 6 exhibit overlapping species composition.

In fact, category 6 also exhibits the largest discrepancies between the *State of Europe's Forests 2011* dataset and the EFT gridded dataset. The most pronounced regional differences are observed in South-East Europe, where category 6 is overestimated by the EFT gridded dataset by approximately 42.0%. This overestimation is accompanied by substantial underestimations of thermophilous deciduous forests (category 8, −21.1%), mountain beech forests (category 7, −11.3%), alder, birch, and aspen forests (category 13, −6.1%), as well as hemiboreal and nemoral mixed forests (category 2, −5.9%).

These discrepancies can be largely attributed to the extensive overlap in species composition among categories 2, 6, 7, and 8, which share several dominant or co-dominant taxa, including *Quercus* spp., *Betula* spp., *Alnus* spp., *Populus tremula*, and *Fagus sylvatica*. In the case of category 2, the observed underestimation may also be explained by the fact that South-East Europe does not fall within the hemiboreal zone, which may further contribute to differences in forest type attribution between the two datasets.

A similar, though less extreme, pattern is observed in Central-East Europe, where category 6 is overestimated by 28.2%, while category 2 (-16.3%) and category 13 (-8.0%) are strongly underestimated by EFTs. This further supports the hypothesis that, in transitional biogeographical zones, differences in the application of hemiboreal masks and species-ranking criteria can systematically shift forest areas from composition-specific categories into broader conditional classes.

Categories 4 and 5 represent deciduous forest types defined by relatively specific species combinations, which contributes to a more stable behavior of these categories across regions when compared with more conditional classes such as category 6. Category 4 (acidophilous oak and oak–birch forests) is primarily characterized by the presence of *Quercus robur*, *Quercus petraea*, and *Betula* spp., and its assignment is further constrained by the application of the acidophilous mask. Category 5 (mesophytic deciduous forests) relies on predefined species combinations involving *Quercus* spp., *Carpinus betulus*, *Fraxinus excelsior*, *Tilia* spp., and *Acer* spp., without the use of mandatory geographic masks.

At the European scale, both categories show moderate variations, with category 4 being underestimated by the EFT gridded dataset (-6.3%) and category 5 slightly overestimated (+3.8%). This overall stability suggests that the rule-based definitions of these categories effectively capture broad deciduous forest types across Europe. However, regional patterns reveal more nuanced dynamics.

In Central-West Europe, category 5 is notably underestimated by EFTs (-8.6%), while category 4 is also underestimated (-4.7%). This pattern suggests that forests dominated by mesophytic deciduous species may be partially reassigned to broader mixed categories when the exact species combinations required by Rule 12 are not fully satisfied. In contrast, in South-East Europe, category 4 shows only minor variation (+0.5%), whereas category 5 is slightly overestimated (−0.03%), indicating a relatively robust classification of deciduous forests in this region despite the high variability observed in other categories.

In Northern Europe, category 4 exhibits negligible variation (−0.02%), reflecting the limited extent of acidophilous oak and oak–birch forests in boreal contexts, while category 5 shows a modest overestimation (−0.12%). In South-West Europe, category 4 is slightly underestimated (+1.0%), and category 5 is overestimated (−2.8%), a pattern that may reflect the coexistence of thermophilous and mesophytic deciduous species and the sensitivity of dominant–co-dominant species ranking in transitional Mediterranean environments.

Categories 9 and 10 represent forest types that are primarily defined within the Mediterranean, Macaronesian, and Anatolian biogeographical contexts and are both constrained by the same geographic masks. Category 9 (broadleaved evergreen forests) is dominated by *Quercus ilex* and *Quercus suber*, whereas category 10 (Mediterranean, Anatolian, and Macaronesian coniferous forests) is characterized by several *Pinus* species and *Abies* spp. The reliance on shared regional masks but

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distinct dominant species makes these two categories particularly sensitive to differences in dominant-species attribution depend on the RPP map.

At the European scale, both categories show relatively limited variation, with category 9 being overestimated by the EFT gridded dataset (−0.7%) and category 10 slightly underestimated (+0.4%). This overall balance suggests a reasonable consistency between the two datasets when aggregated at a continental level. However, regional patterns reveal more pronounced discrepancies.

In South-West Europe, category 9 is substantially overestimated by the EFT gridded dataset (+8.9%), while category 10 is underestimated (-4.6%). This contrasting behavior likely reflects differences in the identification of dominant species within the same Mediterranean mask.

In South-East Europe, variations for both categories are relatively limited, with category 9 showing a slight overestimation (−0.27%) and category 10 with a marginal underestimation (+0.08%). This indicates a more stable attribution of Mediterranean forest types in this region.

Categories 11, 12, and 13 represent forest types that are strongly influenced by hydrological conditions and species composition, and their classification within the EFT framework depends to a large extent on the application of specific geographic masks. Category 11 (mire and swamp forests) and category 12 (floodplain forests) are explicitly constrained by the wetlands and floodplain masks, respectively, whereas category 13 (non-riverine alder, birch, and aspen forests) is defined solely by species composition and is applied when these hydrological masks are not triggered.

At the European scale, category 11 is underestimated by the EFT gridded dataset (-6.2%), while category 12 is overestimated (+3.4%) and category 13 slightly underestimated (-2.2%). These moderate discrepancies suggest that differences in the spatial extent and delineation of wetland- and floodplain-related masks between the EFT gridded dataset and the State of Europe's *Forests 2011* report may play a significant role in determining the final category assignment.

In Northern Europe, the strongest discrepancies are observed, with category 11 being markedly overestimated by the EFT gridded dataset (+12.0%) and category 12 correspondingly underestimated (-12.5%). This near-compensatory pattern strongly indicates that forest areas characterized by similar species assemblages (*Alnus spp.*, *Betula spp.*, *Populus tremula*) may be alternately classified as mire/swamp or floodplain forests depending on the mask applied, rather than reflecting substantive differences in forest composition.

In Central-West Europe, category 12 is overestimated (+4.3%), while categories 11 (-0.9%) and 13 (+2.8%) are underestimated. This pattern suggests that the floodplain mask in the EFT gridded dataset may capture a broader set of riparian forest conditions compared to national statistics, leading to a redistribution of forest area from species-based category 13 toward mask-based category 12.

In South-West and South-East Europe, variations for categories 11 and 12 are generally limited, reflecting the more restricted spatial extent of wetland and floodplain environments. However, in South-East Europe, category 13 is notably underestimated (-6.1%), suggesting that forests dominated by *Alnus*, *Betula*, and *Populus* outside clearly defined wetland or floodplain masks may be partially absorbed into other broadleaved categories within the EFT classification.

Overall, these results indicate that a substantial portion of the discrepancies observed for categories 11, 12, and 13 can likely be attributed to differences in the definition and application of masks (i.e. WETLAND MASK and FOODPLANE MASK).

Category 8, corresponding to thermophilous deciduous forests, is defined by a specific set of broadleaved species, including *Quercus cerris*, *Quercus frainetto*, *Quercus pubescens*, *Quercus pyrenaica*, *Tilia* spp., *Acer campestre*, *Fraxinus ornus*, and *Castanea sativa*, and does not rely on mandatory geographic masks. As a result, its classification depends primarily on the correct identification of dominant and co-dominant species, making this category particularly sensitive to differences in species-ranking between datasets.

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At the European scale, category 8 is moderately overestimated by the EFT gridded dataset (−3.9%), indicating a slight tendency of EFTs to assign thermophilous deciduous species to this category more frequently than reported in the State of Europe's *Forests 2011 report*. However, this overall pattern masks substantial regional variability.

In South-East Europe, category 8 is strongly underestimated by the EFT gridded dataset (+21.1%), representing one of the largest discrepancies observed among all forest types. This underestimation occurs in parallel with a marked overestimation of category 6 in the same region, suggesting a redistribution of forest area from thermophilous deciduous forests into broader mixed categories when species overlap is high. Given that several species defining category 8, particularly *Quercus* spp. and *Tilia* spp., also occur as secondary or co-dominant species in other deciduous and mixed forest categories, differences in dominant–co-dominant species assignment may substantially affect the final classification.

In Central-West and South-West Europe, variations for category 8 are more limited (−0.6% and −2.3%, respectively), indicating a relatively consistent representation of thermophilous deciduous forests by the EFT gridded dataset in regions where these forest types are well established and spatially coherent. In Northern and Central-East Europe, variations are negligible, reflecting the marginal occurrence of thermophilous deciduous species in these biogeographical contexts.

At the country level (fig.9), inconsistencies can be attributed to the shift from one category to another as alredy described above.

However some of the inconsistencies between the EFTs map and the State of Europe's Forests 2011 report can be attributed to the fact that at the time when the FOREST EUROPE pilot approach was used for reporting sustainable forest management indicators by EFTs categories, clear rules establishing connections between tree species composition and forest categories were not available, as highlighted by Giannetti et al. (2018). In fact, the tree species matrix, which associates each species with the correct categories, as presented in the European Atlas of Forest Tree Species, was developed five years later by Pividori et al. (2016). Moreover, Giannetti et al. (2018) found that 63% of the ICP Biosoil plots - particularly in the categories 4, 5, 6 and 8 - had some inconsistencies between dominant species, as quantified by basal area data, and the EFT category identified in the field. So, it is possible that this misclassification affects also the results reported in the State of Europe's Forests 2011 report, since they were based on plot level data that comprise also ICP Biosoil plots.

The current EFT map contains potential errors that may be significant at a local scale, particularly where cumulative probabilities are low and 1 km resolution RPP maps introduce inherent uncertainties. Nevertheless, our results provide a pioneering example of how European-level data can be synthesized into a consistent pan-European EFT cartographic product suitable for various applications. In fact, the EFTs map represents a significant advancement, bridging a critical gap in spatial monitoring, modelling, and reporting of indicators for sustainable forest management. The resulting EFT maps not only serve as a foundational tool for classifying forest areas but also provide systematic means to support forest monitoring and reporting to aid decision-making processes, particularly concerning forest-based adaptation and mitigation strategies, natural disaster precautionary measures, forest biodiversity maintenance and enhancement, renaturation activities and others. These maps are poised to be instrumental in guiding future initiatives focusing on sustainable forest management practices. Indeed, as demonstrated by Barbati et al. (2014), the use of EFTs can enhance question-driven forest monitoring in various ways. EFT-based reporting facilitates the interpretation of variability in sustainable forest management and explicitly for forest biodiversity indicators by allowing for the explicit consideration of ecological differences between EFTs, which cannot be captured using simplistic categories such as broadleaves, coniferous, or mixed as in the Plant Functional Types (PFTs) classification, as used by many vegetation/land surface models. In this regard, the EFTs map can be easily updated with the availability of new RPP maps or when a comprehensive map of forest tree species, including quantitative data on their presence and mixture, becomes accessible. As a result, temporal trends in forest areas can be analyzed to comprehend the expansion or loss of habitats in the context of climate change induced disturbances. In fact, the developed EFTs map, and future update of such map, has the potential to facilitate the monitoring of forest biodiversity indicators across different temporal scales. From a modeling perspective of forest ecosystems, utilizing the EFTs map instead of individual species

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reduces the number of input parameters needed to initialize models and then the associated uncertainty (Dalmonech et al., 2024). In fact, as demonstrated in numerous forest, vegetation/land surface model applications (e.g. Huber et al., 2018; Zaehle et al., 2005, Collalti et al., 2019; Massoud et al., 2019; Dunkl et al., 2023), at increasing the number of model parameters uncertainty increases, thus, the aggregation of functional types/species enables a reduction in the number of species to simulate and in the required input data and species-level (or PFTs-level) parameters for each model while ensuring consistent results across large scales. Furthermore, this aggregation has implications for the computational workload of such models, as it requires less parameterization (if compared to the species-level ones), facilitating a more user-friendly implementation. Furthermore, the adoption of a common classification system across pan-Europe enables uniform parameterization of models continent-wide, eliminating the need for merging or harmonizing national/local data. In the context of forest modeling, especially for the Species Distribution Modelling, the EFTs maps serve as a valuable dataset, contributing to the attainment of consistent and comparable data across Europe or to apply forest models at different and more broader spatial scale in conjunction with others data and forest variables maps (Chirici et al., 2022; Dalmonech et al., 2024; Giannetti et al., 2022; Grünig et al., 2024, 2026; Vangi et al., 2023). Moreover, the EFTs map will also support the reporting obligations that will arise in connection with the Draft EC Forest Monitoring Regulation (European Commission, 2023). However, this approach has several limitations. The use of Boolean masks derived from vector data introduces mapping artifacts, such as unrealistically sharp boundaries. At present, no alternative datasets are available that allow for more accurate identification of environmental transition zones, limiting the ability to address these issues. In addition, the static nature of RPP maps prevents the representation of temporal dynamics. Regular updates based on newly available European-scale data would support more effective monitoring over time. Furthermore, the integration of remote sensing data and complementary cartographic products could enable the production of higher-resolution species maps, by improving classification accuracy and better capturing local and fine-scale variability, while potentially reducing edge effects. Finally, RPP maps do not include important exotic species, such as *Eucalyptus* spp. and *Ailanthus altissima*, within class 14.

5. Data availability

The ETs map gridded dataset across Europe is currently freely available Zenodo. https://doi.org/10.5281/zenodo.18496150 (Giannetti et al., 2026).

6. Conclusion

The rule-based expert system, initially developed by Giannetti et al. (2018) and further refined in this study, holds significant potential for advancing the widespread application of EFTs classification in European-wide national forest monitoring initiatives. The creation of a georeferenced raster map at a 100-meter resolution, along with the associated dataset, facilitates cross-border collaboration and data sharing among EU member states.

The extensive list of forest tree species and quantitative data on their probability of presence have played a pivotal role in generating more accurate and comprehensive pan-European digital maps specific to EFTs. Notably, these RPP maps have opened opportunities for refining EFTs classification, as they provide an extensive list of forest tree species along with quantitative data (probability of finding a species). Furthermore, the integration of RPP maps into the classification algorithm provides new opportunities for future research and improved operational efficiency. By providing detailed information on forest types and their spatial distribution, modelers, policymakers, and forest managers can develop targeted strategies to enhance forest ecosystem resilience, promote carbon sequestration, and conserve biodiversity (Zampieri et al.,

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2021). Moreover, standardized information on forest types facilitates communication within a common European framework (Corona, 2022).

Consistent forest data underpin coherent policies and management practices across Europe, contributing to the objectives of the New European Forest Strategy, the European Green Deal, the EU Biodiversity Strategy, and international commitments such as the Paris Agreement and the Convention on Biological Diversity, particularly in the context of increasing pressures from climate change and other anthropogenic and biotic stressors.

Author contributions

FG, GC, AB: conceptualization; FG, IZ: data curation; FG, AB, GC, IZ: methodology; FG: software; FG, IZ: validation, FG, SL, IZ, AB: writing (original draft). FG, SL, MN, AC, SC, NCT, AL: funding acquisition; MN, SC, AC, EV, EG, GD'A, NCT, LP, JS, GS, IF, YG, DT, GC, PC, MMo, MMa, SL, AL: writing (review and editing).

Competing interests

The authors declare no conflict of interest.

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