Deliverable

3.1 Status on land system scenarios

PathFinder Project

Version: 1.2

25 January 2024

The research leading to these results has received funding from the European Union Horizon Europe (HORIZON) Research & Innovation programme under the Grant Agreement no. 101056907

Executive summary

In this deliverable the results of WP3.1 are reported, focusing on the development of land use and forest management scenarios. As a basis of the scenarios the development of a map of forest management types across Europe is documented that will provide the starting point for forest management scenarios and simulations with various coupled models within a unified spatially-explicit modelling framework.

For the forest management map, five distinct forest management classes are distinguished: primary forest, close-to-nature forestry, combined objective forestry, intensive forestry and very intensive forestry. A decision tree is developed based on the best available spatial data on forest disturbances, tree age, tree species and primary forest. Thresholds are calibrated based on the harvesting intensity map of Verkerk et al. (2015), roundwood production statistics, statistics of Forest Europe (2020), national-level forest management maps and ground images derived from Google Maps Streetview.

The results reveal that Europe only has a minimal part of its forest area classified as primary forest (1%). 11% is classified as very intensive forestry followed by larger fractions of close-to-nature forestry (13%), intensive forestry (30%) and combined objective forestry (45%). The Forest Management Map is integrated into the final Land Use Map of Sandström et al. (2023), serving as input for the modelling framework. All data are made available with documentation in an open repository.

The spatially-explicit modelling framework to simulate scenarios integrates various models to capture the responses of ecosystems and climate to forest management. Three distinct scenarios are formulated, built upon SSP storylines, RCP storylines, the IPBES Nature Futures Framework (NFF) and the policy target map of WP4.1: Forest for nature, Forest for society and Forest as culture. These scenarios will be simulated in the spatially-explicit modelling framework, providing an ex-ante policy assessment.

I. DOCUMENT CONTROL

Project	PathFinder (101056907)
Project Title	Towards an integrated consistent European LULUCF monitoring and policy pathway assessment framework
Date	25 January 2024
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Reviewer/s	Clara Antón Fernández, NIBIO & Victor Jorquera Olave, Albert Ludwigs Universität Freiburg
Activity	WP3, Task 3.1 Land use and forest management scenarios
Dissemination Level	PU
Filename	Deliverable31_v1.2

DISSEMINATION LEVEL

PU	Public, fully open access
RE	Restricted to a group specified by the PathFinder Consortium (including the Commission Services)
CO	Confidential, only for members of the PathFinder Consortium (including the Commission Services)

II. DOCUMENT HISTORY

Version	Date	Author	Change
1.1	18.12.2023	Niels Debonne	
1.2	25.1.2023	Niels Debonne & Niek Scherpenhuijzen	Modified after reviewer comments

III. Abbreviations

NIBIO	Norwegian Institute of Bioeconomy Research
ALU	Albert-Ludwigs University Freiburg
IGN	National Institute of Geographic and Forest Information
VUA	Vrije Universiteit Amsterdam
TI	Thünen Institute of Forest Ecosystems
CFRI	Croatian Forest Research Institute
LUKE	Natural Resources Institute Finland
BFW	Federal Research and Training Center for Forests, Natural Hazards and Landscape
GIS	Slovenian Forestry Institute
UHUL	Czech Forest Management Institute
VTT	Technical Research Centre of Finland Ltd.
CSIC	Consejo Superior de Investigaciones Científicas
CICERO	Center for International Climate Research
UGOE	University of Göttingen
UH	University of Helsinki
TM	TreeMetrics
EVINBO	Eigen Vermogen van het Instituut voor Natuur- en Bosonderzoek
ELO	European Landowners Organisation
IEFC	Institut Européen de la Forêt Cultivée
FMI	Finnish Meteorological Institute
WSL	Swiss Federal Research Institute for Forests Snow and Landscape Research
UB	University of Bristol
JRC	Joint Research Center
EEA	Environmental Agency
EU	European Union
NFF	Nature's Futures Framework
SSP	Shared Socio-economic Pathway
RCP	Representative Concentration Pathway
CLUMondo	Changes in Land Use at a Mondial Scale (land use model)
SDG	Sustainable Development Goal
EFDM	European Forestry Dynamics Model

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1. Contents

1. Introduction

The attainment of the Sustainable Development Goals (SDGs) hinges on the sustainable management of forests (Baumgartner, 2019). Goal 15, specifically, underscores the significance of terrestrial ecosystems, with target 15.2 aiming to promote sustainable management of all types of forests (Schulze et al., 2019). Forests, as carbon sinks, directly contribute to mitigating climate change (SDG 13) by sequestering atmospheric carbon dioxide. Moreover, they are integral to the preservation of biodiversity (SDG 15), serving as habitats for a myriad of plant and animal species. Furthermore, forests provide recreational value and they can be an integral element of broader cultural and historical landscape values. Additionally, they sustain vibrant rural communities, offering resources and livelihoods that are intertwined with their sustainable management (Oldekop et al., 2020).

In recognition of the indispensable role of forests for a liveable and sustainable future, The European Union (EU) has developed policy frameworks aiming to leverage forest management solutions. Prominent among these policies are the European Green Deal, the New Circular Economy Action Plan, the New EU 2030 Forest Strategy, and multiple other guidelines and targets (Di Marzo et al., 2023).

A crucial cornerstone of the success of these policies is the ability to both monitor progress and ex-ante assess policy impacts. This deliverable specifically engages with the latter challenge. Forest systems can be managed in different ways, prioritizing a different set of priorities (Duncker et al., 2012). Depending on, for example, future developments in the bio-economy, carbon sequestration policy, or biodiversity conservation, future patterns of forest management will be different. Moreover, forest systems are in constant interaction with developments in other land systems, such as agricultural and urban systems.

To capture the complexity of responses of forest systems to biophysical and socioeconomic drivers of change, land system models can be used (Verburg et al., 2019). Land system models simulate dynamics in land use, land cover, and land management, in response to demands for land-based goods and services and accounting for zoning and other land use policies.

While European forest systems have been included in land system models (Dou et al., 2023), previous applications lack thematic detail on different forest management regimes and miss important forest-specific drivers and attributes. Furthermore, these models account poorly for ecosystem functioning, leading to unrealistic dynamics in, for example, rotations or natural successions. In the Pathfinder project, land system models are to be developed that address these shortcomings, and in doing so, create models that can realistically inform policy makers.

More specifically, the scope of this deliverable is to provide an update on the development of the land system models and the scenarios that will be simulated by this model. This includes, inter alia, the description of the general modelling infrastructure, CLUMondo (Section 2), the development of the forest management map and its harmonization with non-forest land systems (Section 3), and the parameterization of probability surfaces and biophysical and socioeconomic drivers of change (Sections 4, 5, 6, 7).

2. The CLUMondo modelling infrastructure

Scenarios are formalized and quantified using the CLUMondo model. The CLUMondo model is a land system change model capable of projecting future land system dynamics based on local land system suitability, projected demands for land system services, and miscellaneous information on restrictions, incentives, and (dis-)allowed conversions (van Asselen and Verburg, 2013). An overview of CLUMondo functionality is shown in Figure 1.

CLUMondo requires a land system map at t_0 as a starting point. Land systems are mapping units combining land cover, land use, land management, and the types and quantities of land system services (e.g. m^3 roundwood) generated. The creation of this land system map is described in Section 3, and the quantification of land system services is described in Section 4. Changes in demands for land system services drive land system changes. The allocation of these changes is driven by local suitability and other spatial rules. Different sets of future demands and spatial rules constitute scenarios (Section 7).

CLUMondo generates yearly land system maps until 2100. For each year, the spatial allocation of land systems is computed in an iterative way. In short, at the start of an iteration, each raster cell will be changed to the land system with the highest transition potential for that particular cell, provided that this land system conversion is allowed following conversion rules and restrictions. When checked against the demanded land system services for the year of analysis, this initial allocation will lead to an overproduction of some land system services, and an underproduction of others. CLUMondo then increases the competitive advantage of those land systems producing an underproduced land system service, and vice versa. This changes the transition potentials for the next iterations. This process continues until a solution is found where all demands for land system services are met within specified margins.

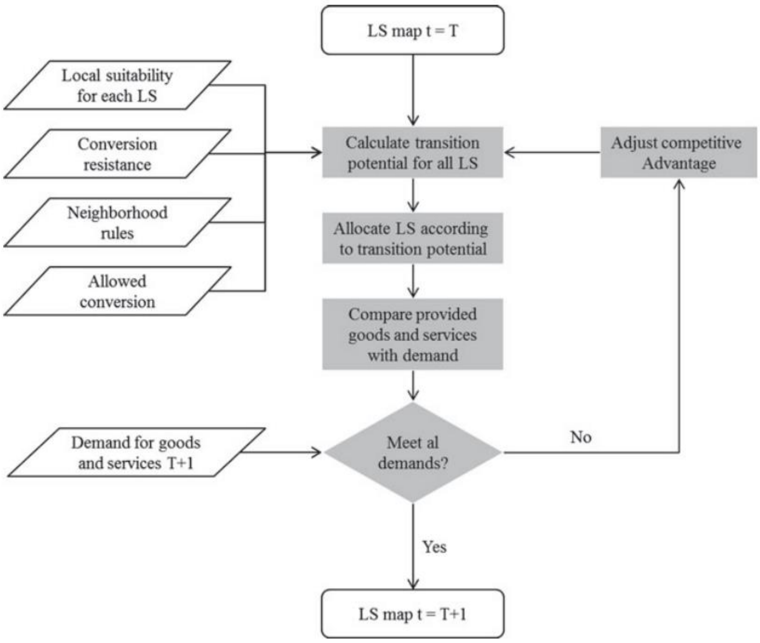

Figure 1: Schematic overview of the functionality of the CLUMondo model. Figure from van Vliet and Verburg (2018)

The CLUMondo application for Pathfinder is implemented at a resolution of $1km^2$. The model distinguishes four regions (North, East, South, West; Figure 2). All model parameters are assumed to be valid for an entire region.

Figure 2: Model regions used in CLUMondo

3. Mapping forest management: conceptualization and implementation

Forest land system scenarios require a starting point, which depicts the initial areas and spatial patterns of different land systems. Different scenarios will originate and diverge from this common basis.

Efforts have been undertaken to establish a precise depiction of forest management practices in Europe. However, these endeavours encounter challenges pertaining to incomplete or incomparable data, leading to the generation of inaccurate forest management maps. Some initiatives have concentrated solely on specific objectives of forest management, such as wood production (Verkerk et al., 2015), harvesting intensity (Levers et al., 2014), or primary forests (Sabatini et al., 2021). Conversely, other attempts have aimed to gauge forest management intensity without distinguishing between different strategies employed (Dou et al., 2021). On a global scale, endeavours have been made to create accurate forest management maps (Lesiv et al., 2022; Schulze et al., 2019), as well as on a regional scale focused for Europe (Hengeveld et al., 2012; Nabuurs et al., 2019). However, these maps collectively suffer from limitations such as inadequate availability of (precise) data, an overestimation of the mixed use class, and/or the inability to enhance the accuracy of the maps through incorporation of new and more reliable data sources.

Forest management encompasses all activities undertaken by forest managers to increase specific outputs from the forest, such as wood production. Consequently, forest management may serve different purposes, including nature conservation, material production, and cultural and spiritual endeavours. Each purpose requires distinct actions to optimize the desired output. These action in turn generate distinct forest characteristics and patterns: felling sizes, felling frequencies, species composition and diversity, age and age diversity will differ in different forest management regimes.

Thus, different management actions and objectives yield varying effects on forests. Although the effects of forest management have been studied on an individual basis, comprehensively assessing the combined impacts of all forest management practices across Europe is challenging due to the lack of spatial data on forest management practices at the European scale. To gain a better understanding of the effects of forest management in Europe, it is essential to develop a comprehensive map delineating the distribution of different types of forest management practices.

This forest management map uses land systems as conceptual mapping units. A land system describes how an area of land is used by humans, including all human processes and activities. These functions can change over time due to various reasons, e.g. socioeconomic (Dou et al., 2021). Thus, land systems are showing the relationship between nature and humans and includes land cover, land use, and land management. The latter includes measures of intensity. The resolution of the final product is 1km^2.

A land system map is not equivalent to a forest cover map. Forests, as defined by the European Environmental Agency and the Food and Agricultural Organization, are areas of at least 0.5 ha with trees higher than 5m and a canopy cover of more than 10% (Forest Information for Europe, 2021). In a land system map, forest *cover* can be present within non-forest land *systems*. For example, agriculture-forest mosaic land systems contain a sizable fraction of forest cover. Because these systems respond to different drivers of change, they are mapped and modelled as a separate land system. To derive forest cover from land systems, backward calculations using lookup tables is required.

3.1 Forest management classes and definitions

Five forest management classes are distinguished along a gradient of management intensity. These categories have been previously conceptualized by Duncker et al. (2012). Categories and definitions are listed in Table 1. The exact implementation of these definitions is based on a decision tree (Figure 3).

This implementation is a rule-based approach, implying that thresholds need to be set and calibrated. Rule-based classification based on secondary data and threshold setting is the most common way to classify land systems (Dou et al., 2021; van Asselen and Verburg, 2012).

Table 1: Forest management classification: definitions

FOREST MANAGEMENT LAND SYSTEM	**DEFINITION**
PRIMARY FOREST	Barely disturbed forest with nature function. No to barely any management in place.
CLOSE-TO-NATURE FORESTRY	Previously disturbed or secondary forest systems where management activities aim to support biodiversity, resilience and climate adaptation, ultimately to conserve and enhance ecosystem functioning.
COMBINED OBJECTIVE FORESTRY	Mixed objective forest systems, where any single objective is not dominant in the management strategy. Functions may include protection, recreation, wood production or other functions.
INTENSIVE FORESTRY	Forest systems dominantly managed for wood production. Management activities include frequent and/or large-scale felling.
VERY INTENSIVE FORESTRY	Forest systems intensely used for wood production. Management activities include very frequent and/or large-scale felling, and tree species may consist of fast-growing species.

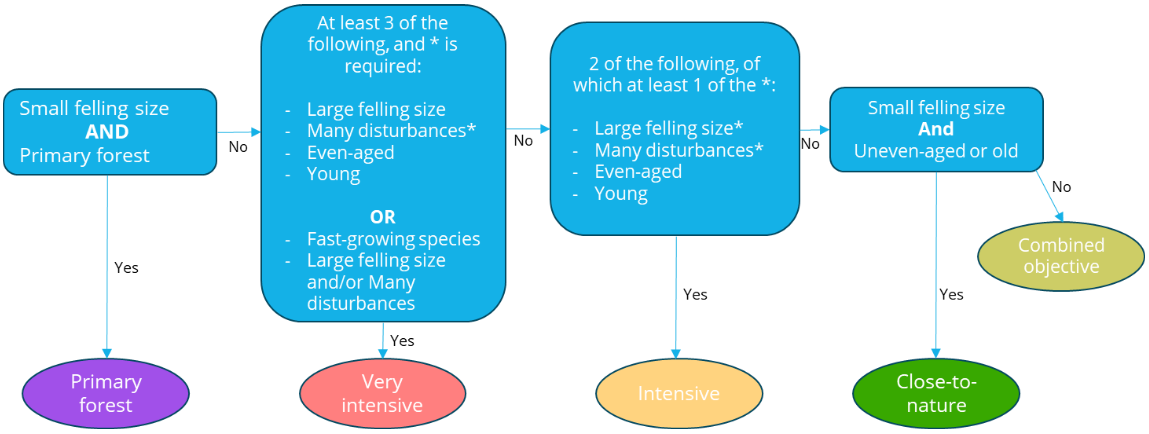

Figure 3: Forest management land system classification decision tree

3.2 Input data and implementation

The forest management land system decision tree is implemented using the data described in Table 2. The following paragraphs describe this data and the thresholds used.

Table 2: Input data for decision tree implementation

Data	Created by	Year	Resolution	Source
Forest type	Copernicus	2018	100m	https://land.copernicus.eu/pan-european/high-resolution-layers/forests/forest-type-1/status-maps/forest-type-2018?tab=mapview
Tree cover density	Copernicus	2018	100m	https://land.copernicus.eu/pan-european/high-resolution-layers/forests/tree-cover-density/status-maps/tree-cover-density-2018
Disturbance, clear cuts and forest cover	Senf and Seidl, 2021	2020	30 m	https://zenodo.org/record/7080016#.ZCVYmt-xWUl
Primary forest	Sabatini et al., 2021	2018	1 km	https://www.nature.com/articles/s41597-021-00988-7#Sec7
Age classes	Pucher et al., 2022	2014 - 2017	10 km	ftp://palantir.boku.ac.at/Public/ImprovedForestCharacteristics/
Tree species	Brus et al., 2012	2012	1 km	https://efi.int/knowledge/maps/treespecies

3.2.1 Forest mask

First, areas that are managed as forest are identified. These areas constitute the forest mask. The forest mask defines the areas which are considered to belong to one of the five forest land systems (Table 1). This forest mask is flexible – different applications of a land system map may warrant the use of different forest masks.

Various European-scale forest layers exist, but these products typically identify tree cover. However, a disturbed area of forest may not have tree cover, but may still be under “forest management”. Conversely, some disturbances are permanent and constitute a land use change away from forest management, to for example agriculture or urban.

Here, the forest mask is derived from Senf and Seidl (2021) and complimented with Copernicus (2020a). The forest cover map of Senf & Seidl (2021) has a resolution of 30m x 30m, in which each pixel is either forest or not forest. This layer is aggregated to 1000m x 1000m, each pixel containing a percentage of forest. As some small areas, mainly coastal islands, were not included in the forest cover map of Senf & Seidl (2021), Copernicus (2018) tree cover density data is used to compliment those areas. Besides, Copernicus tree cover density data is also used in specific areas of Northern Italy, in which the forest cover data of Senf & Seidl is not accurate (Figure 4).

In the context of the Pathfinder model chain, cells with ≥55% forest cover are included in the forest mask. The threshold of 55% is based on European forest area estimates of Forest Europe (2020). Forest Europe (2020) reports per country the area covered by forest. The total area of forest reported is used to determine this threshold. According to Forest Europe, the research area contains 1834000 km2 of forest. Choosing a threshold of 55% results in 1840389 km^2 of forest. We are aware that forest definitions could differ per country, as the data comes directly from the countries. However we found that a threshold of 55% provides accurate results after we validated the forest mask by virtue of case studies using Google Streetview.

The Copernicus (2020a) forest cover mask may omit clear-cut areas that are part of a rotation in a forest management regime. The forest cover map of Senf & Seidl (2021) is less prone to this problem, as it is based on disturbance data from 1986 to 2020, thus accounting for rotational dynamics, and validated with satellite images.

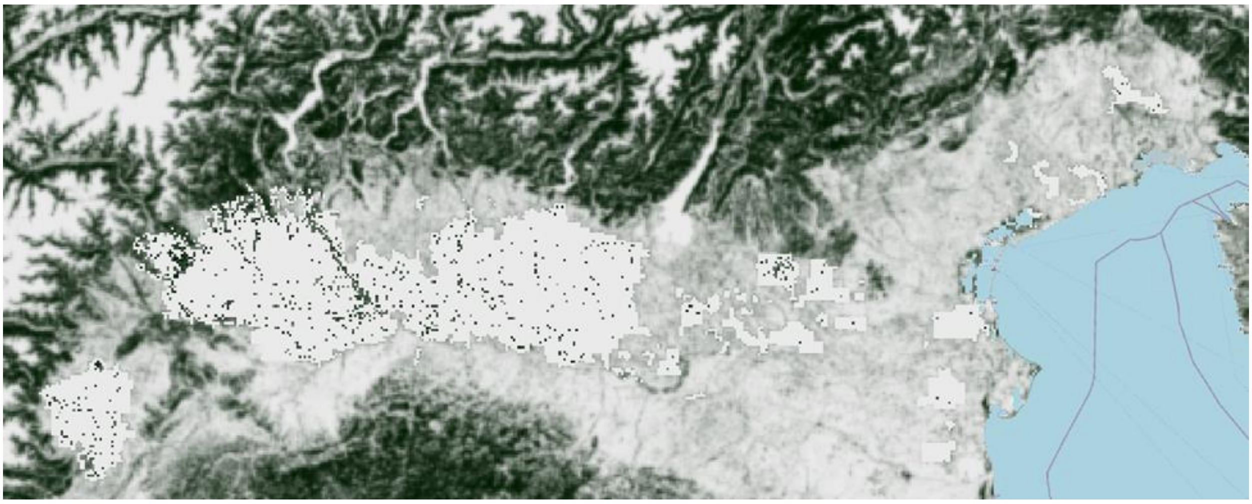

Figure 4: Areas replaced with Copernicus data in Northern Italy

3.2.2 Primary forests

We use the European Primary Forests Database (EPFD) by Sabatini et al. (2021). This is the most complete dataset on European primary forests to date. Primary forests are defined here 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”, following the FAO definition. The implementation of this definition by Sabatini et al. (2021) retains those forests where there are no signs of human intervention, or these signs are strongly blurred by decades (60-80 years) of non-intervention.

The original data is in polygon / point format and was converted to a raster of 1km2 resolution.

Primary forests are found most prominently in Finland and Norway, although smaller patches are also present in, among others, Romania, Bulgaria, Poland, and Slovenia (See Figure 5).

Where (Sabatini et al., 2018) identify an area as being primary forest, our forest management map classifies this area as primary forest, unless medium- or large felling sizes are detected.

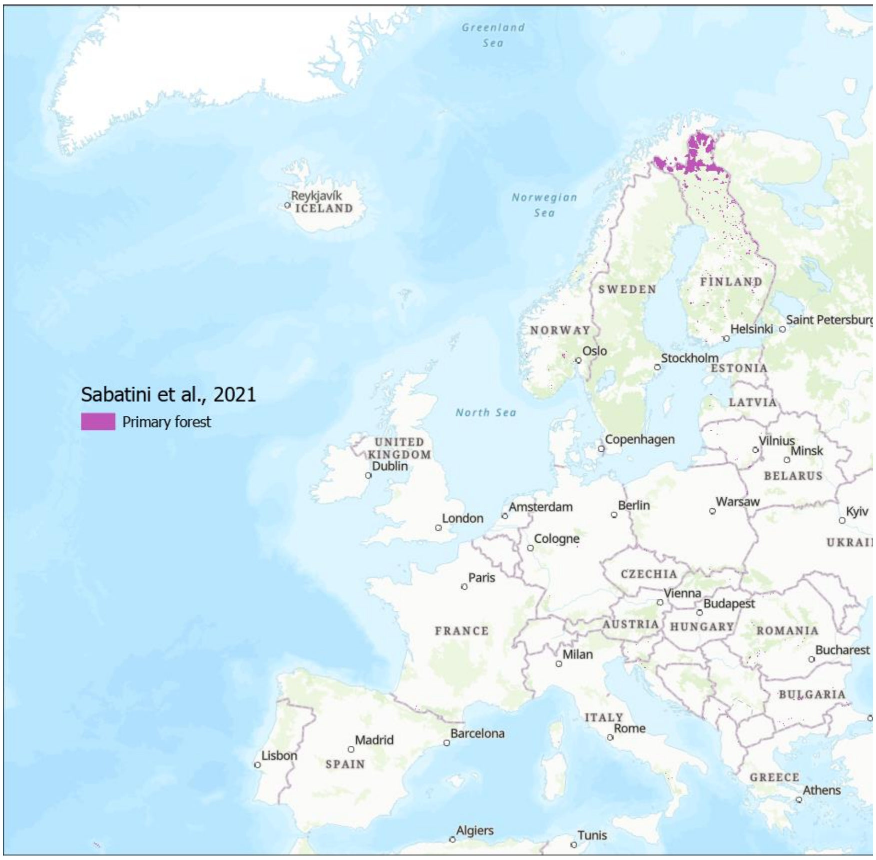

Figure 5: Primary forests (no forest mask applied)

3.2.3 Fast-growing tree species

We use the tree species dataset of Brus et al. (2012). This dataset contains area fractions of 20 different tree species. Of these 20 species, three species were selected as fast-growing species, meaning that a high concentration of these species is an indicator for very intensive forest management. This selection was based on literature (Freer-Smith et al., 2019; Levers et al., 2014; Liu et al., 2018; Nabuurs et al., 2019) and includes species that are very common in intensive wood production systems and simultaneously relatively uncommon in high concentrations in other systems. Selected species are Eucalyptus, Populus, and Robinia.

Where any of the three identified plantation species is dominant (i.e. it has the largest proportion of any of the 20 species), this is considered indicative of very intensive forestry management, depicted in Figure 6. When this occurs in conjunction with large felling sizes and/or frequent disturbances, the area is considered to be under very intensive forestry management.

Figure 6: Areas where either of the three fast-growing species covers at is dominant in the pixel area (no forest mask applied)

3.2.4 Disturbance size and frequency

Using data by Senf & Seidl (2021), average sizes of forest disturbances are mapped. These disturbances can be part of a management regime, although the original data does not distinguish this from (semi-) natural disturbances such as forest fires or tree pests. The original data has a resolution of 30m, and indicates if and when an area was disturbed between 1986 and 2020. A disturbed pixel can only be disturbed once in this dataset, referred to as a disturbed patch, and no distinction is made between human or natural cause. To make the data indicative for forest management regimes, the area of disturbance in units of 9 km^2 was calculated. Disturbance size gives the sum of all disturbances within such a 9km^2 area and disturbance frequency shows how many disturbances occurred on average per year in this area.

Large-scale and frequent disturbances are considered here as being indicative for plantation- or intensive management. Small disturbances are associated with nature management or primary forest.

The thresholds on disturbance size and frequency are outlined in Table 3. Disturbance size is displayed in Figure 7 and disturbance frequency in Figure 8. An explanation of the calibration of disturbance size is given first, followed by disturbance frequency.

First, as outlined in the introduction of this chapter, disturbance size is calibrated using a harvesting intensity map of Verkerk et al. (2015). Second, the results are compared with country-level data on roundwood production. Afterwards, by virtue of case studies and images of the ground situation derived from Google Streetview, the thresholds of disturbance size are finetuned.

The same steps are taken to calibrate disturbance frequency, however the thresholds are mainly calibrated based on figures of Forest Europe (2020). According to Forest Europe data, very intensive forestry covers 3.8% of European forest. The data was delivered by the countries themselves, resulting in different definitions across countries, limiting the use of country-level data. However, it does provide guidance in the calibration process.

As outlined in the decision tree (Figure 3), many disturbances/year is required to classify as very intensive forestry, defined as forestry systems where trees are cut down in a short time period, thus having a high disturbance frequency. Calibrating towards 3.8% very intensive forestry of total European forest, the "Many" in disturbance frequency is set to 11 patches / year / 9km^2.

Furthermore, according to Forest Europe (2020), around 75% of European forest is available for wood supply. In line with the definitions, this implies that the sum of very intensive-, intensive- and combined objective forestry should be at least 75%. Besides age and evenness, the category "Few" in disturbance frequency determines whether a pixel is nature management or multifunctional forest. Senf & Seidl (2021) proposed a value of 1 for this category, which meets this calibration target.

Table 3: Thresholds used for disturbance size and frequency

Disturbance size	**Category**
< 2 ha / 9km^2	Small
3 ha / 9km^2	Medium
> 3 ha / 9km^2	Large
Disturbance frequency	**Category**
< 1 patch / year / 9km^2	Few
1 - 11 patches / year / 9km^2	Some
> 11 patches / year / 9km^2	Many

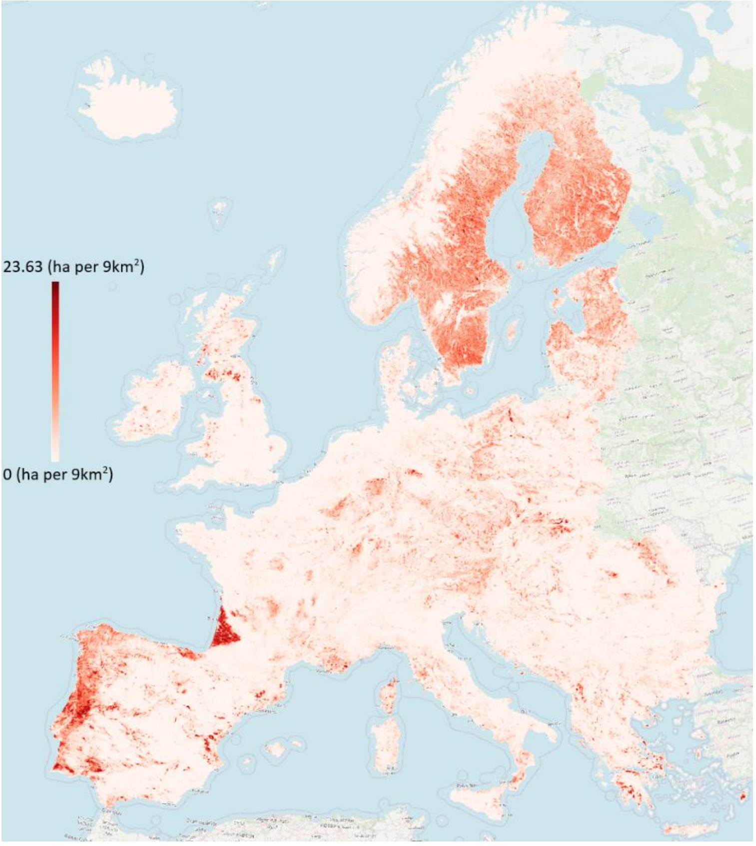

Figure 7: Average felling size (hectares per km^2) (no forest mask applied)

Figure 8: Disturbance frequency (disturbances per year in a window of 9km²) (no forest mask applied)

3.2.5 Forest age and age evenness

Forest age classes are obtained from data by Pucher et al. (2022). This data depicts the fraction of trees by area belonging to a specific age class in 20 year bins in each 8x8km cell.

From this, the dominant age class is obtained. Tree species have different life-cycles, making it difficult to set threshold for the age categories. However, the purpose of the categories is to detect if a forest is a young forest ((very) intensive forestry) or an old forest (primary forest and close-to-nature forestry). Considering this, forest age is categorized as young (dominant age is <20 years), medium (dominant age between 20 and 40 years) and old (remaining age classes) (Figure 9). Subsequently, the age structure is categorized as even-aged when over 40% of forest area belongs to a single 20-year age bin, and as uneven if not. To calibrate evenness, a statistic of Forest Europe (2020) is used. Approximately 71.8% of total European forest is even-aged forest. When we calibrate evenness to 40%, 74.2% of all forest is classified as even-aged forest.

Younger and more even-aged forests are indicative of intensive and very intensive management forests.

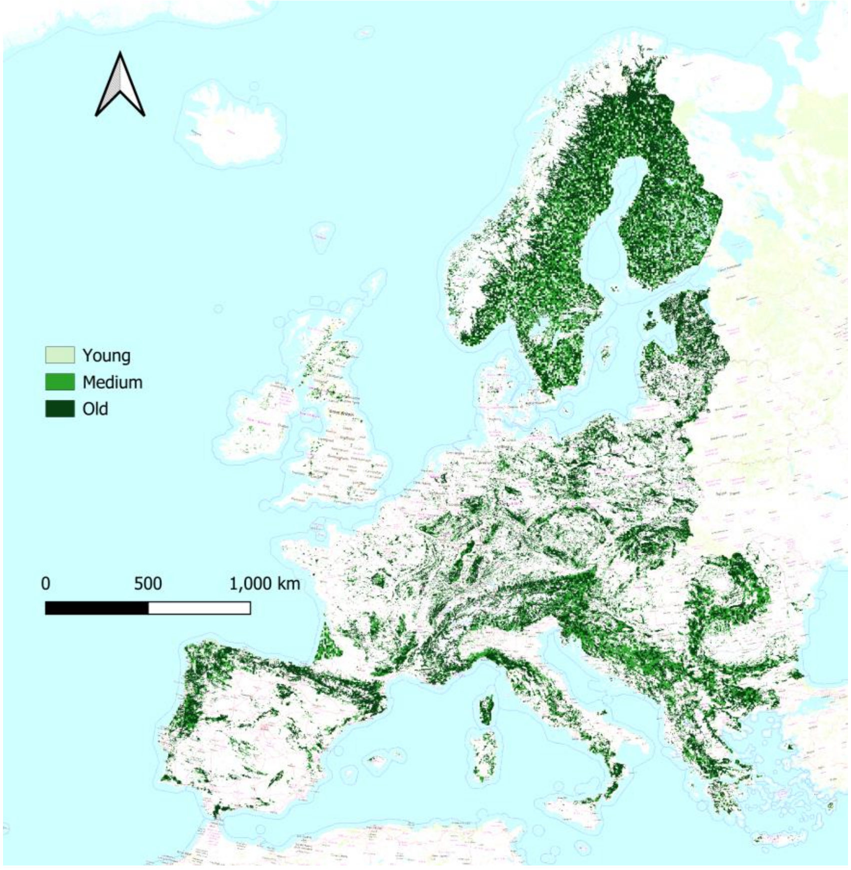

Figure 9: Dominant age classes (forest mask applied)

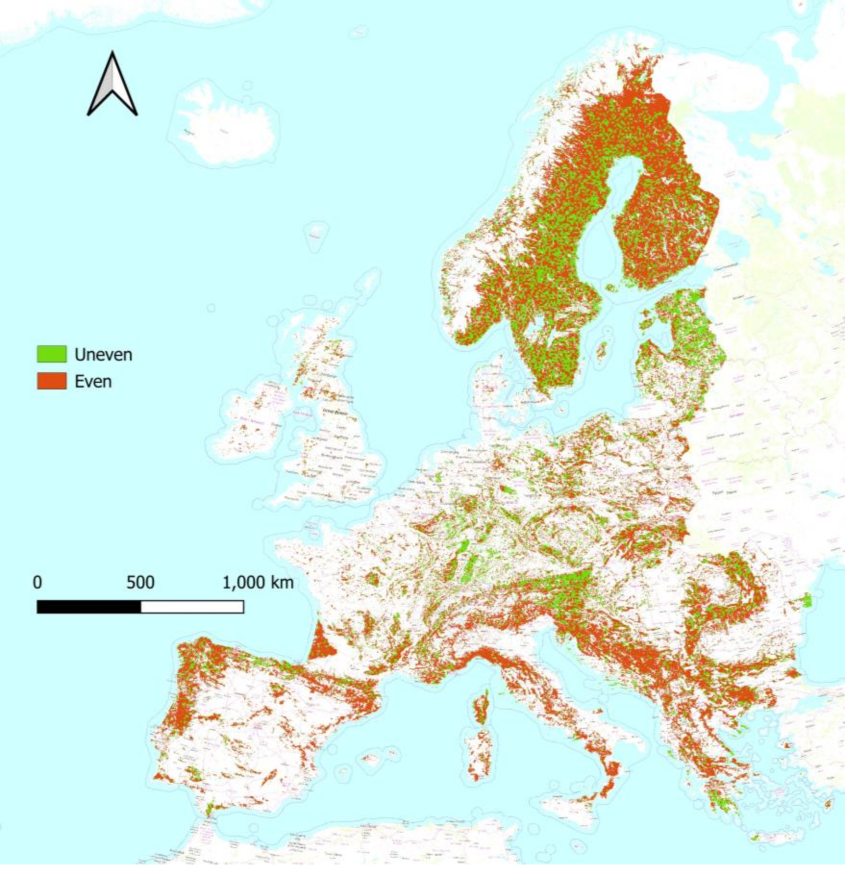

Figure 10: Age evenness. “even” implies that 40% of forest area belongs to a single 20 year age bin (forest mask applied)

3.3 Resulting forest management land system map

Upon implementation of the rules outlined above, the forest management map is shown in Figure 11. Figure 12 shows the distribution of the forest management categories. Figure 13 shows details of specific regions. The most current version of the forest management map is made available on Dataverse.

Figure 11: Forest management land system map

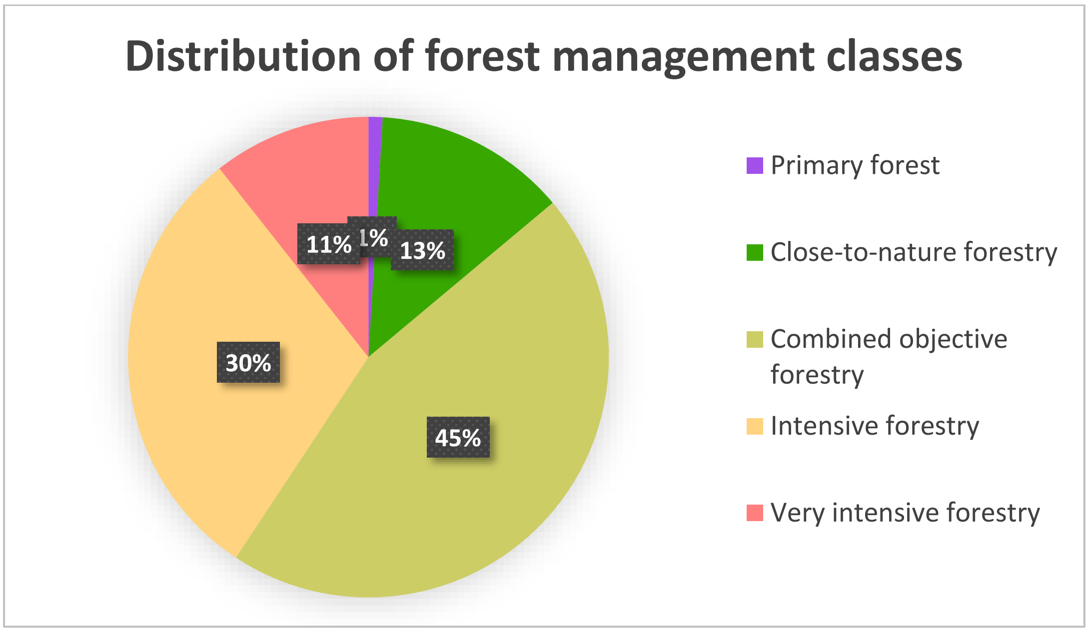

Figure 12: Distribution of forest management classes

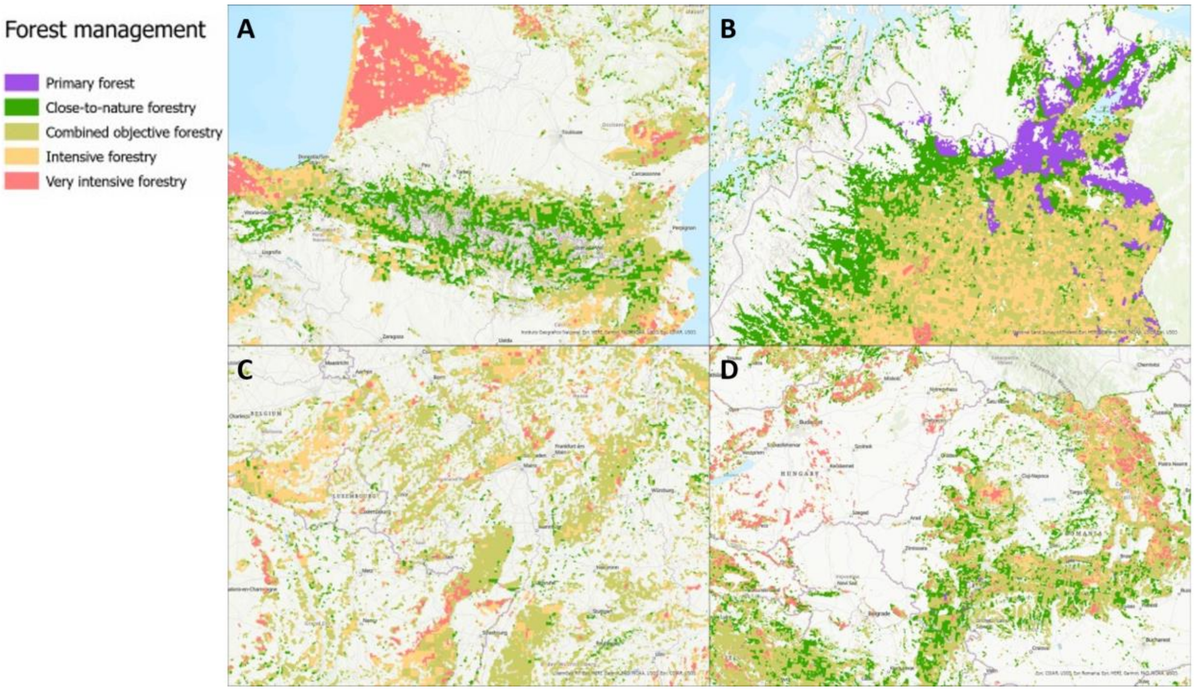

Figure 13: Details of the forest management land system classification for (A) The Pyrenees, Gascogne, Ardèche, Catalonia, Basque Country, (B) Lapland, (C) Wallonia, Luxemburg, Northeast France and Western Germany and (D) Romania, Hungary and Northern Balkans

3.4 Harmonization to a full land system map

Forest land systems exist amidst agricultural, urban, and other land systems. The algorithm to achieve this is shown in Figure 14 and further detailed in Sandström et al. (2023). First of all, every cell contains a certain amount of each land system noted in Figure 14, which is stated in percentages of the total for each cell. Next, the percentages shown in Figure 14 represent the thresholds for each land system. The resulting map is ready for use in modelling (Figure 15).

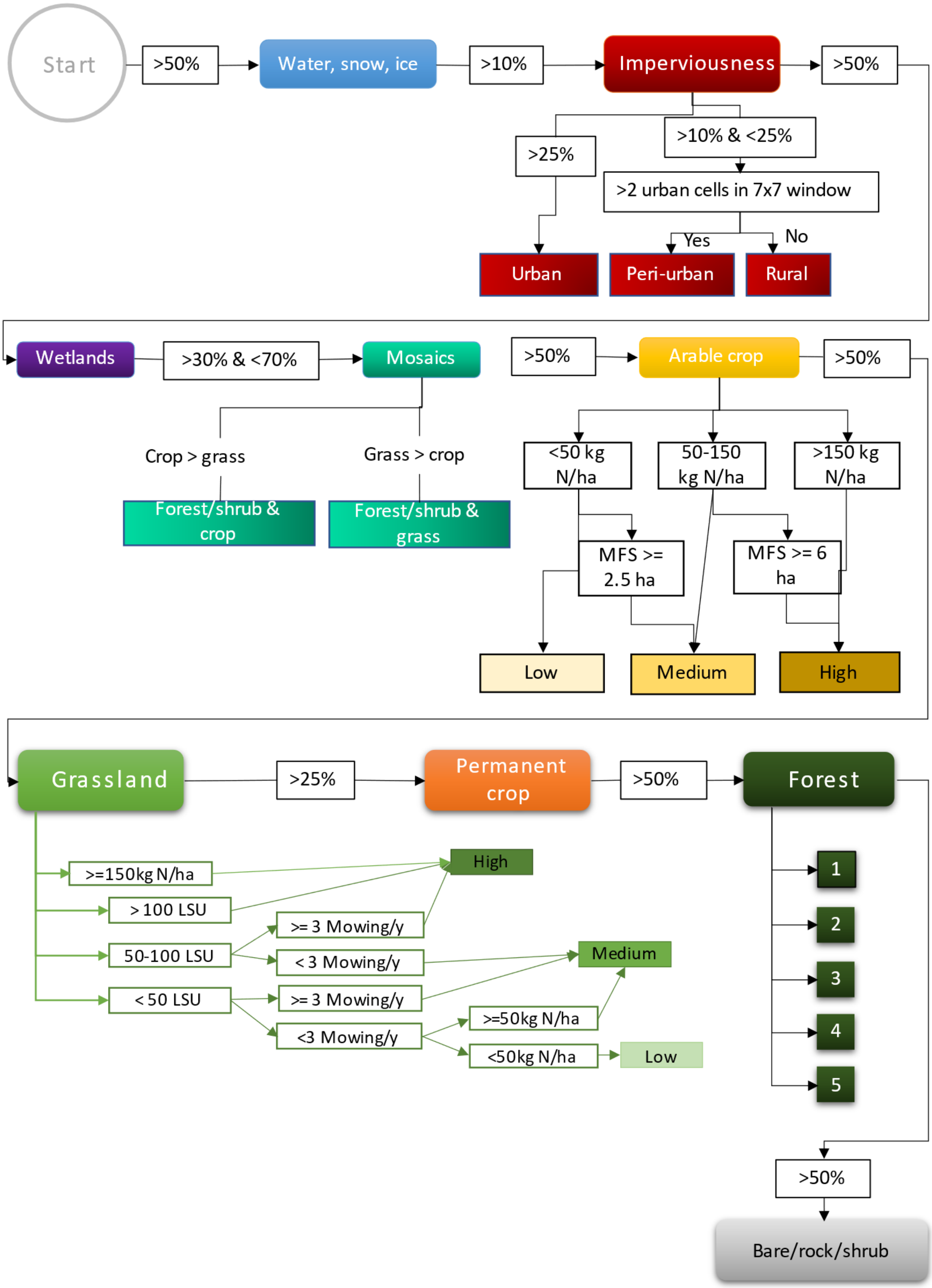

Figure 14: Land system classification algorithm, showing how the forest management land systems are allocated in relation to other land systems

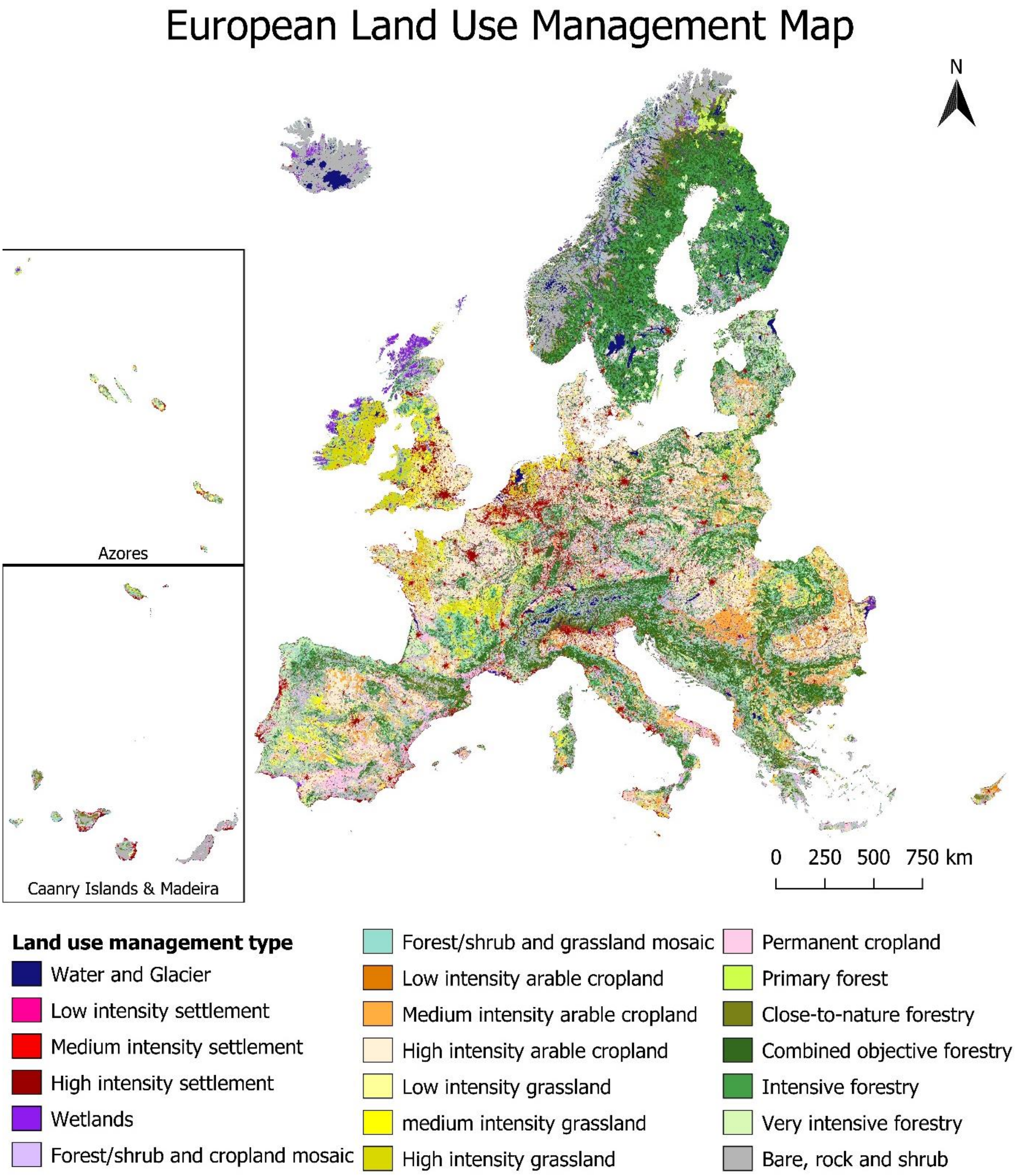

Figure 15: Full land system map of Europe

4. Quantification of land system services

Land system services are goods and non-material benefits obtained from the productive use of land. Each land system may generate multiple land system services, and each land system service may be generated by multiple land systems (i.e. there is a many-to-many relationship between land systems and their services, demonstrated in Figure 16).

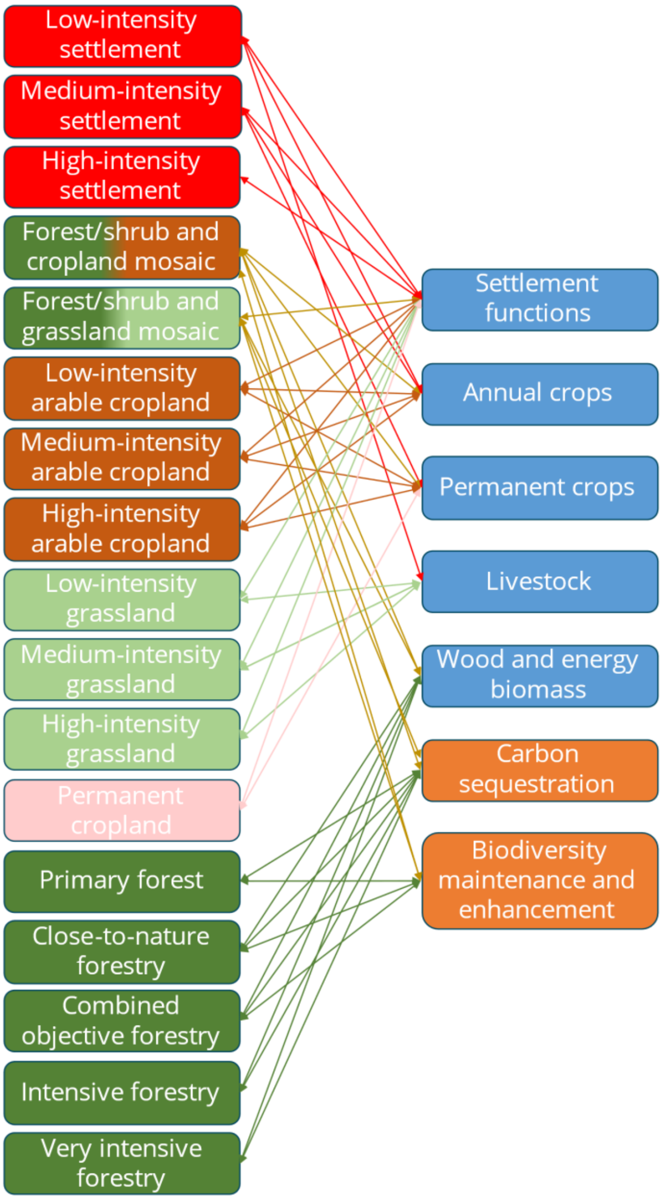

Figure 16: Demonstration of the many-to-many relationship between land systems and their services. Services in orange are suggested novel services serving the purposes of the Pathfinder project.

The suggested land system services for the Pathfinder include (1) Settlement functions, (2) Annual crops, (3) Permanent crops, (4) Livestock, (5) Wood and energy biomass (6) Carbon sequestration, and (7) Biodiversity maintenance and enhancement. The latter two services are specific to the Pathfinder application, although previous work has included versions of these before (Wolff et al., 2018).

The quantification of land system service supply entails specifying how much of each service a single raster cell (1km^2) of that land system can provide. For settlement functions, annual crops, perennial crops and livestock, standard procedures as described in (Dou et al., 2023) will be followed. For wood and energy biomass production, a spatial overlay using data by Verkerk et al. (2015) will initially be used, awaiting more precise quantification options to be delivered by project partners.

Carbon sequestration services will be quantified initially using a spatial overlay with data by Cook-Patton et al. (2020). Developments of the Yasso model (Rantakari et al., 2012), carried out in a different Pathfinder task, will be used when they become available. Procedures to include biodiversity as a land system service have yet to be conceptualized. Following the findings of the policy analysis carried out in work package 4 (Di Marzo et al., 2023), the number of trees, amount of deadwood or species richness may be considered as a quantifiable and policy-relevant indicator, but further input from project partners will be needed to arrive at more holistic biodiversity indicators.

5. Generating probability surfaces

CLUMondo allocates land systems based on local suitability for this particular land system type. Local suitability for a land system is determined by factors such as soil types, accessibility to the nearest city, or terrain. Logistic regressions are used to establish statistically significant relations between these factors and the patterns of land systems at t_0.

A logistic regression estimates the probability of occurrence of a specific land system using Equation 1.

$$P = \frac{1}{1+e^{-(\beta_0+\beta_1 X_1+\beta_2 X_2+\cdots)}} \qquad \text{(Equation 1)}$$

Where P is the probability of a land system occurring in a specific location (raster cell), X_i are explanatory factors (e.g. slope, accessibility), and β_i are estimated coefficients.

For each dynamic land system, a logistic regression model is built. This process is done in 3 steps:

1) Sampling

Using the initial land system map (Section 3) as input, raster cells are sampled for each land system. Samples are required to be (1) balanced (an equal number of cells with and without the sampled land system are selected), (2) contain 10% of the total area of the sampled land system, and (3) distanced (to the extent possible, neighbouring cells are not both sampled).

2) Regression model building

A set of candidate spatial explanatory factors is collected and processed into a geodatabase where each factor is projected onto the same grid. The factors considered are shown in Table 4.

Table 4: Explanatory factors used to estimate land system suitability

Category	Explanatory variable	Original resolution	Description (unit)	Source
Biophysical	DEM	1km	Elevation (m)	(EEA, 2016)
	Slope	1km	Slope (degrees)	(EEA, 2016)
	Clay	500m	Topsoil (0–20 cm) clay content (%)	(Ballabio et al., 2016)
	AWC	500m	Available Water Capacity (AWC)	(Ballabio et al., 2016)
	Bulk density	500m	Bulk density (t m^{-3} (g cm^{-3}))	(Ballabio et al., 2016)
	Sand	500m	Topsoil (0–20 cm) sand content (%)	(Ballabio et al., 2016)
	Silt	500m	Topsoil (0–20 cm) silt content (%)	(Ballabio et al., 2016)
	Coarse fragments	500m	Topsoil (0–20 cm) coarse fragments (%)	(Ballabio et al., 2016)
	pH in water	250m	pH of water in soil (pH*10) in topsoil (0-30 cm)	(Hengl et al., 2017)
	Organic carbon concentration	250m	Soil organic carbon (dg/kg) in topsoil (0-30 cm)	(Hengl et al., 2017)
	Cation exchange capacity	250m	Cation exchange capacity at pH 7 (mmol(c)/kg) in topsoil (0-30 cm)	(Hengl et al., 2017)
Socio-economic	Road density	5’	Densities summed across the five road types (m/km^2)	(Meijer et al., 2018)
	Market access	1km	Index of access to national and international markets	(Verburg et al., 2011)
	Market density	1km	Market importance (GDP/capita)	(Verburg et al., 2011)
	Market influence	1km	Market influence ($ per capita)	(Verburg et al., 2011)
	Accessibility	1km	Travel time to cities (h)	(Weiss et al., 2018)
Climate	Bioclimatic variable 01	1km	Annual Mean Temperature ˚(C)	(Karger et al., 2017)
	Bioclimatic variable 02	1km	Mean Diurnal Range ˚(C)	(Karger et al., 2017)
	Bioclimatic variable 04	1km	Temperature Seasonality (standard deviation)	(Karger et al., 2017)
	Bioclimatic variable 12	1km	Annual Precipitation	(Karger et al., 2017)
	Bioclimatic variable 15	1km	Precipitation Seasonality	(Karger et al., 2017)

In some datasets, few observations were missing. In those cases, nearest neighbour values were taken. A multicollinearity analysis between the explanatory variables was used to avoid the use of highly correlated variables within a single model (ANNEX A). Subsequently, models were built in an iterative process, trying different combinations of variables. Five criteria informed the decision on the optimal model:

- Significance of individual factors ($P < 0.05$)
- Low correlation between factors ($r < 0.7$)
- High Area Under the Curve
- Low risk of over- and underfitting (low Akaike Information Criterion, high McFadden R^2 Adjusted)
- Logical relations (a plausible relation between factors and land systems is identified)

Resulting models are described in Table 5. Some land systems were merged for this analysis as they respond to similar drivers and a more robust model could be parameterized in this way.

Table 5: Logistic regression models. Sign between brackets indicates directionality of contribution. AUC = Area Under the Curve, McF R^2 = McFadden R^2 Adjusted. Regressions are separately calibrated for the four European regions (Figure 2).

Land system	**Explanatory variables (positive / negative)**	**AUC**	**McF R^2**
East			
Low-density rural settlement	Slope (-); Market influence (+); Accessibility (-); Temperature (+); Temperature seasonality (+); SOC (-)	0.71	0.11
Medium-density peri-urban settlement	Slope (-); Market density (+); Market influence (+); Accessibility (-); Temperature (+)	0.85	0.30
High-density urban settlement	Slope (-); Silt (-); Market density (+); Market influence (+); Accessibility (-); Temperature (+)	0.87	0.34
Wetlands	Slope (-); Clay (-); AWC (+); Silt (-); Temperature (+); Diurnal range (-); Temperature seasonality (+); pH (+); SOC (+); CEC (+)	0.95	0.56
Forest, shrub and cropland mosaics	Elevation (-); Clay (-); AWC (+); Road density (+); Market density (-); Precipitation (-); Precipitation seasonality (-); CEC (-)	0.67	0.07
Forest, shrub and grassland mosaic	Clay (-); Coarse fragments (+); Precipitation (+); pH (-); CEC (-)	0.62	0.03
Low-intensity arable cropland	Elevation (-); AWC (+); Road density (+); Temperature seasonality (+); SOC (-)	0.84	0.27
Medium-intensity arable cropland	Slope (-); Clay (+); Silt (+); Market density (-); Temperature (-); Precipitation (-); SOC (-); CEC (+)	0.80	0.25
High-intensity arable cropland	Slope (-); Clay (+); Silt (+); Market density (-); Temperature (-); Temperature seasonality (-); Precipitation (-); Precipitation seasonality (-); pH (+); SOC (-)	0.87	0.37
Low-intensity grasslands	Slope (-); Bulk density (-); Road density (-); Market influence (-); Temperature (-); Diurnal range (+); Precipitation (+); Precipitation seasonality (+); pH (+)	0.72	0.11
Medium-intensity grasslands	Slope (-); Clay (+); Silt (-); Market access (-); Accessibility (-); Temperature (-); Precipitation seasonality (+); SOC (-); CEC (+)	0.72	0.13
High-intensity grasslands	Slope (-); Clay (+); Bulk density (-); Accessibility (-); Temperature (-); Temperature seasonality (-); Precipitation (-); Precipitation seasonality (+); pH (+)	0.81	0.25
Permanent cropland	Slope (+); Clay (+); AWC (-); Accessibility (-); Temperature (+); Precipitation seasonality (+); SOC (-)	0.79	0.22
Primary forest and close-to-nature forestry	Slope (+); Bulk density (-); Sand (-); Road density (-); Market influence (-); Temperature (+); pH (-); SOC (+)	0.82	0.23
Multi-objective forestry	Slope (+); Bulk density (-); Silt (-); Temperature (+); Precipitation (+); Precipitation seasonality (-); pH (-); SOC (+)	0.82	0.24
Intensive and very intensive forestry	Slope (+); Sand (+); Accessibility (+); pH (-); SOC (+)	0.80	0.21

North			
Low-density rural settlement	Elevation (-); Slope (+); Market density (+); Accessibility (-); pH (+)	0.81	0.24
Medium-density peri-urban settlement	Elevation (-); Road density (+); Market access (+); Accessibility (-); pH (+)	0.89	0.40
High-density urban settlement	Elevation (-); AWC (-); Silt (+); Road density (+); Market influence (+); Accessibility (-); Temperature seasonality (-)	0.91	0.46
Wetlands	Slope (-); Clay (-); Temperature (-); Diurnal range (+); Temperature seasonality (-); CEC (+)	0.84	0.28
Forest, shrub and cropland mosaics	Clay (+); AWC (+); Sand (-); Market density (+); Temperature (-); pH (+)	0.80	0.22
Forest, shrub and grassland mosaic	Sand (-); Accessibility (+); Temperature seasonality (-); Precipitation seasonality (-)	0.80	0.21
Low-intensity arable cropland	Elevation (-); AWC (+); Road density (+); Temperature seasonality (+); SOC (-)	0.84	0.27
Medium-intensity arable cropland	Elevation (-); Road density (+); Market access (+); Temperature seasonality (-); Precipitation (-)	0.97	0.64
High-intensity arable cropland	Elevation (-); Market influence (-); Accessibility (-); Temperature (+); pH (+); SOC (-)	0.98	0.79
Low-intensity grasslands	Elevation (-); Sand (-); Accessibility (+); Temperature seasonality (-); pH (+)	0.89	0.39
Medium-intensity grasslands	Temperature (+); Temperature seasonality (-); pH (+); SOC (-)	0.96	0.67
High-intensity grasslands	Slope (-); Bulk density (-); Market access (-); Temperature seasonality (-); SOC (-)	0.84	0.36
Permanent cropland	Slope (+); Road density (+); Accessibility (-); Temperature (+); Temperature seasonality (+); pH (+)	0.93	0.50
Primary forest and close-to-nature forestry	Elevation (+); Slope (+); Clay (-); Market density (-); Diurnal range (-); Precipitation seasonality (+); SOC (+)	0.86	0.37
Multi-objective forestry	Elevation (+); Slope (+); Bulk density (-); Sand (+); Market density (-); Accessibility (-); pH (-)	0.62	0.05
Intensive and very intensive forestry	Elevation (-); Coarse fragments (+); Market density (+); Temperature seasonality (+); Precipitation (-); Precipitation seasonality (-); pH (-)	0.75	0.23

South			
Low-density rural settlement	Elevation (-); Slope (-); AWC (-); Market density (+)	0.62	0.04
Medium-density peri-urban settlement	Elevation (-); Slope (-); Road density (+); Market access (+); Accessibility (-); Diurnal range (-)	0.86	0.31
High-density urban settlement	Elevation (-); Slope (-); Road density (+); Market influence (+); Accessibility (-); Diurnal range (-); Precipitation seasonality (+)	0.86	0.31
Wetlands	Slope (-); AWC (+); Bulk density (-); Silt (-); Temperature (+); Diurnal range (-)	0.96	0.63
Forest, shrub and cropland mosaics	Silt (+); Coarse fragments (+); Market access (+); Accessibility (+); Temperature (-); Temperature seasonality (-); Precipitation seasonality (+); pH (+)	0.60	0.01
Forest, shrub and grassland mosaic	Clay (-); Bulk density (-); Coarse fragments (+); Accessibility (+); Temperature seasonality (-)	0.65	0.05
Low-intensity arable cropland	Elevation (-); AWC (+); Road density (+); Temperature seasonality (+); SOC (-)	0.84	0.27
Medium-intensity arable cropland	Slope (-); AWC (+); Sand (-); Temperature (-); Precipitation seasonality (-); SOC (-)	0.81	0.24
High-intensity arable cropland	Slope (-); AWC (+); Bulk density (+); Sand (-); Coarse fragments (-); Temperature (-); SOC (-); CEC (+)	0.87	0.37
Low-intensity grasslands	Slope (-); Clay (-); Coarse fragments (+); Road density (-); Market density (-); Diurnal range (-); Temperature seasonality (+); Precipitation seasonality (+); CEC (-)	0.77	0.17
Medium-intensity grasslands	Slope (-); Clay (-); Precipitation seasonality (+); pH (-); SOC (-); CEC (-)	0.74	0.14
High-intensity grasslands	Elevation (-); Slope (-); Bulk density (-); Accessibility (+); Temperature seasonality (+); CEC (-)	0.68	0.08
Permanent cropland	Slope (+); Clay (+); Market density (+); Temperature (+); pH (+);SOC (-); CEC (-)	0.83	0.27
Primary forest and close-to-nature forestry	Elevation (+); Slope (+); AWC (+); Bulk density (-); Market density (-); Diurnal range (-); Temperature seasonality (+)	0.88	0.37
Multi-objective forestry	Elevation (+); Slope (+); AWC (+); Sand (+); Diurnal range (-); Temperature seasonality (+); pH (-)	0.84	0.26
Intensive and very intensive forestry	Elevation (-); Slope (+); AWC (+); Bulk density (-); Sand (+); Coarse fragments (+); Diurnal range (+); Temperature seasonality (-); pH (-)	0.82	0.25

West			
Low-density rural settlement	Slope (-); Sand (-); Market density (+); Temperature seasonality (+)	0.65	0.06
Medium-density peri-urban settlement	Slope (-); Road density (+); Market access (+); Accessibility (-); Temperature seasonality (+)	0.81	0.22
High-density urban settlement	Slope (-); Road density (+); Market influence (+); Accessibility (-); Temperature (+); Diurnal range (-)	0.83	0.26
Wetlands	Slope (-); Sand (+); Road density (-); Market access (-); Temperature seasonality (-); Precipitation seasonality (+); SOC (+)	0.98	0.73
Forest, shrub and cropland mosaics	Bulk density (+); Accessibility (+); Temperature seasonality (+); CEC (-)	0.66	0.05
Forest, shrub and grassland mosaic	AWC (+); Bulk density (-); Silt (-); Market access (-); Precipitation (+); pH (-); SOC (-); CEC (+)	0.72	0.10
Low-intensity arable cropland	Elevation (-); AWC (+); Road density (+); Temperature seasonality (+); SOC (-)	0.84	0.27
Medium-intensity arable cropland	Slope (-); Clay (+); Silt (+); Precipitation (-); Precipitation seasonality (+); SOC (-)	0.72	0.10
High-intensity arable cropland	Slope (-); Bulk density (+); Silt (+); Coarse fragments (-); Road density (-); Precipitation (-); Precipitation seasonality (-); pH (+)	0.86	0.32
Low-intensity grasslands	Slope (-); AWC (+); Bulk density (-); Silt (-); Market density (-); Temperature (-); Temperature seasonality (+); CEC (+)	0.68	0.06
Medium-intensity grasslands	Slope (-); AWC (+); Silt (-); Temperature seasonality (-); SOC (-); CEC (+)	0.73	0.12
High-intensity grasslands	Slope (-); Bulk density (-); Market access (-); Market density (+); Temperature seasonality (-); SOC (-); CEC (+)	0.85	0.30
Permanent cropland	Slope (+); Road density (+); Accessibility (-); Temperature (+); Temperature seasonality (+); pH (+)	0.93	0.50
Primary forest and close-to-nature forestry	Slope (+); Road density (-); Market density (-); Temperature (+); Temperature seasonality (+); Precipitation seasonality (-); pH (-)	0.80	0.21
Multi-objective forestry	Slope (+); Temperature (+); Temperature seasonality (+); pH (-)	0.81	0.22
Intensive and very intensive forestry	Slope (+); Silt (-); Coarse fragments (+); Temperature (+); Temperature seasonality (+); pH (-)	0.80	0.22

3) Probability surface generation

For every 1km^2 grid cell, the models described in Table 5 are implemented using Equation 1, resulting in probability surfaces for each land system. Figures below show the probability surfaces for Intensive and Very Intensive forestry for the four model regions, with lighter shades indicating a higher probability. Note that these surfaces do not reflect the possibility of a change towards these land systems (e.g. while Very Intensive Forestry may be highly probable in a specific location, other conversion rules may prohibit a change towards Very Intensive Forestry).

All probability surfaces are shown in ANNEX A.

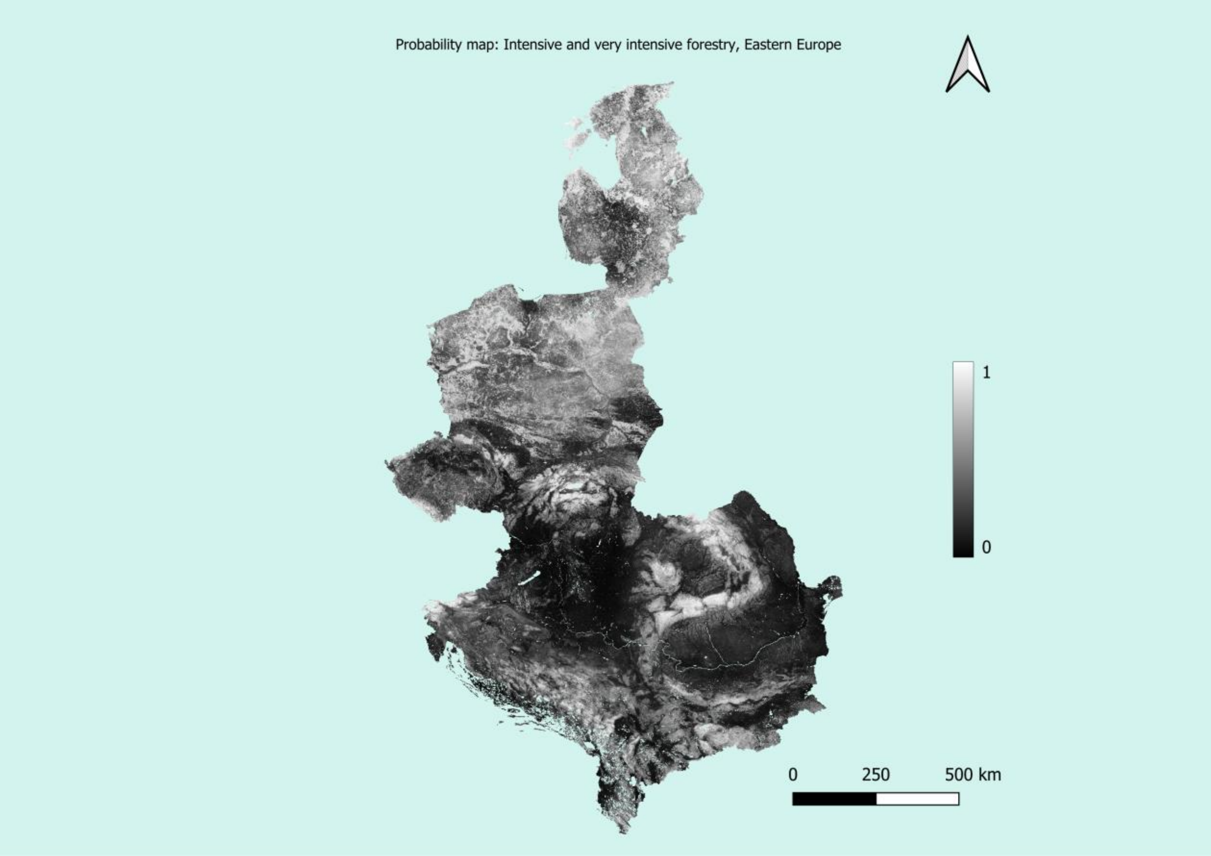

Figure 17: Probability for Intensive or Very Intensive Forestry, Eastern Europe

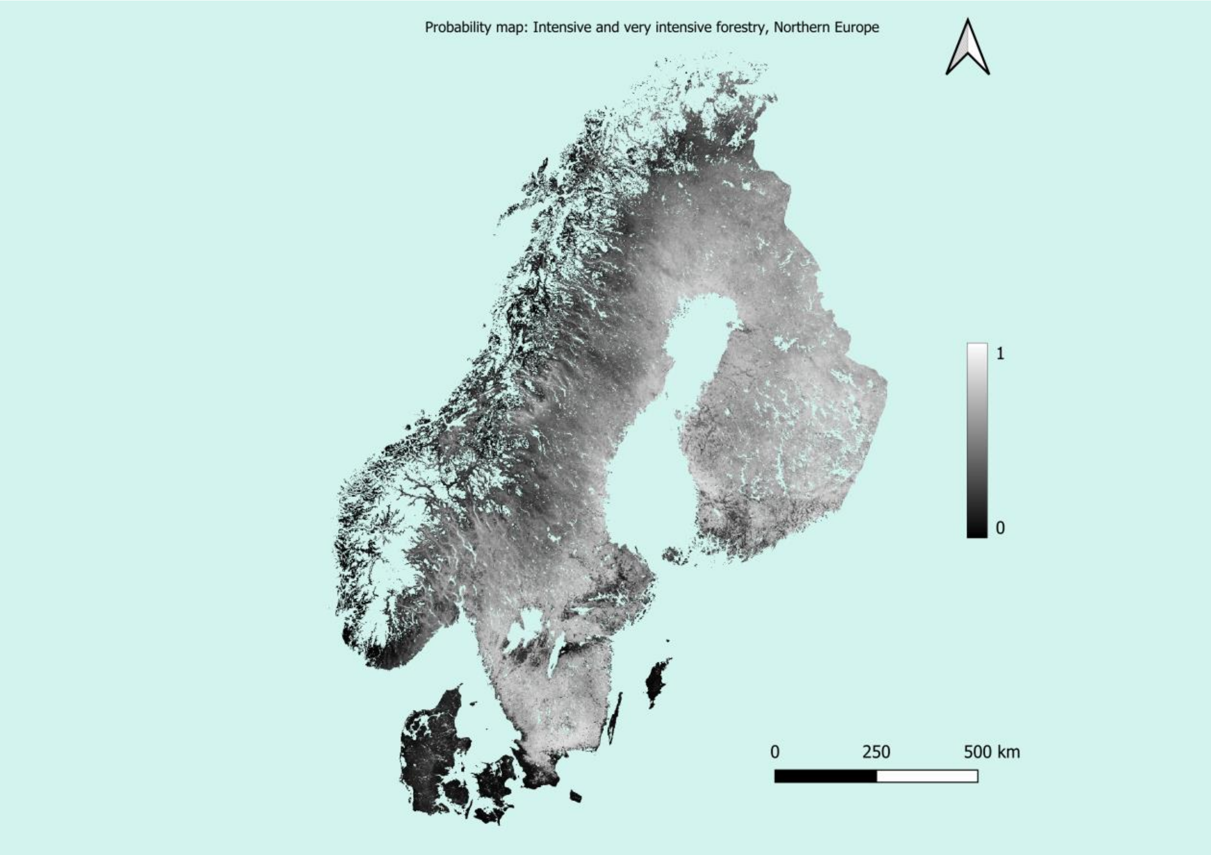

Figure 18: Probability for Intensive or Very Intensive Forestry, Northern Europe

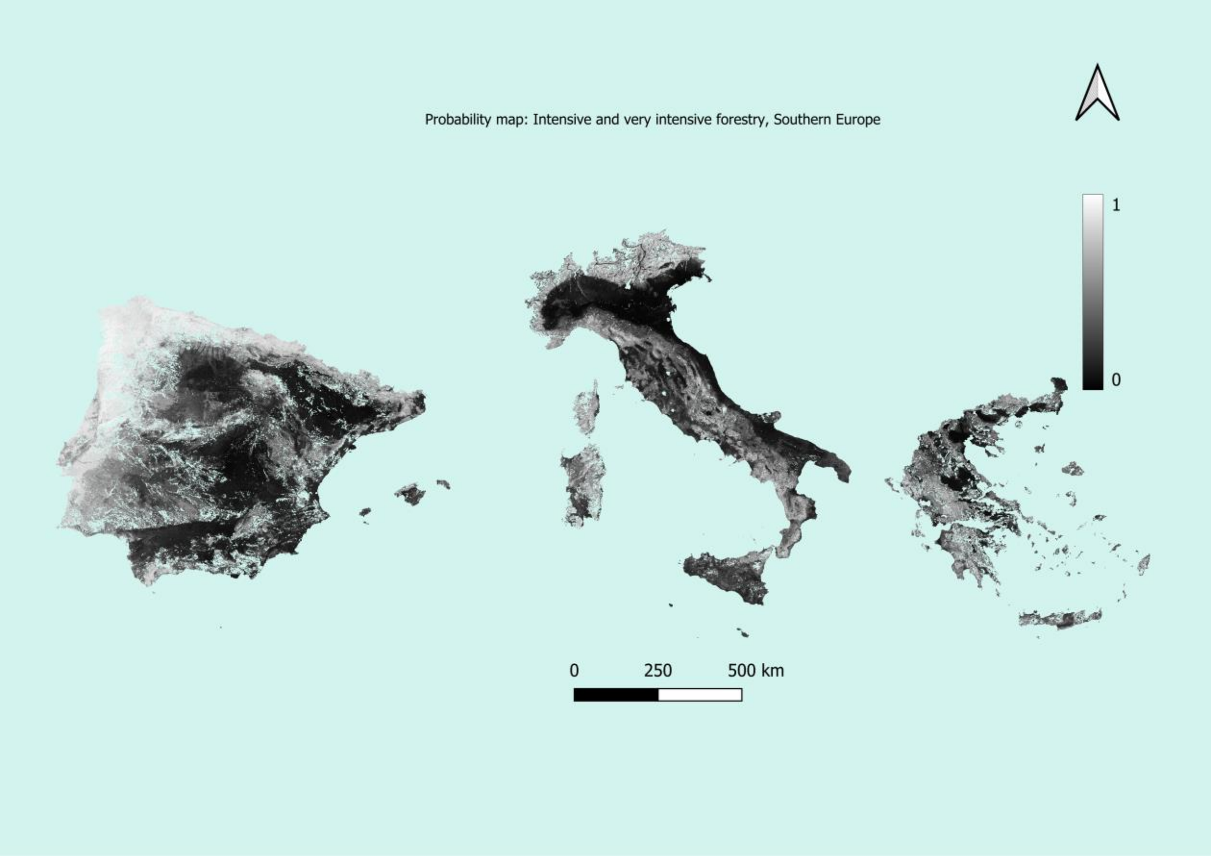

Figure 19: Probability for Intensive or Very Intensive Forestry, Southern Europe

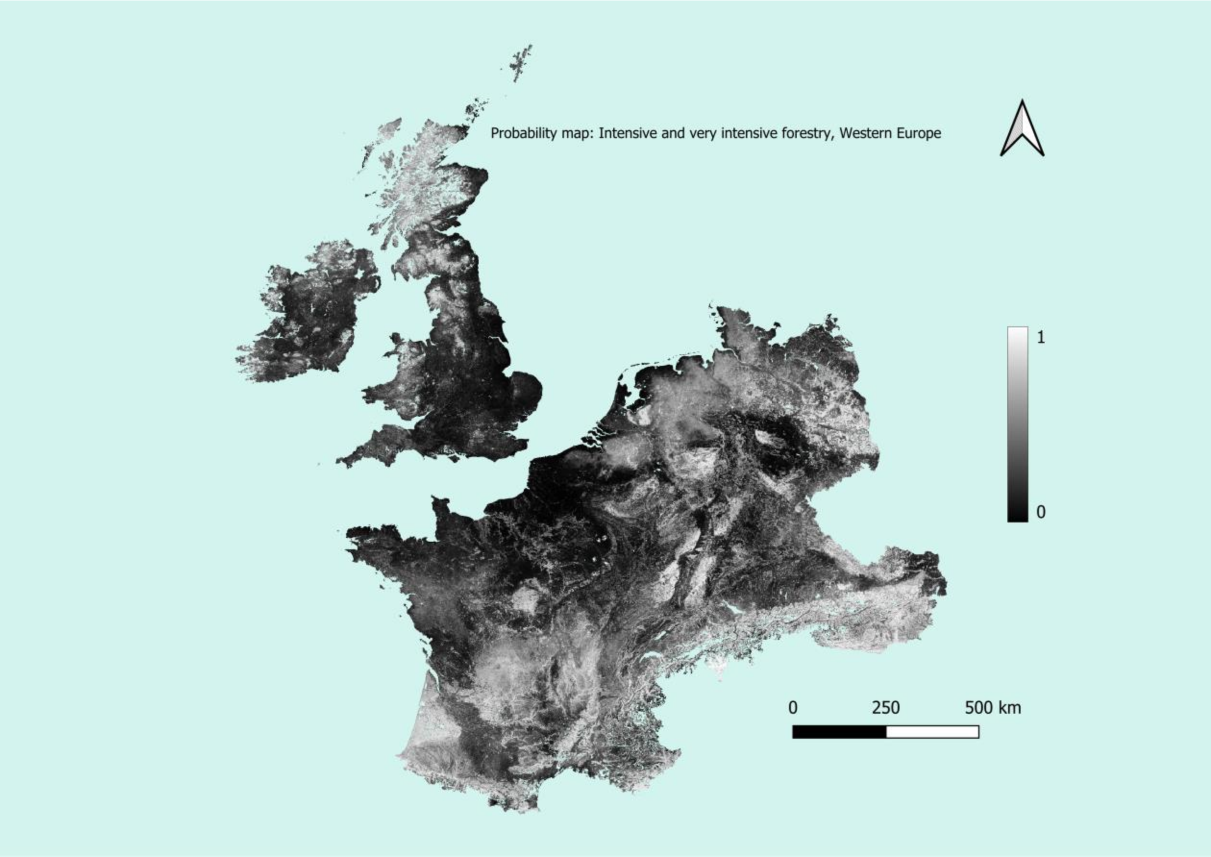

Figure 20: Probability for Intensive or Very Intensive Forestry, Western Europe

6. Introducing ecosystem and climate responses to management

The five forest management categories (Table 1) have distinct forest management activities and, therefore, distinct ecosystem and climate responses. To capture this, the CLUMondo land system modelling framework will be coupled with both forest state modelling and climate modelling capabilities (Figure 21).

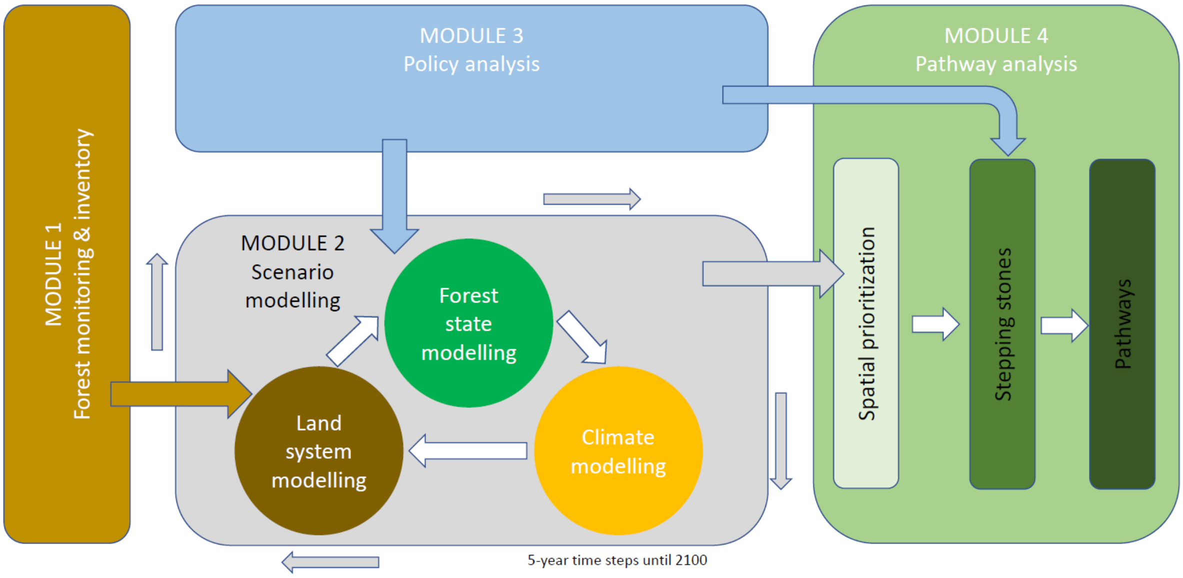

Figure 21: Conceptual framework describing the integration of land system modelling, forest state modelling, and climate modelling, as well as the dependencies with other research steps in the pathfinder project.

6.1 Ecosystem responses using forest state modelling

Progress on developing forest state modelling capabilities that match the resolution and requirements of CLUMondo are described in Majasalmi and Vauhkonen (2023) and outlined in Figure 22. The European Forestry Dynamics Model (EFDM) will be used to simulate the evolution of forest areas under different management regimes. EFDM simulates how key forest state parameters, such as average volume and diameter, evolve through time as a function of their initial state, the management activities applied, and prior information on both activity and transition probabilities.

The EFDM model will be deployed on future land system patterns, as modelled by CLUMondo, in 5-year increments.

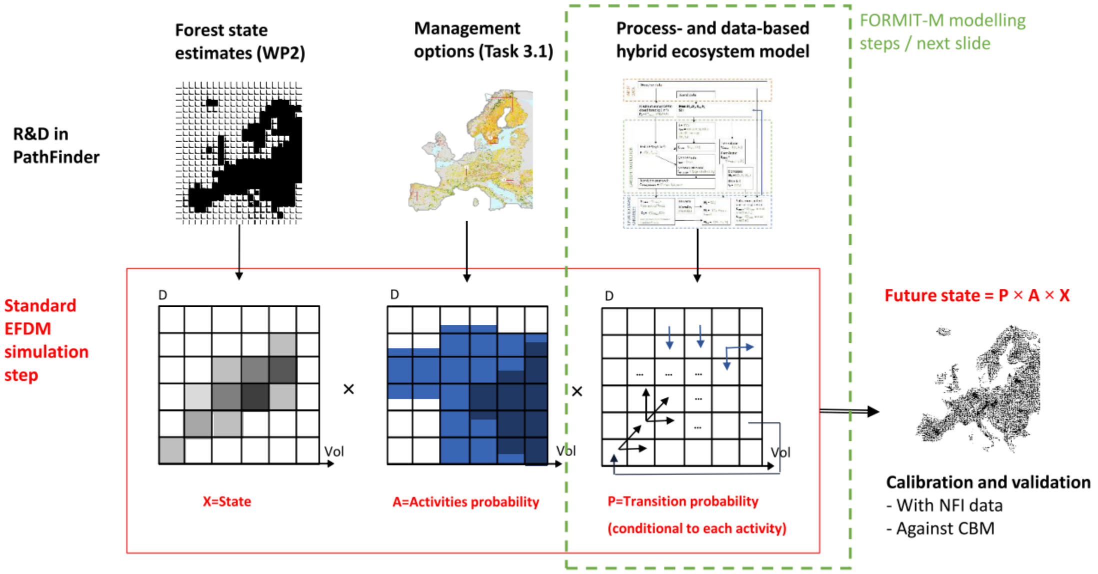

Figure 22: Forest state modelling integration, taken from Majasalmi and Vauhkonen (2023)*.*

6.2 Climate and ecological response modelling

CLUMondo accepts climate variables as explanatory factors for transition probability and suitability (See Table 4). Climate will be implemented as a dynamic driver, meaning that CLUMondo accepts climate change data derived from CHELSA climate modelling. More advanced climate emulation models will be developed in other tasks and feed into the EFDM model, and therefore indirectly also into the CLUMondo model.

Forest disturbance models (fire, pests, windfall) will be developed in other work package tasks and coupled with CLUMondo to simulate ecosystems in a more realistic way.

7. Scenario development

The scenarios to be developed for Pathfinder will produce future land system maps until the year 2100, in yearly time steps. Multiple scenarios will be run, resulting in different land system patterns. This section described progress to date on the development of these scenarios.

The scenarios will be the product of three streams of information: (1) The Shared Socio-economic Pathways (SSPs) and Representative Concentration Pathways (RCPs), which provide a prognosis of broad trends in the world economy and climate changes; (2) The Natures Futures Framework (NFF), which captures differential value perspectives on the desired future of nature; and (3) A European policy target map, provided by Work package 4 of the Pathfinder project, which narrows down likely political trajectories and priorities (Figure 23).

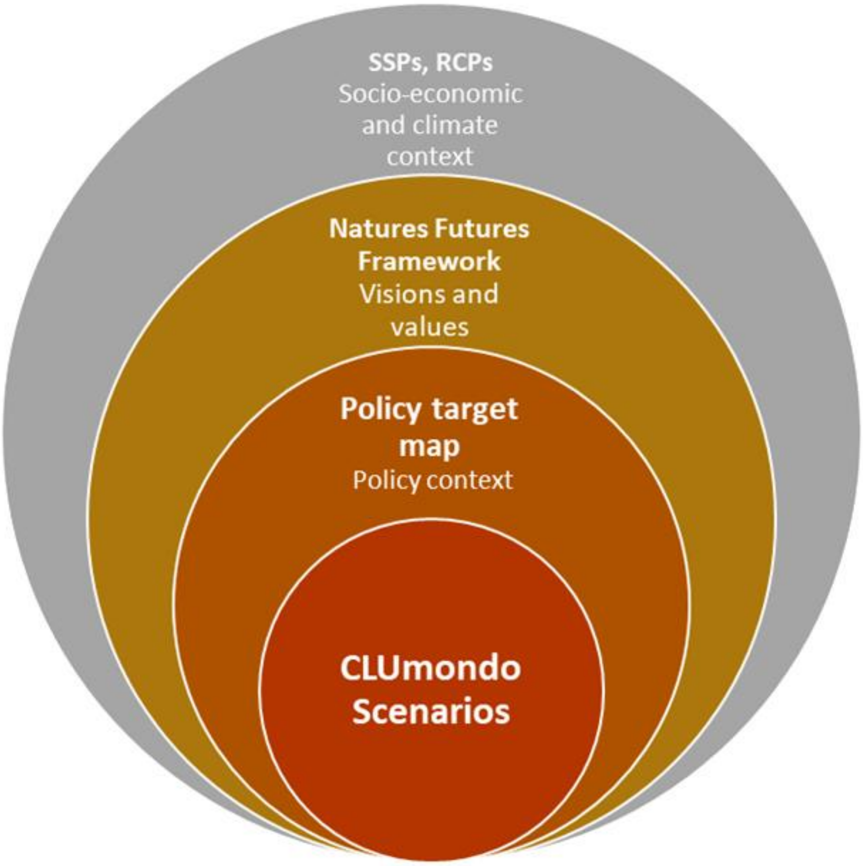

Figure 23: Schematic representation of the scenario building logic

7.1 Socio-economic and climate context

The SSPs (Riahi et al., 2017) are a set of narratives describing internally consistent socio-economic developments. These narratives will be translated into societal demands for goods and services in the future, using GLOBIOM (Dou et al., 2023; Havlík et al., 2011) and CAPRI (Henning and Witzke, 2021). The SSPs serve to provide the baseline demands for annual and permanent crops, livestock, and settlement functions (see Section 4). The storyline of SSP2 (“Middle of the Road”) will be used in all scenarios.

The RCPs (van Vuuren et al., 2011) complement the SSPS by providing spatially explicit forward-looking climate variables, which serve as dynamic drivers to CLUMondo (see Section 5). RCP4.5, corresponding to a future where greenhouse gas emissions peak around 2040 and with an end-of-century warming of between 2 and 3 degrees Celsius. RCP4.5 furthermore assumes substantial negative emissions from afforestation and forest expansions (Thomson et al., 2011).

7.2 Visions and values

To structure scenarios, the IPBES Nature Futures Framework (NFF) (IPBES, 2023; Kim et al., 2023) is deployed. This framework synthesizes the plurality of relations humans and societies may have with nature, and is often used as a starting point for scenario development. It distinguishes three value perspectives that can guide scenario storyline developments: Nature for Nature, Nature for Society and Nature as Culture (Figure 24). Briefly, a Nature for Nature perspective prioritizes protecting nature for its intrinsic value, and may include policies such as rewilding and strictly protected areas. Nature for Society is a perspective where nature is instrumentalized to serve societal needs, which may include the bio-economy but also other ecosystem services such as carbon sequestration. Nature as Culture is a vision where nature is managed to be part of traditions and cultures.

The NFF will be used to differentiate scenarios in such a way that they cover a complete option space. It thereby highlights that multiple land system configurations may be able to fulfil the same overall objectives. For example, the same amount of land-based carbon sequestration may be achieved using dedicated intensive systems or (larger areas of) multifunctional forests, relating to land sparing or land sharing policy priorities respectively.

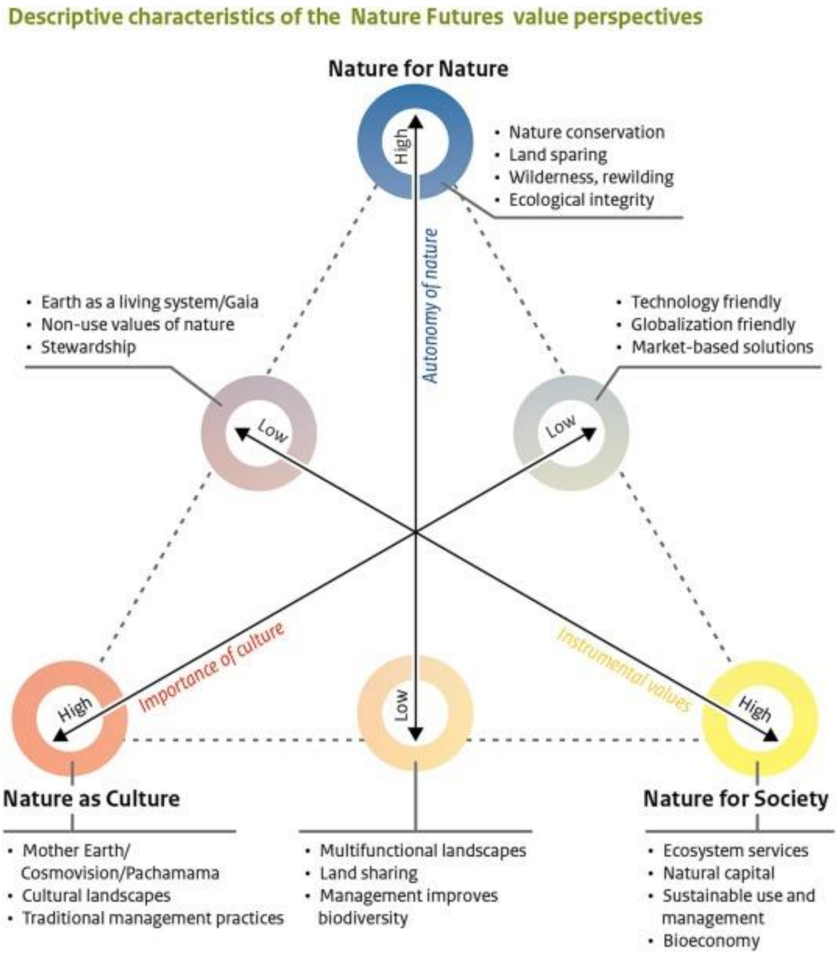

Figure 24: The Nature's Futures Framework (taken from Kim et al., 2023)

7.3 Policy context

Pathfinder's Work Package 4 has delivered a policy analysis on European forest-related policies (Di Marzo et al., 2023). This policy target map identified priorities in future policy developments, which relate to four main themes: (1) future nature conservation policies; (2) future carbon sequestration developments; (3) dynamics in the bio-economy; and (4) the degree of multifunctionality of forest systems.

Trade-offs exist between policy priorities, and choices made to navigate these trade-offs resonate with the NFF value perspectives. For example, maximizing carbon sequestration may be detrimental to both the bio-economy and biodiversity conservation. Our scenarios distribute options to navigate policy trade-offs according to their alignment with NFF values, following (Table 6).

Table 6: Policy realms and corresponding targets and priorities (as identified by WP4.1) and related NFF values

Policy realm	Targets and priorities (WP4.1, non-exhaustive)	Nature's future framework
Biodiversity conservation	• Guidelines on planting new trees • Promote Close-to-nature forestry • Restoration and conservation • Increases in deadwood and native species • Strict protection of primary forests	Nature for Nature
Climate action	• Promote Carbon sequestration • Promote bio-energy	Nature for Society
Bio-economy development	• Stimulation of forestry sector • Support for rural communities and forest-based livelihoods	Nature for Society
Multifunctionality promotion	• Promote recreational and touristic values	Nature as Culture

7.4 CLUMondo scenarios

To bring together the above streams of information, three CLUMondo scenarios are preliminarily suggested, and will be further developed into specific parameterizations (Table 7).

1. Forests for Nature: Policy priorities regarding the promotion of Close-to-nature forestry are implemented. Protected areas are established in places with the highest (potential) biodiversity value.
2. Forests for Society: Bioeconomic, bio-energy, and carbon sequestration targets are prioritized.
3. Forests as Culture: Multifunctionality of forest systems is prioritized.

These brief scenario narratives will then be translated into quantitative parameters legible in the CLUMondo modelling framework. Future demands for goods and services will be derived from the Shared Socioeconomic Pathways (SSPs), but the specific demands for wood, bio-energy, and carbon sequestration will deviate between scenarios. A preliminary parameterization logic is presented in Table 7.

Table 7: Preliminary parameterization logic of scenarios

Scenario	CLUMondo parameterization
Forest for nature	• Increased competitiveness for Close-to-Nature forestry • Demand for nature restoration, biodiversity included • Strict protection of primary forest • Creation of protected areas in places with high biodiversity value • Low demand for wood and biomass
Forest for society	• High demand for wood and biomass • High demand for carbon sequestration • Low or no demand for biodiversity or nature restoration • Increased competitiveness for Low-density rural settlements
Forest as culture	• Increased competitiveness for Combined Objective forestry • Creation of protected areas in places with high (potential) recreation value • Medium demand for wood, biomass and carbon sequestration

Next steps include tabulating future demands for goods and services across the scenarios. Procedures to achieve this are described in Dou et al. (2023) and will be modified for the Pathfinder scenario set.

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ANNEX A

1. Multicollinearity analysis

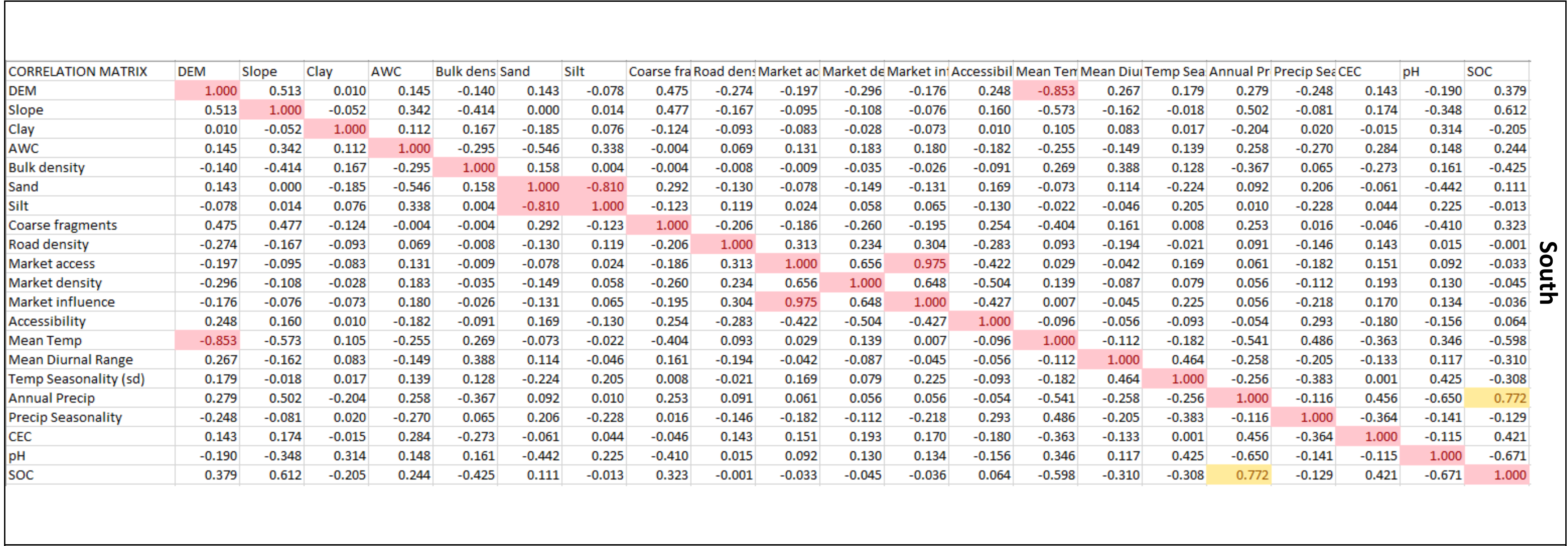
North

CORRELATION MATRIX	DEM	Slope	Clay	AWC	Bulk dens	Sand	Silt	Coarse fra	Road dens	Market ac	Market de	Market in	Accessibil	Mean Tem	Mean Diu	Temp Sea	Annual Pr	Precip Sea	CEC	pH	SOC
DEM	1.000	0.477	-0.147	0.246	0.208	-0.301	0.473	0.574	-0.243	-0.279	-0.331	-0.212	0.443	-0.649	0.124	-0.138	0.434	0.218	0.244	0.195	0.402
Slope	0.477	1.000	-0.172	0.267	0.105	-0.341	0.340	0.443	-0.120	-0.160	-0.205	-0.113	0.307	-0.244	-0.083	-0.308	0.541	-0.030	0.244	0.215	0.370
Clay	-0.147	-0.172	1.000	0.222	0.104	-0.038	0.034	-0.076	0.209	0.338	0.322	0.274	-0.203	0.254	0.193	-0.030	-0.217	-0.044	-0.225	0.030	-0.355
AWC	0.246	0.267	0.222	1.000	0.491	-0.283	0.479	0.387	0.067	0.211	0.178	0.194	-0.050	0.036	0.092	-0.199	0.305	-0.095	0.077	0.135	0.022
Bulk density	0.208	0.105	0.104	0.491	1.000	0.208	0.209	0.370	0.057	0.017	0.027	0.022	-0.040	-0.058	0.179	0.030	0.137	0.078	0.082	-0.037	0.030
Sand	-0.301	-0.341	-0.038	-0.283	0.208	1.000	-0.676	-0.138	0.003	-0.067	0.017	-0.062	-0.242	0.125	0.197	0.299	-0.319	0.102	-0.103	-0.427	-0.068
Silt	0.473	0.340	0.034	0.479	0.209	-0.676	1.000	0.429	-0.091	-0.039	-0.107	-0.015	0.289	-0.303	0.018	-0.081	0.262	0.105	0.144	0.225	0.081
Coarse fragments	0.574	0.443	-0.076	0.387	0.370	-0.138	0.429	1.000	-0.215	-0.173	-0.220	-0.129	0.263	-0.383	0.162	-0.051	0.341	0.176	0.242	-0.002	0.341
Road density	-0.243	-0.120	0.209	0.067	0.057	0.003	-0.091	-0.215	1.000	0.424	0.377	0.355	-0.268	0.408	-0.065	-0.250	-0.107	-0.272	-0.254	0.258	-0.348
Market access	-0.279	-0.160	0.338	0.211	0.017	-0.067	-0.039	-0.173	0.424	1.000	0.808	0.956	-0.465	0.541	0.160	-0.233	-0.180	-0.329	-0.368	0.052	-0.444
Market density	-0.331	-0.205	0.322	0.178	0.027	0.017	-0.107	-0.220	0.377	0.808	1.000	0.767	-0.553	0.662	0.141	-0.301	-0.222	-0.392	-0.475	-0.007	-0.510
Market influence	-0.212	-0.113	0.274	0.194	0.022	-0.062	-0.015	-0.129	0.355	0.956	0.767	1.000	-0.438	0.490	0.206	-0.220	-0.148	-0.298	-0.338	0.024	-0.390
Accessibility	0.443	0.307	-0.203	-0.050	-0.040	-0.242	0.289	0.263	-0.268	-0.465	-0.553	-0.438	1.000	-0.699	-0.208	0.107	0.169	0.359	0.215	0.273	0.289
Mean Temp	-0.649	-0.244	0.254	0.036	-0.058	0.125	-0.303	-0.383	0.408	0.541	0.662	0.490	-0.699	1.000	-0.088	-0.499	-0.104	-0.524	-0.408	-0.017	-0.451
Mean Diurnal Range	0.124	-0.083	0.193	0.092	0.179	0.197	0.018	0.162	-0.065	0.160	0.141	0.206	-0.208	-0.088	1.000	0.321	-0.188	0.218	-0.086	-0.370	-0.079
Temp Seasonality (sd)	-0.138	-0.308	-0.030	-0.199	0.030	0.299	-0.081	-0.051	-0.250	-0.233	-0.301	-0.220	0.107	-0.499	0.321	1.000	-0.514	0.474	0.177	-0.396	-0.020
Annual Precip	0.434	0.541	-0.217	0.305	0.137	-0.319	0.262	0.341	-0.107	-0.180	-0.222	-0.148	0.169	-0.104	-0.188	-0.514	1.000	-0.113	0.440	0.119	0.608
Precip Seasonality	0.218	-0.030	-0.044	-0.095	0.078	0.102	0.105	0.176	-0.272	-0.329	-0.392	-0.298	0.359	-0.524	0.218	0.474	-0.113	1.000	0.399	-0.191	0.199
CEC	0.244	0.244	-0.225	0.077	0.082	-0.103	0.144	0.242	-0.254	-0.368	-0.475	-0.338	0.215	-0.408	-0.086	0.177	0.440	0.399	1.000	-0.050	0.617
pH	0.195	0.215	0.030	0.135	-0.037	-0.427	0.225	-0.002	0.258	0.052	-0.007	0.024	0.273	-0.017	-0.370	-0.396	0.119	-0.191	-0.050	1.000	-0.166
SOC	0.402	0.370	-0.355	0.022	0.030	-0.068	0.081	0.341	-0.348	-0.444	-0.510	-0.390	0.289	-0.451	-0.079	-0.020	0.608	0.199	0.617	-0.166	1.000

West

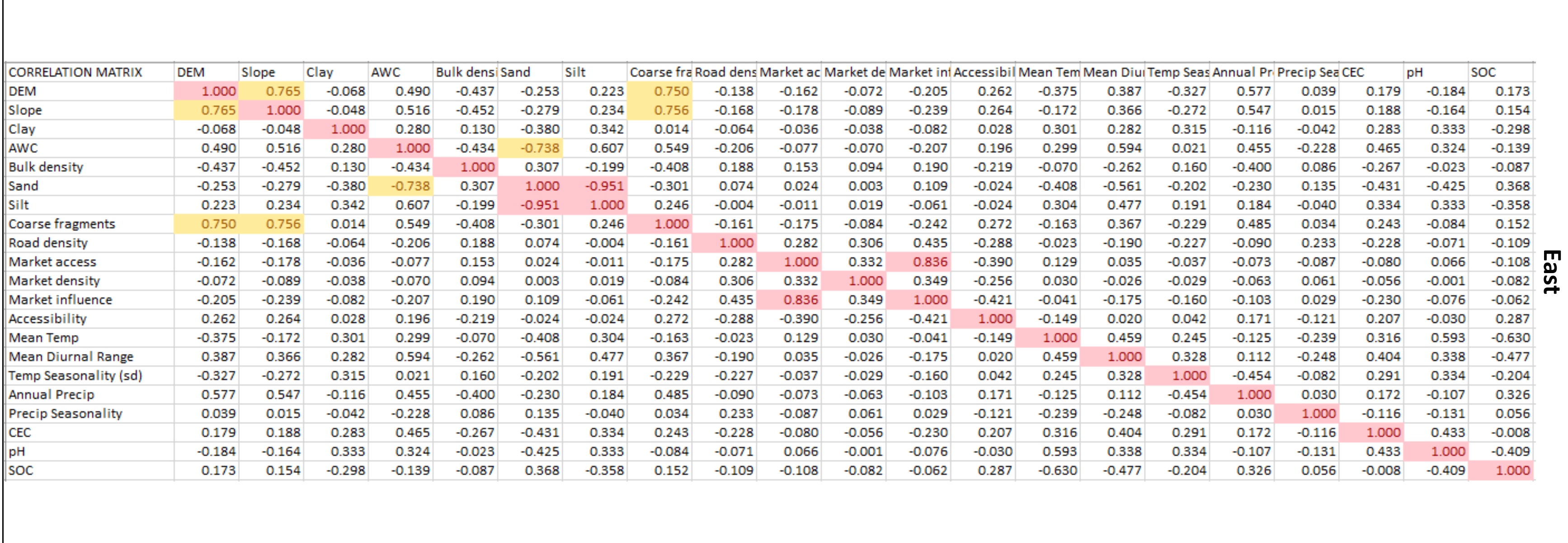
CORRELATION MATRIX	DEM	Slope	Clay	AWC	Bulk dens	Sand	Silt	Coarse fra	Road dens	Market ac	Market de	Market in	Accessibil	Mean Tem	Mean Diu	Temp Seas	Annual Pr	Precip Sea	CEC	pH	SOC
DEM	1.000	0.778	-0.068	0.372	-0.230	-0.100	0.081	0.592	-0.220	-0.201	-0.192	-0.149	0.241	-0.791	0.494	0.430	0.500	0.253	0.238	-0.158	0.051
Slope	0.778	1.000	-0.102	0.355	-0.269	-0.022	-0.003	0.638	-0.271	-0.206	-0.212	-0.161	0.256	-0.623	0.361	0.263	0.560	0.315	0.294	-0.252	0.189
Clay	-0.068	-0.102	1.000	0.356	0.127	-0.504	0.437	0.026	0.102	0.108	0.227	0.079	-0.270	0.195	0.192	0.109	-0.254	-0.180	-0.223	0.395	-0.389
AWC	0.372	0.355	0.356	1.000	-0.167	-0.597	0.480	0.511	-0.089	-0.027	0.024	-0.025	-0.058	-0.134	0.315	0.110	0.221	0.038	0.098	0.205	-0.105
Bulk density	-0.230	-0.269	0.127	-0.167	1.000	0.002	0.120	-0.274	0.225	0.202	0.186	0.174	-0.117	0.129	0.012	0.097	-0.296	-0.205	-0.243	0.102	-0.177
Sand	-0.100	-0.022	-0.504	-0.597	0.002	1.000	-0.939	-0.196	-0.170	-0.093	-0.172	-0.076	0.239	-0.103	-0.262	-0.155	0.116	0.080	0.163	-0.471	0.396
Silt	0.081	-0.003	0.437	0.480	0.120	-0.939	1.000	0.133	0.210	0.110	0.194	0.094	-0.221	0.073	0.237	0.167	-0.128	-0.072	-0.214	0.389	-0.392
Coarse fragments	0.592	0.638	0.026	0.511	-0.274	-0.196	0.133	1.000	-0.282	-0.208	-0.145	-0.184	0.138	-0.421	0.249	0.043	0.457	0.258	0.258	-0.115	0.132
Road density	-0.220	-0.271	0.102	-0.089	0.225	-0.170	0.210	-0.282	1.000	0.404	0.269	0.408	-0.321	0.185	0.077	0.234	-0.343	-0.214	-0.318	0.169	-0.310
Market access	-0.201	-0.206	0.108	-0.027	0.202	-0.093	0.110	-0.208	0.404	1.000	0.589	0.951	-0.467	0.140	0.094	0.164	-0.325	-0.220	-0.298	0.173	-0.304
Market density	-0.192	-0.212	0.227	0.024	0.186	-0.172	0.194	-0.145	0.269	0.589	1.000	0.554	-0.524	0.185	0.200	0.238	-0.416	-0.153	-0.348	0.233	-0.504
Market influence	-0.149	-0.161	0.079	-0.025	0.174	-0.076	0.094	-0.184	0.408	0.951	0.554	1.000	-0.436	0.065	0.096	0.195	-0.279	-0.198	-0.264	0.123	-0.275
Accessibility	0.241	0.256	-0.270	-0.058	-0.117	0.239	-0.221	0.138	-0.321	-0.467	-0.524	-0.436	1.000	-0.311	-0.185	-0.122	0.363	0.233	0.348	-0.327	0.538
Mean Temp	-0.791	-0.623	0.195	-0.134	0.129	-0.103	0.073	-0.421	0.185	0.140	0.185	0.065	-0.311	1.000	-0.092	-0.228	-0.490	-0.119	-0.286	0.425	-0.293
Mean Diurnal Range	0.494	0.361	0.192	0.315	0.012	-0.262	0.237	0.249	0.077	0.094	0.200	0.096	-0.185	-0.092	1.000	0.765	-0.074	0.086	-0.228	0.311	-0.470
Temp Seasonality (sd)	0.430	0.263	0.109	0.110	0.097	-0.155	0.167	0.043	0.234	0.164	0.238	0.195	-0.122	-0.228	0.765	1.000	-0.206	0.049	-0.286	0.233	-0.498
Annual Precip	0.500	0.560	-0.254	0.221	-0.296	0.116	-0.128	0.457	-0.343	-0.325	-0.416	-0.279	0.363	-0.490	-0.074	-0.206	1.000	0.297	0.603	-0.504	0.581
Precip Seasonality	0.253	0.315	-0.180	0.038	-0.205	0.080	-0.072	0.258	-0.214	-0.220	-0.153	-0.198	0.233	-0.119	0.086	0.049	0.297	1.000	0.333	-0.109	0.215
CEC	0.238	0.294	-0.223	0.098	-0.243	0.163	-0.214	0.258	-0.318	-0.298	-0.348	-0.264	0.348	-0.286	-0.228	-0.286	0.603	0.333	1.000	-0.362	0.615
pH	-0.158	-0.252	0.395	0.205	0.102	-0.471	0.389	-0.115	0.169	0.173	0.233	0.123	-0.327	0.425	0.311	0.233	-0.504	-0.109	-0.362	1.000	-0.600
SOC	0.051	0.189	-0.389	-0.105	-0.177	0.396	-0.392	0.132	-0.310	-0.304	-0.504	-0.275	0.538	-0.293	-0.470	-0.498	0.581	0.215	0.615	-0.600	1.000

South



CORRELATION MATRIX	DEM	Slope	Clay	AWC	Bulk dens	Sand	Silt	Coarse fra	Road dens	Market ac	Market de	Market in	Accessibil	Mean Ten	Mean Diu	Temp Sea	Annual Pr	Precip Sea	CEC	pH	SOC
DEM	1.000	0.513	0.010	0.145	-0.140	0.143	-0.078	0.475	-0.274	-0.197	-0.296	-0.176	0.248	-0.853	0.267	0.179	0.279	-0.248	0.143	-0.190	0.379
Slope	0.513	1.000	-0.052	0.342	-0.414	0.000	0.014	0.477	-0.167	-0.095	-0.108	-0.076	0.160	-0.573	-0.162	-0.018	0.502	-0.081	0.174	-0.348	0.612
Clay	0.010	-0.052	1.000	0.112	0.167	-0.185	0.076	-0.124	-0.093	-0.083	-0.028	-0.073	0.010	0.105	0.083	0.017	-0.204	0.020	-0.015	0.314	-0.205
AWC	0.145	0.342	0.112	1.000	-0.295	-0.546	0.338	-0.004	0.069	0.131	0.183	0.180	-0.182	-0.255	-0.149	0.139	0.258	-0.270	0.284	0.148	0.244
Bulk density	-0.140	-0.414	0.167	-0.295	1.000	0.158	0.004	-0.004	-0.008	-0.009	-0.035	-0.026	-0.091	0.269	0.388	0.128	-0.367	0.065	-0.273	0.161	-0.425
Sand	0.143	0.000	-0.185	-0.546	0.158	1.000	-0.810	0.292	-0.130	-0.078	-0.149	-0.131	0.169	-0.073	0.114	-0.224	0.092	0.206	-0.061	-0.442	0.111
Silt	-0.078	0.014	0.076	0.338	0.004	-0.810	1.000	-0.123	0.119	0.024	0.058	0.065	-0.130	-0.022	-0.046	0.205	0.010	-0.228	0.044	0.225	-0.013
Coarse fragments	0.475	0.477	-0.124	-0.004	-0.004	0.292	-0.123	1.000	-0.206	-0.186	-0.260	-0.195	0.254	-0.404	0.161	0.008	0.253	0.016	-0.046	-0.410	0.323
Road density	-0.274	-0.167	-0.093	0.069	-0.008	-0.130	0.119	-0.206	1.000	0.313	0.234	0.304	-0.283	0.093	-0.194	-0.021	0.091	-0.146	0.143	0.015	-0.001
Market access	-0.197	-0.095	-0.083	0.131	-0.009	-0.078	0.024	-0.186	0.313	1.000	0.656	0.975	-0.422	0.029	-0.042	0.169	0.061	-0.182	0.151	0.092	-0.033
Market density	-0.296	-0.108	-0.028	0.183	-0.035	-0.149	0.058	-0.260	0.234	0.656	1.000	0.648	-0.504	0.139	-0.087	0.079	0.056	-0.112	0.193	0.130	-0.045
Market influence	-0.176	-0.076	-0.073	0.180	-0.026	-0.131	0.065	-0.195	0.304	0.975	0.648	1.000	-0.427	0.007	-0.045	0.225	0.056	-0.218	0.170	0.134	-0.036
Accessibility	0.248	0.160	0.010	-0.182	-0.091	0.169	-0.130	0.254	-0.283	-0.422	-0.504	-0.427	1.000	-0.096	-0.056	-0.093	-0.054	0.293	-0.180	-0.156	0.064
Mean Temp	-0.853	-0.573	0.105	-0.255	0.269	-0.073	-0.022	-0.404	0.093	0.029	0.139	0.007	-0.096	1.000	-0.112	-0.182	-0.541	0.486	-0.363	0.346	-0.598
Mean Diurnal Range	0.267	-0.162	0.083	-0.149	0.388	0.114	-0.046	0.161	-0.194	-0.042	-0.087	-0.045	-0.056	-0.112	1.000	0.464	-0.258	-0.205	-0.133	0.117	-0.310
Temp Seasonality (sd)	0.179	-0.018	0.017	0.139	0.128	-0.224	0.205	0.008	-0.021	0.169	0.079	0.225	-0.093	-0.182	0.464	1.000	-0.256	-0.383	0.001	0.425	-0.308
Annual Precip	0.279	0.502	-0.204	0.258	-0.367	0.092	0.010	0.253	0.091	0.061	0.056	0.056	-0.054	-0.541	-0.258	-0.256	1.000	-0.116	0.456	-0.650	0.772
Precip Seasonality	-0.248	-0.081	0.020	-0.270	0.065	0.206	-0.228	0.016	-0.146	-0.182	-0.112	-0.218	0.293	0.486	-0.205	-0.383	-0.116	1.000	-0.364	-0.141	-0.129
CEC	0.143	0.174	-0.015	0.284	-0.273	-0.061	0.044	-0.046	0.143	0.151	0.193	0.170	-0.180	-0.363	-0.133	0.001	0.456	-0.364	1.000	-0.115	0.421
pH	-0.190	-0.348	0.314	0.148	0.161	-0.442	0.225	-0.410	0.015	0.092	0.130	0.134	-0.156	0.346	0.117	0.425	-0.650	-0.141	-0.115	1.000	-0.671
SOC	0.379	0.612	-0.205	0.244	-0.425	0.111	-0.013	0.323	-0.001	-0.033	-0.045	-0.036	0.064	-0.598	-0.310	-0.308	0.772	-0.129	0.421	-0.671	1.000

East



CORRELATION MATRIX	DEM	Slope	Clay	AWC	Bulk densi	Sand	Silt	Coarse fra	Road dens	Market ac	Market de	Market in	Accessibil	Mean Tem	Mean Diu	Temp Seas	Annual Pr	Precip Sea	CEC	pH	SOC
DEM	1.000	0.765	-0.068	0.490	-0.437	-0.253	0.223	0.750	-0.138	-0.162	-0.072	-0.205	0.262	-0.375	0.387	-0.327	0.577	0.039	0.179	-0.184	0.173
Slope	0.765	1.000	-0.048	0.516	-0.452	-0.279	0.234	0.756	-0.168	-0.178	-0.089	-0.239	0.264	-0.172	0.366	-0.272	0.547	0.015	0.188	-0.164	0.154
Clay	-0.068	-0.048	1.000	0.280	0.130	-0.380	0.342	0.014	-0.064	-0.036	-0.038	-0.082	0.028	0.301	0.282	0.315	-0.116	-0.042	0.283	0.333	-0.298
AWC	0.490	0.516	0.280	1.000	-0.434	-0.738	0.607	0.549	-0.206	-0.077	-0.070	-0.207	0.196	0.299	0.594	0.021	0.455	-0.228	0.465	0.324	-0.139
Bulk density	-0.437	-0.452	0.130	-0.434	1.000	0.307	-0.199	-0.408	0.188	0.153	0.094	0.190	-0.219	-0.070	-0.262	0.160	-0.400	0.086	-0.267	-0.023	-0.087
Sand	-0.253	-0.279	-0.380	-0.738	0.307	1.000	-0.951	-0.301	0.074	0.024	0.003	0.109	-0.024	-0.408	-0.561	-0.202	-0.230	0.135	-0.431	-0.425	0.368
Silt	0.223	0.234	0.342	0.607	-0.199	-0.951	1.000	0.246	-0.004	-0.011	0.019	-0.061	-0.024	0.304	0.477	0.191	0.184	-0.040	0.334	0.333	-0.358
Coarse fragments	0.750	0.756	0.014	0.549	-0.408	-0.301	0.246	1.000	-0.161	-0.175	-0.084	-0.242	0.272	-0.163	0.367	-0.229	0.485	0.034	0.243	-0.084	0.152
Road density	-0.138	-0.168	-0.064	-0.206	0.188	0.074	-0.004	-0.161	1.000	0.282	0.306	0.435	-0.288	-0.023	-0.190	-0.227	-0.090	0.233	-0.228	-0.071	-0.109
Market access	-0.162	-0.178	-0.036	-0.077	0.153	0.024	-0.011	-0.175	0.282	1.000	0.332	0.836	-0.390	0.129	0.035	-0.037	-0.073	-0.087	-0.080	0.066	-0.108
Market density	-0.072	-0.089	-0.038	-0.070	0.094	0.003	0.019	-0.084	0.306	0.332	1.000	0.349	-0.256	0.030	-0.026	-0.029	-0.063	0.061	-0.056	-0.001	-0.082
Market influence	-0.205	-0.239	-0.082	-0.207	0.190	0.109	-0.061	-0.242	0.435	0.836	0.349	1.000	-0.421	-0.041	-0.175	-0.160	-0.103	0.029	-0.230	-0.076	-0.062
Accessibility	0.262	0.264	0.028	0.196	-0.219	-0.024	-0.024	0.272	-0.288	-0.390	-0.256	-0.421	1.000	-0.149	0.020	0.042	0.171	-0.121	0.207	-0.030	0.287
Mean Temp	-0.375	-0.172	0.301	0.299	-0.070	-0.408	0.304	-0.163	-0.023	0.129	0.030	-0.041	-0.149	1.000	0.459	0.245	-0.125	-0.239	0.316	0.593	-0.630
Mean Diurnal Range	0.387	0.366	0.282	0.594	-0.262	-0.561	0.477	0.367	-0.190	0.035	-0.026	-0.175	0.020	0.459	1.000	0.328	0.112	-0.248	0.404	0.338	-0.477
Temp Seasonality (sd)	-0.327	-0.272	0.315	0.021	0.160	-0.202	0.191	-0.229	-0.227	-0.037	-0.029	-0.160	0.042	0.245	0.328	1.000	-0.454	-0.082	0.291	0.334	-0.204
Annual Precip	0.577	0.547	-0.116	0.455	-0.400	-0.230	0.184	0.485	-0.090	-0.073	-0.063	-0.103	0.171	-0.125	0.112	-0.454	1.000	0.030	0.172	-0.107	0.326
Precip Seasonality	0.039	0.015	-0.042	-0.228	0.086	0.135	-0.040	0.034	0.233	-0.087	0.061	0.029	-0.121	-0.239	-0.248	-0.082	0.030	1.000	-0.116	-0.131	0.056
CEC	0.179	0.188	0.283	0.465	-0.267	-0.431	0.334	0.243	-0.228	-0.080	-0.056	-0.230	0.207	0.316	0.404	0.291	0.172	-0.116	1.000	0.433	-0.008
pH	-0.184	-0.164	0.333	0.324	-0.023	-0.425	0.333	-0.084	-0.071	0.066	-0.001	-0.076	-0.030	0.593	0.338	0.334	-0.107	-0.131	0.433	1.000	-0.409
SOC	0.173	0.154	-0.298	-0.139	-0.087	0.368	-0.358	0.152	-0.109	-0.108	-0.082	-0.062	0.287	-0.630	-0.477	-0.204	0.326	0.056	-0.008	-0.409	1.000

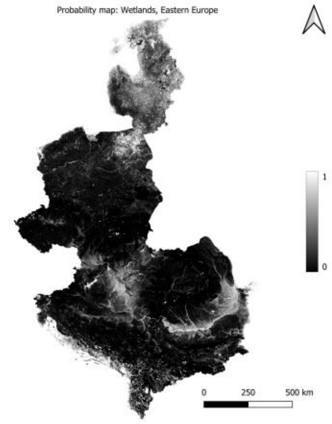
Probability surfaces, Eastern Europe

Low-density rural settlement

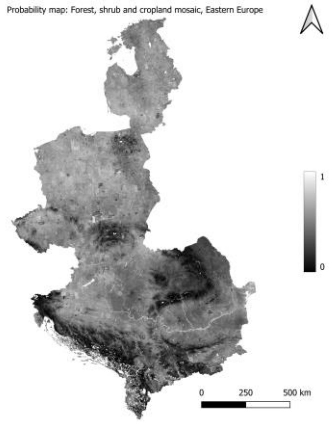
Medium-density peri-urban settlement

High-density urban settlement

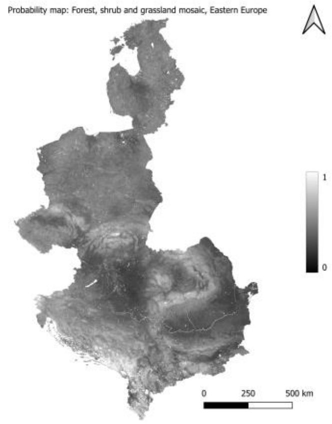
Wetlands



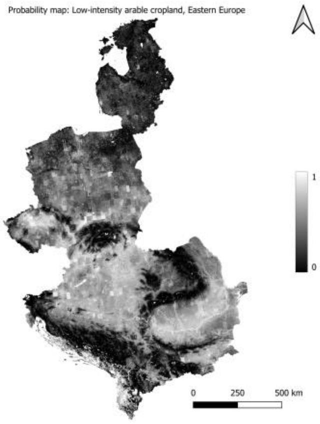
Forest, shrub and cropland mosaics



Forest, shrub and grassland mosaic



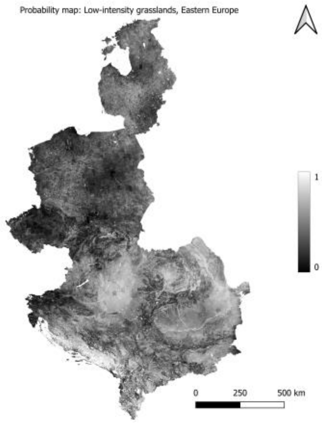
Low-intensity arable cropland



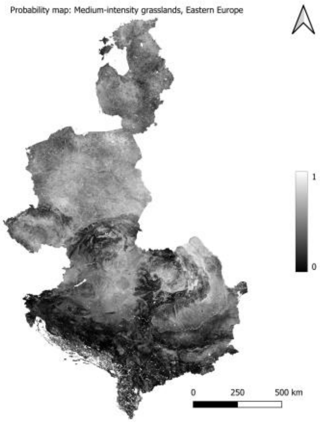
Medium-intensity arable cropland

High-intensity arable cropland

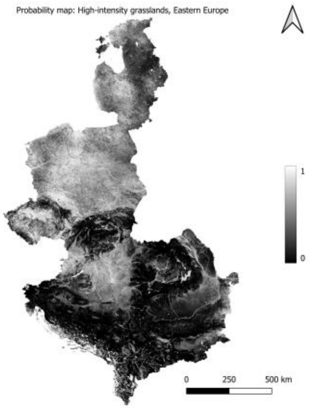
Low-intensity grasslands



Medium-intensity grasslands



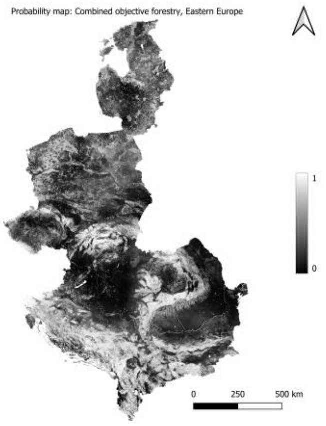
High-intensity grasslands



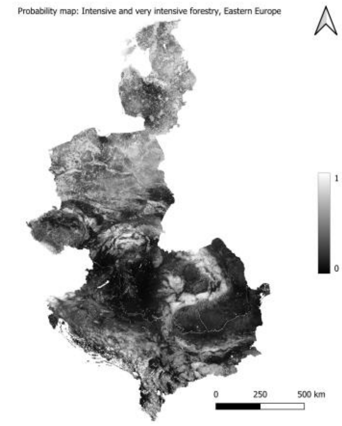
Permanent cropland

Primary forest and close-to-nature forestry

Combined objective forestry



Intensive and very intensive forestry

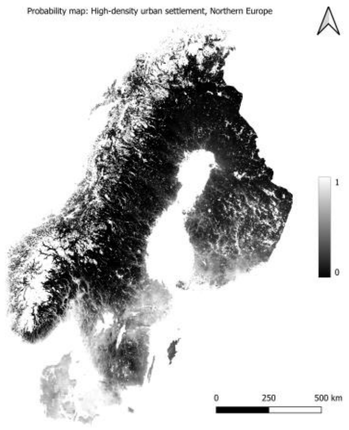


Probability surfaces, Northern Europe

Low-density rural settlement

Medium-density peri-urban settlement

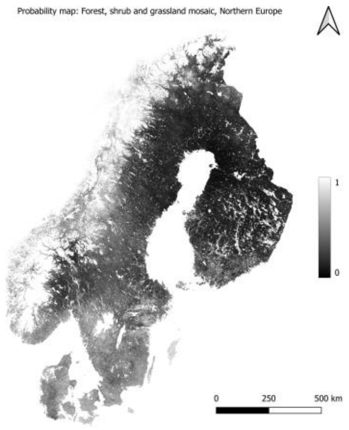
High-density urban settlement



Wetlands

Forest, shrub and cropland mosaics

Forest, shrub and grassland mosaic



Low-intensity arable cropland

Medium-intensity arable cropland

High-intensity arable cropland

Low-intensity grasslands

Medium-intensity grasslands

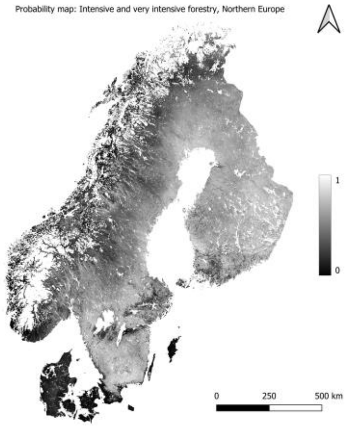
High-intensity grasslands

Permanent cropland

Primary forest and close-to-nature forestry

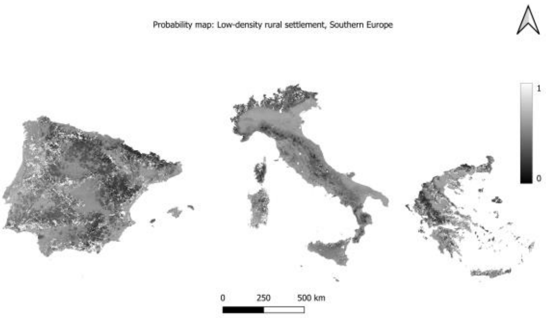
Combined objective forestry

Intensive forestry and very intensive forestry

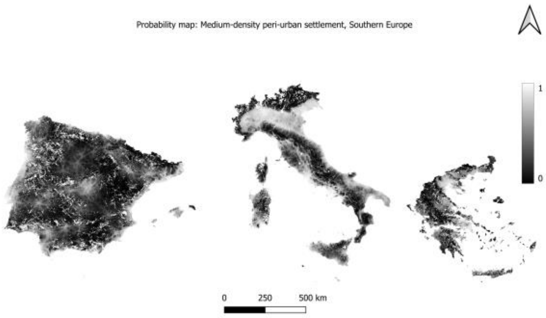


Probability surfaces, Southern Europe

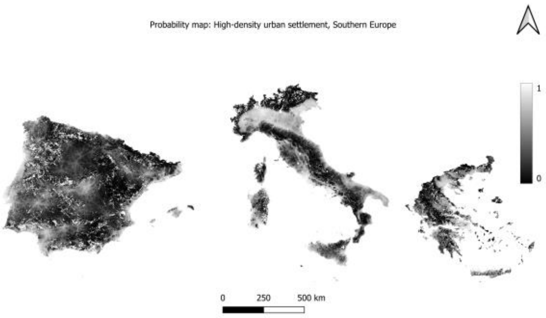
Low-density rural settlement



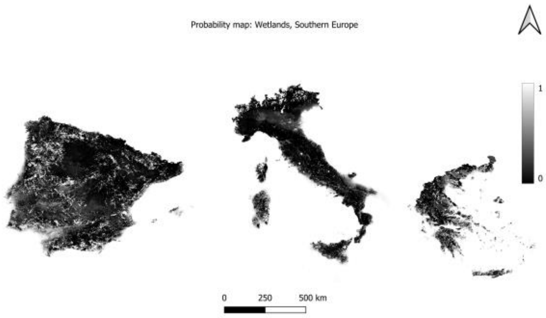
Medium-density peri-urban settlement



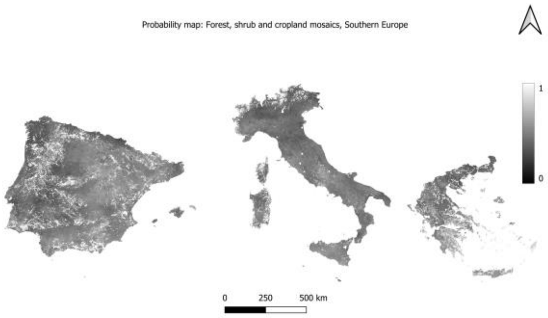
High-density urban settlement



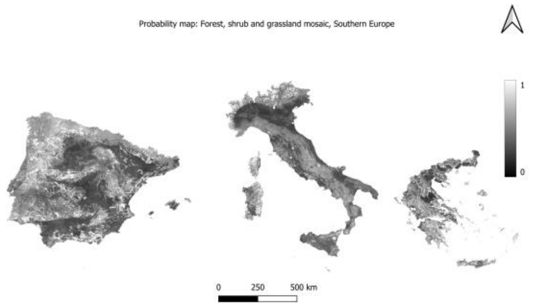
Wetlands



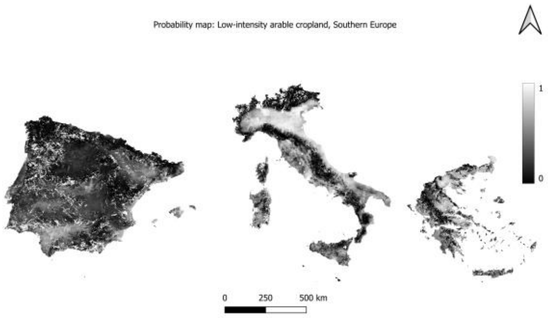
Forest, shrub and cropland mosaics



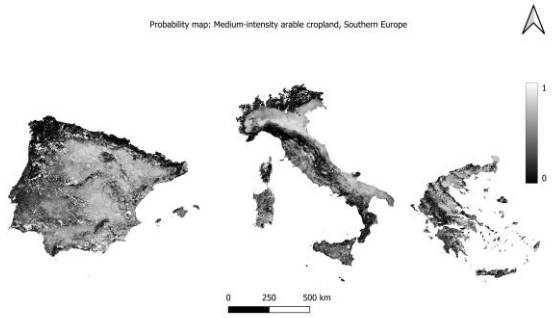
Forest, shrub and grassland mosaic



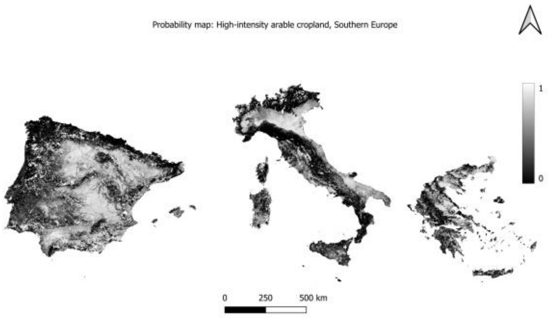
Low-intensity arable cropland



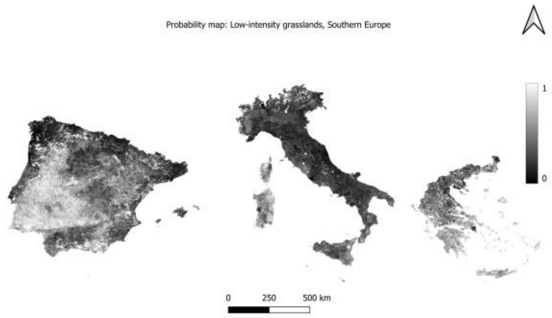
Medium-intensity arable cropland



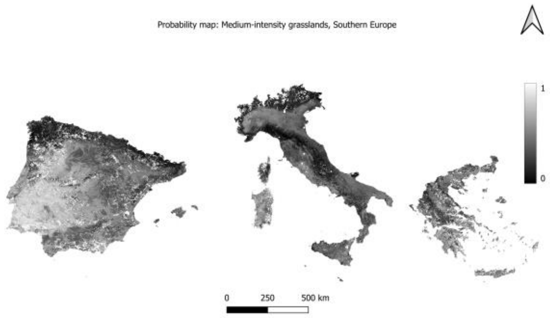
High-intensity arable cropland



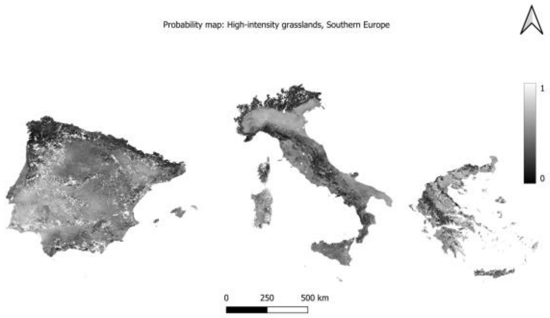
Low-intensity grasslands



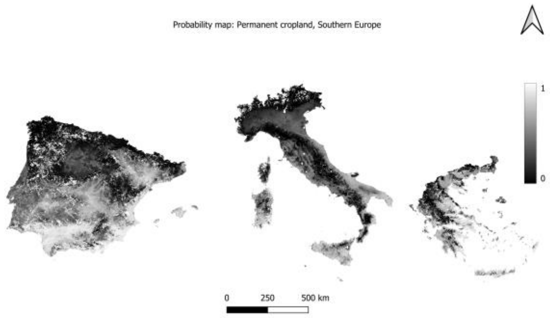
Medium-intensity grasslands



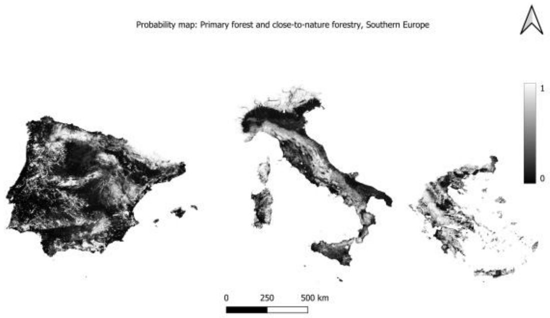
High-intensity grasslands



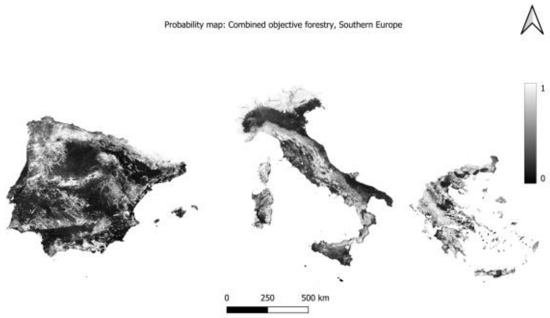
Permanent cropland



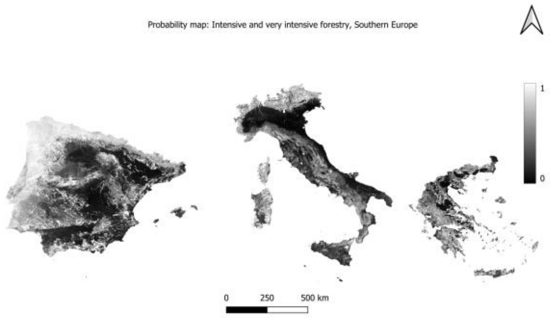
Primary forest and close-to-nature forestry



Combined objective forestry

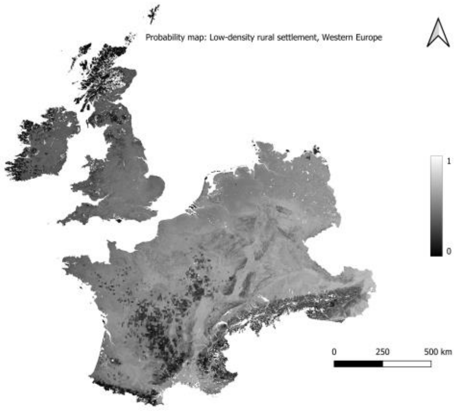


Intensive forestry and very intensive forestry

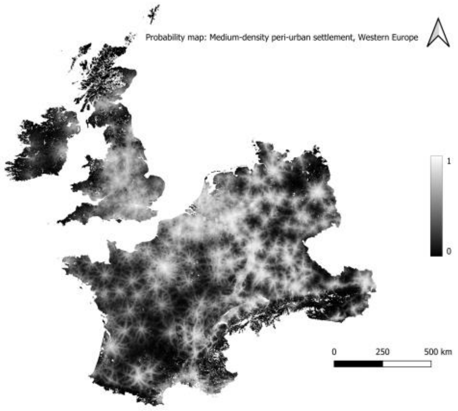


Probability surfaces, Western Europe

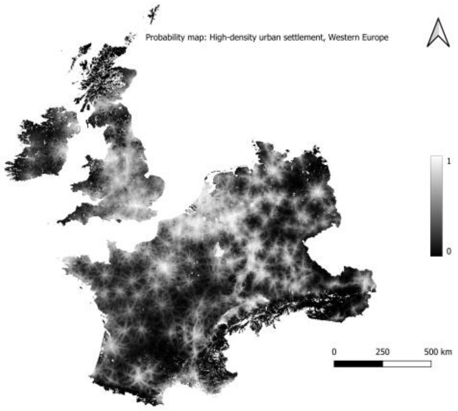
Low-density rural settlement



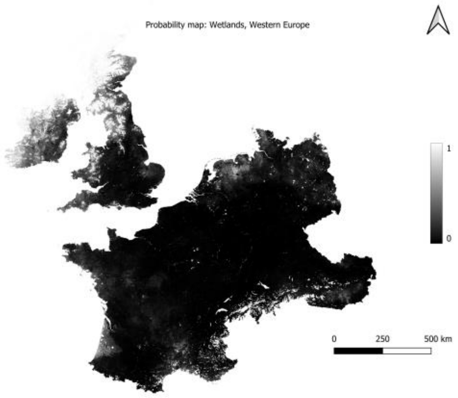
Medium-density peri-urban settlement



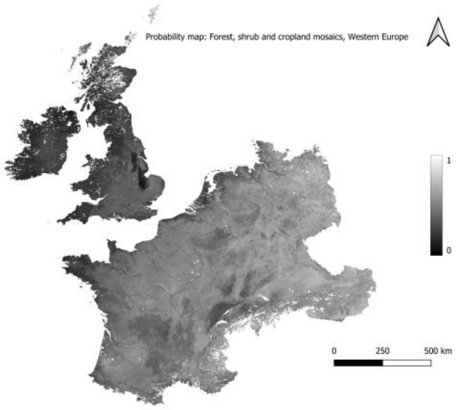
High-density urban settlement



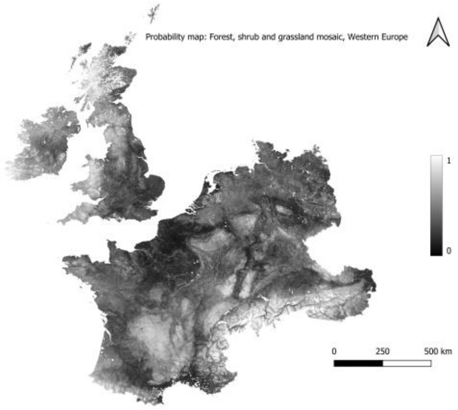
Wetlands



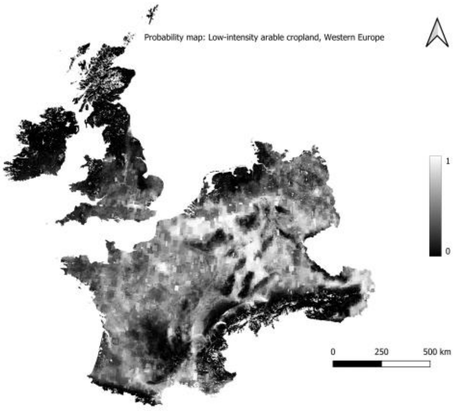
Forest, shrub and cropland mosaics



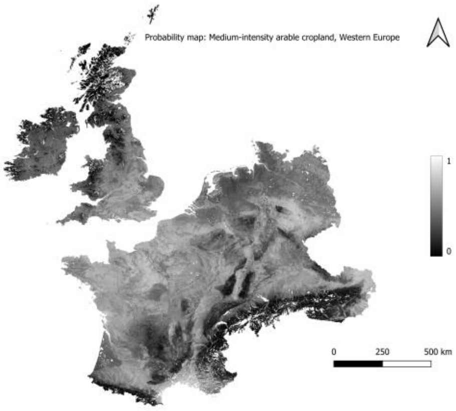
Forest, shrub and grassland mosaic



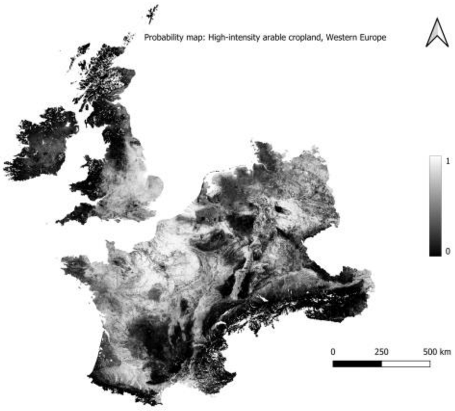
Low-intensity arable cropland



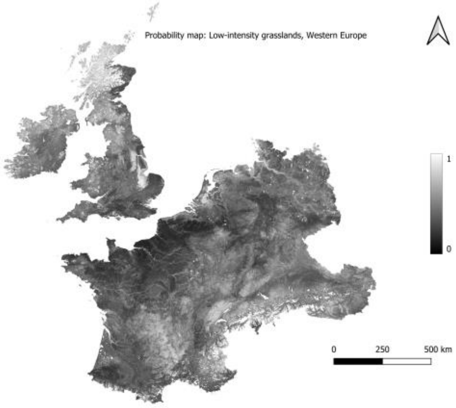
Medium-intensity arable cropland



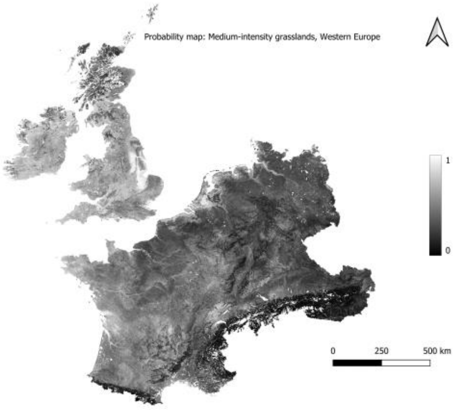
High-intensity arable cropland



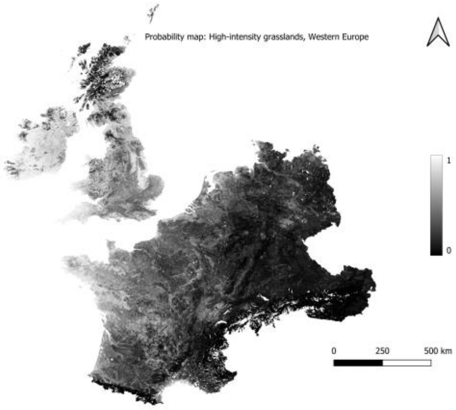
Low-intensity grasslands



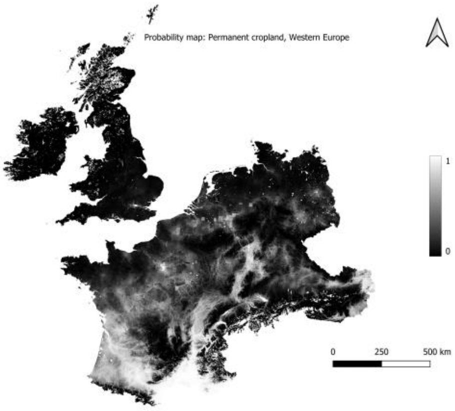
Medium-intensity grasslands



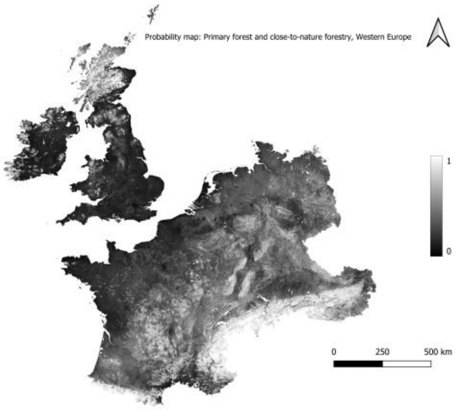
High-intensity grasslands



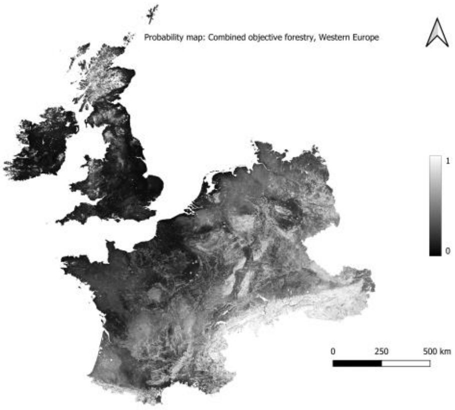
Permanent cropland



Primary forest and close-to-nature forestry



Combined objective forestry



Intensive forestry and very intensive forestry