



Deliverable

D3.6: Demonstration of the scenario framework

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I. DOCUMENT CONTROL

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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

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1.0	11/06/2026	Niek Scherpenhuijzen	First revised version



III. Abbreviations

ALU	Albert-Ludwigs University Freiburg
BFW	Federal Research and Training Center for Forests, Natural Hazards and Landscape
CFRI	Croatian Forest Research Institute
CICERO	Center for International Climate Research
CSIC	Consejo Superior de Investigaciones Científicas
EEA	European Environmental Agency
ELO	European Landowners Organisation
EU	European Union
EVINBO	Eigen Vermogen van het Instituut voor Natuur- en Bosonderzoek
FMI	Finnish Meteorological Institute
GIS	Slovenian Forestry Institute
IEFC	Institut Européen de la Forêt Cultivée
IGN	National Institute of Geographic and Forest Information
JRC	Joint Research Center
LUKE	Natural Resources Institute Finland
NIBIO	Norwegian Institute of Bioeconomy Research
TI	Thünen Institute of Forest Ecosystems
TM	TreeMetrics
UB	University of Bristol
UGOE	University of Göttingen
UH	University of Helsinki
UHUL	Czech Forest Management Institute
VTT	Technical Research Centre of Finland Ltd.
VUA	Vrije Universiteit Amsterdam
WSL	Swiss Federal Research Institute for Forests Snow and Landscape Research



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1. Summary

This deliverable reports the results of PathFinder WP3, Task3.6, presenting the outcomes of the scenario development, the land use simulations using CLUMondo, the forest state modelling using European Forestry Dynamics Model (EFDM), and the subsequent trade-off analysis based on this integrated modelling framework. Ultimately, this deliverable serves to analyse how policy decisions and resulting management actions impact the future supply of forest ecosystem services.

The forest management scenarios were derived from a document analysis and validated through forest stakeholder workshops and a survey, resulting in four distinct scenarios: biodiversity focused forests, participatory forest stewardship, multifunctional forests, and competitive forest industry. These scenarios were subsequently translated into quantitative storylines and projected using the land use model CLUMondo, which included five distinct forest management classes: unmanaged forest, extensive forestry, combined objective forestry, intensive forestry, and very intensive forestry. The CLUMondo results were then used as input for EFDM to simulate forest states, from which production, biomass, and four biodiversity indicators (Gini, Shannon, old-growth and deadwood) were developed. In addition, two disturbance indicators were developed: wind disturbance and bark beetle disturbance. Finally, all indicators were assessed within a trade-off and synergy analysis.

The CLUMondo results indicate that forest management distributions differ substantially among the scenarios. These range from a dominance of extensive forestry in the biodiversity focused forests scenario to a more even distribution in the competitive forest industry scenario, where intensive forestry is the most prevalent class. Despite these contrasting management trajectories, all scenarios demonstrate an increase in total forest area. Moreover, hotspots of forest gain, loss, deintensification, and intensification trajectories are observed across all scenarios, indicating a high likelihood of forest management dynamics occurring in Europe irrespective of the chosen scenario.

The EFDM simulations show that forest productivity increased systematically with higher forest management intensities derived from the CLUMondo projections. When aggregated by scenario, these findings reveal clear contrasting structural trends across Europe. The biodiversity focused forests scenario yields the highest total biomass, deadwood, and old-growth forest areas. Conversely, biomass levels are lowest under the more intensive pathways, which instead maximizes wood production volumes. The integrated modelling framework successfully established a spatially explicit pan-European approach capable of demonstrating forest state dynamics under diverse forest management pathways.

At the European level, the biodiversity indicators increased across the four scenarios from 2020 to 2100, with the largest values for the biodiversity focused forest scenario. However, the differences between scenarios were small, suggesting the insensitivity to management alternatives. While the subindices Gini (indicator of forest complexity) and Shannon (indicator of forest composition) were not strongly affected by management scenarios, the most relevant differences appear in the percentage of mature forests and deadwood stocks, with larger values for the biodiversity focused forests scenario.

The results of the trade-off and synergy analysis show that the various indicators exhibit distinct interactions, which are largely explained by the calibration of the modelling framework. Consequently, these results should be interpreted with this context in mind. Strong synergies occur between production, biomass, old-growth, and deadwood, whereas trade-offs are present with the Shannon and Gini indices. The disturbance indicators show no to very minor interactions with all



other indicators. Finally, the impact of forest management is most visible in the total volume of wood production.

During the application of EFDM, we identified several challenges. First, EFDM requires predefined harvest levels, which necessitated a non-transparent calibration process to produce realistic forecasts after fitting transition probability models based on NFI data. Second, EFDM is only indirectly linked to forest product demand projections (provided by GLOBIOM) and can therefore diverge over time from demand trajectories driven by developments in other economic sectors. This issue likewise required calibration and is, in fact, common to many forest forecasting approaches. Nevertheless, the application of EFDM provided valuable insights, and the methodological framework for coupling different models remains highly useful. For this reason, the approach is presented in this deliverable.

As a risk mitigation measure to ensure realistic pathway analyses in Deliverable 4.5, we also developed an alternative modelling approach, PixSim. Unlike EFDM, PixSim is directly coupled to forest product demand models such as GLOBIOM, thereby maintaining consistency with demand developments in other sectors and avoiding the need for recalibration after fitting growth model parameters. In addition, PixSim provides a more explicit representation of climate feedbacks and operates on high-resolution spatial data, reducing artefacts caused by aggregation and scale mismatches.

Because the development of PixSim was only finalized late in the project, this deliverable merely describes its underlying methodology. The forest structure projections presented here are therefore based on EFDM and serve primarily to illustrate the forecasting framework. PixSim was subsequently applied in the pathway analyses reported in Deliverable 4.5.

2. Introduction

European forests are facing increasing environmental pressures alongside competing management demands from society. Current EU policies position forests as multifunctional tools essential for achieving climate neutrality, restoring biodiversity, and developing the bioeconomy, often resulting in complex trade-offs (Blattert et al., 2023; Di Marzo et al., 2026; Elomina & Pölzl, 2021; Gordeeva et al., 2022; Nijnik et al., 2010; Söderberg & Eckerberg, 2013). Empirical evidence indicates that meeting these demands simultaneously remains a significant challenge, underlining the inherent trade-offs in forest management between timber production, biodiversity, and carbon sequestration (Blattert et al., 2023; Hetemäki et al., 2024; Luyssaert et al., 2018; Morán-Ordóñez et al., 2020; Rybar & Bosela, 2023; Verkerk et al., 2014).

In this deliverable we aim to identify spatial and temporal trade-offs and synergies across European forests, using four stakeholder-informed forest management scenarios. To evaluate these scenarios, we employ a multi-model approach, integrating the land-use model CLUMondo with the forest simulator EFDM. CLUMondo provides spatially explicit projections of land-use and management change, which are subsequently used as input for EFDM to assess impacts on forest structure and ecosystem services. In addition to the European-scale analysis, results are further explored for selected workshop countries, enabling a closer link to stakeholder insights in PathFinder WP4 and supporting the interpretation of trade-offs and synergies in a policy-relevant context.



3. Methods

3.1 Scenario development¹

3.1.1 Document analysis

Future European forest scenarios were developed by translating qualitative stakeholder perspectives into quantitative model parameters through a targeted qualitative document analysis (Bowen, 2009). A policy target map synthesizing key European forest-related regulations (Di Marzo et al., 2023), together with an EU stakeholder frame analysis of the political discourse surrounding the LULUCF Regulation (Di Marzo et al., 2026), informed the identification of five core objectives: forest conservation, climate change mitigation, sustainable harvesting, wood production, and cultural value. We defined three associated management actions per objective (Table 1), representing the essential steps toward achieving the corresponding policy goal.

The first objective, forest conservation, was assessed through management actions identified by Lindenmayer et al. (2006): (1) protecting old-growth forests and reducing human pressures; (2) restoring forest ecosystems and degraded lands; and (3) maintaining biodiversity and ecological functions.

A second objective focuses on climate change mitigation, following Canadell & Raupach (2008): (1) increasing carbon storage through afforestation, reforestation, or restoration; (2) preventing forest loss and degradation to avoid greenhouse gas emissions; and (3) supporting forest management practices aimed at achieving climate neutrality.

The third objective involves sustainable forest harvesting, informed by the principles of sustainable forest management (SFM) outlined by Lattimore et al. (2009) and FAO (2013). Here, management actions include: (1) ensuring wood harvesting does not compromise biodiversity, forest productivity, or ecological health; (2) promoting forest certification and carbon accounting; and (3) enforcing the adoption of sustainable forestry guidelines.

The fourth objective focuses on wood production, reflecting current policy frames that position forests as primary providers of raw materials and central pillars of the European bio-economy (Elomina & Pölzl, 2021). Informed by the growing emphasis on innovation and the deployment of efficient bio-based systems (Jankovský et al., 2021; G. Weiss et al., 2021), the defined management actions include: (1) increasing wood production to support the future bioeconomy demand; (2) improving processing efficiency and increasing yields; and (3) promoting innovation and investment to support the development of wood-based industries and the bioeconomy.

The final objective concerns cultural value, evaluated through IUFRO (2007) guidelines by: (1) preserving local forest landscapes and practices to maintain cultural identity; (2) promoting cultural services such as recreation and eco-tourism; and (3) involving local communities, stakeholders, and forest owners in forest management planning, incorporating local knowledge.

To develop distinct scenarios, we analysed strategic documents from four prominent stakeholder organizations: the Confederation of European Forest Owners (CEPF, 2023), the Confederation of European Paper Industries (CEPI, 2017), the European State Forest Association (EUSTAFOR, 2024), and the World Wide Fund for Nature (WWF, 2025). Document selection was based on three criteria:

¹ Content of this section is adapted from the author's manuscript "Exploring European forest management futures: a stakeholder-informed spatial scenario modelling approach", which is currently under peer review at *Global Environmental Change*.



(1) include a comprehensive and forward-looking perspective on European forests, (2) be produced by large and influential organizations, and (3) represent differing viewpoints.

Following the method introduced by Helfenstein et al. (2022), each document was evaluated and assigned a score for every management action, with zero if not stated or inferred, one if mentioned only, and two if central to the vision. These scores were then synthesized to represent organizational emphasis on the five core objectives, facilitating the translation of visions into cohesive qualitative storylines and the construction of four distinct scenarios. This synthesis resulted in the definition of four distinct scenario narratives which serve as the basis for the subsequent modelling: (1) biodiversity focused forests; (2) participatory forest stewardship; (3) multifunctional forests; and (4) competitive forest industry. More information on the scenarios is provided in Section 4.1.

Table 1. Description of the identified forest objectives, along with three corresponding management actions.

Key objective	Description	Management action
Forest conservation	Protecting and maintaining forests to preserve biodiversity and ecological functions	1. Protect old-growth forests and reduce human pressures across all forest types 2. Restore forest ecosystems and degraded forests 3. Maintain biodiversity and ecological functions
Climate change mitigation	Managing forests to contribute to climate goals by enhancing carbon storage and reducing forest carbon emissions	1. Increase carbon storage through afforestation, reforestation, or restoration 2. Prevent forest loss and degradation to avoid greenhouse gas emissions 3. Support forest management practices aimed at achieving climate neutrality
Sustainable harvesting	Implementing sustainable harvesting practices that allow for the continuous extraction of forest resources without compromising ecological health, biodiversity, and long-term productivity	1. Ensure wood harvesting does not compromise biodiversity, forest productivity, or ecological health 2. Promote forest certification and carbon accounting 3. Enforce the adoption of sustainable forestry guidelines
Wood production	Harvesting of forests to meet demand for wood products and support the bioeconomy	1. Increase wood production to support the future bioeconomy demand 2. Improve processing efficiency and increase yields



		3. Promote innovation and investment to support the development of wood-based industries and the bioeconomy
Cultural value	Preserving cultural identity through traditional forest landscapes and practices, promoting cultural services such as heritage, recreation, and eco-tourism, and fostering community involvement	1. Preserve local forest landscapes and practices to maintain cultural identity 2. Promote cultural services such as recreation and eco-tourism 3. Involve local communities, stakeholders and forest owners in forest management and conservation planning, incorporating local knowledge

3.1.2 Workshops

To validate the document analysis, five stakeholder workshops were conducted. While workshops in Spain, Finland, Austria, and Slovenia were held at the national-level, the workshop in Brussels specifically targeted the EU-level, involving representatives from European institutions. In these workshops, participants discussed each scenario in breakout groups using a risk canvas based on the environmental justice theory of Schlosberg (2007). Participants assessed distribution (“winners” and “losers”), recognition (heard and unheard voices), and procedural issues, alongside potential unintended outcomes, to identify key trade-offs and synergies. Where time allowed, groups rotated between scenarios, and key points were documented in plenary discussions.

3.1.3 Survey

In addition to the workshops, the framework of five objectives was applied in an online survey to quantify stakeholder preferences. Participants allocated 15 points across the objectives, with a six-point maximum per objective. Survey responses were analysed via hierarchical agglomerative cluster analysis using Ward’s minimum variance method (Ward.D2; Murtagh & Legendre, 2014). The optimal number of clusters was determined through dendrogram inspection in combination with silhouette and elbow diagnostics. The resulting prioritization profiles informed the final refinement of the scenario narratives.

3.2 Model implementation of scenarios

3.2.1 CLUMondo

The qualitative scenario narratives were translated into spatially explicit quantitative model parameters to facilitate their implementation within the CLUMondo land-use framework. To assess the long-term impacts of forest management, CLUMondo was executed for the period 2020–2100.

While the simulation period extends to the end of the century, we applied a constant demand projection for all land-use commodities beyond 2050. This decision was made to mitigate the substantial increase in socio-economic and climate-related uncertainty associated with late-century projections. Consequently, the primary analysis of land-system change within this deliverable focuses on the results for the 2050 time step.

3.2.1.1 Spatial extent and land systems

The CLUMondo model was applied across Europe, excluding Iceland, the Canary Islands, Madeira, and the Azores for computational reasons. The study area was divided into four distinct regions to capture regional variations in land system characteristics (Figure 1). This regionalized approach allows for localized suitability regressions and region-specific parameter settings, addressing the diverse biophysical and socio-economic drivers across Europe. The simulation starts in 2020, using



the land system map of E. Sandström et al. (2023), and runs at a 1-km resolution. All spatial data are projected using the ETRS89-LAEA coordinate reference system (EPSG:3035).

The baseline map incorporates 20 land systems: low-intensity settlement; medium-intensity settlement; high-intensity settlement; wetlands; forest/shrub and cropland mosaic; forest/shrub and grassland mosaic; low-intensity arable cropland; medium-intensity arable cropland; high-intensity arable cropland; low-intensity grassland; medium-intensity grassland; high-intensity grassland; permanent cropland; unmanaged forest; extensive forestry; combined objective forestry; intensive forestry; very intensive forestry; water and glaciers; and bare, rock and shrub. The class extensive forestry was previously labelled as "close-to-nature forestry" by Scherpenhuijzen et al. (2025), but was renamed here to better reflect its functional role within the productivity based logic of the CLUMondo framework. Unmanaged forest, water and glaciers, and bare, rock and shrub are kept constant across the simulations. The unmanaged forest class represents primary forest stands based on the Sabatini et al. (2021) database and was held constant because these areas are under strict protection. Furthermore, this class does not expand within the model because the structural complexity and intact ecological functions defining primary forests require centuries to develop, making them impossible to recreate within the simulation horizon (Sabatini et al., 2021). The land systems water and glaciers, and bare, rock and shrub were kept constant over time because they are non-productive and lack the socio-economic drivers required for transitions within the CLUMondo framework.

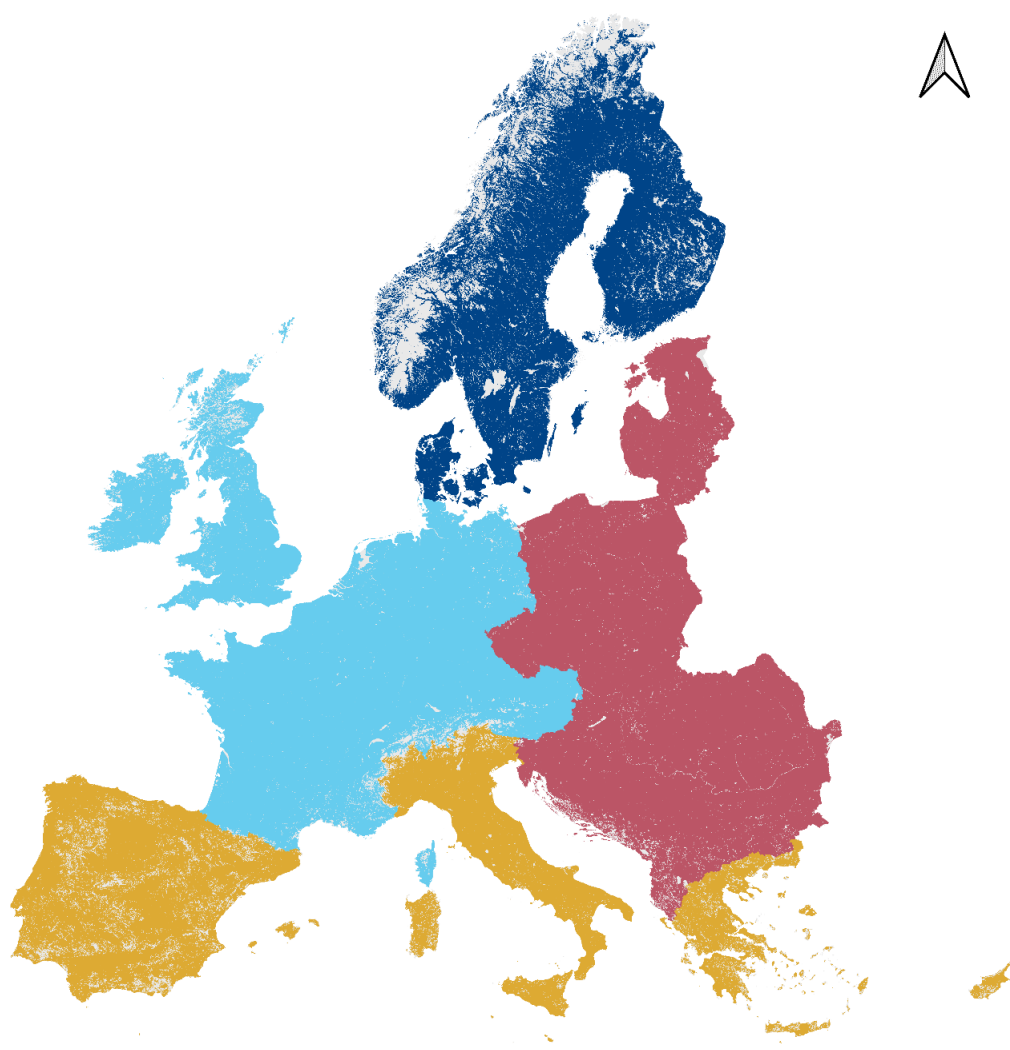


Figure 1. Geographical extent of the study area, categorized into the four modelling regions used within CLUMondo. The grey areas represent land systems that were kept constant.

3.2.1.2 Land system suitability

Spatial suitability for each land system was determined using logistic regression analysis based on a wide range of biophysical, socio-economic, and climate variables (Table 2). Regressions were calibrated independently for each of the four modelling regions. To ensure statistical robustness, a balanced sampling design was applied to account for spatial autocorrelation. Additionally, multicollinearity among variables was tested, and model performance was evaluated using the Akaike Information Criterion (AIC), McFadden adjusted R^2 , and the Area Under The Curve (AUC). Due to the limited prevalence of high-intensity grassland and permanent cropland in Northern Europe, regression coefficients from Western Europe were applied to these systems within the Northern region.

Historical climate averages (1981–2010) were used for the baseline regressions (Karger et al., 2017). Future suitability maps were updated using climate projections under RCP2.6 for the biodiversity focused forests and participatory forest stewardship scenarios, and RCP4.5 for the multifunctional forests and competitive forest industry scenarios. However, climatic suitability for forest land systems was held constant at baseline levels (1981–2010) rather than being updated with future



projections. Preliminary tests showed that dynamic climate updates produced disproportionately high suitability estimates that were ecologically unrealistic. For example, very intensive forestry in Western Europe is mainly found in southern France, which has the warmest climate in Western Europe, and therefore very intensive forestry would substantially increase in suitability across whole Western Europe with temperature increase. To rectify this, tree species probability projections from the EU-TREES4F dataset (Mauri et al., 2022) were integrated to implement realistic ecological restrictions.

Table 2. Input data used in the land system suitability regressions.

Category	Explanatory variable	Original resolution	Description (Unit)	Source
Biophysical	DEM	25m	Elevation (m)	(European Commission DG ENTR, 2012)
	Slope	25m	Slope (degrees)	(European Commission DG ENTR, 2012)
	Slope under 5 degree	25m	Flat slope (%)	(European Commission DG ENTR, 2012)
	Slope above 15 degree	25m	Steep slope (%)	(European Commission DG ENTR, 2012)
	AWC	500m	Available Water Capacity (AWC) (difference of volume water content at 33kPa and 1500kPa (volume fraction))	(Ballabio et al., 2016)
	Bulk density	500m	Bulk density (t m^{-3} (g cm^{-3}))	(Ballabio et al., 2016)
	Clay	500m	Topsoil (0–20 cm) clay content (%)	(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	500m	Topsoil (0-20cm) pH of water in soil (pH)	(Ballabio et al., 2019)
	Organic carbon concentration	500m	Topsoil (0-20cm) soil organic carbon concentration (g/kg)	(de Brogniez et al., 2015)
	Cation exchange capacity	500m	Topsoil (0-20cm) cation exchange capacity (cmol(c)/kg)	(Ballabio et al., 2019)
Socio-economic	Road density	5'	Densities summed across the five road types (m/km^2)	(Meijer et al., 2018)
	Accessibility	1km	Travel time to cities (h)	(D. J. Weiss et al., 2018)
	Travel time healthcare	1km	Motorized travel time to healthcare (min)	(D. J. Weiss et al., 2020)
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 07	1km	Annual range of air temperature (°C)	(Karger et al., 2017)
	Bioclimatic variable 12	1km	Annual precipitation amount (kg m^{-2})	(Karger et al., 2017)
	Bioclimatic variable 15	1km	Precipitation seasonality (kg m^{-2})	(Karger et al., 2017)



3.2.1.3 Scenario input data

The scenarios were operationalized into specific model settings using datasets that define the spatial suitability of land systems and the trajectory of socio-economic demands. We integrated four primary data components: (1) habitat connectivity, (2) future tree species distribution projections, (3) protected areas, and (4) sectoral demand projections.

Habitat connectivity

We applied a connectivity layer to enhance forest suitability in areas with high ecological connectivity. This layer was derived from two normalized current density maps representing the movement potential of large predators and herbivores (Dertien, 2025). We processed these maps to prioritize corridors of high conservation importance while excluding regions that block movement. The resulting connectivity index was integrated into the forest suitability model using weights that reflect a gradient of ecological value across management classes. These weights range from 1 for extensive forestry to 0.25 for very intensive forestry, reflecting empirical evidence that intensified practices diminish functional connectivity by reducing structural heterogeneity and fragmenting habitats (Lunde et al., 2025; Wang et al., 2025). This approach was further modulated by scenario-specific weights to reflect the varying priority assigned to ecological connectivity within each scenario.

Future tree species distribution

To account for climate-driven constraints, we incorporated projections from the EU-TREES4F dataset (Mauri et al., 2022), which models the potential distribution of 67 European tree species under the RCP4.5 scenario for 2095 based on an ensemble of species distribution models. We identified climate stress areas by a projected decline in overall forest suitability, a reduction in climatically viable species, and the absence of common commercial species. In these regions, forest expansion was prohibited due to substantially reduced biophysical suitability for establishment. For existing forests, suitability was reduced along a management gradient, with intensive forest classes receiving the largest reductions to reflect their higher vulnerability to drought, fire, pests, and other climate-related disturbances (Wang et al., 2025).

Protected areas

Protected areas functioned as both a spatial restriction layer and a driver for forest expansion (O'Connor et al., 2021). The dataset used for potential protected area expansion was developed to meet the EU Biodiversity Strategy for 2030 targets of protecting 30% of European land, with 10% under strict protection (European Commission, 2020). It includes three prioritization scenarios: (1) nature conservation, (2) cultural values, and (3) socio-economic prioritization—each building upon existing Natura2000 and national designations. Depending on the scenario, a specific prioritization was selected to define rules for habitat protection and the phase out of intensive land systems in protected zones, within which forest expansion was promoted. This ensures that the modelled conservation efforts remain consistent with current legal frameworks and future policy targets.

Sectoral demand projections

Demand trajectories served as the primary drivers of land system dynamics. We used agricultural and forestry projections from two partial-equilibrium models: CAPRI (Britz & Witzke, 2014) for permanent crops and GLOBIOM (IBF-IIASA, 2023) for arable crops, livestock, and wood production. These models simulate market responses to socio-economic shifts by balancing supply and demand. Data were extracted for two Shared Socioeconomic Pathways (SSPs), to align with our scenarios: SSP1



(Sustainability) for scenarios prioritizing environmental restoration and SSP2 (Middle of the Road) for those emphasizing socio-economic development (Riahi et al., 2017).

Wood demand was represented through roundwood production coupled with scenario-specific bioenergy requirements. To operationalize the 3 billion trees initiative by 2030 (European Commission, 2020), we calculated average tree densities across all land systems using the Crowther et al. (2015) database. We applied a uniform average tree density across all forest classes to ensure this target drove afforestation rather than biasing management intensity shifts. Furthermore, wetland restoration targets were implemented exclusively under the SSP1 scenarios. Potential restoration areas were identified where potential wetland vegetation overlapped with existing agricultural land (Jung, 2024). We applied a demand target representing a 17% increase in wetland area by 2030, aligning with the EU Nature Restoration Law (European Commission, 2024). Finally, housing demand was integrated using population projections from KC et al. (2024) to account for urban expansion across all scenarios.

3.2.1.4 Scenario specific settings

The four scenarios were operationalized into CLUMondo model parameters (Tables 3 and 4; Tables A1–A11). A brief description of each scenario's representation in the model is provided below.

Biodiversity focused forests

This scenario prioritizes conservation and climate neutrality through extensive reforestation, afforestation, and the widespread adoption of close-to-nature management. We used SSP1 demand projections, RCP2.6 climate data, low bioenergy demand, and a tree-planting target of 3 billion trees by 2030, followed by an additional 2 billion trees by 2050. To reflect these priorities, suitability for extensive forestry was increased, while suitability for intensive and very intensive forestry was reduced (Table A11).

Connectivity served as a critical driver for forest suitability, prioritizing expansion that enhances habitat linkages. Extensive forestry was strictly protected from conversion to ensure the development of complex forest structures and the preservation of biodiversity habitats. We integrated protected area data from the nature-conservation prioritization of O'Connor et al. (2021). Within conventional protected areas, conversion toward medium- and high-intensity cropland and grassland, permanent crops, intensive forestry, and very intensive forestry was prohibited. If these land systems were already present in these zones, they were phased out. This logic was further extended in strictly protected areas where low-intensity cropland and grassland were additionally prohibited and phased out, ensuring the total removal of agricultural and intensive silvicultural activities (Table 4).

Participatory forest stewardship

This scenario focuses on biodiversity protection, climate mitigation, and local community involvement, with a focus on maintaining and improving the condition of existing forests. We used SSP1 demand projections, RCP2.6 climate data, medium bioenergy demand, and a tree-planting target of 3 billion trees by 2030, followed by an additional 0.5 billion trees by 2050. Suitability for extensive forestry was increased across the landscape, while all existing forest pixels received a suitability boost to increase their resistance to land system transitions and changes in forest management practices (Table A11).

Consistent with the biodiversity focused scenario, extensive forestry was strictly protected from conversion to support the development of complex structures and habitat preservation. Connectivity



was assigned medium importance as a suitability factor, balancing ecological linkages with established silvicultural practices. We integrated protected area data from the cultural value prioritization of O'Connor et al. (2021) and applied the same exclusion and phase-out logic as described in the biodiversity focused forests scenario (Table 4).

Multifunctional forests

The multifunctional forests scenario aims to balance ecological, economic, and social functions within sustainable forest management. We used SSP2 demand projections, RCP4.5 climate data, medium bioenergy demand, and a tree-planting target of 3 billion trees by 2030, followed by an additional 1 billion trees by 2050. To promote multifunctional management, suitability for combined objective forestry was increased, while suitability for very intensive forestry was reduced (Table A11). To reflect a focus on technological advancement, a 5% innovation-driven increase in roundwood productivity for intensive and very intensive forestry was adopted and phased in linearly until 2050.

Connectivity was incorporated as a factor of low importance for forest suitability, consistent with its secondary role in this scenario. We integrated protected area data from the socio-economic prioritization of O'Connor et al. (2021), applying the same exclusion and phase-out logic as established in the previous scenarios. Within conventional protected areas, high-intensity cropland and grassland, intensive forestry, and very intensive forestry were prohibited. This restriction was extended in strictly protected areas, where medium-intensity cropland and grassland, and permanent crops were additionally prohibited (Table 4).

Competitive forest industry

This scenario emphasizes decarbonization through a bio-based economy, focusing on continuous wood supply and climate mitigation. We used SSP2 demand projections, RCP4.5 climate data, high bioenergy demand, with no additional tree-planting targets adopted. To support these objectives, suitability for intensive and very intensive forestry was increased, while connectivity was excluded as a suitability driver (Table A11). Furthermore, a 10% innovation-driven increase in roundwood productivity for intensive and very intensive forestry was phased in linearly until 2050, reflecting an emphasis on technological advancement.

Protected areas were limited to existing Natura2000 and national designations, following the established exclusion and phase-out logic. Within conventional protected areas, high-intensity cropland and grassland, as well as very intensive forestry, were prohibited. This restriction was further extended in strictly protected areas, where medium-intensity cropland and grassland, permanent crops, and intensive forestry were additionally prohibited (Table 4).

Table 3. Overview of input data and scenario settings.

Scenario	SSP	RCP	Bioenergy demand	Protected area prioritization	Connectivity	Innovation (%)	New trees (billion) 2030 / 2050
Biodiversity focused forests	SSP1	RCP2.6	Low	Nature (30%)	High	0	3 / 2
Participatory forest stewardship	SSP1	RCP2.6	Medium	Culture (30%)	Medium	0	3 / 0.5
Multifunctional forests	SSP2	RCP4.5	Medium	Socio-economic (30%)	Low	5	3 / 1
Competitive forest industry	SSP2	RCP4.5	High	Current status	Not included	10	0 / 0

Note: Innovation is operationalized as a linear percentage increase in roundwood productivity for intensive and very intensive forestry by 2050, relative to 2020 baseline levels.

Table 4. Implementation of protected area data, for both conventional protected areas (PA) and strict protected areas (Strict PA). Years (2030 and 2050) indicate the target date for the complete phase-out of non-permitted land systems. Numerical values represent the weighting factors applied to land system suitability layers within protected areas. Only land systems subject to PA restrictions are included in this table.

Land system	Biodiversity focused forests		Participatory forest stewardship		Multifunctional forests		Competitive forest industry	
	PA	Strict PA	PA	Strict PA	PA	Strict PA	PA	Strict PA
Low-intensity arable cropland	-0.2	2050	-0.2	2050	-0.1	-0.2	-0.1	-0.2
Medium-intensity arable cropland	2050	2030	2050	2030	-0.2	2050	-0.2	2050
High-intensity arable cropland	2030	2030	2030	2030	2050	2030	2050	2030
Low-intensity grassland	-0.2	2050	-0.2	2050	-0.1	-0.2	-0.1	-0.2
Medium-intensity grassland	2050	2030	2050	2030	-0.2	2050	-0.2	2050
High-intensity grassland	2030	2030	2030	2030	2050	2030	2050	2030
Permanent croplands	2050	2030	2050	2030	-0.2	2050	-0.2	2050
Extensive forestry	+0.2	+0.4	+0.2	+0.4	+0.2	+0.4	0	0
Combined objective forestry	0	0	+0.1	+0.2	+0.1	+0.2	0	0
Intensive forestry	2050	2030	2050	2030	2050	2030	0	2050
Very intensive forestry	2030	2030	2030	2030	2030	2030	2050	2030

3.2.2 European Forestry Dynamics Model (EFDM)

EFDM is a large-scale forest scenario model used in PathFinder to simulate European forest structure, growth, management and carbon over 2020–2100 at 1 km² resolution. It is parameterized from National Forest Inventories (NFIs), remote sensing maps, climate-based productivity data and management scenarios from CLUMondo. The full details of the modelling approach and results are provided in PathFinder WP3, Task 3.2 (Majasalmi, 2026).

3.2.2.1 EFDM model structure

EFDM is a matrix-based model in which forest area transitions between fixed states at 5-year intervals, driven by transition probabilities and management activity probabilities: no management (noman), thinning (thin), and final felling (ff). The main state variables are stem volume class (10 classes), species group (10 groups), region (North/Central/South), climate productivity class (P0; the number of classes varies by region and species group), forest management intensity class (FM-class), and a growth limitation class (NAI_lim), which was later introduced for calibration purposes.



The management activities considered are *noman*, *thin*, and *ff*. At each time step, the area within each state cell is divided according to activity probabilities, after which the area is transferred using activity-specific transition probabilities. Activity probabilities are estimated from paired NFI plots by region, FM-class, and stem volume class, while additional rules enforce realistic management patterns (e.g. no final felling in very low volume classes and only *noman* in FM1, which corresponds to unmanaged/protected areas). The probabilities are further regionally calibrated to align simulated harvest levels with FAO statistics.

In EFDM, final felling transition probabilities transfer stands to the lowest stem volume class, independent of region, thereby initiating regeneration. Thinning transitions are estimated from observed “drops” between stem volume classes in paired NFI plots, differentiated by species group and region. Transitions under *noman* (growth) are derived from empirical relationships between observed 5-year stem volume increments and the maximum gross primary productivity (maxGPP)-based productivity class (PO_class) for each species group and region. These relationships combine NFI observations with FORMIT-M regeneration simulations to compensate for the limited representation of small trees in the NFI data.

3.2.2.2 Data inputs and preprocessing

Paired NFI plots from 10 countries were used to quantify stem volume change and identify management interventions. Plots were classified into the management activities *noman*, *thin*, and *ff* based on stem volume loss thresholds and, where available, recorded intervention flags. Since the time period between consecutive inventories varied between countries and datasets, all observations were scaled to correspond with 5-year time period. Then all data were aggregated into regional 5-year management probabilities for the North, Central, and South regions, and into species–volume–region transition matrices (Majasalmi, 2026).

Remote sensing forest maps (from PathFinder WP2) were used to construct the initial 2020 forest state (state0). The input data consisted of 10 m resolution stem volume maps and species-group percentage cover maps produced in WP2. These datasets were aggregated into EFDM stem volume classes and further summarized to 1 km² grid cells before assignment to countries. Differences between the resulting estimates and Eurostat/FAO statistics (Eurostat, 2020; FAO, 2025b) for forest area and growing stock were analysed and later used to evaluate model robustness at the country level (Majasalmi, 2026).

Productivity and regeneration processes in EFDM were parameterized using FORMIT-M simulations and maxGPP estimates generated with the PRELES model. FORMIT-M provided regeneration growth dynamics, while PRELES produced climate-sensitive maxGPP estimates under RCP2.6 and RCP4.5 scenarios. FORMIT-M was used to generate regeneration plot-pair data for stands aged 0–5 years for each generalized species group and region. These data were appended to the *noman* NFI dataset to compensate for the underrepresentation of small trees in the NFI data. Historical maxGPP values linked to NFI plot pairs were grouped into PO_classes by region and species group to represent potential growth and its climate-driven changes up to 2100 (Majasalmi, 2026).

An EFDM coefficient table was developed to convert forest states (i.e. forest area classes defined by stem volume class, species group, and region) into forest structural variables and carbon-related properties. The table includes estimates of growing stock and associated stand attributes (stem density, diameter, height, and basal area), harvested volume from thinning and final felling, and biomass components (stem, branch, foliage, and roots) derived from IPCC biomass conversion and expansion factors (BCEFs) and allometric metamodels. Deadwood estimates were derived from NFI plot pairs and smoothed across volume classes and species groups using polynomial functions. Litter



estimates for different biomass components were estimated using regressions based on International Co-operative Programme on Assessment and Monitoring of Air Pollution Effects on Forests (ICP Forest) combined with Carbon Budget Model-style (CBM) turnover rates, with additional constraints applied to avoid unrealistic values in very low or very high stem volume classes (Majasalmi, 2026).

Harvest residues were estimated by assuming that all non-stem biomass and 5% of stem biomass (representing stumps) remained on site, with residue amounts scaled according to the proportion of volume removed during harvest operations. These forest property estimates form the linkage between EFDM and the Yasso soil carbon model (Liski et al., 2005).

3.2.2.3 Calibration and coupling to Yasso

A preliminary EFDM simulation for the period 2020–2025 was used to calibrate harvesting activity probabilities. Regional probabilities for thinning (thin) and final felling (ff) were iteratively adjusted so that simulated roundwood removals corresponded to FAO-reported harvest statistics at the regional scale. During calibration, the relative management intensity gradients between FM-classes and the relative differences among stem volume classes were preserved to maintain relative management patterns between scenarios.

Initial simulations based on the unadjusted noman transition matrices produced net annual increment (NAI) estimates that were systematically higher than FAO statistics. To address this, a growth limitation class (NAI_lim) was introduced at the grid-cell level using a JRC-derived NAI map. Three limitation levels were defined: NAI_lim = 0, where both growth and management activities were halted; NAI_lim = 1, where growth rates were reduced; and NAI_lim = 2, where default growth transitions were retained. The growth limitation class was applied to modify noman transition probabilities while leaving the general structure of the transition matrices unchanged. Following calibration, the simulated regional average NAI was more consistent with FAO estimates.

EFDM outputs were coupled with the Yasso soil carbon model to simulate soil carbon dynamics. For each 5-year EFDM time step, biomass turnover, litter production, and harvest residue inputs were converted to annual inputs by biomass component and aggregated into generalized coniferous and deciduous groups. These inputs were fed into Yasso20 together with climate data from the climate model combination MPI-M-MPI-ESM-LR/SMHI-RCA4_v1.

3.2.2.4 Implementation of CLUMondo scenarios in EFDM

Four scenarios covering the period 2020–2100 were implemented by combining socio-economic pathways (SSPs), radiative forcing pathways (RCPs), and spatially explicit forest management intensity classes derived from CLUMondo/GLOBIOM simulations: Biodiversity Focused (BF, RCP2.6–SSP1), Participatory Forest Stewardship (PFS, RCP2.6–SSP1), Multifunctional Forests (MF, RCP4.5–SSP2), and Competitive Forest Industry (CFI, RCP4.5–SSP2). For all scenarios, CLUMondo provides forest management intensity classes (FM-classes 1–5) at 1 km² spatial resolution for successive simulation periods. The FM-classes were used in EFDM as external drivers of forest management intensity.

EFDM simulations were conducted at 5-year intervals from 2020 to 2100 (Majasalmi, 2026). Prior to each simulation step, two spatially explicit variables were updated for every forest grid cell: PO_class, representing climate-sensitive productivity, derived from FORMIT-M maxGPP simulations under either the RCP2.6 or RCP4.5 climate pathway and interpolated through time; and FM-class, representing forest management intensity, obtained from CLUMondo scenario outputs. FM-classes were updated dynamically between 2020 and 2050 and subsequently held constant until 2100. For each time step, EFDM applied: first activity probabilities determined by stem volume class, FM-class,



region, and NAI_lim; and second transition matrices for noman, thin, and ff based on species group, region, PO_class, and NAI_lim. These transitions redistributed forest area among state classes, producing updated forest structure, harvested volumes, biomass stocks, and litter inputs for subsequent Yasso simulations. Species groups were assumed to remain constant throughout the simulations and therefore did not vary between scenarios or over time.

The EFDM framework was driven simultaneously by climate and land-use pathways. Climate pathways (RCP2.6 and RCP4.5) influenced forest productivity through changes in PO_class trajectories and affected soil carbon dynamics through the climate forcing applied in Yasso20. Land-use and management pathways (BF, PFS, MF, and CFI) influenced forest dynamics through the FM-class trajectories derived from CLUMondo (Majasalmi, 2026). Together, these combined drivers generated alternative long-term trajectories in forest structure, harvest levels, biomass accumulation, and soil carbon dynamics. Owing to uncertainties in the initial forest maps and model parameterization, the results were interpreted primarily in terms of relative differences among scenarios rather than absolute estimates.

3.2.3 PixSim

PixSim is an open-source forest growth simulator specifically designed for high-resolution, pixel-level forest simulations based on wall-to-wall forest resource maps (Cattaneo, Astrup & Antón Fernández, 2024). It predicts forest structure attributes, including aboveground biomass (AGB), growing stock volume (V), basal area (G), and mean diameter (D), as functions of current biomass, dominant species group, biogeographic region, and site productivity (GPPx). Through its explicit linkage to site productivity, PixSim is climate-sensitive and can be used to forecast forest development under different climate scenarios.

PixSim meets country-level biomass production demands by prioritizing forest stands according to their proximity to the next scheduled management intervention. The timing and magnitude of interventions and thus biomass removals are determined by the selected forest management regime and must be provided as input. Similarly, projections of country-level biomass demand, reflecting requirements from other sectors of the economy, are supplied externally and guide harvesting decisions within the simulation.

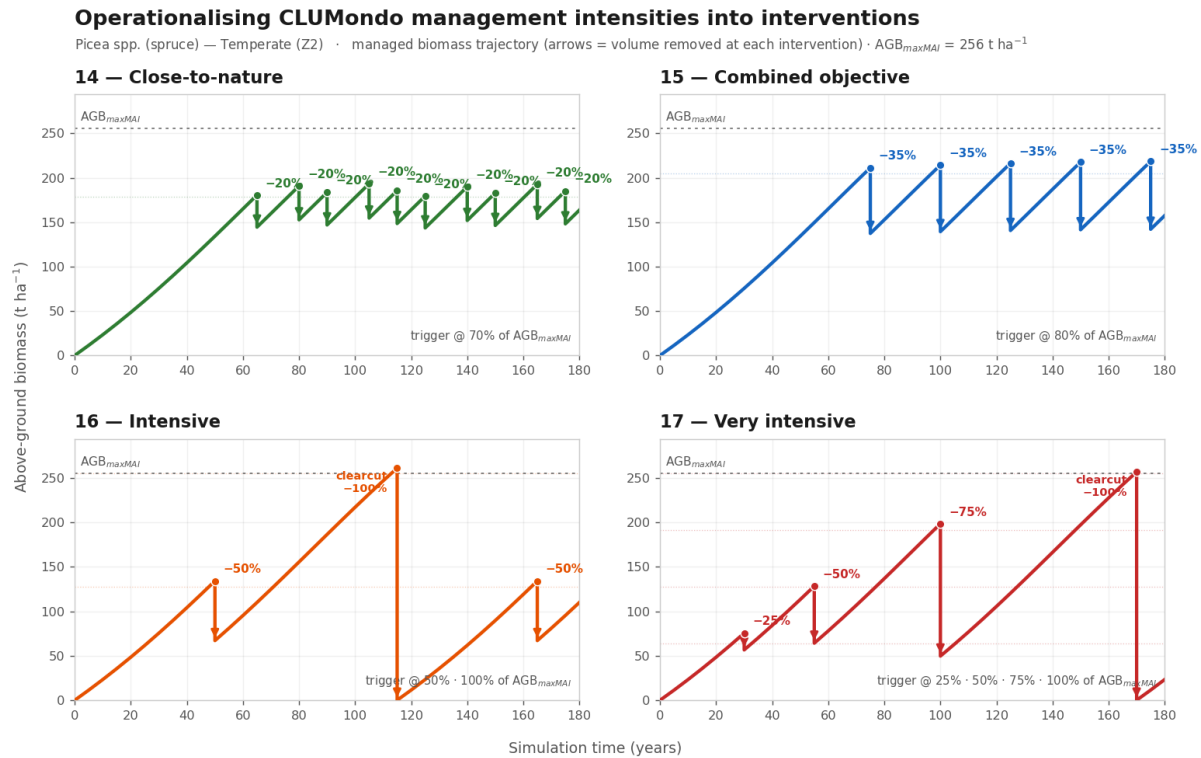
Unlike conventional forest growth simulators used for forest management planning, which typically operate on stand-level averages, PixSim models each pixel individually. This approach preserves and exploits within-stand heterogeneity, allowing fine-scale variation in forest conditions to influence growth dynamics. At the same time, operational management practices are respected, meaning that interventions such as thinning and final harvest are applied uniformly to all pixels belonging to the same forest stand.

In contrast to large-scale forest scenario models such as EFI-ScenSpace, which project National Forest Inventory (NFI) plot observations, PixSim operates directly on wall-to-wall forest resource maps. This provides an important bridge between global climate and biomass-demand scenario models, which are typically spatially explicit, and traditional forest growth models used at local scales for forest management planning.

For the PathFinder project, the original PixSim core software was substantially optimized to handle European-scale forest attribute maps at 10 m spatial resolution. Growth models for AGB, V, G, and D were developed for the ten dominant forest species groups represented in the PathFinder maps and calibrated for the corresponding European biogeographic regions using harmonized NFI data collected across Europe.



Forest management intensities derived from the CluMondo framework were translated into intervention schedules represented as biomass removal frequencies and magnitudes over time. These intervention patterns form the basis for simulating management activities under alternative future forest management and biomass-demand scenarios:



To support spatially explicit simulations, a Europe-wide forest stand map was generated using the Superpixel segmentation algorithm based on AlphaEarth embeddings for the year 2021 within Google Earth Engine. European-wide pixel-level site productivity scenarios under various climate scenarios were developed using Copernicus LAI time series and as input and harmonized NFI data for validation (manuscript in preparation). The resulting site productivity scenarios are made available through the Pathfinder Portal as GPPx maps, which can be accessed at <https://portal.pathfinder-heu.eu/>.

Country-level biomass demand projections from GLOBIOM were provided through collaboration with the sister project ForestNavigator.

3.3 Trade-off and synergy analysis

3.3.1 Indicators

In this deliverable we consider four indicators that are analysed for their performance under the scenarios and how they develop spatial and temporal trade-offs, including trade-offs between the indicators: (1) production, (2) biomass, (3) biodiversity, and (4) disturbances.

3.3.1.1 Production

Forest production represents the volume of wood removed through thinning and final felling within a 1 km^2 grid cell. Because EFDM operates with 5-year time steps, the model output values represent



cumulative harvest volumes over each period rather than annual removals. The indicator reflects harvesting pressure by integrating both intermediate and final harvest operations.

Forest production estimates were directly influenced by forest management intensity maps derived from CLUMondo. The coupling of EFDM and CLUMondo assumed that changes in forest management intensity correspond to changes in harvesting pressure. To facilitate integration with CLUMondo outputs, probabilities of thinning, final felling, and no management were parameterized at a 1 km² spatial resolution using NFI plot data-based activity and transition probabilities. Because CLUMondo forest management information was unavailable for a subset of forested grid cells in the EFDM input data, the management map was gap-filled using an earlier, unfiltered version to ensure complete spatial coverage.

The influence of management intensity on harvested wood was assessed indirectly through model calibration, in the absence of spatially explicit reference data. Initial growing stock volume strongly influences simulated harvest levels and forest development trajectories. Therefore, regional harvest calibration was conducted against Eurostat statistics (Eurostat, 2020), while forest growth rates were adjusted to produce realistic estimates of growth. These calibrations influence long-term projections, as harvest allocation and management intensity are constrained by the simulated development of forest resources over time.

A key source of uncertainty is the initialization of growing stock volume distributions (Miettinen et al., 2025). Harmonized pan-European data describing forest volume-class distributions at 1 km² resolution were not available for all 41 countries included in the analysis, preventing direct calibration of initial volume distributions. As a result, any bias in the initial growing stock estimates may propagate through both harvest and growth calibrations, as these parameters were adjusted to produce plausible regional-scale outcomes based on available input data for the 2020–2025 period. Given that total growing stock was overestimated in many EU countries, forest production estimates are also likely biased upwards, despite the applied calibrations.

3.3.1.2 Biomass

A biomass indicator including both above- and below-ground components represents the total amount of living organic matter in vegetation within a 1 km² grid cell. Biomass was calculated as the sum of stem, branch, foliage, and root components and derived using a combination of allometric metamodells and IPCC BCEFs.

Biomass components were estimated for all regions, species groups ($n = 10$), and volume classes using NFI-based volume-bin mean forest structural properties; this procedure is referred to as EFDM coefficient table construction. The resulting table was used to convert forest area distributions across volume classes into forest structural attributes. The construction of the coefficient table involved integrating multiple data sources and modelling assumptions, and a formal error assessment was not undertaken. This is partly because the 10 species groups were defined primarily based on remote sensing considerations related to the separability of tree species across Europe, rather than ecological or forest management criteria.

A key source of uncertainty in the resulting biomass estimates arises from the initialization of growing stock volume distributions, similarly to forest production (Section 3.3.1.1), as biomass is derived from species-group- and region-specific parameterizations applied to the underlying volume-bin area distributions. Consequently, any bias in the initial volume distributions propagates into the biomass estimates. These uncertainties are further affected by potential biases in EFDM activity and transition probabilities.



3.3.1.3 Biodiversity

The biodiversity indicators are based on the output of EFDM. Forest biodiversity was quantified using various indicators of potential forest biodiversity integrating four key ecological components (Gosselin & Larrieu, 2020):

3.3.1.3.1 Forest structure - Gini

Forest structure, i.e., the heterogeneity in tree size. Considering the results of the study on structural indicators applied to national forest inventories (Moreno-Fernández et al., 2025) it was quantified using the Gini Index (Gini, 1921). Originally developed in economics, this index is now widely applied to evaluate forest structural complexity (Myllymäki et al., 2024). Because the European Forestry Dynamics Model (EFDM) output lacks tree-level data, the index was adapted to assess structure via the variability across volume bins, calculated as follows:

$$Gini\ index = \frac{\sum_{i=1}^n (2i-n-1) \cdot vol_i}{n \sum_{i=1}^n vol_i} \quad (1)$$

where n is the number of volume bins within a given pixel, vol_i is the volume sorted in ascending order, and i is the rank of the volume bin. The index ranges between 0 and 1, where a value of 0 indicating absolute equality in volume bins and equal to 1 indicating the maximum volume bins inequality. Furthermore, because volume bins can occupy varying areas within each pixel, observations were weighted by the specific area occupied by each bin. We used the *gini.wtd* function in the R package *dineq* (Schulenberg, 2018) to calculate the Gini Index.

3.3.1.3.2 Forest compositional diversity - Shannon

Forest compositional diversity measures the abundance of the species within the study area. In this case, forest compositional diversity was calculated using the Shannon Index (Shannon, 1948) at the pixel level:

$$Shannon's\ Diversity\ Index = - \sum_{s=1}^S vol_s \ln vol_s \quad (2)$$

where vol is the relative volume of each s group of species (from $s = 1$ to 9). The main limitation of this index is that, at the pixel level, the group of species does not change over time. Therefore, temporal variations are associated to changes in volume. The index ranges between 0 (a single group of species in the pixel) to the logarithmic of S , with, larger values of the index implying larger compositional diversity. This index has been applied to quantify forest composition in European National Forest Inventories (Moreno-Fernández et al., 2026).

3.3.1.3.3 Old-growth - Percentage of mature forests

Mature forests are related to naturalness and to biodiversity features. We calculated this index as the percentage of area occupied by the volume bins 9 and 10, which are equivalent to 415 and 600 units. The main limitation is that EFDM simulations does not include the delimitation of protected areas, which can impact the spatial-temporal dynamics of this index.

3.3.1.3.4 Deadwood

Amount of deadwood, calculated as the aboveground dead biomass expressed in tons per ha. Deadwood is recognized as an important biodiversity indicator as it serves as a habitat for several life forms (Parajuli & Markwith, 2023; Parisi et al., 2024; Shuvo et al., 2026).



3.3.1.4 Disturbances

3.3.1.4.1 Modelling framework

The disturbance indicator for Task 3.6 is derived from two process-based models coupled with the European Forest Dynamics Model (EFDM): the ForestGALES/*fgr* model for windstorm damage and the *IpsR* model for European spruce bark beetle (*Ips typographus*) damage. Both models are implemented as R packages and were applied across Europe using EFDM outputs and the climate variables compiled within PathFinder for the RCP2.6 and RCP4.5 scenarios. All calculations are made in the R modelling framework to simplify the modelling process and to ensure all disturbance interactions are incorporated.

The input data required by both disturbance models, stand-level standing volume, mean diameter, mean height, stand density and species composition, are taken directly from EFDM outputs at each 5-year time step.

ForestGALES/*fgr* is the R version of the ForestGALES decision support system originally developed by Forest Research in the United Kingdom and applied in several other countries (Hale et al., 2015; Locatelli et al., 2022; Quine et al., 2021). It uses a standard risk framework where risk is determined by both the vulnerability of a stand and the probability of the hazard occurring at a level sufficient to cause damage. The model first estimates the critical wind speed (CWS) at which trees are likely to be damaged, either by uprooting or stem breakage, using biomechanical relationships parameterized with tree-pulling experiments (Nicoll et al., 2006) and green wood strength measurements (Lavers, 1969). It then assesses the wind hazard from a Weibull distribution of hourly mean wind speeds at the stand location, with a conversion from mean wind load to gust load that depends on tree height, between-tree spacing and the distance to forest edges (Quine et al., 2021). The risk of wind damage is computed as the probability that the local wind climate, including gusts, exceeds the stand's critical wind speed.

IpsR is an R implementation of a bark beetle population model that originates from LandClim (Schumacher et al., 2004). It was further developed by Temperli et al. (2013) and implemented in the ORCHIDEE land surface model by Marie et al. (2024). The package was written as part of the PathFinder project. It is used to calculate the annual biomass of Norway spruce (*Picea abies*) trees attacked and killed by bark beetles. The model accounts for host attractiveness, water stress, a species-specific spruce factor and a proxy for reduced nitrogen and carbohydrate reserves resulting from intense resource competition (Marie et al., 2024). Climatic drivers are represented through the cumulative effective degree days for beetle reproduction (DDeff), calculated following Wermelinger & Seifert (1998), and the maximum monthly drought intensity over a three-year window expressed as the maximum plant water stress (PWSmax), derived from the Standardised Precipitation Evapotranspiration Index (SPEI) (Vicente-Serrano et al., 2010). The proportion of Norway spruce in the stand is included as a vulnerability factor, given that mixed-species forests have been shown to be more resilient to bark beetle infestations than pure spruce stands (Nardi et al., 2023). The model returns the probability of a stand being attacked, the probability of a successful attack, the biomass attacked and the biomass killed by bark beetles.

3.3.1.4.2 Model outputs and assumptions

ForestGALES/*fgr* returns the probability of damage for each EFDM cell and time step (Locatelli et al., 2022), while *IpsR* returns the volume of biomass attacked and the volume of biomass killed by bark beetles for the simulation year (Marie et al., 2024).

Several model assumptions shape these outputs and should be considered when interpreting them.



For the windstorm model:

- The minimum essential inputs to ForestGALES/fgr are stand mean or top height, mean DBH, average between-tree spacing and species, together with the Weibull A and k parameters of the local wind climate (Locatelli et al., 2022). Stand height and DBH are taken from EFDM outputs.
- Damage is computed at the stand level. ForestGALES/fgr predicts the wind speed at which damage has a 50% probability of occurring for either individual trees within a stand or the entire stand treated together. This European run uses the stand-level formulation consistent with the EFDM resolution.
- The wind climate is derived from Weibull A and k parameters, which determine the return period of specific wind speeds (Troen & Petersen, 1989). The Weibull parameters for Europe were downloaded from the Global Wind Atlas². ForestGALES/fgr was originally calibrated under British forestry conditions (Quine et al., 2021), and parameterizations for some broadleaf species, in particular streamlining and drag, remain at a preliminary stage (Locatelli et al., 2022).
- Damage propagation through newly exposed edges after felling or prior storm damage is not represented (Gardiner, 2021).

For the bark beetle model:

- The essential inputs to IpsR are forest type (boreal or temperate), average tree diameter, stand density, the fraction of Norway spruce by area (FNS_area), the total living biomass of Norway spruce, the total recently dead biomass (≤ 1 year), DDeff, PWSmax and the previous-year beetle activity and biomass killed (Marie et al., 2024).
- DDeff is calculated from the formulation in Wermelinger & Seifert (1998), with parameter values from Temperli et al. (2013) and Baier et al. (2007). The sum of degree-days for one bark beetle generation is set to 547 °C-days.
- Drought is represented through PWSmax, derived from SPEI over a three-year window and rescaled to a 0–1 range, where 0 corresponds to no drought and 1 to extreme drought (Vicente-Serrano et al., 2010).
- The model applies to Norway spruce only and assumes a binary classification of forest type as boreal or temperate. Mixed stands are represented through FNS_area, which weights vulnerability by the spruce fraction (Nardi et al., 2023), but interactions with other host species are not modelled.
- Outbreak dynamics depend on past beetle activity and biomass killed in the previous year, so the model carries memory across time steps.

A general assumption shared by both models is that they are driven by EFDM stand attributes aggregated to a 1 km² European grid; within-cell heterogeneity in species composition, while stand structure and microclimate are not considered. Climate inputs are drawn from EURO-CORDEX regional climate simulations using the MPI-M-MPI-ESM-LR global climate model and the SMHI-RCA4

² <https://globalwindatlas.info/en/>



regional climate model for RCP2.6 and RCP4.5 (Vautard et al., 2021). SPEI was calculated every year and the value used was the minimum in the last 3 years to account for accumulated drought conditions (Lawal et al., 2024; Marie et al., 2024). All disturbance calculations are conducted in R 4.4.3 (R Core Team, 2025) and the disturbance models are made available as R packages (fgr, IpsR) for use within and beyond PathFinder.

3.3.2 Assessment of trade-offs and synergies

Trade-offs and synergies between indicators are assessed based on directional changes relative to the 2020 baseline and the Pearson R correlation matrices on the European scale. The analysis is restricted to grid cells that were classified as forests in the initial land system map from CLUMondo, ensuring that the results represent predominantly forest-dominated pixels and avoiding mixed land-use effects. The Pearson correlation coefficient (r) is calculated for each scenario and for 2030, 2050 and 2100, resulting in correlation matrices where values approaching +1 indicate synergies and values approaching -1 indicate trade-offs.

This analysis is complemented with a spatial analysis of directional change consensus among the scenarios. For each indicator, grid cell, scenario, and selected time step (2030, 2050, 2100), changes are classified as increase, decrease, or stable using indicator-specific thresholds. This ensures that only meaningful changes are considered, while negligible changes are treated as stable. For each indicator, the threshold for meaningful change was derived from the mean absolute change across all forest pixels and all four scenarios between 2020 and the relevant time step, multiplied by 0.25. This approach was used as some indicators are more static from nature than others, and therefore need a separate threshold, while absolute values are preferred over percentages, because ecological limits and processes constrain growth at high values, so using relative changes would set disproportionately large thresholds for already high values, while low values—which can grow more rapidly—would have very low relative thresholds, potentially exaggerating increases.

We developed agreement maps across scenarios per indicator pair, with the following classification:

- Strong trade-off/synergy: three or four scenarios show the same interaction, without both synergy and trade-off occurring.
- Weak trade-off/synergy: one or two scenarios agree, without both synergy and trade-off occurring.
- No interaction: Either both trade-offs and synergies were found across scenarios, or all scenarios resulted in no interaction.

3.3.3 Forest management impact

The analysis is conducted for the years 2030, 2050, and 2100, allowing for the assessment of long-term management effects. Results from all scenarios are combined at the European level to capture the full range of management trajectories. To assess the impact of forest management changes, we calculated the Pearson correlation coefficient between forest management intensity and each indicator.

3.3.4 Workshop country-level analysis

To support the co-development of forest management pathways within PathFinder WP4, this analysis downscales the pan-European results to the specific subset of countries where stakeholder workshops were conducted. For selected workshop countries, indicator trajectories are analysed per scenario to support comparison with stakeholder perspectives. Results are presented in tabular form for the years 2020, 2030, 2050, and 2100. For each indicator, absolute values are reported to provide insight into the magnitude of change.

4. Results

4.1 Forest management scenarios

4.1.1 Document evaluation

Scoring results from the four documents reveal diverging policy visions for the future of European forests (Table 5; Figure 2). The greatest differences in perspective appear in the forest conservation and wood production objectives. While some stakeholders strongly emphasize ecological and protective functions, others prioritize economic and industrial dimensions. Cultural value also shows variation, though the divergence is less pronounced. There is broad consensus on involving local stakeholders, yet the importance of preserving landscapes and promoting cultural services varies.

Common ground exists regarding climate change mitigation and sustainable harvesting, with all documents assigning these objectives moderate to high importance. While sustainable harvesting is broadly agreed upon, with only some differences in how central it is to each vision, climate change mitigation strategies differ significantly. Some actors prioritize conservation and restoration to enhance carbon sequestration, whereas others emphasize the bio-economy and the substitution effect of wood products. This reflects shared climate concerns but fundamentally different implementation strategies.

Based on the document analysis (Table 5), four forest scenarios were developed. Each reflects a distinct combination of priorities, shaped by the management actions addressed in the source documents. While some areas of common ground exist, particularly around sustainable harvesting and climate mitigation, the variation in emphasis led to clearly differentiated scenario outcomes (Figure 2).

Table 5. Scoring of management actions for each document. A score of 0 indicates that the action was neither mentioned nor implied; a score of 1 signifies that the action was mentioned or implied but was not a central focus; and a score of 2 reflects that the action was central to the perspective presented in the document.

Key objective	Management action	Scenario			
		I	II	III	IV
Forest conservation	Protect old-growth forests and reduce human pressures across all forest types	2	1	1	0
	Restore forest ecosystems and degraded forests	2	1	0	0
	Maintain biodiversity and ecological functions	2	2	2	0
	Total	6	4	3	0
Climate change mitigation	Increase carbon storage through afforestation, reforestation, or restoration	2	1	1	1
	Prevent forest loss and degradation to avoid greenhouse gas emissions	2	1	1	0
	Support forest management practices aimed at achieving climate neutrality	2	2	2	2
	Total	6	4	4	3
Sustainable harvesting	Ensure wood harvesting does not compromise biodiversity, forest productivity, or ecological health	2	2	2	1
	Promote forest certification and carbon accounting	1	0	2	1
	Enforce the adoption of sustainable forestry guidelines	2	2	2	1
	Total	5	4	6	3
Wood production	Increase wood production to support the future bioeconomy demand	0	1	2	2
	Improve processing efficiency and increase yields	0	0	1	2



	Promote innovation and investment to support the development of wood-based industries and the bioeconomy	0	1	2	2
	Total	0	2	5	6
Cultural value	Preserve local forest landscapes and practices to maintain cultural identity	1	2	2	0
	Promote cultural services such as recreation and eco-tourism	0	1	2	0
	Involve local communities, stakeholders and forest owners in forest management and conservation planning, incorporating local knowledge	1	2	1	1
	Total	2	5	5	1

Note: I = Biodiversity focused forests, II = Participatory forest stewardship, III = Multifunctional forests, and IV = Competitive forest industry.

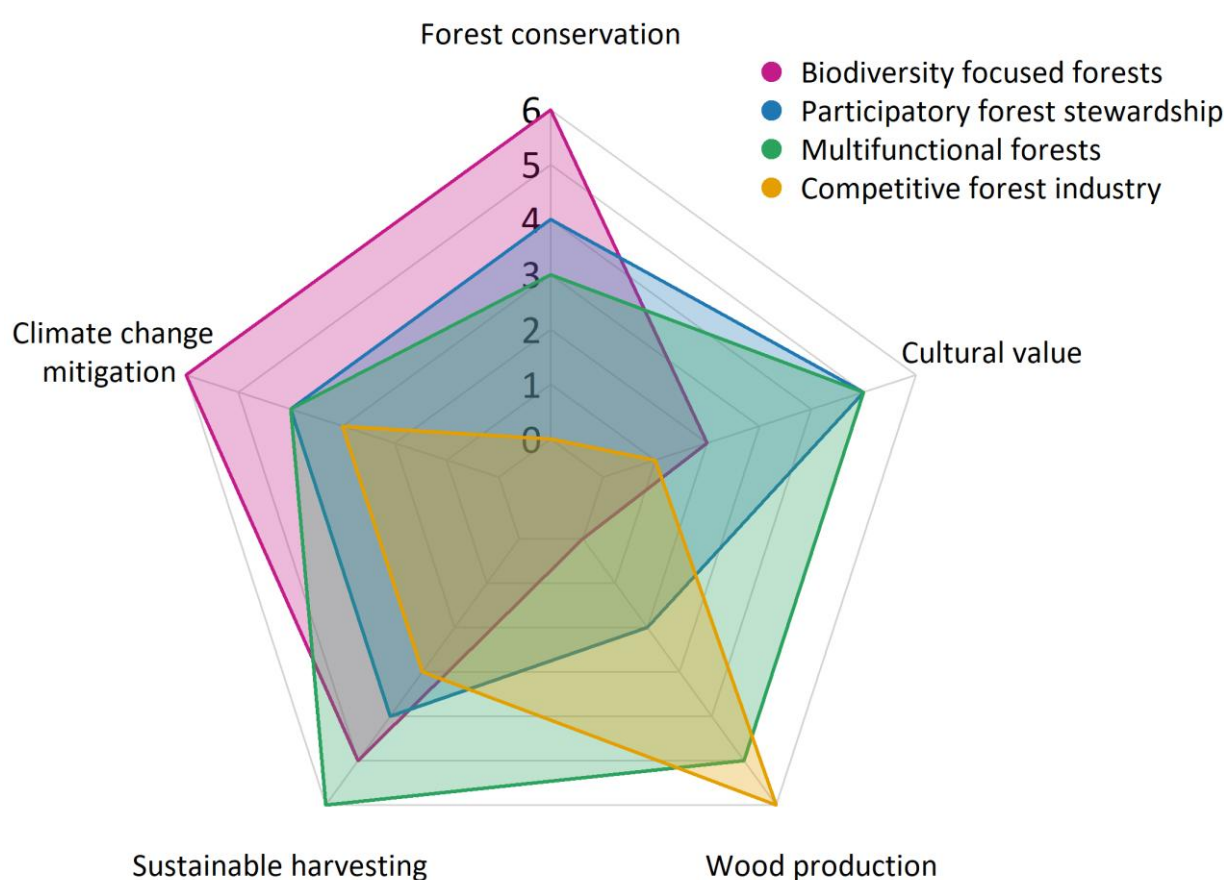


Figure 2. Comparison of the four forest scenarios across five key objectives: forest conservation, climate mitigation, sustainable harvesting, wood production, and cultural value. The scoring of our four scenarios is presented: biodiversity focused forests (pink), participatory forest stewardship (blue), multifunctional forests (green), and competitive forest industry (orange). Axes represent the cumulative scores of three management actions per objective (maximum score of 6); higher values indicate a more central role in the scenario vision.

4.1.1.1 Biodiversity focused forests

The WWF (2025) vision centres on forest conservation and climate change mitigation. It strongly emphasizes the strict protection of all remaining primary and old-growth forests, active restoration of degraded ecosystems, and halting biodiversity loss. Afforestation, reforestation, and close-to-nature forest management are key strategies in achieving the overarching goal of climate neutrality.



Furthermore, the full implementation of the EU Deforestation and Forest Degradation Regulation is highlighted as a vital tool to address both conservation and climate objectives.

Sustainable harvesting is encouraged within clear ecological boundaries. WWF (2025) advocates for keeping biomass demand within sustainable limits, explicitly prioritizing biodiversity and protection over industrial production. While forest certification and carbon accounting are not explicitly discussed, the vision aligns with many principles of certified forestry through its emphasis on regulation and ecological integrity.

Conversely, cultural values receive limited attention. Although close-to-nature management indirectly supports the maintenance of forest landscapes, it remains a secondary theme. Stakeholder engagement and local contexts are acknowledged only briefly and are not embedded as core elements of the strategic vision. Notably, wood production is entirely absent from the vision set out by WWF (2025).

4.1.1.2 Participatory forest stewardship

The core message of the CEPF (2023) vision is the maintenance of biodiversity and support for climate mitigation, with strong involvement of local forest owners and communities. Cultural value is central to this scenario. Sustainable forest management (SFM) is rooted in local knowledge, which inherently supports the preservation of cultural landscapes and traditional practices. Engaging local stakeholders is presented as a prerequisite for achieving resilient, multifunctional forests. Cultural services such as recreation and eco-tourism receive moderate attention, as they are not a primary focus.

Forest conservation is emphasized through continuous, ecologically responsible forest use rather than through strict protection or large-scale restoration. While explicit references to protection and restoration are limited, well-managed forests are portrayed as essential for conserving biodiversity and maintaining ecosystem functions.

Climate change mitigation is acknowledged through the role of forests as carbon sinks and the importance of SFM. Although specific mitigation strategies are not detailed, the emphasis on healthy, long-lived forests implicitly addresses forest degradation and contributes to broader climate goals.

Sustainable harvesting is a key principle in the vision outlined in CEPF (2023), stating that forest use must not compromise biodiversity or ecosystem services. While specific mechanisms like carbon accounting are not addressed, the commitment to operating within ecological limits is strongly expressed.

Finally, wood production is not a central focus but is indirectly supported through calls for investment and innovation in SFM. The document highlights the need to adapt silvicultural practices to climate change and improve forest systems. The bioeconomy is mentioned briefly, and while it is not elaborated upon, it does imply increased wood use. However, the overarching emphasis remains on ecological sustainability rather than industrial expansion. This results in only a partial alignment with wood production goals.

4.1.1.3 Multifunctional forests

The vision of EUSTAFOR (2024) is to promote a sustainable, innovation-driven bioeconomy through multifunctional forest management. Sustainable harvesting is foundational to this vision, ensuring ecological, economic, and social forest functions are maintained over the long-term.

Wood production is strongly supported through innovation and the promotion of a growing bioeconomy. The document highlights the importance of product development and market



innovation as drivers of the forestry sector. While productivity increases are implied, they are not explicitly prioritized.

Cultural value receives notable attention, with frequent references to the preservation of forest landscapes and cultural services such as recreation and tourism. These are integrated into one of EUSTAFOR's SFM principles. Although stakeholder engagement and the inclusion of forest expertise are promoted, the direct involvement of local communities and the integration of traditional knowledge are not central to the vision.

Climate change mitigation is addressed by linking SFM to broader climate goals, including the substitution of fossil-based materials with forest-based products. While carbon storage is acknowledged, specific actions such as afforestation, reforestation, and restoration are not discussed in detail. The vision of EUSTAFOR (2024) includes efforts to reduce degradation through proactive management, though the prevention of forest loss is not explicitly mentioned.

Finally, forest conservation is present but less developed. While EUSTAFOR (2024) emphasizes maintaining and enhancing biodiversity, it lacks specific commitments to concrete conservation measures—such as strict protection, restoration of degraded ecosystems, or reducing human pressure on old-growth forests.

4.1.1.4 Competitive forest industry

CEPI (2017) presents a vision centred on the advancement of a competitive, wood-based bioeconomy through innovation, productivity, and intensified forest use. As stated in the report, their vision is built on “long-term decarbonization linked with product innovation, market developments, enhanced productivity and process efficiency.” In this scenario, forests are managed primarily to ensure a continuous wood supply, with industrial development and economic growth as central goals. Decarbonization is closely tied to bioeconomic expansion, positioning wood production as both a climate and economic strategy.

Sustainable harvesting is acknowledged as a necessity for maintaining long-term wood availability. These practices are promoted to support bioeconomic goals and ensure that productivity is not compromised. However, broader ecological concerns—such as biodiversity or forest health—are not addressed. While the document references emissions trading schemes and carbon pricing to reduce emissions, these instruments are not central to the vision. Sustainable harvesting is treated less as an independent priority and more as a technical condition required to sustain industrial output.

Climate change mitigation is addressed primarily through the substitution of fossil-based materials and carbon storage in harvested wood products. The document advocates for climate policies that leverage the combined benefits of carbon sinks, product storage, and substitution. Notably, the strategy does not include measures to prevent forest loss or degradation. Instead, mitigation is rooted in industrial decarbonization rather than ecological restoration or protection.

Finally, cultural value receives limited attention, with no explicit mention of cultural services, traditional practices, or forest landscapes. Local communities are acknowledged as contributors to innovation, particularly in developing bio-based alternatives to fossil products, indicating some recognition of their role in the forest-based sector. However, there is no mention of their involvement in forest governance, cultural practices, or landscape preservation. Forest conservation is not addressed in the vision presented by CEPI (2017).



4.1.2 Workshop results

Run on a common activity structure, the five workshops offer useful insight into the 4 developed scenarios across very different European forest governance contexts. In this section we provide country level context, stakeholder feedback on developed scenarios, and the resulting 'desired future' results which asked participants to reflect on scenarios and develop a vision for the country's context. All of this information was used to help inform the development of scenarios to ensure they best reflected differing contexts across the four distinct European regions.

4.1.2.1 Spain

The Madrid workshop revealed a participant community broadly aligned on the diagnosis of Spain's forest challenge, even where they diverged on solutions. Forests were consistently framed as ecologically vital yet, socially and politically undervalued, chronically under-resourced, and increasingly defined by fire risk; understood as both a symptom and a driver of degradation, compounded by land abandonment and climate change. A recurring underlying tension framed the discussion: Spanish forests are seen as central to national climate goals yet, without improved management, at risk of shifting from carbon sinks to carbon sources.

The reaction to PathFinder's four scenarios provided insightful outputs. Participants strongly favoured the multifunctional forests narrative as the most balanced and inclusive vision, while cautioning that "satisfying everyone a little" requires constant negotiation and could itself generate conflict. They largely rejected participatory forest stewardship as ill-suited to Spain's fragmented ownership and weak active-management culture, and were broadly critical of the competitive forest industry model on ecological grounds (with a minority noting it could reduce fuel loads). The biodiversity focused forests storyline drew the strongest opposition and was repeatedly described as a "no-go" for Spain, given fire risk, rural dependence on active use, and cultural preferences for managed, accessible forests.

This fed directly into a shared vision of the desired future: the resilient forest, actively managed, less dense, more connected and less fragmented, safe, healthy. And, multifunctional, underpinned by a renewed relationship between people and forests built on awareness, education, recreation, and productivity. Both breakout groups independently converged on a similar set of priorities, lending these conclusions notable internal consistency.

4.1.2.2 Finland

The Helsinki workshop surfaced a stakeholder community whose relationship with forests was framed first through recreation and a deep cultural and emotional bond, with access to forests treated as a high priority. Forests were valued as multifunctional, economically important for wood-based products, but also equally significant for non-wood products, aesthetics, and ecology. The dominant anxieties were overuse and overharvesting, climate change (especially drought), potential land-use change, and a distinctive concern for the intergenerational loss of forest knowledge as society urbanizes. Throughout, forests were positioned as central to Finland's climate targets and green transition.

Reactions to the developed scenarios showed a clear ordering of preference. Multifunctional forests were strongly preferred, described as both traditional and forward-looking. It was the scenario in which participants named "Finland" itself as the main beneficiary. However, participants warned that achieving effective multifunctionality is highly dependent on good governance and implementation, otherwise it could be easily co-opted as rhetoric to justify inaction. Participatory forest stewardship was seen as potentially empowering small owners but disadvantaging industry and large forest owners, with the caveat that Finnish local communities also tend to be pro-industry. The competitive



forest industry scenario produced the most transparent winner/loser analysis - benefiting industry, investment funds, owners, and bioenergy/green-chemistry chains while marginalising environmental non-governmental organisations (ENGOS), recreational users, inland fisheries, and the Sámi. The scenario clearly presented trade-offs with biodiversity, water quality, and climate-neutrality goals in Finland. The biodiversity focused scenario and its objectives was viewed as economically unviable in the Finnish context and as requiring management changes participants were reluctant to embrace.

The desired future centred on preserving multifunctionality was defined to include timber production, culture, recreation, and well-being together, alongside access rights, limited extraction, clean water, and biodiversity objectives. Participants envisioned more species-diverse, climate-resilient forests; stressed transmitting forest knowledge to future generations; and insisted that conservation and climate objectives must not erode the economic role of Finnish forests. Governance, they argued, should be grounded in justice and fairness through an iterative process of checks and balances.

4.1.2.3 Austria

At the Vienna workshop several participants' expressed concern for the perceived shift from bottom-up, voluntary approaches toward top-down EU policymaking, set against the structural fact that private landowners hold over 80% of Austria's forests. Conflicting and contradictory EU targets, the difficulty of multi-level governance, and insufficient stakeholder engagement framed much of the discussion, alongside biodiversity loss, a declining carbon sink, and growing tension between recreational/tourism use and forest-based economic activity. Calls for stronger payment-for-ecosystem-services schemes, science-based decision-making, and better public education recurred throughout.

The storyline exercise unfolded differently here than in Spain or Finland. Participants struggled to treat the storylines as realistic, arguing that Austria already pursues all of the goals simultaneously and that separating them risks implying the forest industry is unwilling to meet biodiversity targets; several participants maintained that efficient harvesting and biodiverse forests are mutually reinforcing. This debate consumed much of the session, so only two storylines were examined in depth. Competitive forest industry was seen as making all actors in the forestry supply chain as both winners and losers (short-term gains, long-term degradation) and with biodiversity and non-wood/recreational users as clear losers, ENGOS and state authorities marginalized, processing plants poorly adapted to climate-driven species shifts, and neither Paris nor Green Deal targets met. Participatory forest stewardship was felt to align well with the Austrian context; discussion centred on representation and voice rather than winners and losers, elevating small owners while reducing large companies' influence, with trade-offs around slower decision-making (which some viewed as acceptable for long-term management) and questions about who would meaningfully be heard.

The desired future again converged on multifunctionality; enabling growth of timber and non-wood products, expanding renewable wood use, recreation, hazard protection, biodiversity as essential to forest health, and the preservation and expansion of the carbon-sink function. Future attention was needed to address site-specific climate adaptation for Austrian forests and further research on invasive species. The one openly contested element was whether to establish a fixed share (a 10% quota was cited) of strictly protected forest, or whether sustainable management makes such a quota unnecessary.

4.1.2.4 Slovenia

The Ljubljana workshop revealed a participant community whose stakes were grounded in everyday, personal forest use like firewood collection, recreation, hiking, mushroom picking, honey harvesting.



The forests were part of stakeholder's national identity and cultural landscape, with public access treated as essential. Climate change and forest health were the dominant threats (disturbances, pests, disease), alongside the forests' climate-mitigation role and the preservation of ecosystem and species diversity. A characteristic Slovenian framing recurred throughout: multifunctionality and close-to-nature management were treated as established principles, though participants were split between those prioritizing biodiversity and conservation and those emphasizing greater investment in bioeconomy. Governance concerns centred on ownership rights and their effect on sustainable management.

The storyline exercise was shortened to a general discussion, but produced a distinctive result: many participants felt Slovenia was best represented by the biodiversity focused forests storyline, arguing the country is already ahead of the contested Nature Restoration Law targets through strict harvesting rules and high conservation standards. They reasoned that even an EU shift toward competitive forest industry would not greatly raise Slovenian harvesting, because the strong institutional framework and highly prescriptive, locally based Slovenian Forest Service (SFS) management plans would constrain it. On participatory forest stewardship, participants saw growing engagement among small owners but expected the SFS's prescriptive role to continue ensuring adherence to close-to-nature principles. In effect, Slovenia's strong centralized management makes several of the storylines feel already managed-for or institutionally bounded.

The desired future emphasized site-appropriate, climate-adapted species management within preserved close-to-nature plans; continued public access to valued non-wood products (honey, chestnuts, mushrooms); a stronger, currently underutilized bioeconomy role for wood as a fossil substitute; better public education; and a strong wish for more active owner engagement and consolidation of fragmented holdings, with the forest share of land use kept unchanged.

4.1.2.5 Brussels

The Brussels workshop oriented focus at the pan-European level, with participants repeatedly being confronted with the difficulty of generalizing across a continent of divergent sub-regional environment and governance realities. The opening stakes echoed the national workshops: forest health and resilience, multifunctionality, biodiversity as the basis of resilience, and ecosystem-service delivery, however, were framed more insistently through their relation to EU policy ambition. Participants stressed fragmentation pressures (population, urban expansion, land-use change), the challenge of decision-making under deep "unknowns," and a perceived erosion of trust between EU/Member State policymakers and forest owners that they felt needs to be rebuilt. Weak, non-comparable forest monitoring was singled out as a root cause of a divisive policy arena.

The storyline exercise was distinctive as we first discussed the four scenarios with two IPCC SSP scenarios (the sustainability-oriented SSP1 and the middle of the road SSP2) in which the scenarios would be run, making feasibility explicitly contingent on the wider world order. Competitive forest industry was widely judged non-viable for Europe in the long-term (short-term winners only, undermining all other goals) especially as the challenges would not be met in the SSP2 scenario. Multifunctional forests were seen as benefiting society over the long run but as essentially the current trajectory, with participants again questioning whether "multifunctionality" is coherent or merely perpetual compromise (and noting its success would differ sharply between SSP1 and SSP2); Biodiversity focused forests produced clear winners and losers, an almost exclusively anthropocentric framing (not including non-human actors), and strong concern about leakage (production simply shifting outside Europe). Finally, participatory forest stewardship was viewed as a balanced, culturally resonant approach (reinforced by the COVID recreation shift) but one risking decentralized, mixed market signals and disadvantaging large Nordic forestry companies.



The desired future was deliberately cautious about a single European vision, settling on forest expansion only where ecologically suitable, resilience understood as species and (universally) genetic diversity, conservation of old-growth and mature forests, a strong adaptive wood industry, better integration into global systems, and enhanced cultural and landscape values, with one participant proposing a need for a paradigm shift beyond multifunctionality toward landscape-scale governance.

4.1.2.6 Overall workshop review of scenarios

Competitive forest industry was the most consistently rejected storyline, but for multifaceted reasons. It was judged short-termist and ultimately self-defeating everywhere. The Brussels workshop framed it as lacking long-term vision (short-term winners only, long-term catastrophe for forest health and the industry itself), and Austria described the forestry supply chain as being ultimately losers in this scenario. Winners were named almost identically across workshops (wood-sector investors, the bioeconomy and wood-processing, and in Finland also workers and right-leaning parties), as were losers (biodiversity, recreation, non-wood users, water quality and inland fisheries, with NGOs, the Sámi, and recreational publics marginalized). Two contextual nuances stand out: Spain and, more tentatively, Austria noted a possible silver lining that intensified management could reduce fuel loads and wildfire risk in Spain, while Austria added a specific structural concern that efficiency-driven species shifts would strand specialized processing plants. Most workshops concluded this storyline would meet neither the Paris nor Green Deal targets.

Multifunctional forests was the preferred storyline wherever it was discussed at length (Spain's "everyone wins," Finland's "Finland is the main beneficiary," the EU's "society benefits in the long term"), but the praise was always qualified by the same structural critique: multifunctionality is perpetual negotiation and compromise, risks satisfying every interest only "a little bit" and thereby generating new conflict, depends heavily on definition and implementation, and can marginalize weaker actors even when everyone is nominally "heard" (Finland specifically named foreign workers, non-Finnish speakers, and smaller stakeholders). The EU added that biodiversity is the intended synergy within this scenario but that uniform species selection and heavy management demands are real unintended risks.

Biodiversity focused forests was the most context-dependent storyline and the sharpest dividing line within and across workshops. Spain rejected its "Forest for Nature" management approach outright as a fire-driven "no-go". Finland judged a biodiversity-focused model economically unviable and likely harmful to the broader economy, with the forestry sector's concerns going unheard. Austria split visibly along sectoral lines, strongly enough that one participant insisted the "bad" rating be reframed as opposed by the forest sector but supported by more conservationist leaning participants. Slovenia was the striking outlier, with participants feeling the country is best represented by this storyline and already ahead of Nature Restoration Law targets through its prescriptive management regime. The EU produced the most analytically detailed reading, clear winners (owners of unproductive land receiving non-management compensation, biodiversity actors, society via ecosystem services) and losers (productive forestry and the wood supply chain), and prominent concern about leakage (production shifting outside Europe) and pest vulnerability from high standing stocks.

Participatory forest stewardship flipped almost entirely on national ownership structure and management culture. Spain rejected it as ill-suited to fragmented ownership, a weak active-management culture, and populations physically and socially distant from forests, suggesting it might fit Northern Europe better. Finland was mixed, small forest owners would gain financial independence while industry and large forest owners lost influence, but local communities (described as pro-industry) might still go unheard, with possible gains for tourism. Austria found it



the best-aligned storyline, shifting the discussion from winners and losers to representation and voice, and noting that slower, more deliberative decision-making is not necessarily a drawback for long-term forest management. Slovenia saw rising small-owner engagement but expected the SFS's prescriptive role to keep it bounded by close-to-nature principles. The EU saw it as balanced and culturally resonant (reinforced by the COVID recreation shift) but warned of decentralized, mixed market signals, weaker management accountability, harm to large Nordic companies, and the risk of strong lobby coalitions undermining smaller-scale participatory arrangements.

4.1.3 Survey results

The survey analysis identified four distinct stakeholder orientations across the European landscape (Figure 3). Of the 30 responses received from across Europe, 19 were considered valid for the cluster analysis, as 11 participants either provided incomplete point allocations or skipped the prioritization section. While diagnostic tests indicated potential sub-structures at higher cluster counts, the four-cluster solution provided the most cohesive representation of diverging priorities while aiding the comparison with the four scenarios developed in this study (Figure 4).

The results primarily revealed two overarching orientations: one centred on forest conservation and another emphasizing multifunctionality and wood production. Cluster 1 ($n = 6$) focuses on forest conservation (mean = 4.7), followed by climate change mitigation (mean = 4.0) and sustainable harvesting (mean = 3.8), while largely rejecting wood production (mean = 0.5). Conversely, Cluster 2 ($n = 4$) emphasizes wood production (mean = 4.8) while maintaining a baseline requirement for forest conservation (mean = 3.3). Cluster 3 ($n = 3$) prioritizes sustainable harvesting (mean = 5.0) and climate change mitigation (mean = 4.3), while almost neglecting cultural value (mean = 0.7). Cluster 4 ($n = 6$) represents a balanced or multifunctional orientation with points distributed relatively evenly across all objectives, except for forest conservation, which receives the lowest emphasis in this group (mean = 1.7).

Across all clusters, climate change mitigation and sustainable harvesting were consistently rated as medium to high priorities. Specifically, climate change mitigation and sustainable harvesting received scores of ≥ 3 from 16 and 18 respondents, respectively (Table 6). In contrast, cultural value received the lowest overall prioritization, with 17 respondents scoring the objective at ≤ 3 . Despite these points of agreement, wood production and forest conservation scores varied significantly across the sample.

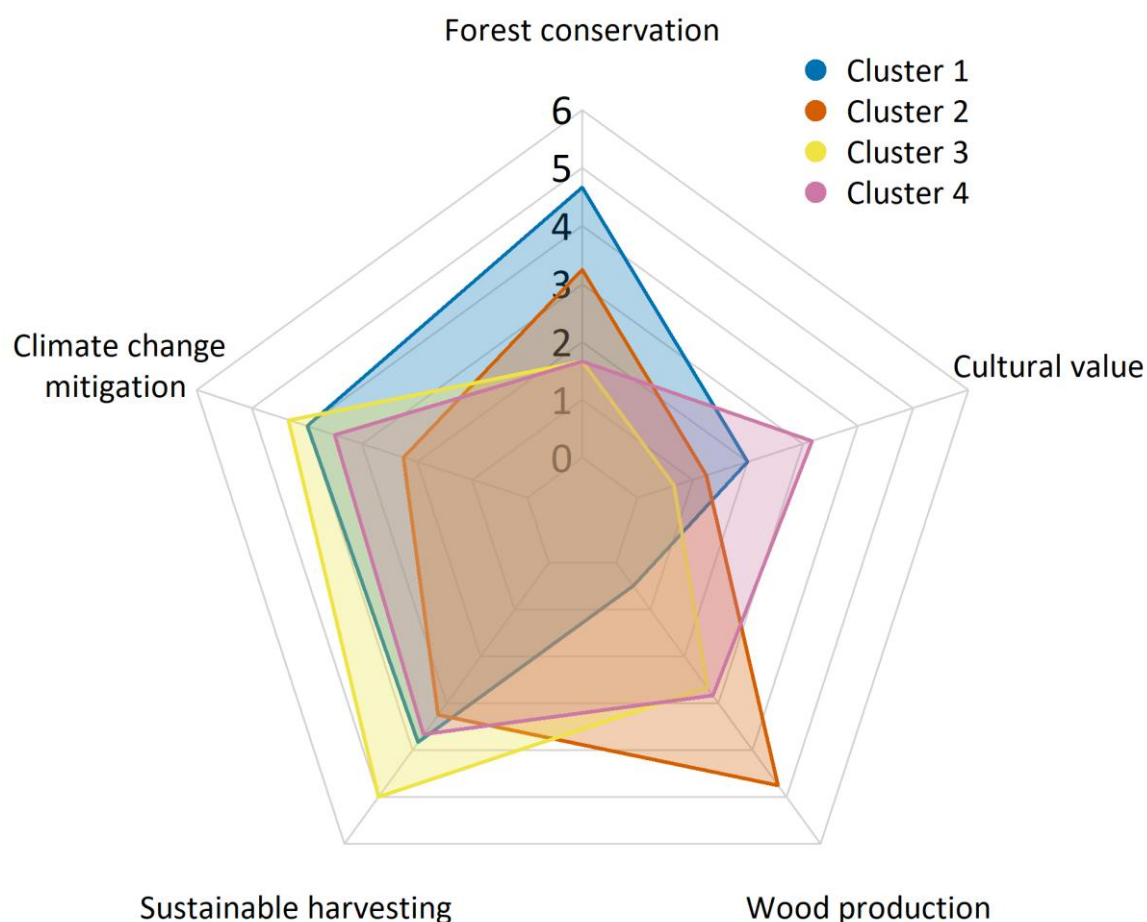


Figure 3. Four stakeholder clusters identified from survey data (N = 19) using Ward’s hierarchical clustering. Radar chart axes represent the cluster centroids across five core forest management objectives. Participants were required to allocate a fixed budget of 15 points across these objectives (with individual scores ranging from 0 to 6), where higher values indicate a greater prioritization within the stakeholder profile.

Table 6. Stakeholder survey responses (N = 19) show the allocation of 15 points across five forest objectives. Responses are sorted by the clusters identified.

Respondent ID	Cluster	Forest conservation	Climate change mitigation	Sustainable harvesting	Wood production	Cultural value
R3	1	4	4	4	0	3
R4	1	4	4	4	1	2
R10	1	4	4	3	1	3
R21	1	6	3	3	0	3
R26	1	5	5	3	1	1
R30	1	5	4	6	0	0
R9	2	4	1	4	5	1
R12	2	2	4	3	5	1
R14	2	2	2	2	6	2
R29	2	5	2	4	3	1
R5	3	1	5	5	3	1
R11	3	2	5	5	2	1
R19	3	2	3	5	3	0
R2	4	1	4	4	3	3
R6	4	3	3	3	3	3
R8	4	1	4	4	4	2
R13	4	3	3	3	3	3
R23	4	1	4	4	1	4

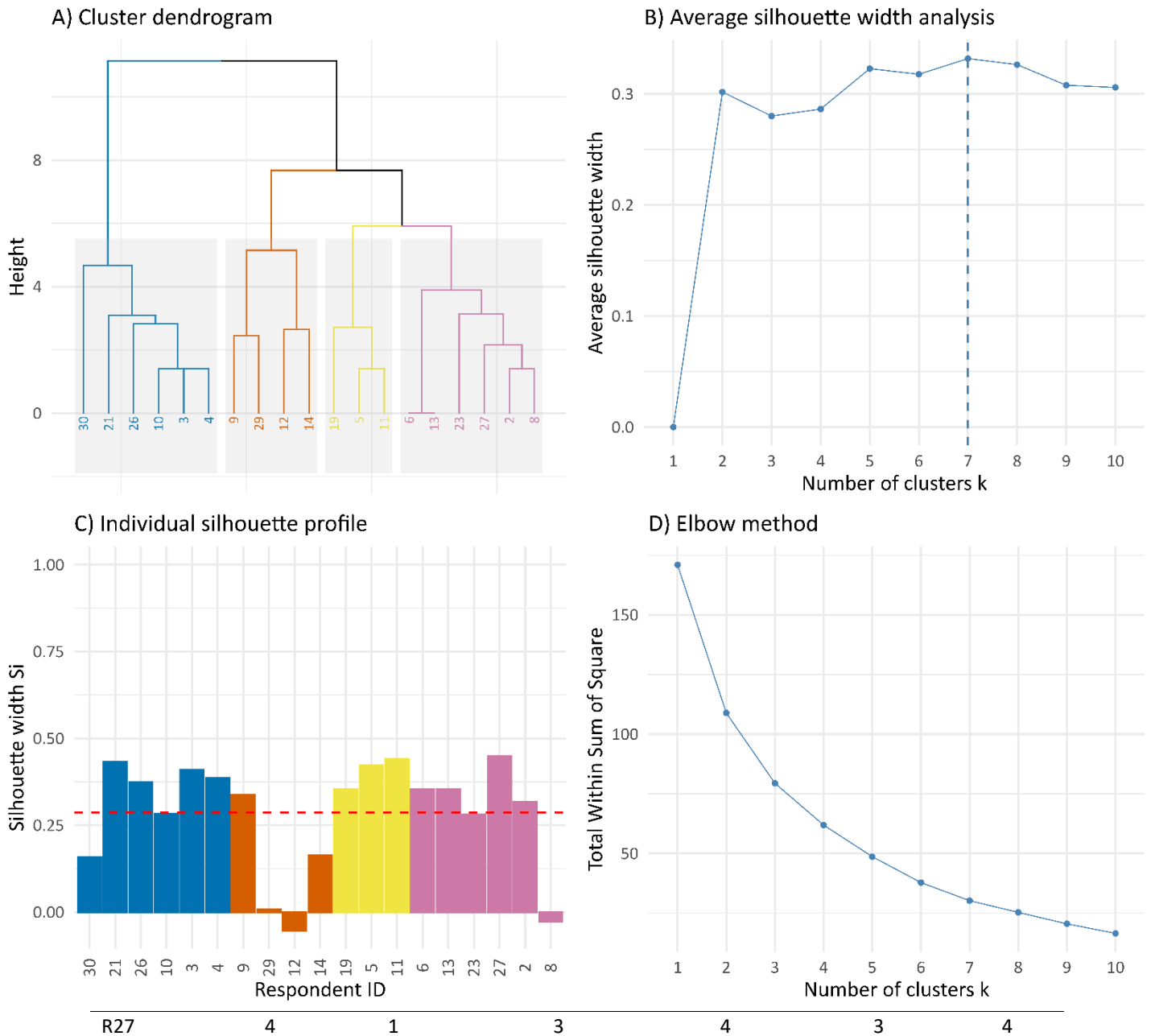


Figure 4. Cluster validation diagnostics and structural analysis. **A)** Cluster dendrogram, where coloured branches identify the clusters (colours match clusters displayed in Figure 3). **B)** Average silhouette width across potential cluster numbers, with the dashed line indicating the optimal number of clusters. **C)** Individual silhouette profiles, with colours aligning to the cluster and the red line indicating the average silhouette score. **D)** Elbow method results.



4.2 Scenario results

4.2.1 CLUMondo

The four scenarios result in distinct land system configurations across Europe by 2050, reflecting divergent policy priorities, environmental restrictions, and market demand trajectories (Figure 5; full spatial distributions per scenario are provided in Figures B1–B4). These differences underscore the sensitivity of European land systems and forest management to alternative future pathways (Figure 6A). The biodiversity focused forests scenario is characterized by a high share of extensive forestry (21.97% of total land area; Table B1). The participatory forest stewardship scenario features a more balanced mix of extensive forestry (13.30%) and combined objective forestry (14.66%). The multifunctional forests scenario emphasizes combined objective forestry (24.04%). Finally, the competitive forest industry scenario exhibits a more even distribution across management classes, with intensive forestry (12.19%) being the most prevalent.

Despite these differences in management composition, total forest area increases under all scenarios, with net gains ranging from 0.96% to 4.87% of Europe's total land area (Figure 6B; Table B1). This expansion is largely driven by the conversion of mosaic land systems, which serve as the primary source for new forest areas across the continent (Tables B2–B5).

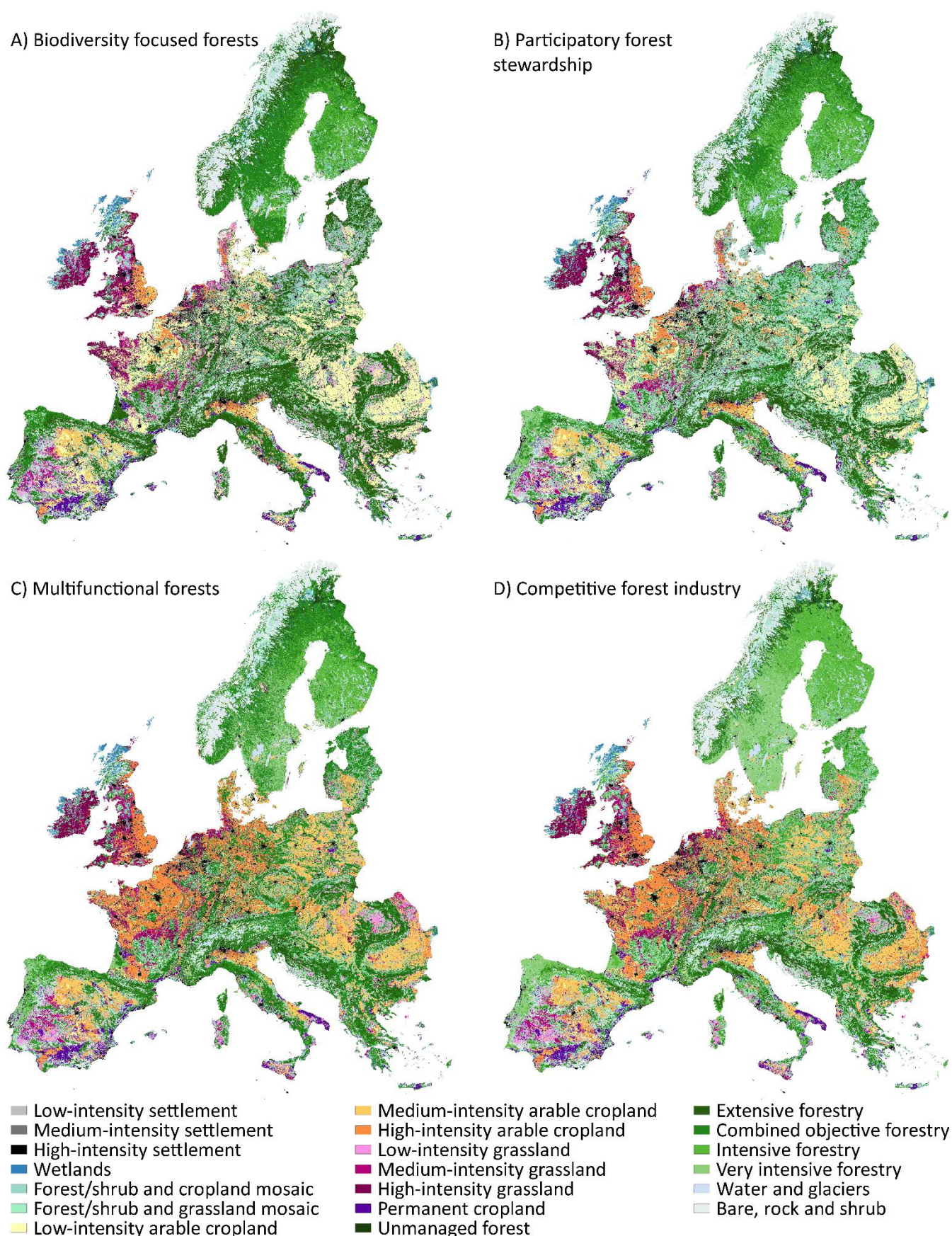


Figure 5. Projected land system maps across Europe in 2050 under four forest management scenarios: **A)** biodiversity focused forests; **B)** participatory forest stewardship; **C)** multifunctional forests; **D)** competitive forest industry.

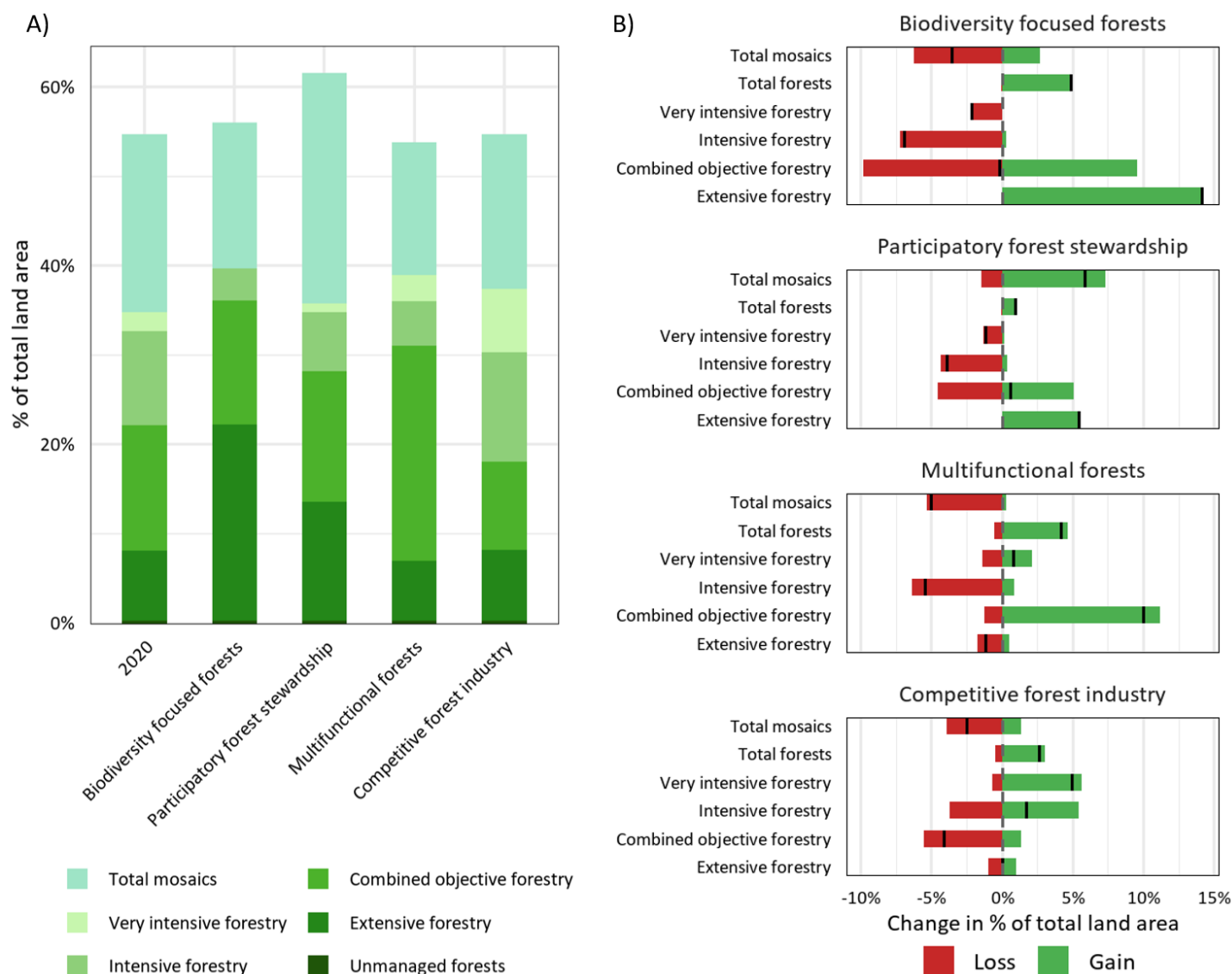


Figure 6. Comparison of forest management trajectories and land area shares across four future scenarios in Europe (2020–2050). **A)** The proportional share of land area per forest management class and aggregated mosaics in the 2020 base year versus the four scenarios in 2050, expressed as a percentage of the total land area. **B)** Gains, losses, and net change for the forest management classes, excluding unmanaged forests as this class stays stable, and for the aggregated classes of forests and mosaics, expressed in % of total land area with the black line indicating the net change.

4.2.1.1 Biodiversity focused forests

In the biodiversity focused forests scenario, forest area increases by 4.87% of Europe's total land area by 2050. Forest loss is negligible, with gains occurring primarily through conversion of mosaic land systems and, to a lesser extent, cropland and grassland (Table B1; Table B2).

Changes within the forest sector are characterized by widespread deintensification. No forest intensification is observed under this scenario. Instead, the majority of existing forests transition toward extensive forestry, which expands by 14.10% of the total land area. Combined objective forestry exhibits a marginal net decrease of 0.19%, as gains from non-forest conversions and forest deintensification are outweighed by the shift toward extensive forestry. Intensive forestry declines from 10.47% to 3.55% of total land area, while very intensive forestry is nearly phased out, representing only 0.05% by 2050 (Table B1).



Regional patterns highlight a shift toward combined objective forestry in most of Sweden, whereas intensive forestry remains dominant in Finland (Figure B5). In Southern Europe and mountainous regions, such as the Alps, Italy, and the Balkans, forest expansion is concentrated around existing forest edges, accompanied by the conversion of combined objective forestry to extensive forestry (Figure B6). Similar deintensification trends occur in the Iberian Peninsula, albeit some intensive and very intensive forestry persists, particularly in Galicia (Figure B7).

4.2.1.2 Participatory forest stewardship

Forest area increases by 0.96% of Europe's total land area by 2050 under the participatory forest stewardship scenario, representing the smallest forest expansion among the four scenarios. In contrast to the other scenarios, mosaic land systems expand substantially, increasing by 5.88% of the total land area. Forest loss remains negligible, with gains occurring primarily through the conversion of mosaic land systems, followed by grassland and cropland (Table B1; Table B3).

Forestry changes are less pronounced than in the other scenarios. Management remains largely stable or undergoes deintensification, with only limited intensification observed. Extensive forestry expands by 5.43% of the total land area, while combined objective forestry increases modestly by 0.60%, reflecting both localized forest expansion and deintensification. Intensive forestry declines by 3.93% of total land area, and very intensive forestry decreases by 1.14%, leaving 1.03% of Europe's total land area under very intensive forest management by 2050 (Table B1).

Deintensification is most pronounced in Eastern Europe, whereas Western and Northern Europe show more moderate changes in management intensity. Forest expansion is limited in these regions, where mosaic land systems cover broad areas (Figure B8). Southern Europe experiences comparatively higher levels of forest expansion, albeit with slightly less deintensification, as most existing very intensive forests remain in place.

4.2.1.3 Multifunctional forests

A net increase in forest area of 4.15% of Europe's total land area occurs by 2050 under the multifunctional forests scenario. Despite this net gain, forest loss is also observed, particularly within intensive forestry. As in the other scenarios, the majority of forest expansion results from the conversion of mosaic land systems (Table B1; Table B4).

Management outcomes in this scenario reflect a combination of intensification and deintensification processes. Extensive forestry decreases by 1.16% of the total land area, whereas combined objective forestry expands markedly by 9.98%. While intensive forestry declines by 5.46% of total land area, very intensive forestry increases by 0.80%, indicating that both intensification and deintensification occur within this scenario (Table B1).

While the transition toward combined objective forestry is pronounced across Europe, regional patterns remain distinct. In Southern and Western Europe, prominent forest expansion is primarily associated with transitions toward combined objective forestry. Conversely, Eastern Europe exhibits widespread deintensification, with intensive and very intensive forestry becoming largely absent as existing forests transition toward extensive forestry (Figure B9). In contrast, Northern Europe shows a pronounced increase in very intensive forestry alongside a substantial expansion of combined objective forestry (Figure B10).

4.2.1.4 Competitive forest industry

In this scenario, the forest area increases by 2.59% of Europe's total land area by 2050. Gains are primarily concentrated within the intensive forestry classes, while losses are most frequent within



current combined objective forestry. Consistent with the other pathways, forest expansion is driven by the conversion of mosaic land systems, cropland, and grassland (Tables B1; Table B5).

Management composition shifts significantly toward higher intensity classes. Extensive forestry remains largely stable, increasing by only 0.06% of the total land area. However, combined objective forestry declines substantially by 4.14% of total land area, reflecting a broad transition toward more intensive management. Intensive forestry increases by 1.72% of total land area, driven by both forest expansion and management intensification. Very intensive forestry exhibits the most substantial growth, expanding by 4.95% of total land area by 2050 (Table B1).

Strong spatial contrasts define this scenario. In Northern Europe, management shifts toward higher intensities, resulting in vast areas of intensive and very intensive forestry (Figure B11). In contrast, Eastern Europe exhibits deintensification, with transitions toward extensive forestry (Figure B12). Furthermore, the spatial pattern of forest expansion differs from other scenarios, as new forest cover primarily emerges under intensive forestry rather than combined objective forestry. These expansion areas are visible in multiple regions, including the west coast of the United Kingdom, Ireland, and western France (Figure B13). In the Iberian Peninsula, extensive areas of very intensive forestry are observed, specifically in Galicia and Portugal (Figure B14).

4.2.1.5 Spatial agreement in forest cover

The scenarios reveal both overlapping and diverging spatial patterns of forest cover change across Europe (Figure 7A; Figure B15). Forest gains dominate the landscape, whereas forest losses are notably less pronounced. While most existing forests remain stable, high agreement for forest gain is concentrated in the mountainous regions of Southern Europe. More moderate but spatially consistent gains occur in parts of France, Germany, Poland, the Czech Republic, the Carpathians, and Denmark. Conversely, forest loss is spatially limited but concentrated in the Iberian Peninsula, the Balkans, France, southern Sweden, and southern Finland. These areas of strong forest gain and loss indicate regions where forest cover change represents a robust outcome across scenarios.

4.2.1.6 Spatial agreement in management intensity

Despite substantial differences in forest management distributions between scenarios, clear spatial patterns of intensification and deintensification emerge when results are aggregated across all four scenarios (Figure 7B; Figure B16). Areas of strong agreement highlight regions where directional changes in management intensity are consistently projected, while mixed trajectories indicate spatial uncertainty in management responses where scenario outcomes diverge.

Deintensification hotspots are most pronounced in Eastern Europe, where large forest areas show consistent reductions in management intensity. Western Europe exhibits more fragmented and moderate deintensification patterns. Southern Europe shows a combination of stable management and divergent trajectories, as some areas intensify while others undergo deintensification.

Consistent intensification signals are distributed across large portions of Sweden and Norway. However, a prominent cluster of mixed trajectories in southern and central Sweden identifies areas where scenarios diverge between intensification and deintensification. Northern Scandinavia displays a more spatially heterogeneous response. Rather than scenario divergence, this region is characterized by a fragmented patchwork of weak intensification and deintensification occurring in close proximity. In contrast, southern Finland is predominantly stable, characterized by weak intensification in the west and more prominent deintensification toward the east.

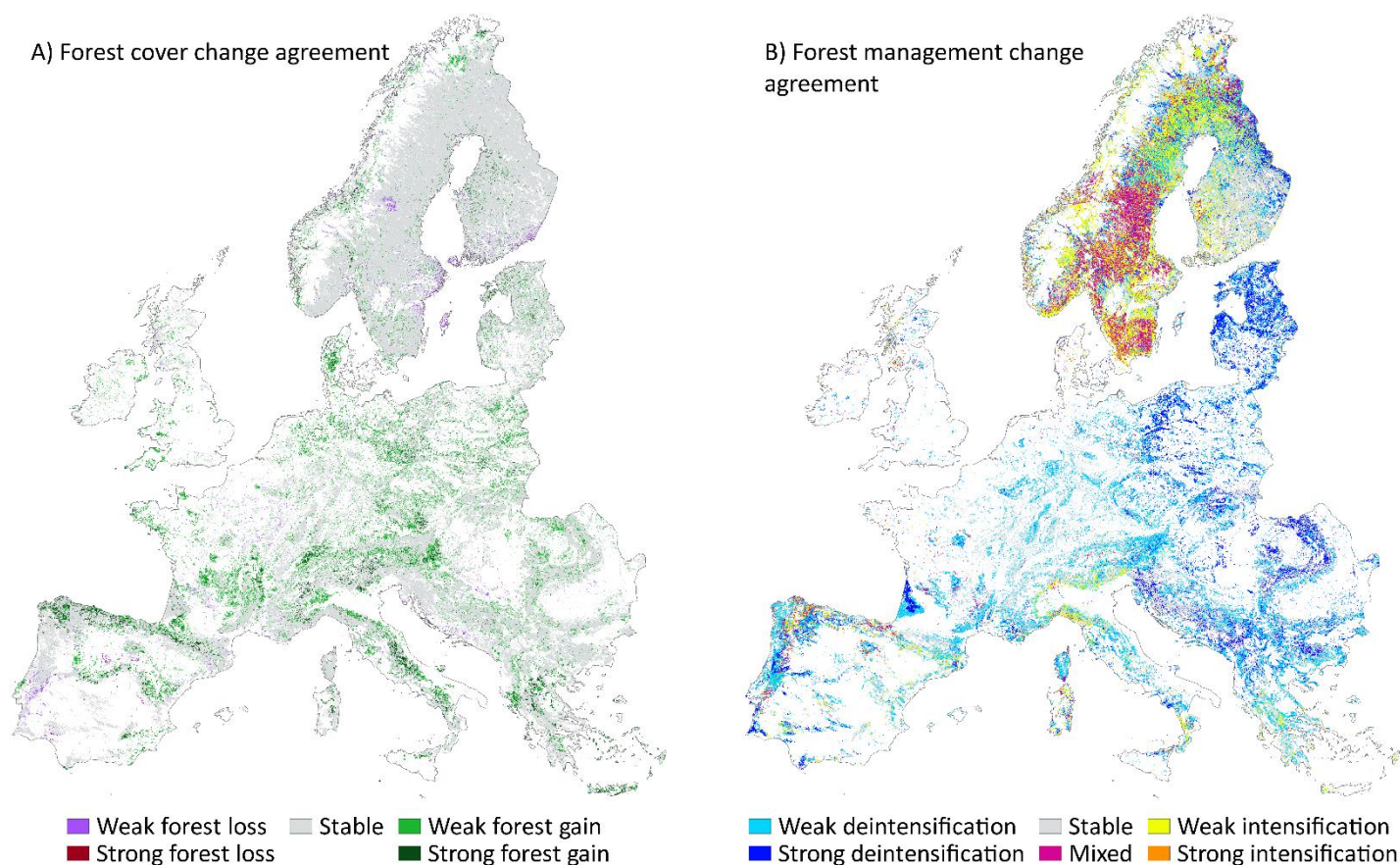


Figure 7. A) Spatial agreement in forest gain and loss across four forest management scenarios (2020–2050). Weak gain/loss denotes areas transitioning from non-forest to forest/forest to non-forest in one or two scenarios, while strong gain/loss indicates agreement among three or four scenarios. Light grey areas represent forests that remain stable across all scenarios. **B)** Spatial agreement in forest management intensification and deintensification (2020–2050). Weak change denotes pixels where one or two scenarios project a consistent directional change in management intensity, and no scenario indicates the opposite trend, whereas strong change reflects agreement among three or four scenarios. Mixed trajectories indicate pixels exhibiting both intensification and deintensification across scenarios. Grey areas represent stable forest management.

4.2.2 EFDM

Extensive exploration and validation of the EFDM outputs can be found from PathFinder WP3, Task 3.2 (Majasalmi, 2026).

4.2.3 Biodiversity indicator

At the European level, the biodiversity indices showed varying results (Figure 8). The inspection of the trends revealed different temporal patterns for each subindex. Forest structure, quantified through the Gini Index, increased for the four scenarios from 0.22 in 2020 to ~ 0.36 in 2050. The increment is larger for the competitive forest industry and multifunctional forests scenarios, with the biodiversity focused forests and participatory forest stewardship scenarios showing the lowest increments. However, these differences were minimal. A similar pattern was also found for the group of species compositional index, i.e., Shannon Index, which increased from 1.38 in 2020 and stagnated at 1.44 by 2035. The percentage of mature forest, with an average value of 16.7% decreased for the four scenarios. In particular, the percentage of mature forest under the biodiversity focused forests scenario was 15%, 14% under participatory forest stewardship while competitive forest industry and multifunctional forests depicted values around 13%. Finally, deadwood decreased for all the scenarios, except for biodiversity focused forests, which exhibited a value of 6.6 Mg/ha in 2050. The



drop in deadwood is more evident in the competitive forest industry (6.3 Mg/ha in 2010) and multifunctional forests scenarios (6.4 Mg/ha in 2010).

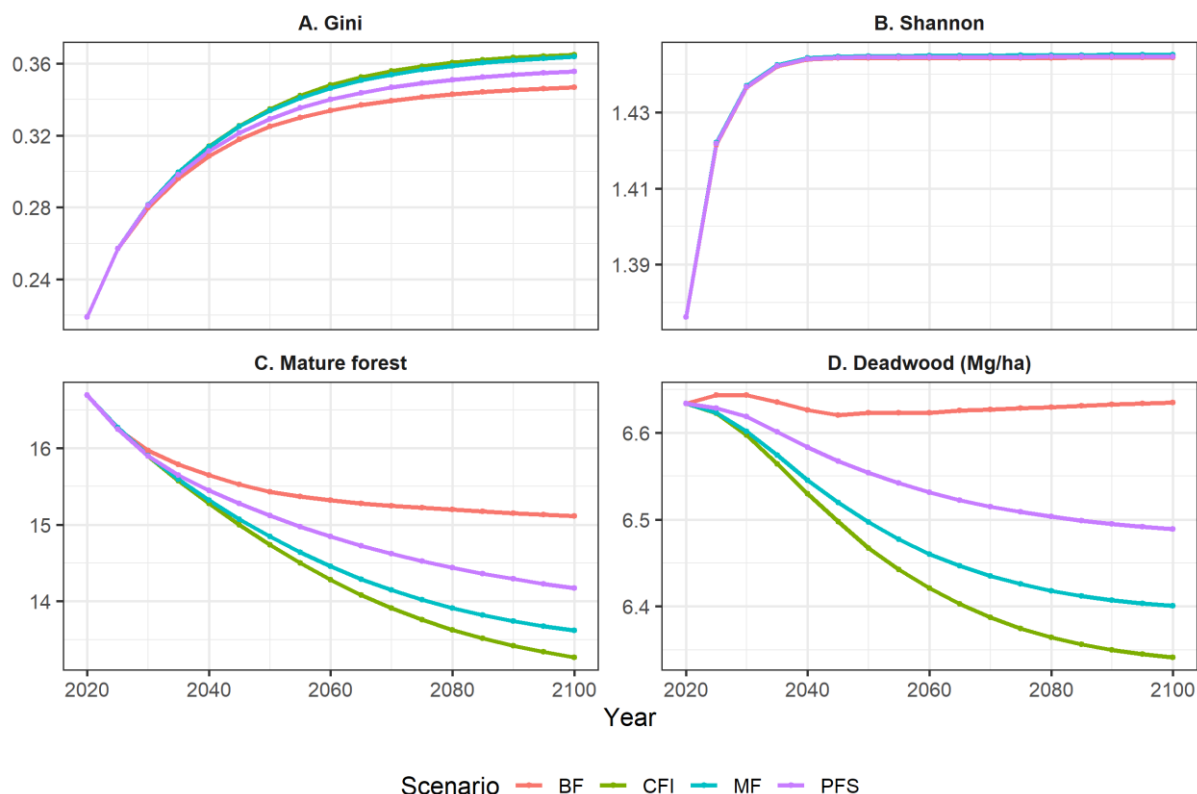


Figure 8. Temporal trends of the four biodiversity subindices for the four scenarios (BF = biodiversity focused forests, CFI = competitive forest industry, MF = multifunctional forests, PFS = participatory forest stewardship).

4.3 Trade-off and synergy results

In the analysis below we provide the results for 2050. Correlation matrices as well as the spatial distribution maps of indicator pairs for 2030 and 2100 are provided in Figures C1–C4.

4.3.1 Interactions per scenario

The Pearson correlation matrices revealed highly consistent relationships between the indicator pairs across all four forest management scenarios in 2050 (Figure 9). Statistically strong synergies (positive correlations) were observed within the production-oriented and structural-diversity indicators. Specifically, a strong positive correlation was sustained across all scenarios between production and biomass ($r = 0.79$ to 0.85), as well as between old-growth and deadwood ($r = 0.50$ to 0.56). Furthermore, both production and biomass exhibited positive correlations with old-growth ($r \geq 0.62$) and deadwood ($r \geq 0.62$) regardless of the scenario.

Conversely, trade-offs (negative correlations) were consistently minor to moderate and primarily centred around the Gini index and Shannon diversity. The Gini index displayed a persistent trade-off with deadwood across all strategies, peaking under the competitive forest industry scenario ($r = -0.46$). Indicators related to forest disturbances, namely bark beetle attack (BB attack) and wind damage, showed very small correlations with all other indicators across all scenarios.

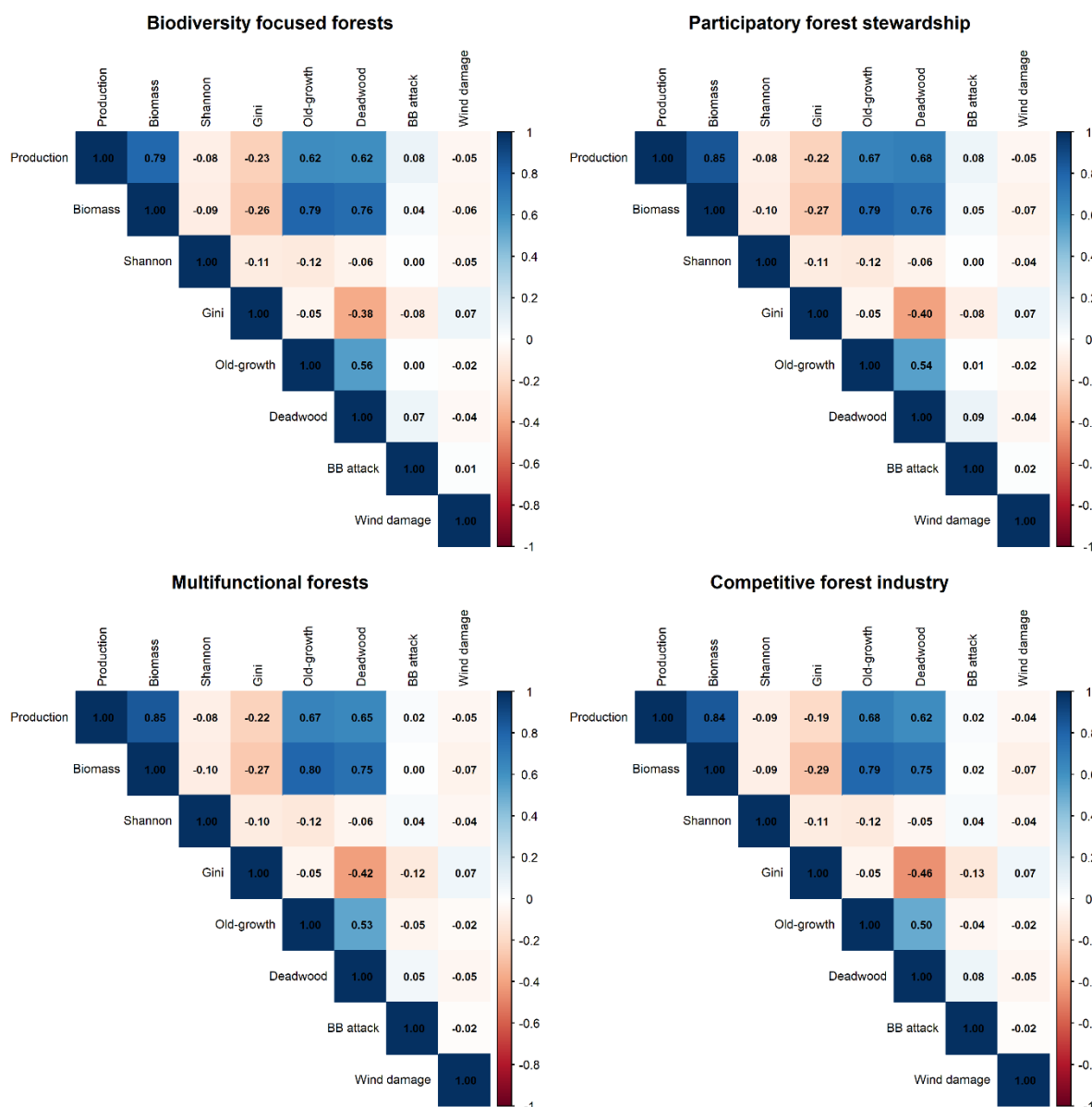


Figure 9. Pearson correlation matrix of the indicators evaluated across the four forest management scenarios for 2050. Blue denotes synergies (positive correlations) and red denotes trade-offs (negative correlations).

4.3.2 Spatial agreement among scenarios

The spatial mapping of indicator interactions across the four forest management scenarios for the year 2050 revealed distinct geographic patterns and degrees of consensus among the indicator pairs (Figure 10). While the Pearson correlation matrices demonstrated an overarching consistency in the general direction of indicator relationships across scenarios (Figure 9), the spatial mapping uncovers significant regional variations across Europe.

Because production and biomass maintain a widespread, strong spatial synergy across Europe, their respective interactions with biodiversity and disturbance indicators follow similar patterns. The indicator pairs consisting of production, biomass, old-growth, and deadwood resulted in mostly synergies across Europe. However, in specific regions, such as parts of Southern Scandinavia, Estonia, and Portugal, the interactions shift into trade-offs. The interaction between production/biomass and Shannon/Gini shows mixed results, with widespread trade-offs across Eastern Europe and parts of Northern- and Central Europe. In terms of forest disturbances, both interactions with production and biomass are characterized by a lack of spatial interaction with bark beetle attack and wind damage, matching the near-zero linear correlations observed in the Pearson matrices



(Figure 9). However, localized exceptions occur. Wind damage demonstrates distinct trade-offs with both production and biomass in specific hotspots, most notably across the Eastern Alps and Southern France. Meanwhile, bark beetle attack paired with production/biomass reveals highly mixed, localized results; prominent trade-offs are concentrated in Southern Sweden and the Eastern Alps, whereas minor patches of spatial synergy occur elsewhere.

The biodiversity indicators themselves do not universally show synergies when mapped spatially. While the combinations of Shannon and Gini consistently display synergies across the continent, pairs combining these indices with structural attributes like old-growth and deadwood reveal notable regional trade-offs. Specifically, Shannon and Gini exhibit distinct directional trade-offs when paired with old-growth and deadwood in Eastern Europe. When paired with deadwood, these trade-offs also expand into Northern Europe. The interaction between deadwood and old-growth as a pair is characterized by widespread spatial synergies, except for Northern Europe.

The pairs including the disturbance indicators reveal a strong absence of interactions. For the bark beetle attack combinations, Shannon and Gini display distinct trade-offs in Northern Europe alongside mixed interactions surrounding the Alps. Deadwood and bark beetle attack yield mixed results, marked by distinct synergies in Southern Sweden and Southern Finland, but shifting to trade-offs in the Eastern Alps. Furthermore, old-growth paired with bark beetle attack exhibits trade-offs across Scandinavia and Eastern Europe. The wind damage combinations, pairings with Shannon and Gini demonstrate highly mixed results across Europe, with Southern France and the United Kingdom displaying localized trade-offs, while the Alps show patches of synergy. When wind damage is paired with deadwood and old-growth, distinct clusters of trade-offs are visible across the Eastern Alps and Southern France. Finally, the direct interaction between the two disturbance indicators themselves, bark beetle attack and wind damage, is characterized by an exceptionally low amount of spatial interaction across the entire European map, showing only minor, scattered instances of weak trade-offs.

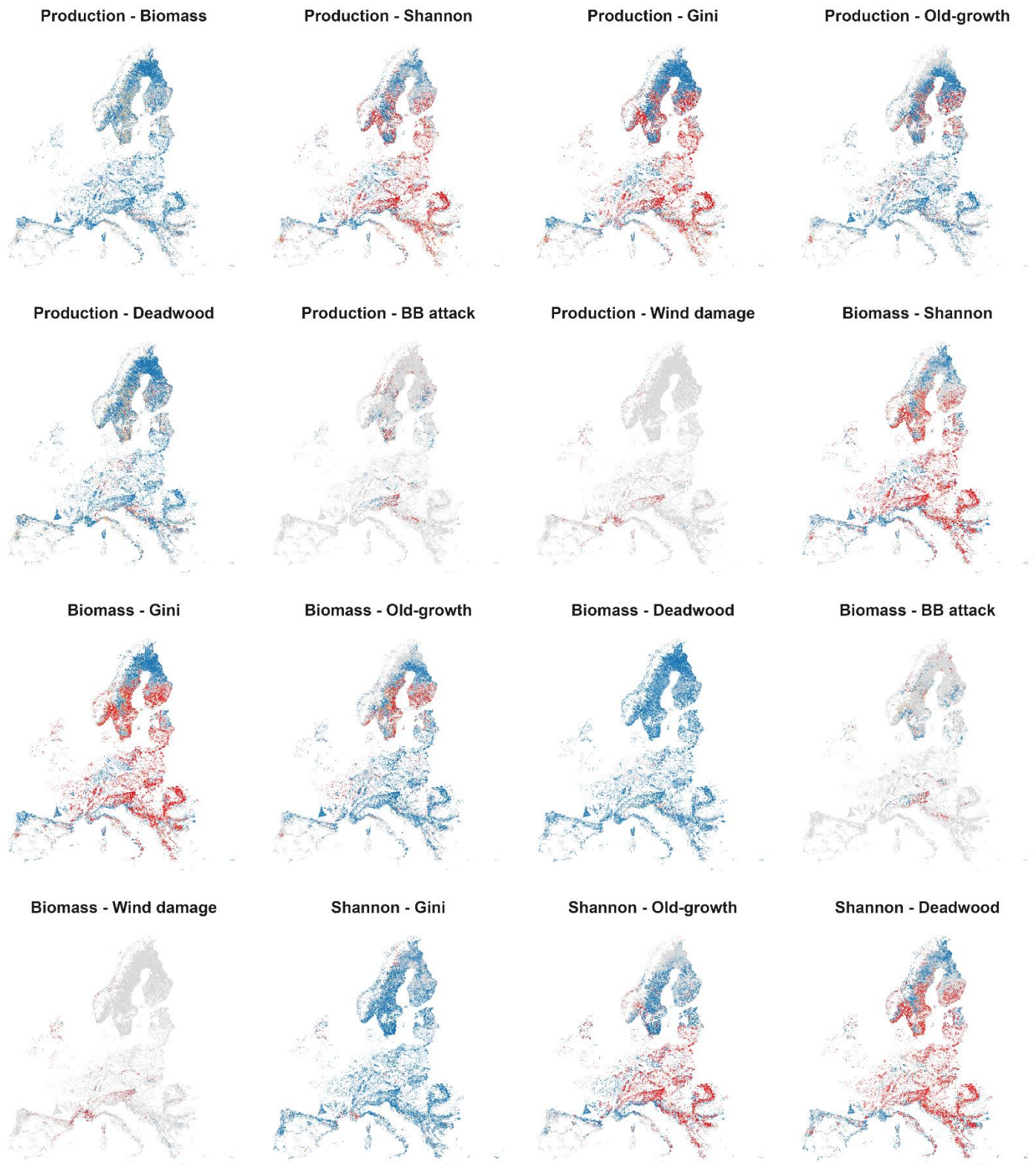


Figure 10. Spatial distribution maps of indicator pairs for the year 2050 across four forest management scenarios based on directional change thresholds. Interaction strength is classified by scenario consensus: strong synergy (same directional change in 3–4 scenarios; blue scale), weak synergy (same change in 1–2 scenarios; light blue), strong trade-off (opposite directional change in 3–4 scenarios; red), and weak trade-off (opposite change in 1–2 scenarios; orange). Panels show no interaction if results are mixed or if no interactions occurred in any scenario. (Figure continued on next page).

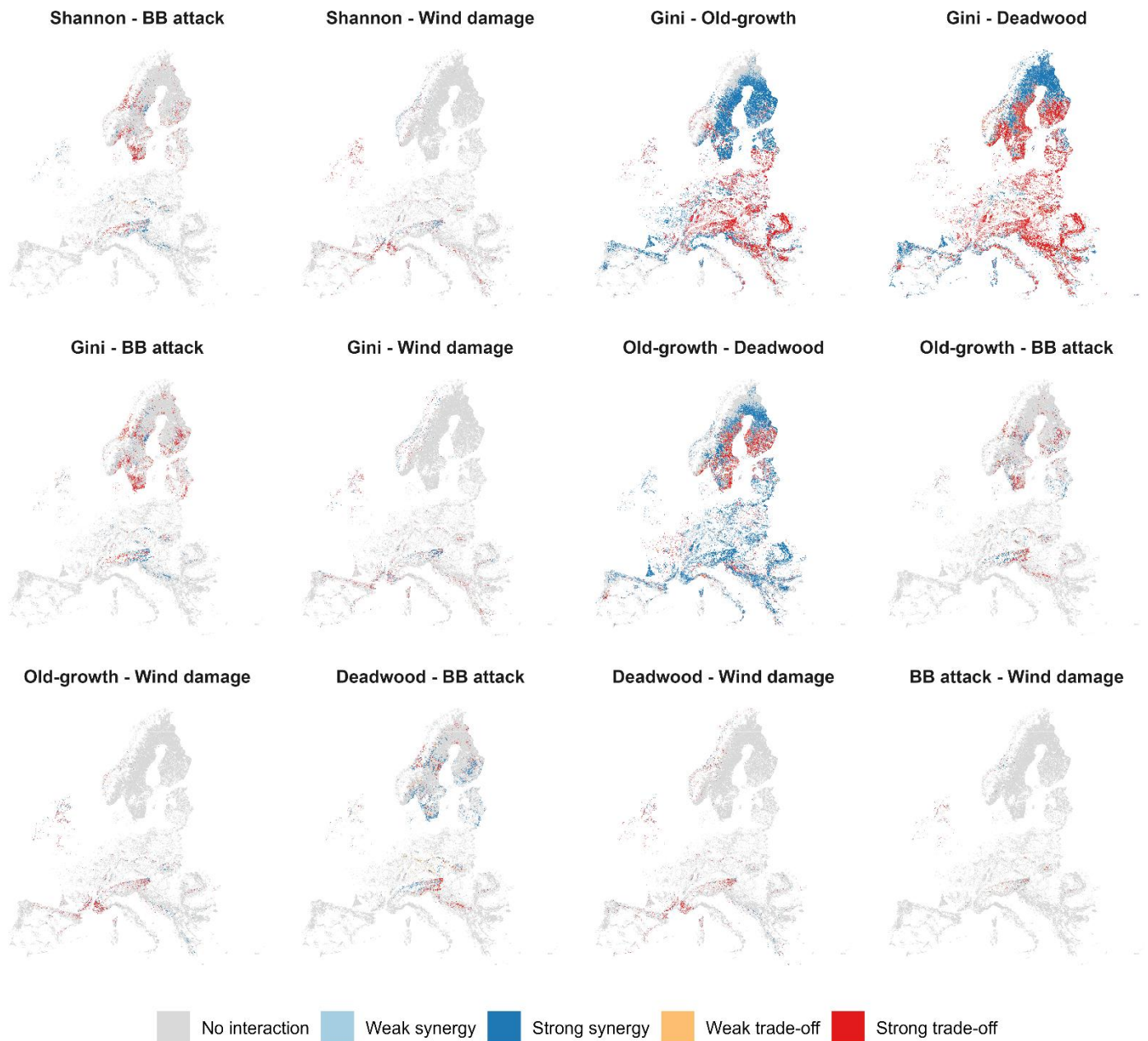


Figure 10. (Continued).



4.3.3 Intertemporal stability and trends

Comparing the Pearson correlation matrices across the simulation timeline (2030, 2050, and 2100) reveals high intertemporal stability in the direction of indicator interactions, paired with a progressive intensification of correlation strengths over time (Figures 9, C1, and C2). Under all four forest management scenarios, existing coefficients generally become more extreme as the timeline advances toward 2100. For example, the synergy between production and biomass under the biodiversity focused forests scenario increases from $r = 0.70$ (2030) to $r = 0.79$ (2050), peaking at $r = 0.82$ by 2100. The temporal intensification observed in the Pearson matrices is also reflected on a landscape level, where combinations pairing production and biomass with biodiversity metrics (Gini, Shannon, old-growth, and deadwood) develop stronger and more continuous spatial interactions by the end of the century.

4.3.4 Forest management impact

Evaluating the Pearson correlation coefficients between forest management intensity and the modelled indicators across the simulation timeline reveals contrasting temporal trajectories and predominantly weak relationships (Table 7). Production maintains a consistently positive relationship with management intensity, though its strength declines over the century, dropping from $r = 0.46$ in 2030 to $r = 0.19$ by 2100. In contrast, several indicators exhibit a temporal shift in the direction of their interaction. Biomass transitions from a weak positive synergy in 2030 ($r = 0.04$) to a weak trade-off by 2100 ($r = -0.05$), while the Gini index displays the inverse pattern, shifting from a minor trade-off ($r = -0.05$) to a more pronounced positive synergy ($r = 0.18$) by the end of the century. Structural biodiversity metrics demonstrate a continuous divergence over time; old-growth maintains a weak but diminishing positive relationship, whereas deadwood develops a progressively stronger trade-off with management intensity, decreasing from $r = -0.06$ in 2030 to $r = -0.14$ by 2100. Finally, Shannon, bark beetle attack, and wind damage show near-zero correlations with forest management intensity throughout the century.

Table 7. Pearson R correlation between forest management intensity changes and indicator changes compared to 2020, for 2030, 2050, and 2100.

Indicator	2030	2050	2100
Production	0.46	0.32	0.19
Biomass	0.04	-0.01	-0.05
Shannon	-0.02	-0.02	-0.02
Gini	-0.05	0.08	0.18
Old-growth	0.12	0.09	0.05
Deadwood	-0.06	-0.10	-0.14
Bark beetle attack	0.01	0	0.02
Wind damage	0	0.01	0.01

4.3.5 Workshop country-level analysis

4.3.5.1 Spain

The results for Spain reveal that mean production increases by 2100 across all scenarios, with the pathway showing the least production growth (biodiversity focused forests) yielding the highest standing biomass accumulations (Table 8). Notably, biomass is projected to increase over the century even under the competitive forest industry scenario. Structural biodiversity metrics like old-growth and deadwood expand across all pathways but increase the most under the biodiversity focused forest scenario. Concurrently, Gini rises across all scenarios, most pronounced under the competitive forest industry scenario, while Shannon increases slightly but remains mostly scenario independent. Finally, disturbance risks show a decrease in wind damage risk, while bark beetle attack risk remains consistently at zero throughout the simulation.



Table 8. Mean indicator values across forest management scenarios (BF = biodiversity focused forests, PFS = participatory forest stewardship, MF = multifunctional forests, CFI = competitive forest industry) and simulation time steps (2020, 2030, 2050, and 2100) for Spain.

Indicator	Scenario	2020	2030	2050	2100
Production (m ³ per 5 years)	BF	269	232	276	356
	PFS	269	297	340	394
	MF	269	301	347	394
	CFI	269	322	384	410
Biomass (t/km ²)	BF	6483	6777	7286	8089
	PFS	6483	6674	6987	7411
	MF	6483	6658	6940	7257
	CFI	6483	6636	6820	6936
Shannon	BF	1.08	1.13	1.14	1.14
	PFS	1.08	1.13	1.14	1.14
	MF	1.08	1.13	1.14	1.14
	CFI	1.08	1.13	1.14	1.14
Gini	BF	0.261	0.295	0.317	0.330
	PFS	0.261	0.299	0.334	0.363
	MF	0.261	0.299	0.335	0.368
	CFI	0.261	0.299	0.340	0.379
Old-growth (%)	BF	1.14	1.81	3.23	5.78
	PFS	1.14	1.79	2.98	4.68
	MF	1.14	1.76	2.93	4.45
	CFI	1.14	1.76	2.80	3.79
Deadwood (t/ha)	BF	3.48	3.67	3.96	4.38
	PFS	3.48	3.61	3.77	3.96
	MF	3.48	3.60	3.74	3.89
	CFI	3.48	3.58	3.67	3.71
Bark beetle attack	BF	0	0	0	0
	PFS	0	0	0	0
	MF	0	0	0	0
	CFI	0	0	0	0
Wind damage	BF	0.012	0.011	0.009	0.007
	PFS	0.012	0.011	0.010	0.008
	MF	0.012	0.011	0.010	0.009
	CFI	0.012	0.011	0.010	0.009

4.3.5.2 Finland

Finland exhibits trends similar to Spain, though with smaller differences between the scenarios (Table 9). Mean production increases by 2100 across all pathways, while standing biomass expands concurrently, peaking expectedly under the lowest production pathway (biodiversity focused forests). Shannon increases slightly over time but remains entirely independent of the management scenario. Gini also rises across scenarios, showing narrow margins that favour the more productive scenarios. Both old-growth and deadwood expand continuously over the century, with the highest gains recorded under the least intensive management pathways. Finally, forest risk profiles for both bark beetle attack and wind damage remain consistently low.



Table 9. Mean indicator values across forest management scenarios (BF = biodiversity focused forests, PFS = participatory forest stewardship, MF = multifunctional forests, CFI = competitive forest industry) and simulation time steps (2020, 2030, 2050, and 2100) for Finland.

Indicator	Scenario	2020	2030	2050	2100
Production (m ³ per 5 years)	BF	926	964	1033	1065
	PFS	926	1001	1072	1062
	MF	926	1023	1088	1112
	CFI	926	1042	1115	1098
Biomass (t/km ²)	BF	5460	5673	6005	6358
	PFS	5460	5627	5834	5979
	MF	5460	5584	5720	5909
	CFI	5460	5558	5617	5765
Shannon	BF	1.08	1.13	1.13	1.13
	PFS	1.08	1.13	1.14	1.14
	MF	1.08	1.13	1.14	1.14
	CFI	1.08	1.13	1.14	1.14
Gini	BF	0.247	0.330	0.393	0.424
	PFS	0.247	0.332	0.400	0.435
	MF	0.247	0.331	0.404	0.439
	CFI	0.247	0.332	0.406	0.437
Old-growth (%)	BF	1.54	3.55	5.77	8.24
	PFS	1.54	3.54	5.50	7.07
	MF	1.54	3.53	5.29	7.14
	CFI	1.54	3.50	5.06	6.52
Deadwood (t/ha)	BF	4.50	4.68	4.82	4.94
	PFS	4.50	4.65	4.72	4.75
	MF	4.50	4.62	4.67	4.72
	CFI	4.50	4.60	4.61	4.65
Bark beetle attack	BF	0.002	0.002	0.002	0.001
	PFS	0.002	0.002	0.002	0.001
	MF	0.002	0.002	0.001	0.002
	CFI	0.002	0.002	0.001	0.002
Wind damage	BF	0	0	0	0
	PFS	0	0	0	0
	MF	0	0	0	0
	CFI	0	0	0	0

4.3.5.3 Austria

In contrast to Spain and Finland, Austria exhibits downward trajectories for several core indicators. Mean production declines across all scenarios by 2100, dropping most rapidly under the biodiversity focused forests scenario before all scenarios converge to a similar level by the end of the century. Standing biomass also decreases over time, though the biodiversity focused forests scenario successfully retains the highest relative volume. Gini increases across all scenarios, peaking under intensive management. Shannon increases sharply until 2030 and then stabilizes, remaining entirely scenario independent. Old-growth declines substantially across all scenarios—with the sharpest losses under intensive management—while deadwood decreases slightly, mostly under the more



productive scenarios. Finally, while bark beetle attack risk remains constant, wind damage risk increases slightly over time, particularly under the more intensive scenarios.

Table 10. Mean indicator values across forest management scenarios (BF = biodiversity focused forests, PFS = participatory forest stewardship, MF = multifunctional forests, CFI = competitive forest industry) and simulation time steps (2020, 2030, 2050, and 2100) for Austria.

Indicator	Scenario	2020	2030	2050	2100
Production (m ³ per 5 years)	BF	3136	2427	1996	1640
	PFS	3136	2627	2079	1635
	MF	3136	2661	2110	1641
	CFI	3136	2668	2122	1645
Biomass (t/km ²)	BF	24285	22244	19901	17666
	PFS	24285	21908	19159	16765
	MF	24285	21878	19006	16516
	CFI	24285	21863	18963	16412
Shannon	BF	1.50	1.60	1.61	1.61
	PFS	1.50	1.60	1.61	1.61
	MF	1.50	1.60	1.61	1.61
	CFI	1.50	1.60	1.61	1.61
Gini	BF	0.185	0.231	0.269	0.293
	PFS	0.185	0.233	0.279	0.304
	MF	0.185	0.233	0.281	0.307
	CFI	0.185	0.234	0.281	0.309
Old-growth (%)	BF	62.0	49.4	38.6	29.1
	PFS	62.0	48.8	36.4	26.0
	MF	62.0	48.8	35.9	25.2
	CFI	62.0	48.8	35.8	25.0
Deadwood (t/ha)	BF	9.61	9.51	9.25	8.98
	PFS	9.61	9.44	9.16	8.88
	MF	9.61	9.43	9.14	8.85
	CFI	9.61	9.43	9.13	8.84
Bark beetle attack	BF	0.013	0.012	0.014	0.014
	PFS	0.013	0.012	0.014	0.014
	MF	0.013	0.013	0.014	0.014
	CFI	0.013	0.013	0.014	0.014
Wind damage	BF	0.093	0.093	0.096	0.108
	PFS	0.093	0.094	0.100	0.113
	MF	0.093	0.094	0.102	0.115
	CFI	0.093	0.095	0.102	0.116

4.3.5.4 Slovenia

Slovenia displays highly stable, tightly clustered indicator pathways with minimal variation among the scenarios. Mean production remains relatively flat across the century, experiencing an initial dip by 2030—primarily under less intensive scenarios—before recovering by 2050 and converging to a slightly lower baseline across all pathways by 2100. Biomass follows a similar minor downward trend, with the largest losses occurring under the more intensive scenarios. Shannon increases until 2030 and then stabilizes, remaining scenario independent, while Gini rises steadily and peaks under



intensive management. The old-growth trajectory shows a slight initial expansion up to 2050 before declining by 2100, with the sharpest decreases driven by intensive management. Concurrently, deadwood decreases slightly, particularly under the most productive scenarios. Finally, bark beetle attack risk increases slowly under all pathways, while wind damage risk completely drops to zero by 2100.

Table 11. Mean indicator values across forest management scenarios (BF = biodiversity focused forests, PFS = participatory forest stewardship, MF = multifunctional forests, CFI = competitive forest industry) and simulation time steps (2020, 2030, 2050, and 2100) for Slovenia.

Indicator	Scenario	2020	2030	2050	2100
Production (m ³ per 5 years)	BF	1569	1500	1557	1465
	PFS	1569	1500	1556	1463
	MF	1569	1561	1579	1466
	CFI	1569	1536	1563	1464
Biomass (t/km ²)	BF	21001	21264	21173	20075
	PFS	21001	21239	21148	20053
	MF	21001	21077	20730	19423
	CFI	21001	21168	20885	19683
Shannon	BF	1.78	1.86	1.88	1.88
	PFS	1.78	1.86	1.88	1.88
	MF	1.78	1.86	1.88	1.88
	CFI	1.78	1.86	1.88	1.88
Gini	BF	0.155	0.207	0.252	0.302
	PFS	0.155	0.208	0.252	0.302
	MF	0.155	0.208	0.258	0.320
	CFI	0.155	0.206	0.253	0.313
Old-growth (%)	BF	43.1	44.9	44.9	41.9
	PFS	43.1	44.9	44.9	41.9
	MF	43.1	45.2	45.0	40.3
	CFI	43.1	45.3	45.3	40.9
Deadwood (t/ha)	BF	9.30	9.22	9.01	8.51
	PFS	9.30	9.21	9.00	8.51
	MF	9.30	9.17	8.88	8.26
	CFI	9.30	9.20	8.94	8.36
Bark beetle attack	BF	0.005	0.005	0.006	0.006
	PFS	0.005	0.005	0.006	0.006
	MF	0.005	0.005	0.006	0.007
	CFI	0.005	0.005	0.006	0.006
Wind damage	BF	0.003	0.001	0.001	0
	PFS	0.003	0.001	0.001	0
	MF	0.003	0.001	0.001	0
	CFI	0.003	0.001	0.001	0



5. Discussion

5.1 Forest management scenarios

The workshop and survey results reveal a structured heterogeneity among European stakeholders, characterized by a primary divergence along the conservation–production axis. While climate change mitigation and sustainable harvesting received broad support, priorities differed substantially along this axis, consistent with previous studies (Hengst-Ehrhart & Schraml, 2020; Nijnik et al., 2010; Sandström et al., 2016). Notably, stakeholders aligned with production-oriented clusters acknowledged a minimum level of forest conservation and climate change mitigation, recognizing that long-term forest health and resilience are necessary to maintain productive future forests (Forest Europe, 2026). This informed the decision to retain the current level of protected areas in the competitive forest industry scenario. Conversely, the consistently low prioritization of cultural values in the survey was a dominant trend across nearly all stakeholders, suggesting that in the context of current forest management trade-offs, cultural objectives are perceived as less relevant compared to goals directly linked to the bioeconomy, conservation, and climate urgency. Our findings resonate with broader policy trends, where national bioeconomy strategies emphasize climate action, forest conservation, and circular economy principles while largely neglecting social sustainability, equity, and collaboration (Warchold et al., 2025).

Furthermore, the feedback from regional workshops underscores that every scenario entails significant trade-offs and challenges. While the multifunctional forests scenario emerged as the most plausible middle ground, the exploration of more conflicting visions remains crucial. These divergent paths highlight the sensitivity of the forest sector to future management directions, where areas of consensus suggest robust trends, while regions of strong divergence reflect high sensitivity to future management directions.

5.2 CLUMondo

Our results indicate a general trend of forest expansion at the continental scale, although scattered forest losses are also observed, consistent with historical trends of forest growth in Europe (Forest Europe, 2026). Furthermore, projections of continued agricultural land abandonment suggest further potential for forest expansion (Fayet et al., 2022; Perpiña Castillo et al., 2021; van der Zanden et al., 2017). Within the model framework, this expansion is primarily driven by simulated increases in tree planting and wood production defined in the scenarios, as well as changes in demands for agricultural and livestock products that lower land system competition. However, regional exceptions exist, with the multifunctional forests and competitive forest industry scenarios indicating forest losses in Northern Europe and France due to agricultural pressure. The spatial distribution of these changes is influenced by forest suitability and spatial restrictions. Forest cover changes in Southern Europe are largely driven by climate stress areas, where forest losses were recorded in vulnerable areas and new forests emerged in mountainous regions. This modelled shift is consistent with literature reporting reduced forest productivity and declining climatic suitability in Southern Europe, leading to an upward shift in suitable species ranges (Dyderski et al., 2018; Pretzsch et al., 2023). Ultimately, these findings suggest that while European forest expansion may continue, its location is heavily dependent on future forest suitability and land system competition.

Forest management trajectories in this study are highly sensitive to scenario-specific societal demands and policy directions. Intensification is primarily observed in scenarios with high wood demand, such as multifunctional forests and competitive forest industry. Conversely, the biodiversity focused forests and participatory forest stewardship scenarios lead to widespread deintensification. This divergence confirms that inherent trade-offs between production and conservation goals



strongly shape management outcomes across the continent (Hetemäki et al., 2024; Rybar & Bosela, 2023; Verkerk et al., 2014). One of the most robust findings is the widespread consensus on deintensification, particularly in Eastern Europe and within protected areas, reflecting lower wood demand in specific scenarios and the prioritization of conservation. This finding aligns with stakeholders' perspectives that EU environmental policies entail socio-economic trade-offs for regional and existing underdeveloped industries (Di Marzo et al., 2026). However, other regions show more diverging results, with Northern Europe proving highly sensitive to societal demands. For instance, in the multifunctional forests scenario, forestry in Northern Europe shifts toward combined objective forestry. To maintain wood production levels under this shift, the model compensates by increasing very intensive forestry in other areas. This model behaviour empirically demonstrates the leakage effects that workshop participants cautioned against when discussing the biodiversity focused forests scenario. These dynamics align with a recent study assessing the EU Biodiversity Strategy for 2030, which suggests that increasing protection levels can induce internal leakage through heightened harvesting pressure elsewhere in the forest sector (Di Fulvio et al., 2025). Similar dynamics were identified by Rätty et al. (2023), who applied the EFDM model for Finland and found that expanded protected areas can lead to higher harvesting levels outside protected zones. Taken together, these patterns indicate that policy interventions in one region can systematically reshape management pressures elsewhere.

Several limitations regarding modelling choices and data availability should be considered when interpreting these results. First, the assumed productivity increases of 5% and 10% in the multifunctional forests and competitive forest industry scenarios represent a significant assumption. Empirical evidence for such long-term gains remains limited, and their feasibility is uncertain given ecological constraints and the unpredictable response of forests to future climatic conditions (Ammer, 2019). Second, while climate suitability is incorporated and disturbances are included in the final trade-off analysis, CLUMondo does not explicitly represent forest disturbances such as fires, storms, and pest outbreaks, despite their increasing importance as threats to European forests (Forzieri et al., 2021; Langenbacher et al., 2025; Patacca, Lindner, Lucas-Borja, et al., 2023; Seidl et al., 2017; Senf & Seidl, 2021). These mega-trends and possible cascading impacts may shift scenarios to very different forest futures, not incorporated in our set of scenarios. Third, data availability and model structure necessitated the use of five management intensity classes. Although we successfully integrated broader forest classes and detailed input data for the forest sector, the model defines these classes primarily by productivity. This limits the ability to capture stand-level characteristics and detailed silvicultural practices. As a result, the scenarios are best interpreted as illustrating broad spatial patterns and dominant forest processes at the European scale, showing relative differences between regions and scenarios rather than precise or locally specific management trajectories.

5.3 European Forestry Dynamics Model (EFDM)

The CLUMondo scenario assumptions were subsequently translated into quantitative silvicultural representations using EFDM. The EFDM matrix-based representation assumes that the selected state variables sufficiently capture the dominant drivers of forest dynamics and management behaviour (Kuronen & Rätty, 2023). A key modelling assumption concerns the definition of the EFDM state space. In the PathFinder framework, stand stem volume was selected as the main dynamic variable, while tree-species group, geographic region, forest management intensity, climate-response class (PO_class), and relative growth class (NAI_lim) were used as stratifying variables (Majasalmi, 2026). The model therefore assumes that these variables adequately represent regional differences in forest growth, management intensity, and climate sensitivity across Europe. Forest age was not included as an explicit state variable, implying that age-related growth dynamics are indirectly represented through stem-volume classes.



Another important assumption relates to the harmonisation of forest management activities across Europe. Due to differences in NFI methodologies and reporting practices among countries, all interventions were simplified into three broad activity classes: no management (noman), thinning (thin), and final felling (ff). This simplification assumes that diverse silvicultural practices can be meaningfully represented within these generalized categories without substantially compromising regional realism (Packalen et al., 2014; Schelhaas et al., 2007; Vauhkonen et al., 2019). Threshold-based classification rules were also required to separate management impacts from natural disturbances when direct intervention labels were unavailable in NFI data.

The EFDM parameterisation further assumes that observed NFI plot-pair dynamics are representative of future forest behaviour under similar conditions. Transition probabilities for growth and management were estimated empirically from paired NFI measurements originating from only ten European countries. Consequently, the model assumes that these observations adequately capture broader European forest dynamics despite uneven geographical coverage and differences in data density between regions. Regionalisation into North, Central and South Europe was introduced to reduce this limitation and to account for broad climatic and management differences across Europe.

Climate change impacts on forest growth were incorporated using potential maximum gross primary productivity (maxGPP). Here, an important assumption is that changes in maxGPP can serve as a proxy for changes in forest growth. The modelling framework therefore assumes an empirical relationship between potential productivity and observed stem-volume growth, while largely omitting explicit representation of physiological processes such as respiration or nutrient limitations. In the absence of soil fertility data its effects on growth were assumed to be captured by JRC NAI map data, and modified transition probabilities quantifying present day growth (Avitabile et al., 2024).

The approach also assumes that current species distributions broadly reflect habitat suitability and that future growth responses can be inferred from present-day climate-productivity relationships. The climate-sensitive growth modelling also required substantial generalisation of tree-species groups. Because the PathFinder species groups were originally developed for remote-sensing separability rather than ecological similarity, each group contains multiple species with differing physiological and silvicultural characteristics. The EFDM implementation therefore assumes that species grouped together respond similarly to management and climate drivers. In addition, species composition shifts between species groups were not simulated; instead, future changes were allowed only within existing species groups. This implies an assumption of relatively stable broad species composition over time despite changing climate conditions.

Regeneration modelling introduced further assumptions. Since NFI data lacked sufficient information on young stands, regeneration processes were accounted using FORMIT-M outputs (Härkönen et al., 2019). Regeneration was assumed to occur using the same species group that existed before final felling, and relatively intensive planting densities were applied across regions. This assumes that future forest regeneration practices remain largely management-driven and that political or ecological shifts in regeneration preferences do not fundamentally alter species establishment patterns.

Several assumptions were also introduced to ensure model stability and consistency (Majasalmi, 2026). For example, activity probabilities were constrained so that increasing forest management intensity classes systematically increased harvesting probabilities. Similarly, transition matrices were manually adjusted where sparse data produced unrealistic outcomes. These modifications assume



that expert-driven corrections improve realism more effectively than relying solely on sparse empirical observations.

Finally, the PathFinder EFDM framework assumes that sequential updating of climate-response variables and forest management intensity classes at each five-year timestep adequately captures temporal changes in climate and management regimes. Unlike traditional EFDM applications using static transition probabilities, the PathFinder approach dynamically updates inputs over time, enabling closer integration with external models such as CLUMondo and soil carbon model Yasso (Viskari et al., 2022). In the PathFinder simulations, CLUMondo-based forest management scenarios were assumed to remain constant after 2050, implying that future management trajectories stabilise during the second half of the simulation period. Because Yasso simulations were parameterised using litterfall and harvest-residue inputs derived directly from EFDM outputs, the assumptions embedded within EFDM also propagate into the soil carbon modelling. Consequently, assumptions regarding forest growth, harvesting intensity, regeneration dynamics, climate sensitivity, and species composition directly influence Yasso predictions of belowground carbon dynamics.

5.3.1 Production

The forest production indicator was defined as the sum of final felling and harvested wood volumes, representing harvesting pressure across Europe. Scenario-dependent wood demand was derived from GLOBIOM and spatially allocated into forest management intensity classes (FM-classes) using CLUMondo data (Scherpenhuijzen et al., 2025, 2026), while the corresponding forest management actions were implemented in EFDM. At the EU level, the indicator provides a consistent representation of harvest pressure based on spatially and temporally varying forest management intensities under the simulated scenarios.

EFDM activity and transition probabilities were linked to CLUMondo forest management intensity classes (FM-classes) by overlaying paired NFI plot data with the gapfilled 2020 CLUMondo management intensity map and deriving FM-class-specific activity probabilities. To account for uncertainties in the initial forest area and growing stock estimates, activity probabilities were subsequently calibrated iteratively against Eurostat 2020 roundwood production statistics (wood in the rough, over bark) using the first 5-year simulation period, ensuring that simulated harvest levels were consistent with observed production (Eurostat, 2020).

The 2020 European roundwood demand projected by GLOBIOM and used to drive CLUMondo was close to FAOSTAT estimates (~ 533 million $\text{m}^3 \text{yr}^{-1}$), whereas EFDM simulated somewhat higher harvest levels (~ 603 million $\text{m}^3 \text{yr}^{-1}$) (FAO, 2025b). This difference is largely explained by differences in volume definitions, forest area estimates, and initial growing stock distributions. EFDM uses NFI-derived stem volumes reported over bark (including stem tops), whereas GLOBIOM roundwood demand is expressed as under-bark steurostatem volume.

EFDM-simulated wood production increased systematically across the management scenarios, reflecting the increasing harvest pressure prescribed through the CLUMondo FM-classes. However, simulated production levels were not perfectly aligned with the original GLOBIOM demand estimates because harvesting in EFDM was constrained by forest volume distributions, growth dynamics, and the activity probabilities associated with each FM-class. Overall, the differences between EFDM production and GLOBIOM demand remained moderate (with the exception of the biodiversity focused forests scenario) and suggest that the simulated production levels are plausible.

It should also be noted that EFDM was not calibrated to reproduce GLOBIOM demand projections. Instead, calibration was performed against observed present-day harvest levels using the 2020



CLUMondo FM-classes and Eurostat production statistics (Eurostat, 2020; Scherpenhuijzen et al., 2025). The fact that EFDM-simulated wood production remained below GLOBIOM demand under the most intensive competitive forest industry scenario in 2050 and under both the multifunctional forests and competitive forest industry scenarios in 2100 suggests that the availability of mature forest stands suitable for harvesting may become increasingly constrained if current management practices continue. This interpretation is consistent with previous European modelling studies indicating that increasing harvest intensity and wood demand may limit both future wood supply and the capacity of forests to maintain strong carbon sinks (Pilli et al., 2022).

The production indicator has several limitations. First, EFDM-simulated production is constrained by model structure, including initial forest volume distributions, growth rates, and activity and transition probabilities for different harvest types. These constraints may limit the full realisation of demand in regions where mature forest resources are insufficient or where forest volume distributions differ from that assumed in CLUMondo. Second, harvesting activity is driven solely by CLUMondo FM-classes, without scenario-specific calibration of harvest behaviour. Third, forest growth assumptions were not harmonised between EFDM and CLUMondo, which may affect the temporal development of GSV and, consequently, future harvest potential. Fourth, the current formulation does not explicitly distinguish between forests available and not available for wood supply, which limits representation of protection status and management constraints.

Overall, the production indicator should be interpreted as a scenario-based measure of potential harvesting pressure derived from present-day regional harvest levels and projected management intensities, providing a harmonised pan-European representation of forest resource use under the modelled pathways.

5.3.2 Biomass

The biomass indicator was defined as the sum of aboveground biomass (AGB) and belowground biomass (BGB). In EFDM, consistency between growing stock volume (GSV) and biomass estimates was maintained using biomass conversion and expansion factors (BCEF) from IPCC (2006). Biomass models were first used to estimate the relative proportions of individual biomass components (e.g., stem and foliage biomass), which were then applied to partition BCEF-derived total AGB among the different components. Belowground biomass was subsequently derived from AGB using the IPCC (2006) root-to-shoot ratios. As a result, GSV, AGB, and BGB dynamics are inherently linked within the modelling framework. While several pan-European datasets are available for AGB (e.g., Avitabile (2023)), corresponding BGB datasets remain scarce because belowground biomass is difficult and costly to measure directly and remains challenging to estimate using remote sensing approaches (e.g., Dlamini et al. (2025)).

To evaluate the spatial plausibility of the biomass estimates, the initial 2020 EFDM AGB map was compared with the pan-European biomass map of Avitabile (2023). The comparison showed generally consistent large-scale spatial patterns and biomass levels, with lower biomass densities in northern Europe and higher values in central and eastern Europe, particularly in the Alpine and Carpathian regions. However, EFDM produced somewhat higher and more spatially continuous biomass densities, especially across central Europe, likely reflecting the higher spatial resolution of the forest property maps used for model initialization (Miettinen et al., 2025).

The projected 2100 biomass distribution largely retained the broad spatial patterns observed in 2020. However, biomass development was spatially heterogeneous, with increases projected mainly in northern and western Europe and parts of the Mediterranean, while declines were concentrated



in central and eastern Europe, particularly in the Alpine, Balkan, and eastern European forest regions (Majasalmi, 2026).

Previous European studies have generally projected continued increases in living biomass carbon stocks during the twenty-first century despite declining growth rates (Pilli et al., 2022). However, several large-scale modelling studies have also suggested that continued application of current management regimes may gradually constrain forest growth potential and harvest availability. For example, Vauhkonen et al. (2019) projected annual fellings to increase from approximately 500 million $\text{m}^3 \text{yr}^{-1}$ in 2015 to 540 million $\text{m}^3 \text{yr}^{-1}$ by 2030, after which both harvest levels and growing stock increments began to stabilize, indicating a potential long-term reduction in growth and supply potential. Similarly, Pilli et al. (2022) projected a gradual weakening of the forest carbon sink due to forest ageing, as older forests accumulate biomass more slowly than younger stands. Eggers et al. (2008) reached comparable conclusions, projecting that under high-demand scenarios harvest removals could eventually exceed forest increment, resulting in declining growing stock and forest carbon stocks towards the end of the century. The biomass trends observed in the present study are therefore broadly consistent with previous findings highlighting the combined influence of forest ageing and harvest pressure on long-term biomass development.

Several limitations should be considered when interpreting the biomass indicator. First, climate impacts on forest growth are represented indirectly through productivity modifiers derived from present-day NFI data and potential GPP projections, and therefore species-specific responses to future climatic conditions are only partially captured. Second, disturbances such as drought, wildfire, windthrow, and insect outbreaks were not explicitly simulated. Consequently, the indicator primarily reflects the effects of forest management and ageing under the assumed climate and management scenarios. The results should therefore be interpreted as indicative projections of long-term biomass development rather than precise forecasts of future forest conditions.

5.3.3 Biodiversity

Winter et al. (2008) identified 16 key variables for assessing and reporting European biodiversity. Some of these key variables are the horizontal structure, tree species, development phase, naturalness, big logs and snags, which are included directly or through proxies in our biodiversity index. Marín et al. (2021) also considered, among other components, tree species diversity and horizontal structure, combining extent and spatial pattern of the forest. Borghi et al. (2024) highlight the importance of accounting for composition, forest structure and deadwood in the monitoring of biodiversity and naturalness. In this line, Storch et al. (2018) proposed a composite index including some components of deadwood, tree attributes, species richness in the tree and regeneration layer. Ette et al. (2023) also incorporate information on the tree layer structure, deadwood and tree species diversity in their assessment of forest diversity. However, these studies include other measures of biodiversity, such as genetic biodiversity, regeneration, decay classes, occurrence of microsites, and mean or variability in tree size. These indicators are also considered in the Index of Biodiversity Potential composed by indicators of stand level and landscape or context (Gosselin & Larrieu, 2020), in our case we included those available in the frame of the EFDM and at stand level.

Contrary to expectations, none of the four biodiversity subindices were sensitive to the management scenarios. Rather, their temporal trends for all of them were quite similar for Europe as a whole; however, we found differences among countries.

It is worth noting that the definition and results of this potential biodiversity indicator are constrained by the EFDM model. One limitation is that species groups remain constant within each pixel in the EFDM simulations. It was assumed that the extinction of a given species leads to its



replacement by other species within the same group. This assumption was necessary given the lack of data to evaluate the accuracy of the tree-species group classification (Majasalmi, 2026) and substantial uncertainties regarding future tree species preferences across different regions of Europe. This, together with the limited number of species groups (10), explains why the compositional index (Shannon index) showed only minor differences among scenarios, as it primarily reflects changes in volume-bin distributions, which were similar across scenarios due to comparable thinning and final felling regimes, and the fact that alternative management approaches (e.g. continuous cover forestry) were not represented in the model scenarios.

In the case of the Gini index, the volume-bin distributions originally lacked young/small volume classes. Moreover, the volume bins were not equally spaced (i.e. 0–1, 1–10, 10–25, 25–48, 48–80, 80–122, 122–204, 204–313, 313–517, 517– ∞). Under increasing forest management intensity, forest area became more evenly distributed across volume bins, which led to higher Gini index values in more intensively managed forests, consistent with increased landscape-level fragmentation. Despite this, our results reveal inter-country temporal variations.

5.3.4 Disturbances

Large-scale assessments of forest disturbance in Europe have largely relied on compilations of reported damage volumes by agent (Patacca et al., 2023) or on satellite-based mapping of observed disturbance footprints (Senf & Seidl, 2021). ForestGALES/fgr and IpsR differ from these approaches in that they are process-based models that predict damage probability and damaged volume from stand structure and climate drivers, consistent with the mechanistic modelling reviewed by Gardiner et al. (2008) for wind damage and developed by Temperli et al. (2013) and Marie et al. (2024) for bark beetle outbreaks. This means the results can be decomposed into their drivers in a way that is harder to achieve with empirical risk scores: damage probability can be traced back to stand height and growing stock for ForestGALES/fgr, or to degree days for beetle reproduction (DDeff), maximum plant water stress (PWSmax) and the spruce fraction for IpsR (Hale et al., 2015; Hlásny et al., 2021).

Several points should be kept in mind when interpreting these results at the European scale. Critical wind speeds decrease as trees grow taller, so ForestGALES/fgr is intrinsically sensitive to forest maturity and growing stock accumulation (Gardiner et al., 2010; Hale et al., 2015); spatial patterns of simulated wind damage therefore reflect the underlying age and volume structure of European forests as much as the wind climate itself. Where the European wind climate is poorly resolved, the model inherits this uncertainty, and the absence of damage propagation through newly exposed edges in ForestGALES/fgr means estimates can be conservative where progressive edge damage is important (Gardiner, 2021). For bark beetles, IpsR combines a climatic trigger (DDeff and PWSmax) with stand structural variables, the proportion of Norway spruce and the available recently dead biomass as breeding substrate to estimate damage probability and affected biomass. The model is sensitive to temperature, allowing multivoltinism when DDeff exceeds the per-generation threshold within a single season, and to the choice of SPEI accumulation period through PWSmax (currently set to 3 years). Because both models are driven by EFDM stand attributes aggregated to a 1 km² grid, outputs should be interpreted as expected damage signals at the grid-cell scale rather than as stand-level predictions. Within these boundaries, the models provide a mechanistically grounded and spatially explicit signal of expected disturbance impact across European forests, complementing rather than replacing empirical and remote sensing-based products.

5.4 Trade-off and synergy analysis

A trade-off and synergy analysis was conducted to assess the relationships between key forest functions and to evaluate the impact of forest management practices on these dynamics. Trade-off



analyses are widely established in this field, with extensive literature demonstrating major trade-offs between production and bioeconomy goals and biodiversity conservation objectives (Blattert et al., 2023; Hetemäki et al., 2024; Luyssaert et al., 2018; Morán-Ordóñez et al., 2020; Nijnik et al., 2010; Rybar & Bosela, 2023; Söderberg & Eckerberg, 2013; Verkerk et al., 2014; Warchold et al., 2025).

As the results are derived from a modelling framework with specific assumptions and limitations, they should be interpreted with appropriate caution. At the overarching scale, the Pearson correlation coefficients reveal negligible differences between the scenarios. However, several specific indicator interactions emerge.

A strong spatial synergy is observed between production and biomass, as large biomass sites have higher probability to final felling and thinning. Similarly, a synergy is present between old-growth and large biomass/production forest areas because old-growth forest was defined as the largest growing stock forests, while sequential thinning practices target more frequently semi-volume stands. Deadwood also displays a strong synergy with both production and biomass, which is controversial. A large amount of deadwood is likely associated with higher biomass in old-growth forest NFI plots, reflecting structural complexity and mortality processes. The correlation between production and deadwood, however, is primarily driven by the EFDM structure, where higher growing stock forests are subject to more intensive harvesting. As a result, this apparent relationship does not necessarily reflect a direct ecological linkage between the two variables.

Shannon shows a small trade-offs with production and biomass, as a higher production decreases the diversity in volume bins. Similarly, the Gini index also shows a trade-off with production and biomass, as higher production leads to more balanced forest volume-class distributions through the creation of young stands via silvicultural interventions.

In contrast to these dynamics, both wind and fire disturbance indicators show very low correlation coefficients, suggesting that production, biomass, and biodiversity have a negligible impact on disturbance risks. Those results could be explained by most of the research area keeping an almost constant risk over time, and the complexity of the dynamics behind those risks.

The broader impact of forest management practices on these indicators reveals weak relationships overall, with the exception of production. Production exhibits a substantial synergy with management intensity, as the model inherently generates higher yields where management is intensified. Interestingly, this relationship weakens over time, suggesting that while management intensity remains constant, wood availability for extraction decreases in certain regions, thereby limiting potential harvest volumes. Similar patterns have been observed by Vauhkonen et al. (2019), who argue that growing stock volume and fellings stagnate after 2030.

Analyses at the national level reveal further structural patterns. While production and biomass display a strong synergy at the pixel level, they show contrasting trends when aggregated by scenario. The biodiversity focused forests scenario yields the highest total biomass and lowest production volumes, whereas competitive forest industry shows the inverse. Similarly, deadwood and old-growth peak within the biodiversity focused forests scenario. These findings align with ecological expectations and confirm that less intensive management regimes preserve higher levels of deadwood, old-growth, and biomass compared to intensive management.

Ultimately, because these results are heavily shaped by structural modelling choices and constraints, the direct interpretation of the outputs remains constrained by the underlying assumptions. To validate these trends and enhance the robustness of the assessment, a complementary forest simulator, PixSim, is currently under development. Future research should prioritize the integration



of dynamic land-use changes and evolving forest management practices into simulators to generate outputs that are less dependent on rigid model assumptions, thereby providing a more flexible foundation for trade-off and synergy analyses.



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IV. Annex A: Supplementary information on CLUMondo files

1. Input files

The CLUMondo model was parameterized using several key parameter files. The *allow* matrix defines which conversions are allowed, including spatial or time restrictions. The *lusconv* input file establishes which systems are prioritized to meet specific demands. Standard configurations and



land-system elasticities—calibrated to reflect resistance to change—are contained in the *main* file. Productivity coefficients, specifying the quantity of demand provided by each land system, are defined in the *lusmatrix*, and *locspec* files provide additional spatial weights to modify suitability. Finally, neighbourhood parameters were utilized to incorporate spatial dependency into land-system suitability. All parameter files are publicly accessible through the dedicated repository (Scherpenhuijzen et al., 2026).

1.1 Allow matrix

Conversion rules differ across scenarios and regions. Regional differences include minimum forest rotation lengths—set at 10 years in Southern Europe, 20 years in Western and Eastern Europe, and 30 years in Northern Europe—to prevent unrealistically rapid harvesting of young stands. Rotation lengths vary by species and site conditions; therefore, we applied relatively low minimum values to avoid overly constraining land-use dynamics. Conversion towards forests is not permitted within climate-stress areas. There are no climate-stress areas in Northern Europe, therefore this restriction does not apply to this region. In addition, region-specific altitude thresholds were applied where above this threshold conversion from mosaics towards cropland, grassland, and forests is not allowed: 500m in Northern Europe, 2000m in Eastern Europe, and 2400m in Western and Southern Europe. These thresholds approximate the regional tree line and were set relatively high to exclude only areas where conversion is clearly unrealistic, given the lack of detailed spatial tree line data.

Further regional differences apply to settlement development. Conversion from other land systems towards medium-intensity settlements is only allowed in Western and Eastern Europe. This was necessary as the model would otherwise develop unrealistic clusters of low-intensity settlements in those regions. In Northern Europe, permanent cropland was kept fully stable, including demand, as the limited extent of permanent cropland would otherwise exceed acceptable error margins, resulting in the model not finding a solution.

Scenario-specific rules were also applied. In the biodiversity focused forests and participatory forest stewardship scenarios, extensive forestry and wetlands are protected and therefore are not allowed to convert to other land systems. In contrast, such conversions are permitted in the multifunctional forests and competitive forest industry scenarios. In addition, in the first two scenarios, conversion from cropland, grassland, and mosaic systems to wetlands is allowed, whereas this is not permitted in the latter two scenarios.

Several rules apply across all scenarios. Permanent cropland must be at least five years old before conversion is allowed, as this land system is a long-term investment. Forests must be at least 40 years old before they can transition to extensive forestry, following the definition in Scherpenhuijzen et al. (2025). A forest age map was used to assign initial stand ages to all forest classes at the start of the simulation (Besnard et al., 2021). The original map data had a resolution of 100 meters and were upscaled to 1 km using the median value within each aggregation unit. In areas where no data were available, gaps were filled using the nearest-neighbour method. Urban areas can only intensify and cannot be converted to other land systems or deintensified. Forests within protected areas cannot be converted to other land systems, although transitions between forest management types are permitted. Besides, intensification is not allowed within protected areas. Finally, conversions among cropland, grassland, mosaic, and forest systems are permitted, subject to the rules described above.

1.2 Lusconv



The *lusconv* settings are consistent across regions but vary by scenario depending on demand inclusion (Table A1). When a specific demand is absent from a scenario, it is excluded from the *lusconv*. These values establish the priority order for land system transitions to fulfil regional demands, with higher values assigned to more intensive systems to ensure they receive the greatest priority.

Table A1. *Lusconv* settings for all regions and scenarios, depending on demand inclusion. Higher values indicate higher priority for a land system to fulfil the respective demand.

Land system	Housing	Arable crops	Permanent crops	Livestock	Wood production	Tree demand	Wetlands
Low-intensity settlement	1	-1	-1	-1	-1	-1	-1
Medium-intensity settlement	2	-1	-1	-1	-1	-1	-1
High-intensity settlement	3	-1	-1	-1	-1	-1	-1
Wetlands	-1	-1	-1	-1	-1	-1	1
Forest/shrub and cropland mosaic	0	1	0	0	-1	1	-1
Forest/shrub and grassland mosaic	0	0	0	1	-1	1	-1
Low-intensity arable cropland	0	2	0	0	-1	-1	-1
Medium-intensity arable cropland	0	3	0	0	-1	-1	-1
High-intensity arable cropland	0	4	0	0	-1	-1	-1
Low-intensity grassland	0	0	0	2	-1	-1	-1
Medium-intensity grassland	0	0	0	3	-1	-1	-1
High-intensity grassland	0	0	0	4	-1	-1	-1
Permanent cropland	0	0	1	0	-1	-1	-1
Extensive forestry	0	0	0	0	1	1	-1
Combined objective forestry	0	0	0	0	2	1	-1
Intensive forestry	0	0	0	0	3	1	-1
Very intensive forestry	0	0	0	0	4	1	-1

1.3 Main

Conversion elasticities for forest classes vary by scenario, while all other land system classes maintain consistent values (Table A2). Elasticity values range from 0 to 1, where 0 indicates no resistance to conversion and 1 represents full resistance.

Table A2. Conversion elasticity values for each land system under different scenarios from the *main* file. Values closer to 0 indicate low resistance to conversion, whereas values closer to 1 indicate high resistance.

Land system	Biodiversity focused forests	Participatory forest stewardship	Multifunctional forests	Competitive forest industry
Low-intensity settlement	0.5	0.5	0.5	0.5
Medium-intensity settlement	0.6	0.6	0.6	0.6
High-intensity settlement	1	1	1	1
Wetlands	0.9	0.9	0.9	0.9
Forest/shrub and cropland mosaic	0.7	0.7	0.7	0.7
Forest/shrub and grassland mosaic	0.7	0.7	0.7	0.7
Low-intensity arable cropland	0.4	0.4	0.4	0.4
Medium-intensity arable cropland	0.5	0.5	0.5	0.5
High-intensity arable cropland	0.6	0.6	0.6	0.6
Low-intensity grassland	0.4	0.4	0.4	0.4
Medium-intensity grassland	0.5	0.5	0.5	0.5
High-intensity grassland	0.6	0.6	0.6	0.6
Permanent cropland	0.8	0.8	0.8	0.8
Extensive forestry	0.9	0.9	0.8	0.8
Combined objective forestry	0.7	0.7	0.8	0.6
Intensive forestry	0.6	0.6	0.7	0.6
Very intensive forestry	0.5	0.5	0.7	0.6

1.4 Lusmatrix

The *lusmatrix* is calculated regionally to reflect productivity variations across Europe, while remaining constant across scenarios.



To determine housing productivity, all land systems were overlaid with the population grid of Batista e Silva et al. (2021). For cropland, grassland, and forest systems, we calculated the average population among all subclasses to prevent the model changing the intensity of those land systems to fulfil housing demand (Table A3).

Table A3. Housing productivity (population/km²) of each land system per region.

Land system	West	East	North	South
Low-intensity settlement	467.21	523.46	480.57	400.80
Medium-intensity settlement	599.70	785.65	864.61	517.46
High-intensity settlement	2469.57	2758.30	2001.23	2598.98
Wetlands	2.65	5.80	0.38	18.76
Forest/shrub and cropland mosaic	39.84	39.37	22.40	36.99
Forest/shrub and grassland mosaic	43.74	52.58	19.92	34.59
Low intensity arable cropland	44.74	43.92	33.11	22.86
Medium-intensity arable cropland	44.74	43.92	33.11	22.86
High-intensity arable cropland	44.74	43.92	33.11	22.86
Low-intensity grassland	47.07	62.25	32.37	23.78
Medium-intensity grassland	47.07	62.25	32.37	23.78
High-intensity grassland	47.07	62.25	32.37	23.78
Permanent cropland	72.02	79.12	74.65	41.07
Extensive forestry	15.27	12.79	4.73	18.65
Combined objective forestry	15.27	12.79	4.73	18.65
Intensive forestry	15.27	12.79	4.73	18.65
Very intensive forestry	15.27	12.79	4.73	18.65

Arable cropland productivity was derived exclusively for arable cropland land systems and the forest, shrub, and cropland mosaic. All other land systems were assigned a value of zero, as they do not produce arable crops. Medium-intensity cropland was overlaid with the GlobalWheatYield4km dataset (Luo et al., 2022) to estimate productivity. Developing ratios solely based on this data resulted in unrealistic values. Therefore, we estimated low- and high-intensity cropland values by overlaying the land systems with nitrogen input data (Koeble et al., 2024), using the same dataset employed for the initial land system map (E. Sandström et al., 2023). We corrected for the non-linear relationship between nitrogen input and yield using a Michaelis-Menten function, resulting in approximate low/medium/high intensity ratios of 0.75/1/1.2 (Table A4). These ratios were then applied to the medium-intensity cropland values, resulting in the final productivity estimates for all arable cropland classes (Table A5). For forest, shrub, and cropland mosaics, the share of arable cropland within each mosaic was multiplied by the low-intensity cropland productivity.

Table A4. Nitrogen ratios of the arable cropland classes per region, including the final ratio. Only the final ratio was corrected using a Michaelis-Menten function.

Land system	West	East	North	South	EU	Final ratio
Low-intensity arable cropland	0.635	0.456	0.739	0.566	0.454	0.75
Medium-intensity arable cropland	1	1	1	1	1	1
High-intensity arable cropland	1.414	1.001	1.337	1.541	1.444	1.2

**Table A5.** Arable cropland productivity (tons/km²) of each land system per region.

Land system	West	East	North	South
Low-intensity settlement	0	0	0	0
Medium-intensity settlement	0	0	0	0
High-intensity settlement	0	0	0	0
Wetlands	0	0	0	0
Forest/shrub and cropland mosaic	205.96	162.21	291.19	45.53
Forest/shrub and grassland mosaic	0	0	0	0
Low-intensity arable cropland	544.68	416.32	658.07	199.47
Medium-intensity arable cropland	726.24	555.09	877.43	398.93
High-intensity arable cropland	871.49	666.11	1052.92	797.86
Low-intensity grassland	0	0	0	0
Medium-intensity grassland	0	0	0	0
High-intensity grassland	0	0	0	0
Permanent cropland	0	0	0	0
Extensive forestry	0	0	0	0
Combined objective forestry	0	0	0	0
Intensive forestry	0	0	0	0
Very intensive forestry	0	0	0	0

Permanent crop demand is driven exclusively by the permanent cropland system, with all other land systems assigned a value of zero. Productivity for this system was calculated by dividing the baseline permanent crop production from CAPRI by the total area of permanent cropland.

Livestock provision is fulfilled by grassland systems and forest, shrub, and grassland mosaics. Medium-intensity grassland productivity was estimated using livestock data from Malek et al. (2024). Due to limited grassland coverage in Northern Europe, productivity values from Western Europe were applied to that region. Cattle grazing served as the primary indicator for grassland productivity. In Southern Europe, where grasslands are predominantly grazed by sheep and goats, both cattle and sheep/goat grazing layers were used. Average productivity across Europe was calculated using cattle and sheep/goat grazing data from the same dataset, resulting in low/medium/high intensity ratios of 0.47/1/1.62. These ratios were multiplied with the productivity found for medium-intensity grassland, resulting in the final livestock productivity (Table A6). For the forest, shrub, and grassland mosaic, the average grassland share within this mosaic was calculated and multiplied by the productivity value of low-intensity grassland per region.

Table A6. Livestock productivity (LSU/km²) of each land system per region.

Land system	West	East	North	South
Low-intensity settlement	0	0	0	0
Medium-intensity settlement	0	0	0	0
High-intensity settlement	0	0	0	0
Wetlands	0	0	0	0
Forest/shrub and cropland mosaic	0	0	0	0
Forest/shrub and grassland mosaic	23.70	19.54	23.79	4.04
Low-intensity arable cropland	0	0	0	0
Medium-intensity arable cropland	0	0	0	0
High-intensity arable cropland	0	0	0	0
Low-intensity grassland	62.22	51.52	62.22	12.05
Medium-intensity grassland	133.44	110.49	133.44	25.84
High-intensity grassland	215.65	178.56	215.65	41.76
Permanent cropland	0	0	0	0
Extensive forestry	0	0	0	0
Combined objective forestry	0	0	0	0
Intensive forestry	0	0	0	0
Very intensive forestry	0	0	0	0

Wood is produced by forest land systems and mosaics, with productivity ratios derived from National Forest Inventory (NFI) data across ten countries: Norway, Sweden, Germany, Austria, Poland,



Slovenia, Spain, Belgium, Czechia, and Ireland. This data contained volume observations for each plot (vol0 and vol1). We calculated the percentage change for each plot and assigned the plot to the corresponding volume percentage change interval of 20%. We overlaid the plot locations with the forest management map of Scherpenhuijzen et al. (2025), and for each forest management class, we derived the final distribution over the 20% intervals. This distribution was corrected for the average timespan between vol0 and vol1, per forest management class. We used this distribution to calculate the ratios, indicating the yearly occurrence of a volume decrease per 20% interval per forest management class (Table A7). We only considered the volume intervals indicating a decrease in volume.

Table A7. Annual occurrence of volume decreases (%) per 20% interval and forest management class, derived from NFI data. The volume change intervals indicate the percentage of vol1 compared to vol0.

Volume change interval	Extensive forestry	Combined objective forestry	Intensive forestry	Very intensive forestry
0 - 0.2	0.068952	0.242565	0.387237	0.637008
0.2 - 0.4	0.091240	0.183592	0.204773	0.360605
0.4 - 0.6	0.185266	0.285743	0.306762	0.388062
0.6 - 0.8	0.504953	0.587633	0.635833	0.567450
0.8 - 1	1.714751	1.634421	1.695555	1.123917

Next, we applied a formula to calculate the ratios. We multiplied the annual occurrence of a volume decrease per 20% interval with the average value of that interval (for the volume change interval of 0 – 0.2 this value is 0.9; for the interval of 0.2 – 0.4 it is 0.7; for the interval of 0.4 – 0.6 it is 0.5; for the interval of 0.6 – 0.8 it is 0.3; and for the interval of 0.8 – 1 it is 0.1) and normalized the ratios to combined objective forestry = 1 (Table A8). We used one ratio for the whole Europe, as the NFI data did not contain enough observations for each region to derive regional ratios.

Table A8. Resulting ratios for wood production per forest management class, derived from NFI data.

	Extensive forestry	Combined objective forestry	Intensive forestry	Very intensive forestry
Calculation result	0.541519	0.829426	1.005540	1.302389
Normalized ratios	0.652884	1	1.212332	1.570229

We multiplied the ratios with the average wood production (m^3/km^2) to derive the final wood production values per forest management class (Table A9). This was done by dividing the regional roundwood production by its total forest area (FAO, 2025a, 2025b). For the mosaic land systems, we calculated the average share of forests per mosaic and multiplied this with the extensive forestry wood production value.

**Table A9.** Wood production (m³/km²) of each land system per region.

Land system	West	East	North	South
Low-intensity settlement	0	0	0	0
Medium-intensity settlement	0	0	0	0
High-intensity settlement	0	0	0	0
Wetlands	0	0	0	0
Forest/shrub and cropland mosaic	114.73	107.77	73.70	23.98
Forest/shrub and grassland mosaic	109.99	112.03	54.23	23.26
Low-intensity arable cropland	0	0	0	0
Medium-intensity arable cropland	0	0	0	0
High-intensity arable cropland	0	0	0	0
Low-intensity grassland	0	0	0	0
Medium-intensity grassland	0	0	0	0
High-intensity grassland	0	0	0	0
Permanent cropland	0	0	0	0
Extensive forestry	285.33	252.66	154.77	84.64
Combined objective forestry	437.04	386.99	237.06	129.63
Intensive forestry	529.83	469.16	287.40	157.16
Very intensive forestry	686.25	607.66	372.24	203.56

The tree density for each land system was determined by overlaying the initial land system map with the global dataset from Crowther et al. (2015) (Table A10). For forest management classes, a uniform average tree provision was applied across all forest types. This calibration ensures that the model responds to tree demand through forest expansion rather than artificial management shifts within existing stands. Furthermore, tree provision values for wetlands were reduced by 50% to correct for overestimates caused by shrub-like vegetation. This adjustment assumes that approximately half of the wetland vegetation consists of standing trees, providing a more accurate representation of actual tree cover.

Table A10. Number of trees (per km²) of each land system per region.

Land system	West	East	North	South
Low-intensity settlement	9354	5743	38863	11272
Medium-intensity settlement	8452	5977	30939	7879
High-intensity settlement	5175	2599	15549	3751
Wetlands	8865	20734	17648	5188
Forest/shrub and cropland mosaic	15089	11441	35489	14305
Forest/shrub and grassland mosaic	19127	15039	36463	16370
Low-intensity arable cropland	3163	1717	10022	935
Medium-intensity arable cropland	1882	1933	4813	982
High-intensity arable cropland	2017	2832	2889	1369
Low-intensity grassland	8358	2908	22748	4499
Medium-intensity grassland	3965	2938	6234	6360
High-intensity grassland	2830	1474	19275	6961
Permanent cropland	4500	4492	11743	4780
Extensive forestry	53387	47863	69328	53114
Combined objective forestry	53387	47863	69328	53114
Intensive forestry	53387	47863	69328	53114
Very intensive forestry	53387	47863	69328	53114

Demand for wetland restoration is expressed in terms of total wetland area. Consequently, the wetland provisioning coefficient was set to 1 for the wetland land system, while all other land systems were assigned a value of 0.

1.5 Locspec

Location-specific weights were applied to multiple land systems, varying by scenario and region (Table A11). Weights for urban land systems, wetlands, mosaics, and forests were applied to all pixels, irrespective of the presence of protected areas. Weights for arable cropland, grassland, and



permanent cropland were applied only to pixels outside protected areas, with corresponding weights within protected areas reported in Table 4.

For urban land systems, a negative weight was applied to low-intensity settlements and a positive weight to high-intensity settlements to limit excessive urban sprawl. Wetland restoration was guided toward suitable areas identified through potential vegetation mapping (Jung, 2024). Areas overlapping with agricultural land systems (arable cropland and grassland) in the initial land system map received the additional wetland weight.

Mosaic systems received weights to regulate deintensification from grassland and cropland toward mosaics and to balance forest expansion and mosaic formation. In addition, mosaics were less prioritized in the biodiversity focused forests scenario to avoid forest fragmentation.

Weights were also applied in the biodiversity focused forests scenario to arable cropland and grassland land systems. In the West, North, and South region, negative weights were applied to low-intensity systems to discourage deintensification, with an additional positive weight applied to high-intensity grassland in the West. Demand under SSP1 decreases substantially in the East region, requiring the application of negative weights to medium- and high-intensity arable cropland and grassland systems to obtain optimized results.

The *locs*pec weights applied to forest land systems follow the rationale of the scenario storylines. In biodiversity focused forests, we applied a strong positive weight to extensive forestry, a negative weight to intensive forestry, and a strong negative weight to very intensive forestry. In participatory forest stewardship we applied a strong positive weight to extensive forestry and a positive weight to all other forest pixels present in the initial land system map. In multifunctional forests we applied a positive weight to combined objective forestry and a negative weight to very intensive forestry. In competitive forest industry we applied positive weights to both intensive forestry and very intensive forestry. The *locs*pec files of the forest systems include the original suitability maps together with the *locs*pec weights reported here, as well as additional weights derived from climate change data, protected area data, and connectivity data, as described in Section 4.3. The original suitability map was retained, and the regression component in the regression file was constrained to yield zero, practically solving the issue described in Section 4.2. For forest systems, the weights reported in Table S6 for protected areas are applied on top of the weights provided in Table A11.

Table A11. *Locs*pec weights for all land systems per scenario and region. Weights for urban land systems, wetlands, mosaics, and forests were applied to all pixels, irrespective of the presence of protected areas. Weights for arable cropland, grassland, and permanent cropland were applied only to pixels outside protected areas, with corresponding weights within protected areas reported in Table 4. For forest land systems, the weights provided in Table 4 are applied in addition to the weights reported in this table.

Land system	Biodiversity focused forests				Participatory forest stewardship				Multifunctional forests				Competitive forest industry			
	West	East	North	South	West	East	North	South	West	East	North	South	West	East	North	South
Low-intensity settlement	-0.5	-0.5	-0.3	-0.2	-0.5	-0.5	-0.3	-0.2	-0.5	-0.5	-0.3	-0.2	-0.5	-0.5	-0.3	-0.2
Medium-intensity settlement	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
High-intensity settlement	0.5	0.5	0.3	0.2	0.5	0.5	0.3	0.2	0.5	0.5	0.3	0.2	0.5	0.5	0.3	0.2
Wetlands	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0	0	0	0	0	0	0	0
Forest/shrub and cropland mosaic	-0.4	-0.5	-0.4	-0.4	0	0	0	0	0	0.2	0	0.1	0	0	0	0
Forest/shrub and grassland mosaic	-0.4	-0.5	-0.4	-0.4	0	0	0	0	0	0.2	0	0.1	0	0	0	0
Low-intensity arable cropland	-0.2	0	-0.2	-0.2	0	0	0	0	0	0	0	0	0	0	0	0
Medium-intensity arable cropland	0	-0.2	0	0	0	0	0	0	0	0	0	0	0	0	0	0
High-intensity arable cropland	0	-0.2	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Low-intensity grassland	-0.2	0	-0.2	-0.2	0	0	0	0	0	0	0	0	0	0	0	0
Medium-intensity grassland	0	-0.2	0	0	0	0	0	0	0	0	0	0	0	0	0	0
High-intensity grassland	0.2	-0.2	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Permanent cropland	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Extensive forestry	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0	0	0	0	0	0	0	0
Combined objective forestry	0	0	0	0	0.2*	0.2*	0.2*	0.2*	0.2	0.2	0.2	0.2	0	0	0	0
Intensive forestry	-0.2	-0.2	-0.2	-0.2	0.2*	0.2*	0.2*	0.2*	0	0	0	0	0.2	0.2	0.2	0.2
Very intensive forestry	-0.4	-0.4	-0.4	-0.4	0.2*	0.2*	0.2*	0.2*	-0.2	-0.2	-0.2	-0.2	0.2	0.2	0.2	0.2



Note: * indicates that the weight is applied only to pixels belonging to the corresponding land system in 2020, rather than to all pixels within the region.

1.6 Neighbourhood

Neighbourhood effects were applied to high-intensity settlements, high-intensity cropland, extensive forestry, and combined objective forestry, as these land systems typically occur in clusters. Using a 3×3 neighbourhood matrix, high-intensity settlements interact with their own class with a weight of 0.4. High-intensity cropland interacts with itself at a weight of 0.5 and with high-intensity grassland at a weight of 0.3. Extensive forestry has a weight of 0.4 with its own class, while combined objective forestry has a weight of 0.5 with itself and 0.3 with extensive forestry.

V. Annex B: Supplementary CLUMondo results

Table B1. Land system shares (%) in 2020 and 2050 by scenario. Δ indicates the difference in percentage points between the baseline year and 2050 projections. The table shows both aggregated land systems and all subcomponents.

Land system	2020	Biodiversity focused forests		Participatory forest stewardship		Multifunctional forests		Competitive forest industry	
		2050	Δ	2050	Δ	2050	Δ	2050	Δ
Settlements	5.87	6.39	0.52	5.97	0.10	5.93	0.06	5.91	0.04
Low-intensity settlement	1.21	1.17	-0.04	1.05	-0.16	1.15	-0.06	1.14	-0.07
Medium-intensity settlement	2.11	2.59	0.48	2.21	0.10	2.07	-0.04	2.06	-0.05
High-intensity settlement	2.55	2.62	0.07	2.70	0.15	2.71	0.16	2.71	0.16
Wetlands	1.14	1.39	0.25	1.40	0.26	0.99	-0.15	1.09	-0.05
Mosaics	19.84	16.32	-3.52	25.72	5.88	14.82	-5.02	17.31	-2.53
Forest/shrub and cropland mosaic	7.91	7.51	-0.40	11.84	3.93	5.75	-2.16	6.69	-1.22
Forest/shrub and grassland mosaic	11.93	8.82	-3.11	13.88	1.95	9.06	-2.87	10.62	-1.31
Arable croplands	19.06	15.86	-3.20	13.46	-5.60	19.33	0.27	19.07	0.01
Low-intensity arable cropland	3.15	12.40	9.25	8.92	5.77	1.41	-1.74	1.62	-1.53
Medium-intensity arable cropland	12.35	2.03	-10.32	1.99	-10.36	10.57	-1.78	10.26	-2.09
High-intensity arable cropland	3.56	1.43	-2.13	2.55	-1.01	7.35	3.79	7.19	3.63
Grasslands	8.22	9.14	0.92	6.48	-1.74	8.93	0.71	8.18	-0.04
Low-intensity grassland	2.20	4.21	2.01	1.51	-0.69	2.91	0.71	1.88	-0.32
Medium-intensity grassland	4.14	2.64	-1.50	2.05	-2.09	3.39	-0.75	3.83	-0.31
High-intensity grassland	1.87	2.30	0.43	2.92	1.05	2.63	0.76	2.48	0.61
Permanent croplands	1.93	2.09	0.16	2.08	0.15	1.91	-0.02	1.91	-0.02
Forests	34.83	39.70	4.87	35.79	0.96	38.98	4.15	37.42	2.59
Unmanaged forest	0.26	0.26	0	0.26	0	0.26	0	0.26	0
Extensive forestry	7.87	21.97	14.10	13.30	5.43	6.71	-1.16	7.93	0.06
Combined objective forestry	14.06	13.87	-0.19	14.66	0.60	24.04	9.98	9.92	-4.14
Intensive forestry	10.47	3.55	-6.92	6.54	-3.93	5.01	-5.46	12.19	1.72
Very intensive forestry	2.17	0.05	-2.12	1.03	-1.14	2.97	0.80	7.12	4.95
Water and glaciers	2.84	2.84	0	2.84	0	2.84	0	2.84	0
Bare, rock and shrub	6.26	6.26	0	6.26	0	6.26	0	6.26	0

Legend used for **Table B2–B5**:

ID	Land system	ID	Land system
0	Low-intensity settlement	9	Low-intensity grassland
1	Medium-intensity settlement	10	Medium-intensity grassland
2	High-intensity settlement	11	High-intensity grassland
3	Wetlands	12	Permanent cropland
4	Forest/shrub and cropland mosaic	13	Extensive forestry
5	Forest/shrub and grassland mosaic	14	Combined objective forestry
6	Low-intensity arable cropland	15	Intensive forestry
7	Medium-intensity arable cropland	16	Very intensive forestry
8	High-intensity arable cropland		

**Table B2.** Transition matrix biodiversity focused forests.

ID	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
0	54841	5455	47	0	0	0	0	0	0	0	0	0	0	0	0	0	0
1	0	101625	3150	0	0	0	0	0	0	0	0	0	0	0	0	0	0
2	0	0	126625	0	0	0	0	0	0	0	0	0	0	0	0	0	0
3	0	0	0	56895	0	0	0	0	0	0	0	0	0	0	0	0	0
4	177	1648	54	133	270347	59	5103	133	1447	17310	7057	12544	2167	0	71394	3369	163
5	539	5582	148	926	109	408099	10176	1518	4645	3405	1443	2748	6986	0	143287	3115	352
6	323	428	28	950	14742	96	127174	74	927	2948	2341	4395	593	0	1510	18	0
7	95	5395	75	2193	70522	96	383940	92135	72	15577	12404	26253	1611	0	3519	18	0
8	25	5340	101	1722	12330	1345	78383	5869	58311	5184	1425	4277	129	0	2568	0	0
9	847	477	16	2591	629	11551	2792	1017	3918	70811	233	1153	5816	0	7584	13	0
10	8	1971	31	1488	949	10573	4098	227	1399	84147	92985	32	982	0	6978	7	0
11	0	185	2	2310	1132	5464	376	5	77	7411	12961	62661	9	0	595	1	0
12	0	1	0	39	2338	946	3948	16	65	1853	47	207	85386	0	1151	0	0
13	0	0	0	0	0	0	0	0	0	0	0	0	391181	0	0	0	0
14	25	168	13	0	0	0	1	0	5	0	0	0	1	485411	213380	0	0
15	763	423	12	0	0	0	329	3	41	452	67	11	0	173520	182929	161669	0
16	523	207	5	0	4	0	242	48	37	153	54	1	0	41838	54572	8271	1891

Table B3. Transition matrix participatory forest stewardship.

ID	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
0	52380	7857	106	0	0	0	0	0	0	0	0	0	0	0	0	0	0
1	0	98012	6763	0	0	0	0	0	0	0	0	0	0	0	0	0	0
2	0	0	126625	0	0	0	0	0	0	0	0	0	0	0	0	0	0
3	0	0	0	56895	0	0	0	0	0	0	0	0	0	0	0	0	0
4	0	33	16	383	364507	1300	4660	158	2488	503	646	3633	215	0	11351	2536	676
5	0	23	27	286	444	547445	169	8	418	3041	2617	13583	1644	0	19187	1537	2649
6	24	202	40	915	18035	9595	114841	985	4257	1117	592	2853	1983	0	1007	72	29
7	24	967	119	4822	110426	66551	273095	92861	30828	2914	8460	16590	5014	0	1112	102	20
8	0	1090	251	1755	16299	20974	42070	4547	86673	1085	511	785	549	0	410	9	1
9	0	722	23	1649	28257	16795	3937	127	1050	33340	2893	9321	5900	0	5253	158	23
10	0	750	101	2096	38675	16388	2177	116	677	29847	78459	31316	1644	0	3337	214	78
11	0	392	36	663	7142	8920	31	3	146	1803	7398	66237	0	0	366	34	18
12	0	0	1	4	4687	2102	2059	4	11	937	13	28	85466	0	679	6	0
13	0	0	0	0	0	0	0	0	0	0	0	0	0	391181	0	0	0
14	0	0	2	2	1	1	137	7	21	126	12	309	500	221538	474385	63	1900
15	2	14	1	0	35	4	171	2	21	188	26	315	432	39983	170191	307088	1746
16	1	11	0	0	47	5	67	1	15	269	52	100	83	8326	41292	13439	44138

Table B4. Transition matrix multifunctional forests.

ID	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
0	56300	3944	99	0	0	0	0	0	0	0	0	0	0	0	0	0	0
1	0	96723	8052	0	0	0	0	0	0	0	0	0	0	0	0	0	0
2	0	0	126625	0	0	0	0	0	0	0	0	0	0	0	0	0	0
3	0	1	1	49337	0	0	3	7	48	0	0	20	0	0	7348	118	12
4	3	49	3	0	272046	55	29283	7794	29890	31	123	1340	29	0	48309	3535	615
5	0	0	0	0	1414	447496	881	1363	890	77	3	24419	15	0	113692	2097	731
6	776	1590	0	0	2322	486	26200	35443	33458	28063	20505	3560	2601	0	1524	18	1
7	23	153	1	0	616	440	443	426804	157618	9898	562	7172	837	0	9297	41	0
8	0	57	14	0	131	458	3966	16503	137980	2826	2854	1934	217	0	10064	5	0
9	1	18	0	0	2433	280	1887	15431	1547	76801	613	2301	1111	0	6971	54	0
10	0	25	0	0	3627	474	2529	9795	2860	21492	139889	7805	98	0	17071	208	2
11	0	0	0	0	340	449	2225	12	44	663	1129	79998	12	0	8293	21	3
12	0	2	0	0	646	24	960	800	538	1397	24	46	90090	0	1470	0	0
13	8	22	0	0	634	14	809	443	181	141	1	1603	8	307259	77949	1854	255
14	52	122	1	0	22	0	327	200	138	143	1	83	5	23040	637515	31398	5957
15	2	19	1	0	1082	130	360	8297	100	1144	1523	302	29	2698	200344	204337	99851
16	0	0	0	0	726	85	138	2414	31	2088	1376	69	0	342	55003	5171	40403

Table B5. Transition matrix competitive forest industry.

ID	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
0	55673	4565	105	0	0	0	0	0	0	0	0	0	0	0	0	0	0
1	0	96770	8005	0	0	0	0	0	0	0	0	0	0	0	0	0	0
2	0	0	126625	0	0	0	0	0	0	0	0	0	0	0	0	0	0
3	0	0	0	54091	0	0	16	55	45	2	0	15	0	0	644	964	1063
4	0	40	1	0	279447	11	42408	12839	23407	91	206	1562	30	0	5712	17618	9733
5	0	0	0	0	69	512062	975	5141	1200	177	27	18969	17	0	8075	32657	13709
6	785	1015	0	0	23957	755	23336	43269	32405	14938	7828	3104	2388	0	600	2038	129
7	4	117	1	0	6659	435	128	425793	147237	7430	471	7298	728	0	1195	11447	4962
8	0	49	14	0	1331	330	5489	3749	149082	2342	5920	2224	316	0	936	4735	492
9	0	4	0	0	11362	11522	1494	8722	871	62473	654	1805	505	0	2445	6693	898
10	0	0	0	0	6787	2230	1533	143	1668	812	173522	2114	1	0	1210	12462	3393
11	0	0	0	0	56	437	2346	5	8	54	1322	81721	2	0	276	6849	113
12	0	2	0	0	983	35	953	133	586	186	5	158	90869	0	671	958	458
13	0	4	1	0	275	0	548	936	182	257	4	970	5	343962	11020	22600	10417
14	0	5	0	0	1147	1	1260	5080	340	2807	191	2923	69	46171	425772	124579	88659
15	0	1	0	0	174	0	222	3106	91	1074	31	264	14	3858	29254	335929	146201
16	0	1	0	0	298	140	17	855	10	743	40	29	0	335	5313	26377	73688



Figure B1. Biodiversity focused forests scenario result for Europe in 2050.

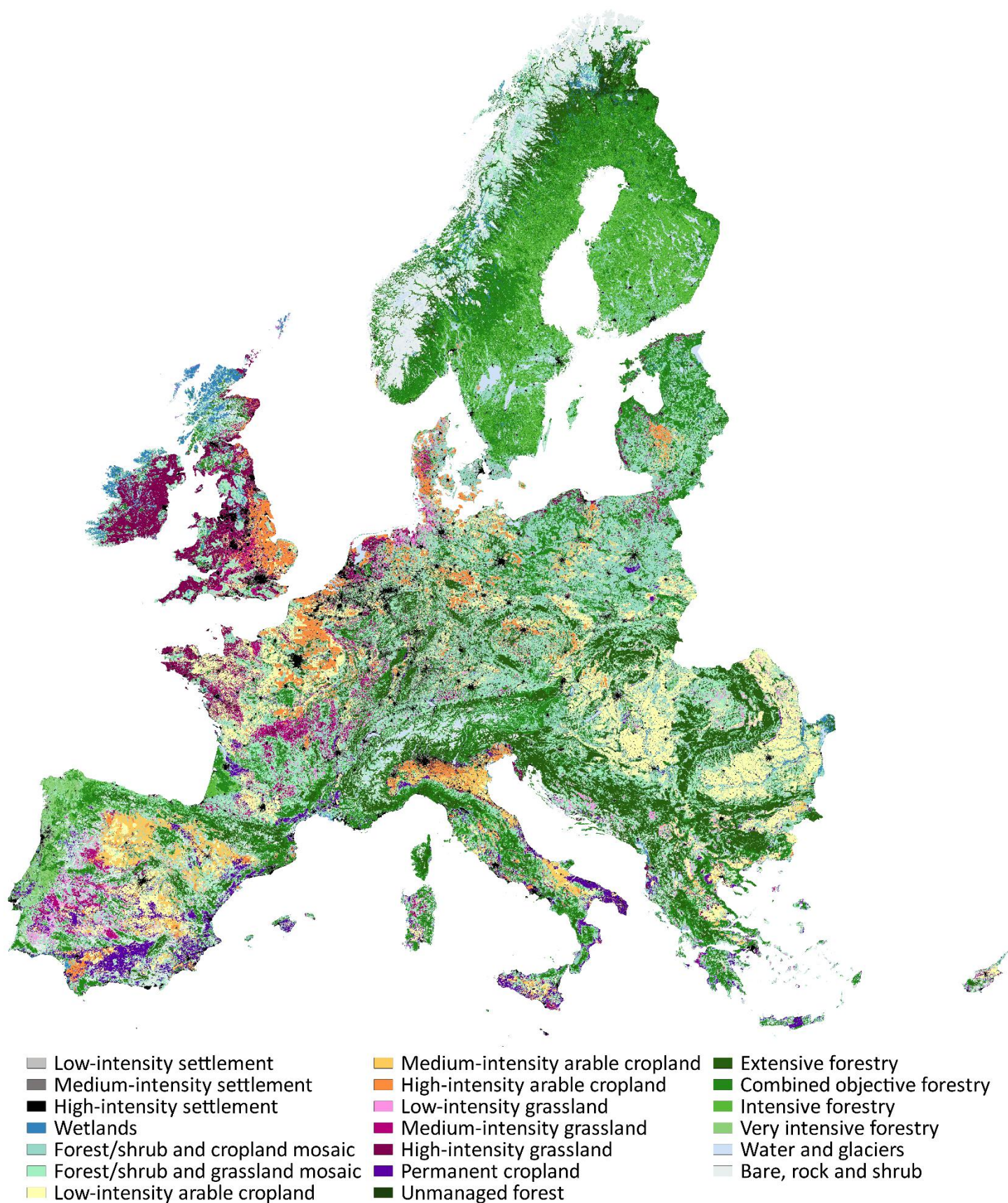


Figure B2. Participatory forest stewardship scenario result for Europe in 2050.

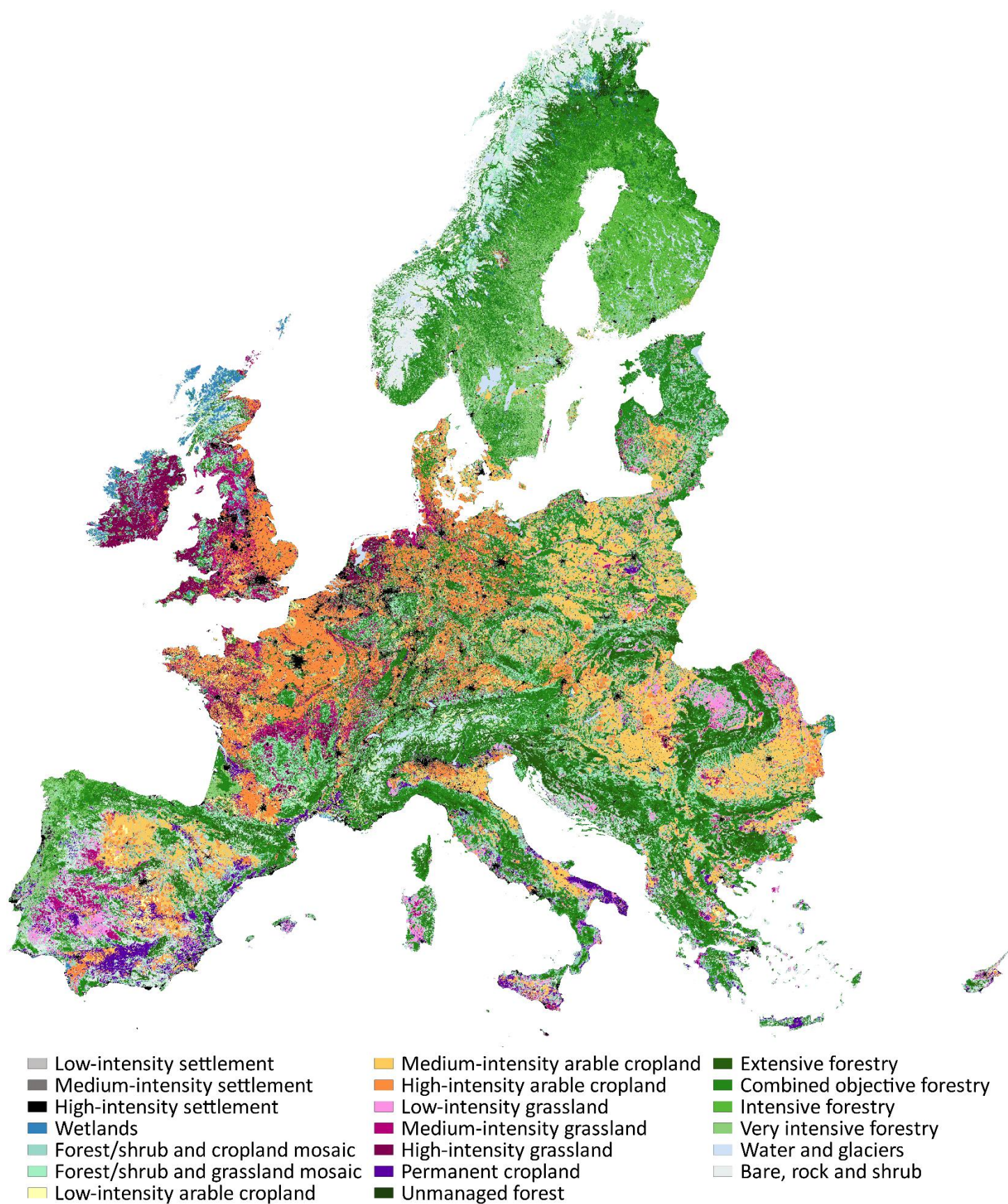


Figure B3. Multifunctional forests scenario result for Europe in 2050.

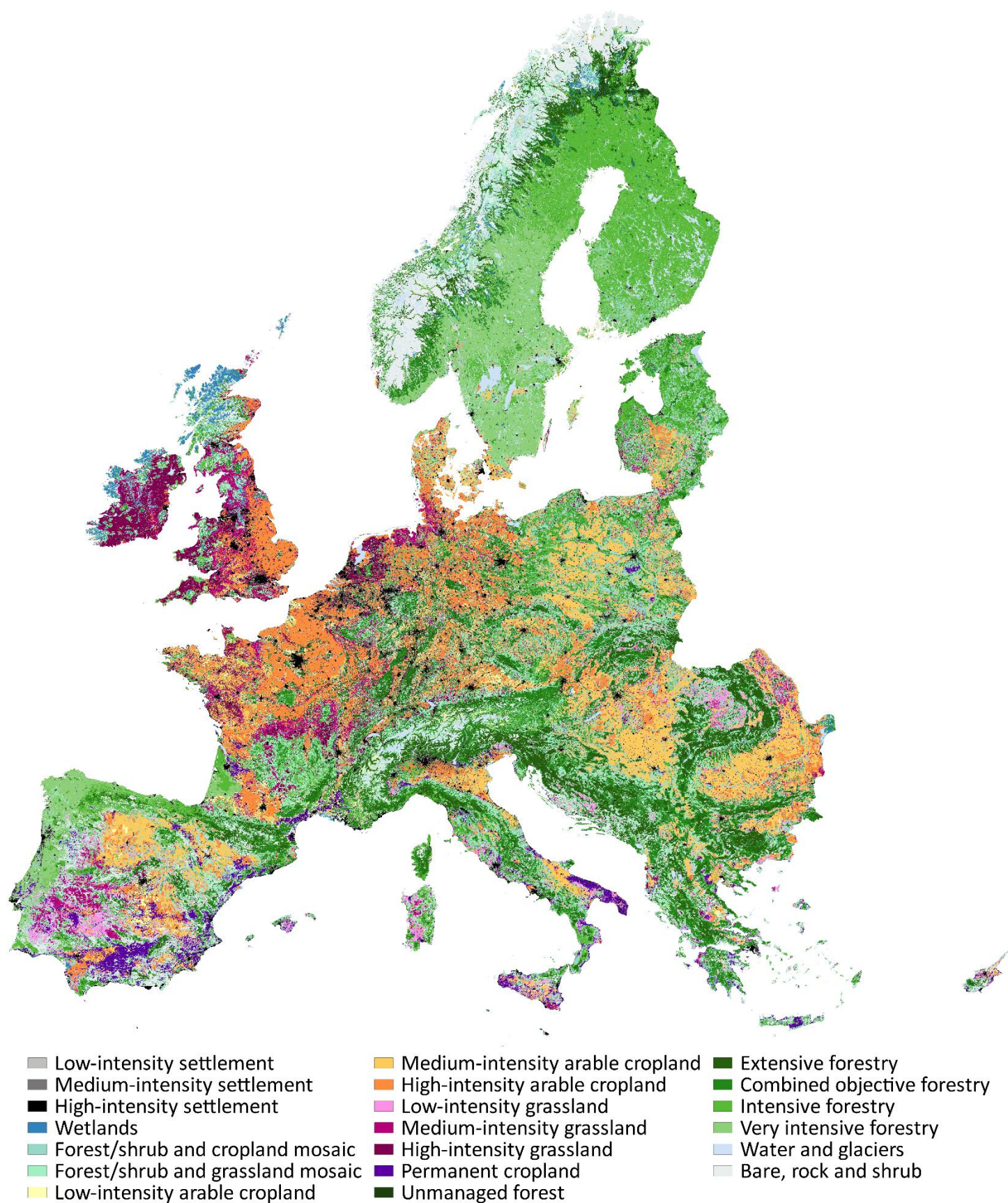


Figure B4. Competitive forest industry scenario result for Europe in 2050.



Land systems

- Low-intensity settlement
- Medium-intensity settlement
- High-intensity settlement
- Wetlands
- Forest/shrub and cropland mosaic
- Forest/shrub and grassland mosaic
- Low-intensity arable cropland
- Medium-intensity arable cropland
- High-intensity arable cropland
- Low-intensity grassland
- Medium-intensity grassland
- High-intensity grassland
- Permanent cropland
- Unmanaged forest
- Extensive forestry
- Combined objective forestry
- Intensive forestry
- Very intensive forestry
- Water and glaciers
- Bare, rock and shrub

0 100 200 km

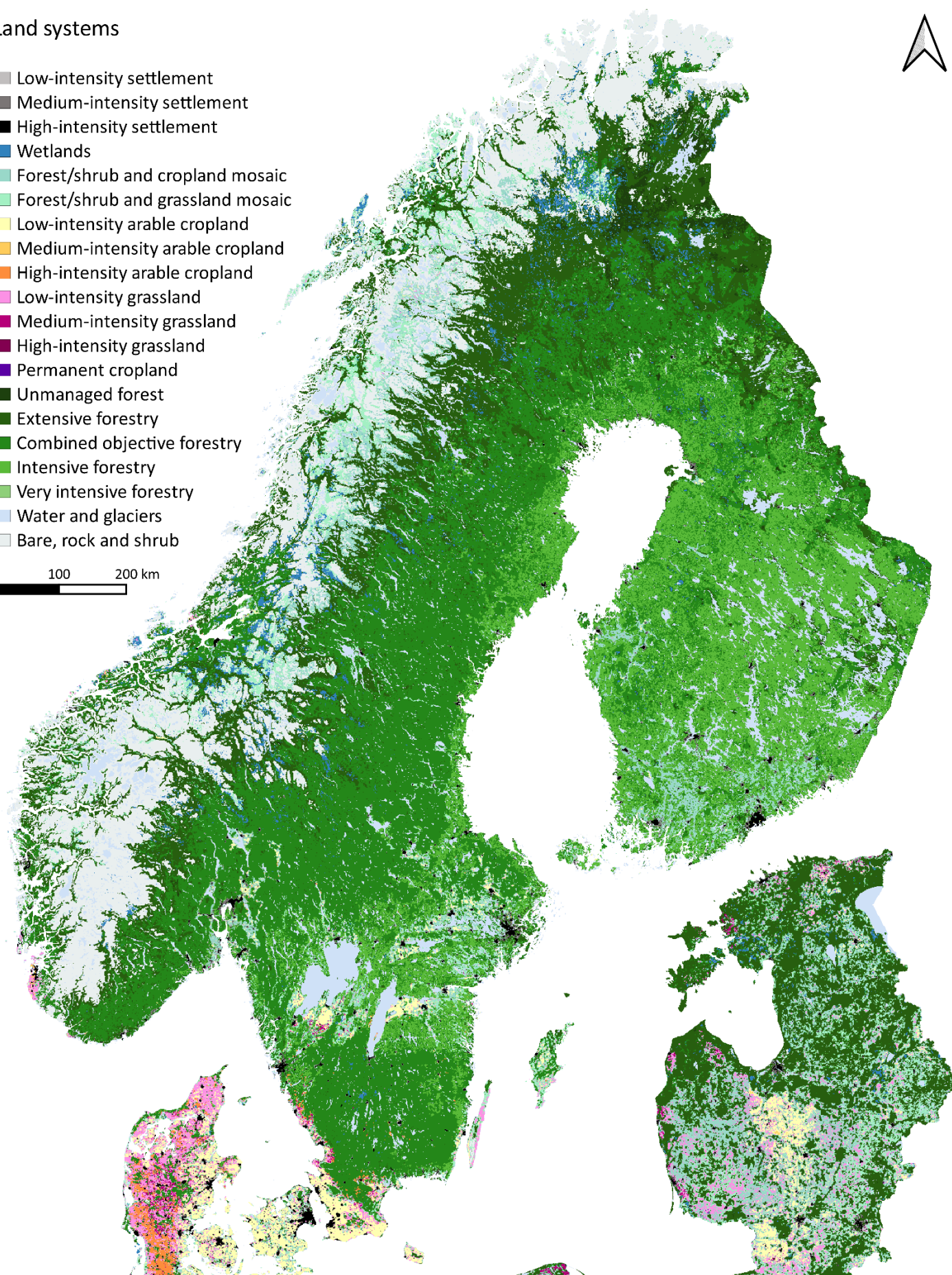


Figure B5. Biodiversity focused forests scenario result for northern Europe in 2050.

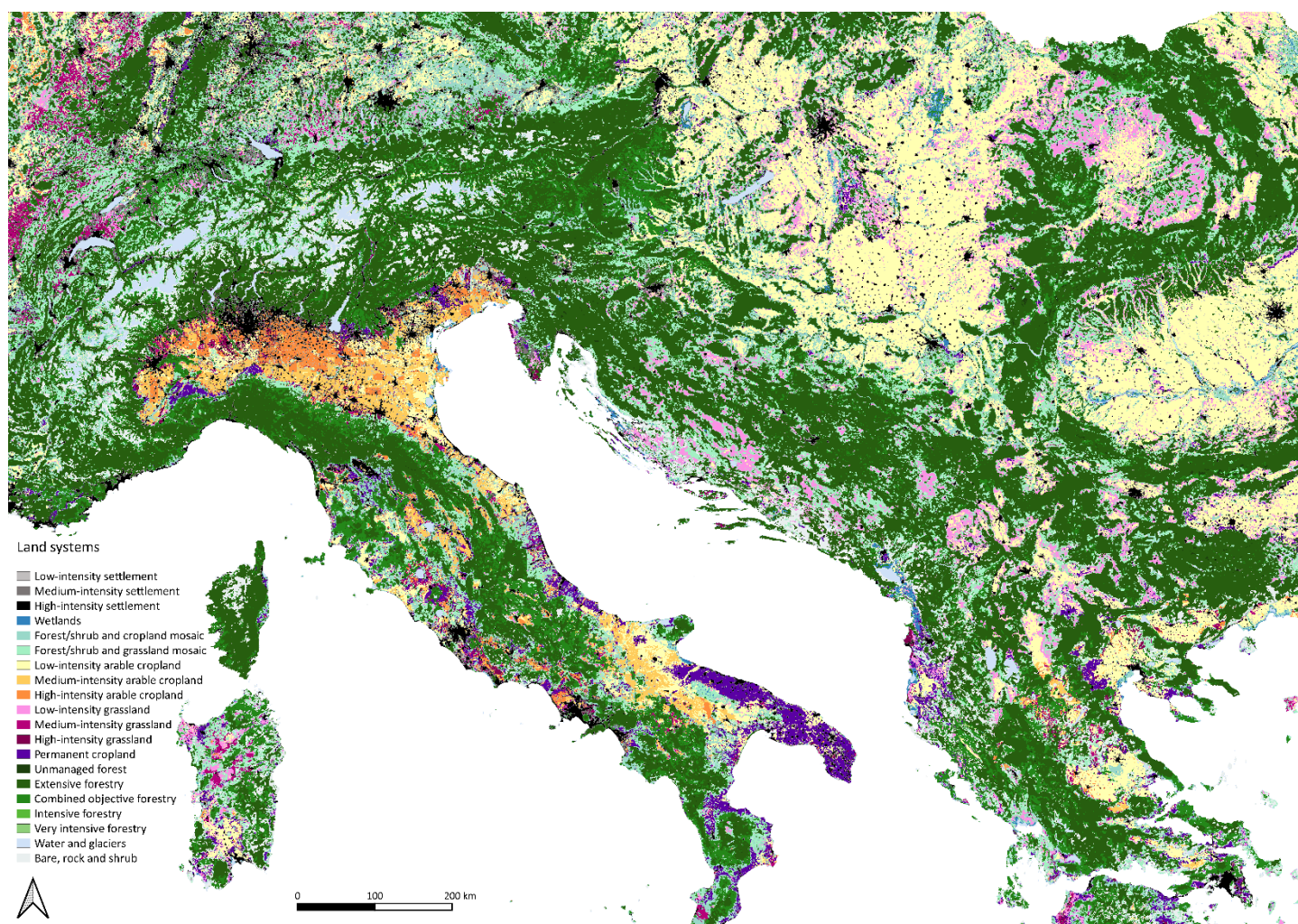


Figure B6. Biodiversity focused forests scenario result for Italy, Alpes, and the Balkans in 2050.

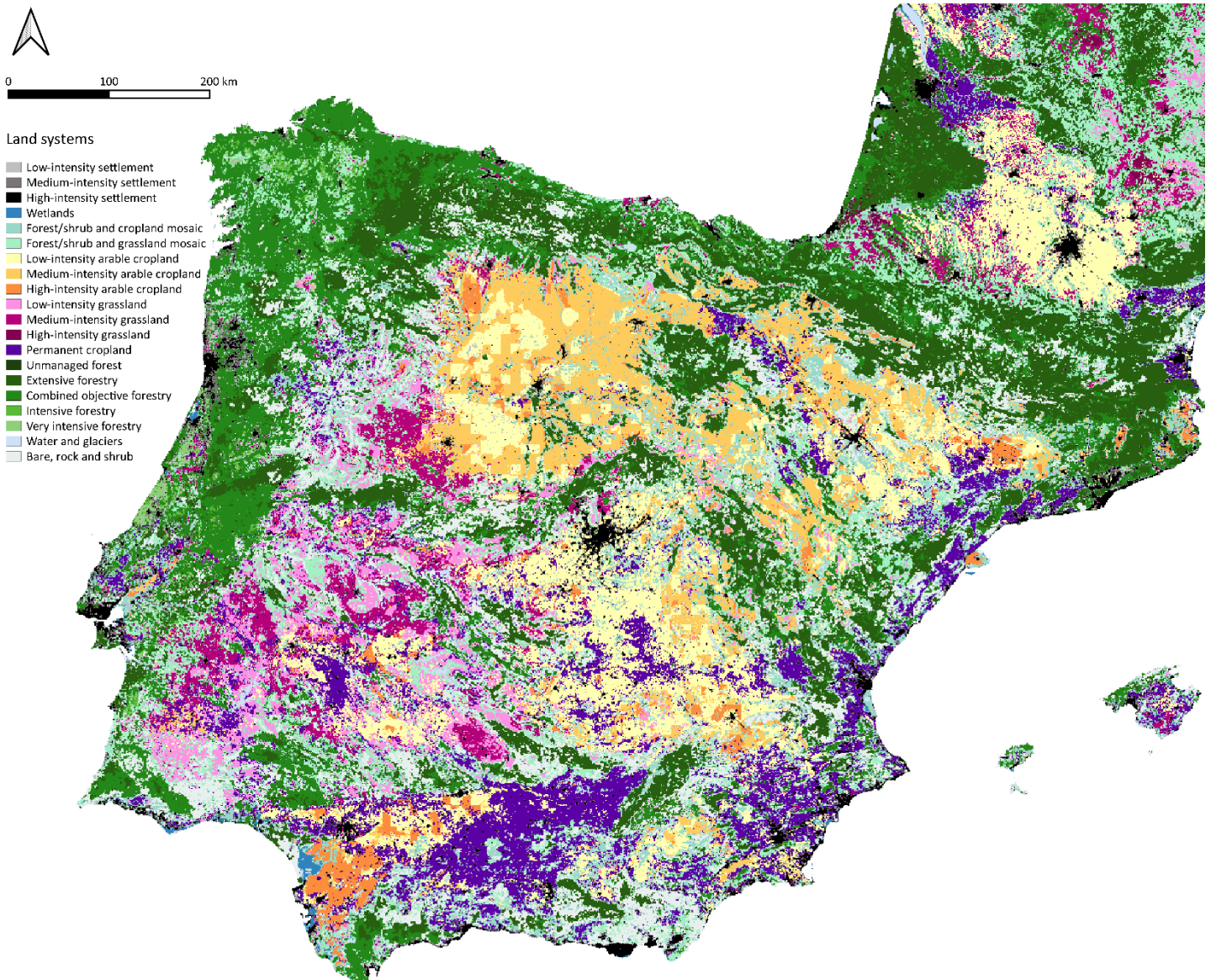


Figure B7. Biodiversity focused forests scenario result for the Iberian Peninsula and southwestern France in 2050.

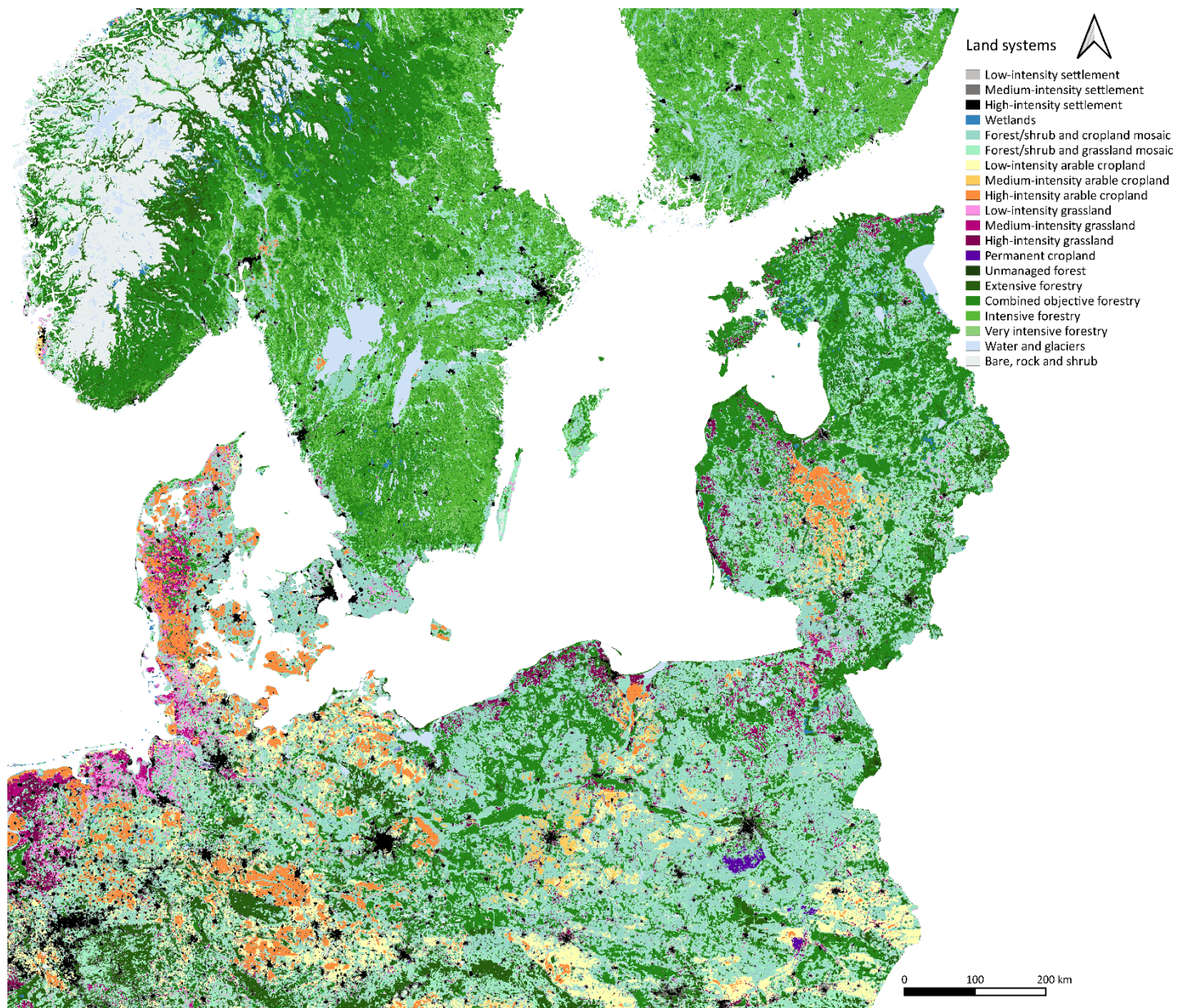


Figure B8. Participatory forest stewardship scenario result for southern Scandinavia, Denmark, the Baltics, Poland, and northern Germany in 2050.

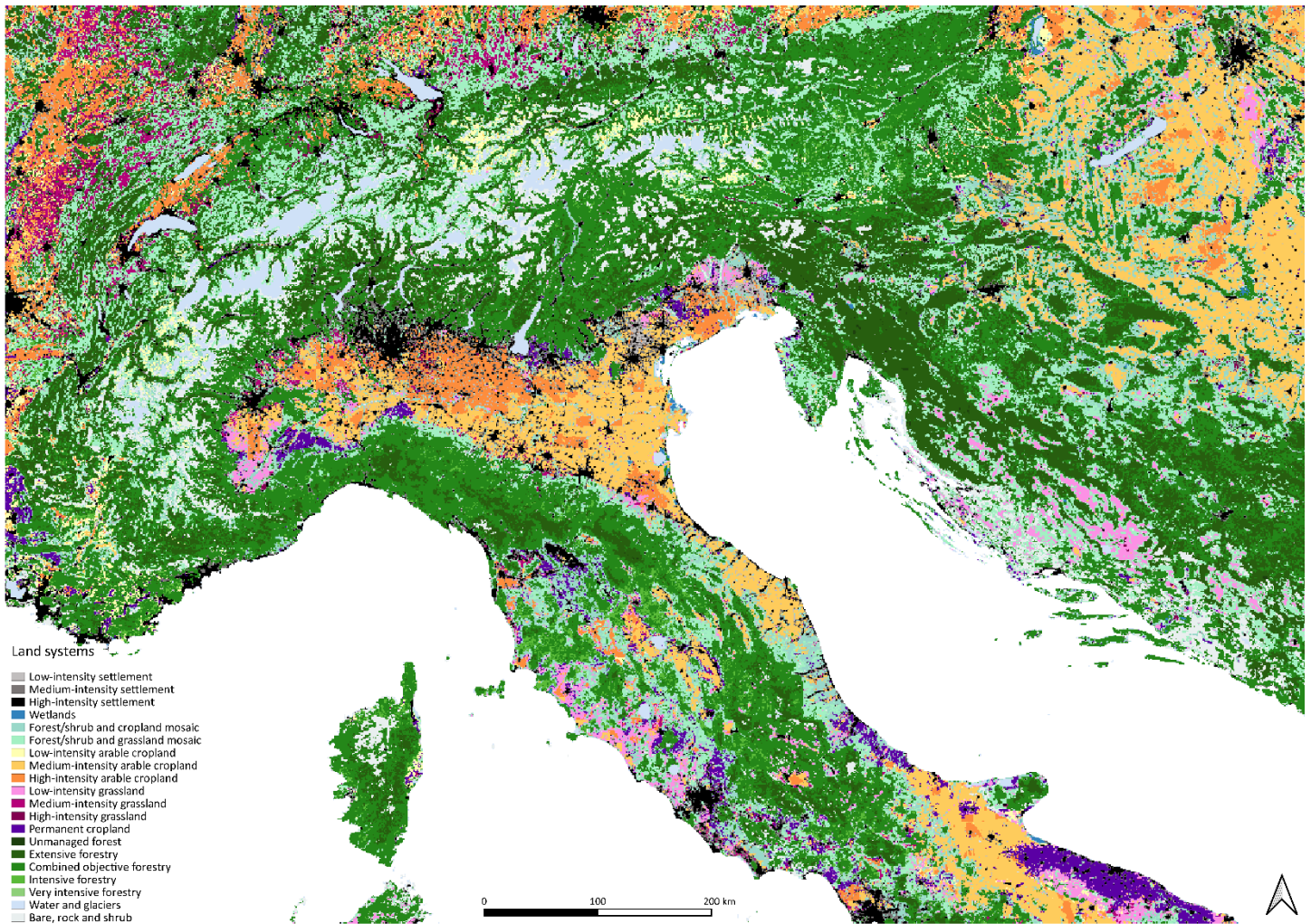


Figure B9. Multifunctional forests scenario result for the Alps, Italy, and the western part of the Balkans in 2050.



Land systems

- Low-intensity settlement
- Medium-intensity settlement
- High-intensity settlement
- Wetlands
- Forest/shrub and cropland mosaic
- Forest/shrub and grassland mosaic
- Low-intensity arable cropland
- Medium-intensity arable cropland
- High-intensity arable cropland
- Low-intensity grassland
- Medium-intensity grassland
- High-intensity grassland
- Permanent cropland
- Unmanaged forest
- Extensive forestry
- Combined objective forestry
- Intensive forestry
- Very intensive forestry
- Water and glaciers
- Bare, rock and shrub

0 100 200 km

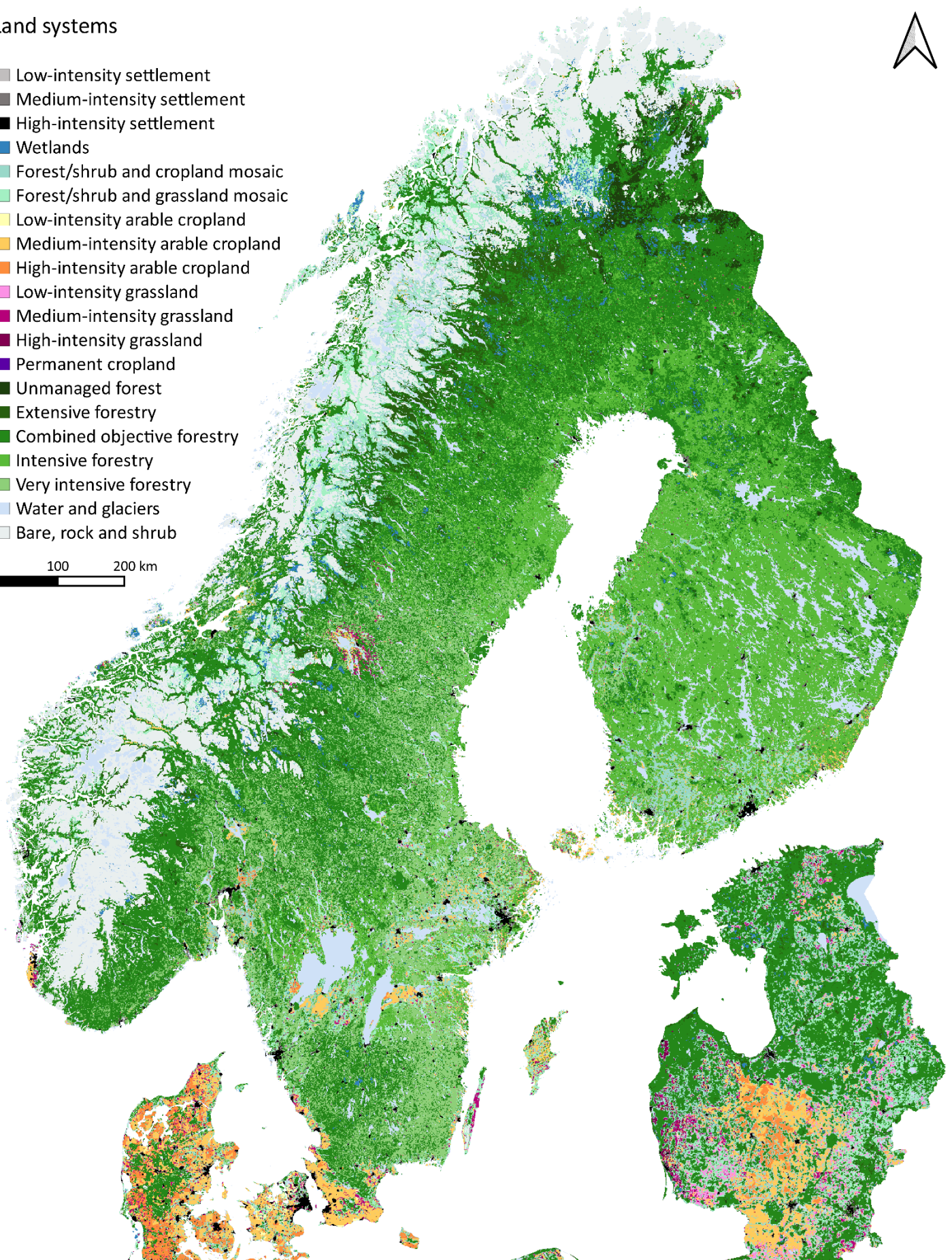


Figure B10. Multifunctional forests scenario result for northern Europe in 2050.



Land systems

- Low-intensity settlement
- Medium-intensity settlement
- High-intensity settlement
- Wetlands
- Forest/shrub and cropland mosaic
- Forest/shrub and grassland mosaic
- Low-intensity arable cropland
- Medium-intensity arable cropland
- High-intensity arable cropland
- Low-intensity grassland
- Medium-intensity grassland
- High-intensity grassland
- Permanent cropland
- Unmanaged forest
- Extensive forestry
- Combined objective forestry
- Intensive forestry
- Very intensive forestry
- Water and glaciers
- Bare, rock and shrub

0 100 200 km

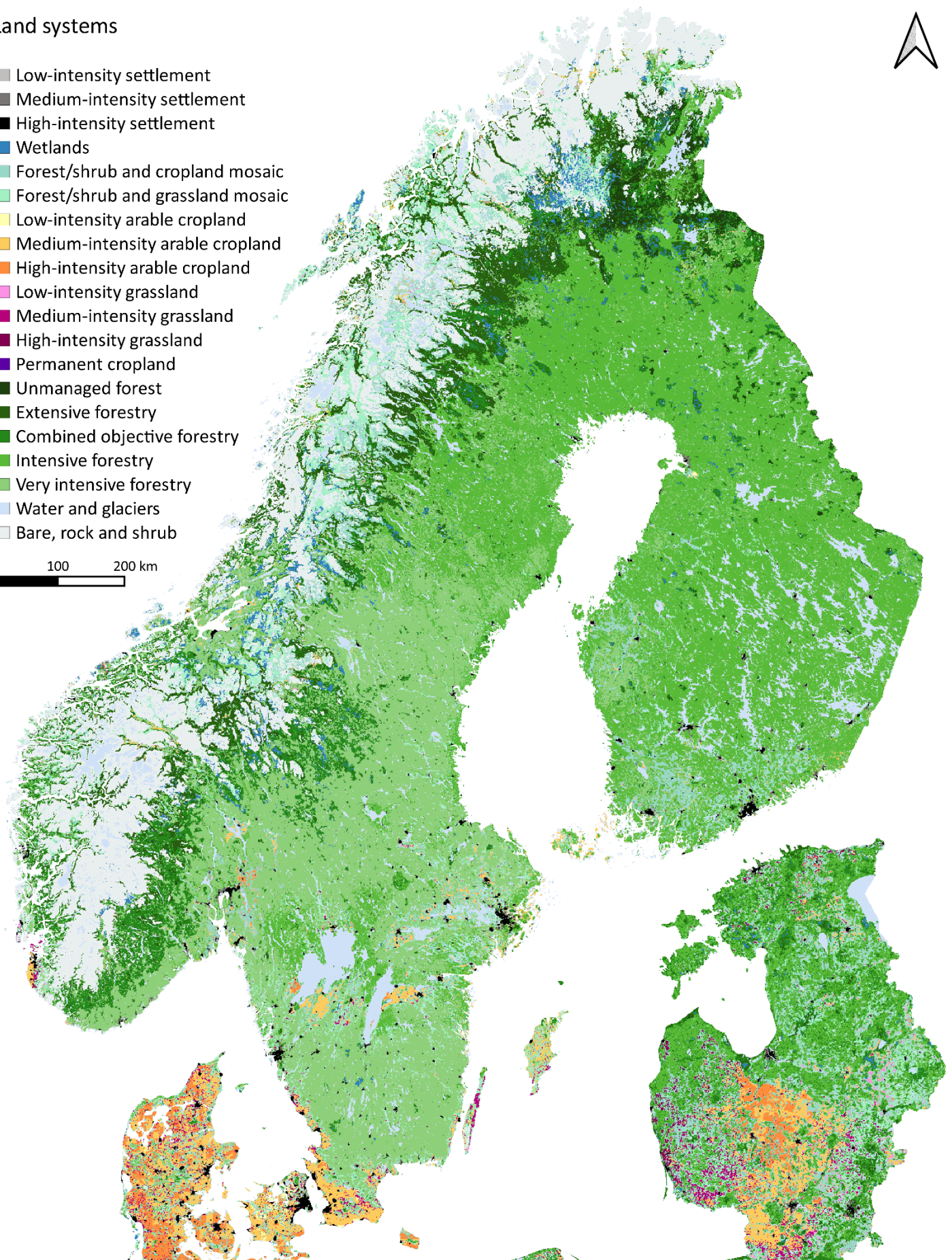


Figure B11. Competitive forest industry scenario result for northern Europe in 2050.

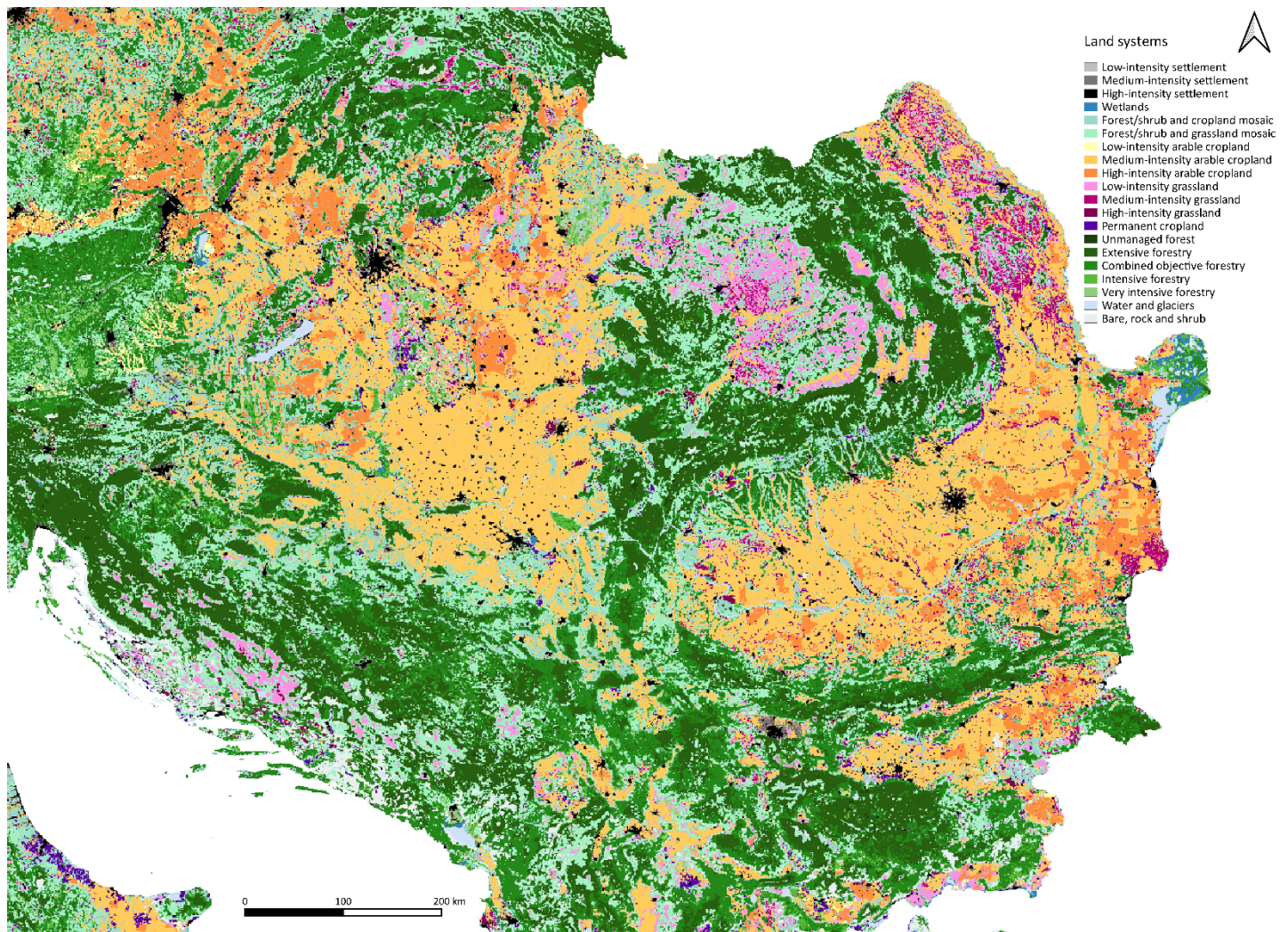


Figure B12. Competitive forest industry scenario result for eastern Europe in 2050.

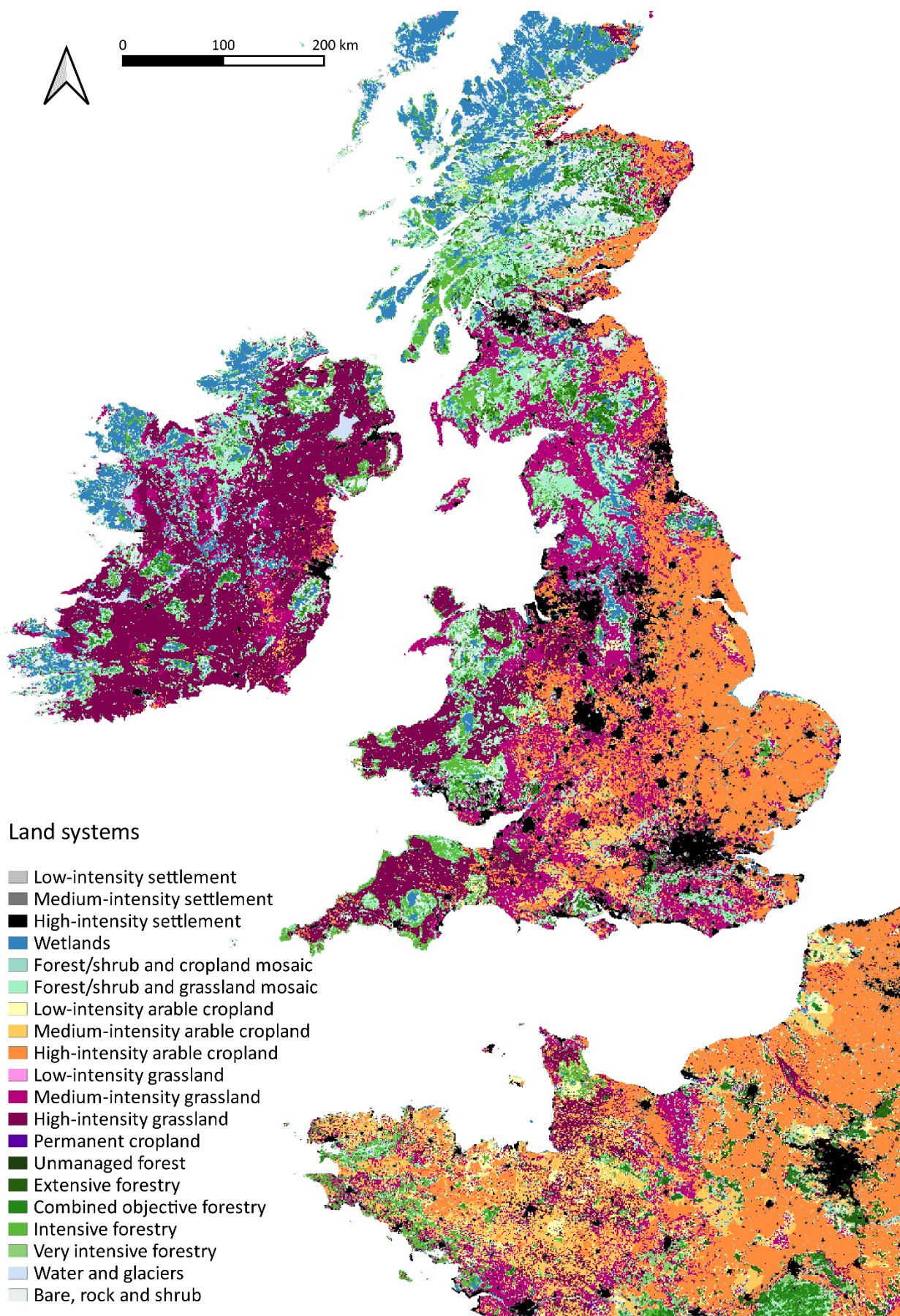


Figure B13. Competitive forest industry scenario result for the United Kingdom and northwestern France in 2050.

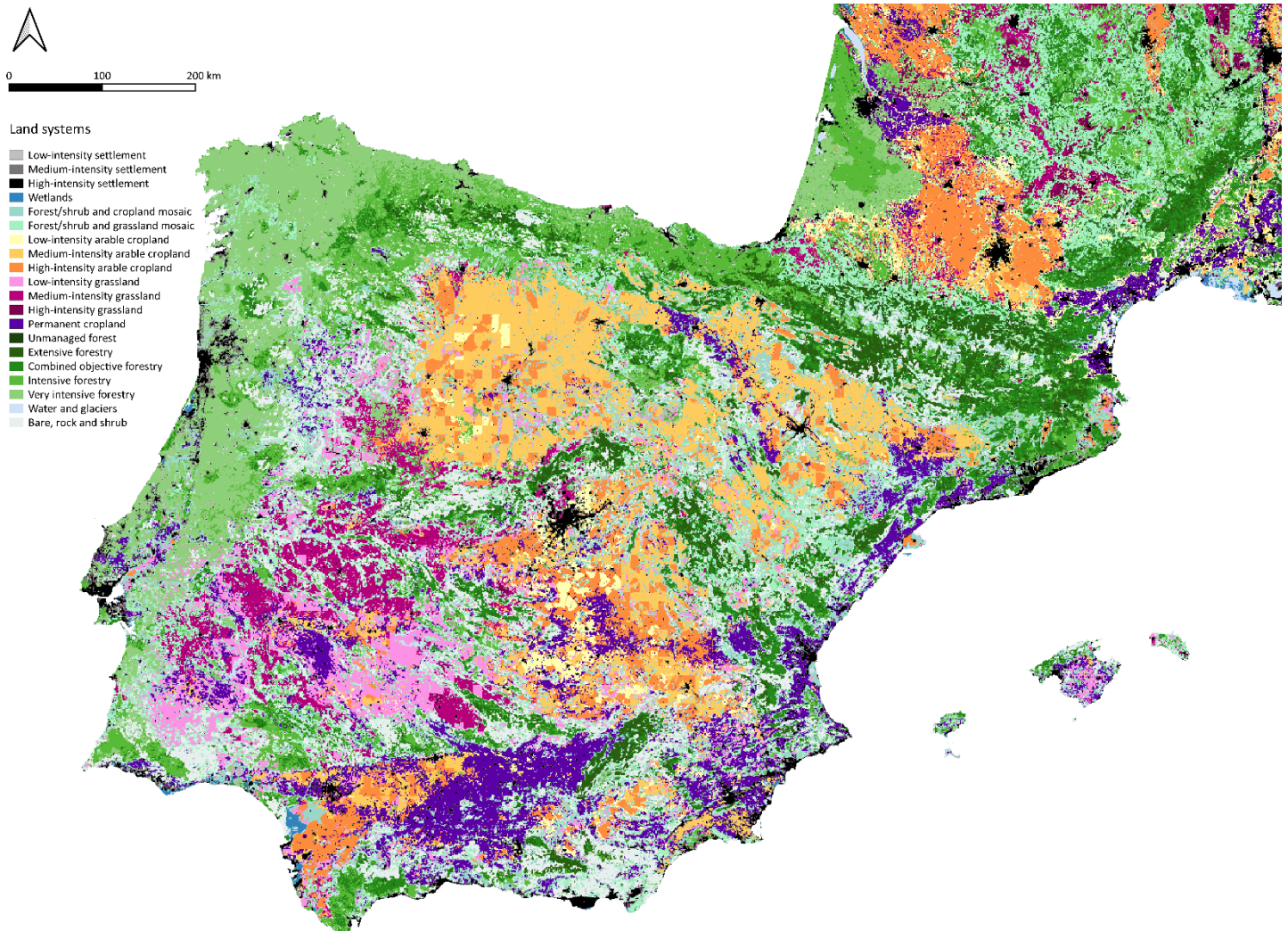


Figure B14. Competitive forest industry scenario result for the Iberian Peninsula and southwestern France in 2050.

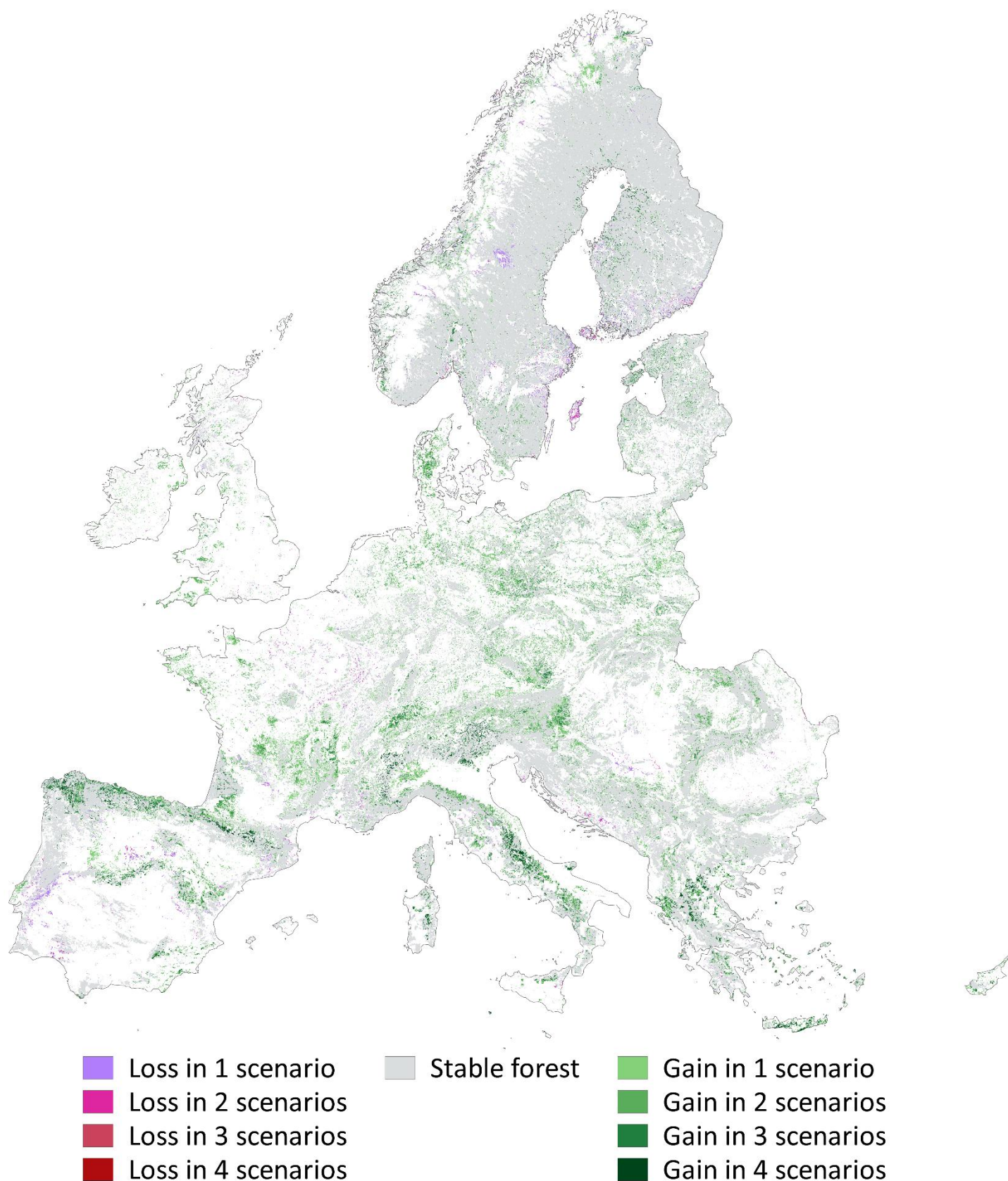


Figure B15. Spatial agreement of forest cover change across all scenarios. This map displays the full range of scenario consensus for forest gain and loss.

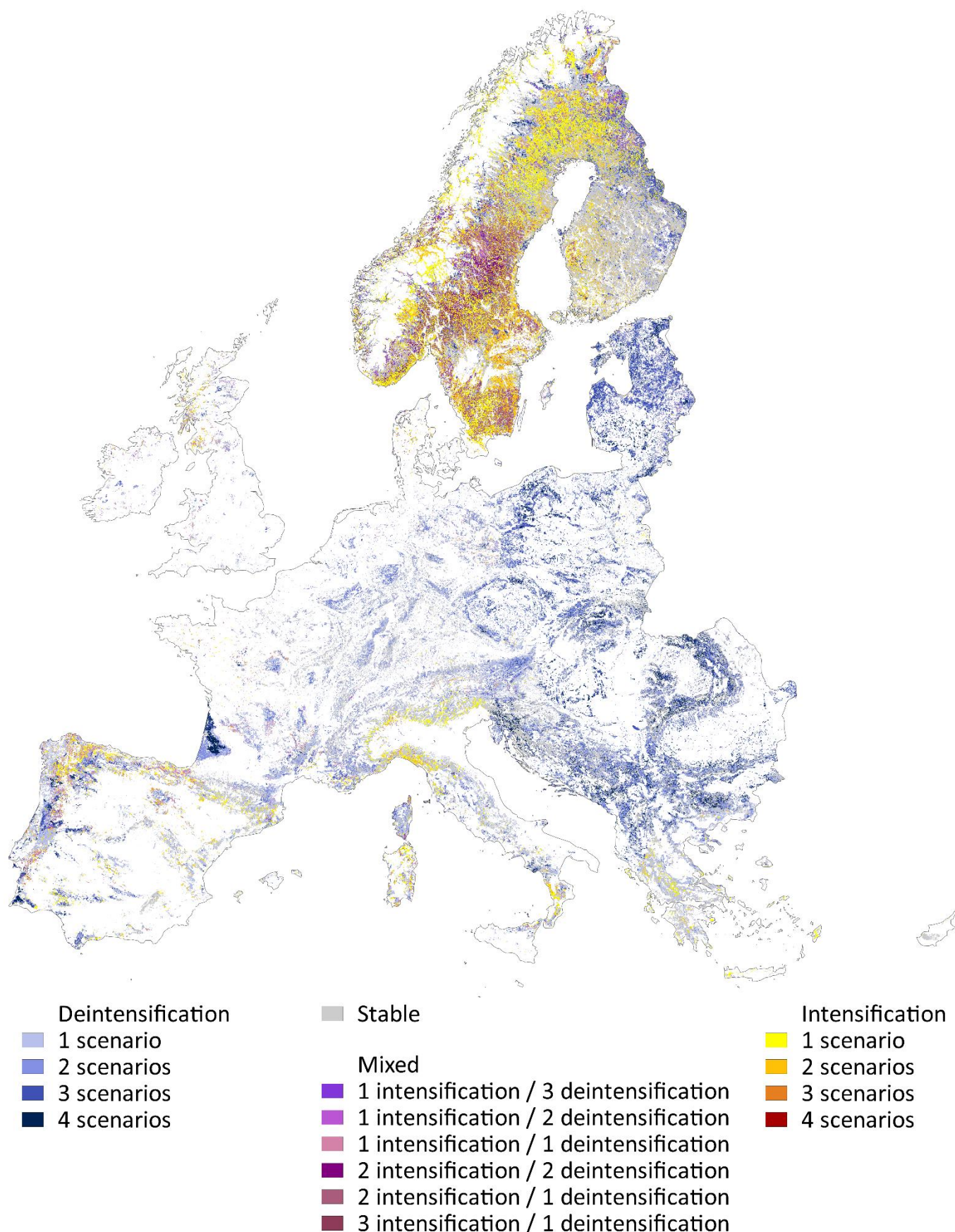


Figure B16. Comprehensive spatial agreement of forest management intensity change in persisting forests. This map illustrates all possible combinations of intensification and deintensification across the four scenarios.



VI. Annex C: Complementary trade-off and synergy analysis results

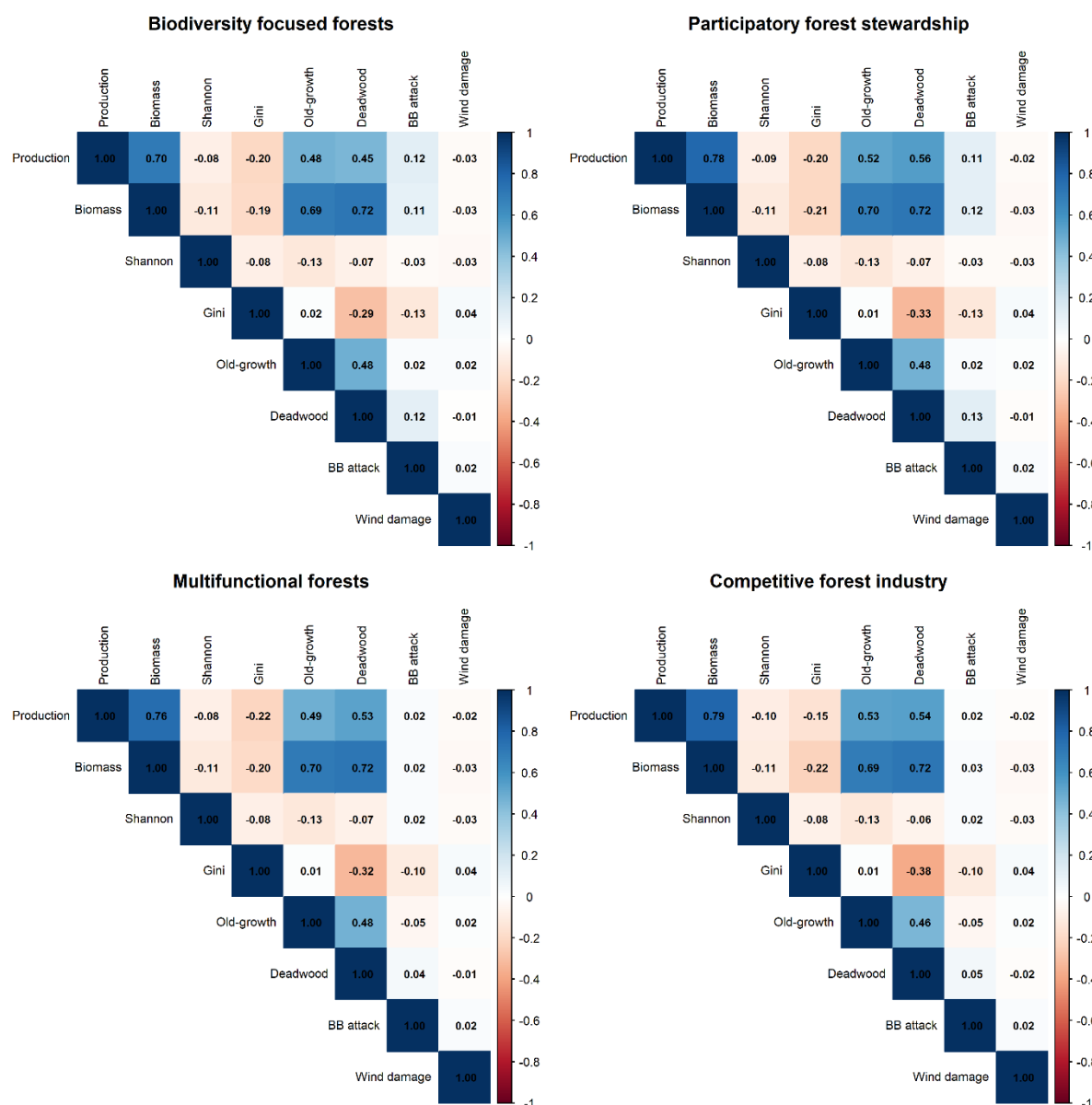


Figure C1. Pearson correlation matrix of the indicators evaluated across the four forest management scenarios for 2030. Blue denotes synergies (positive correlations) and red denotes trade-offs (negative correlations).

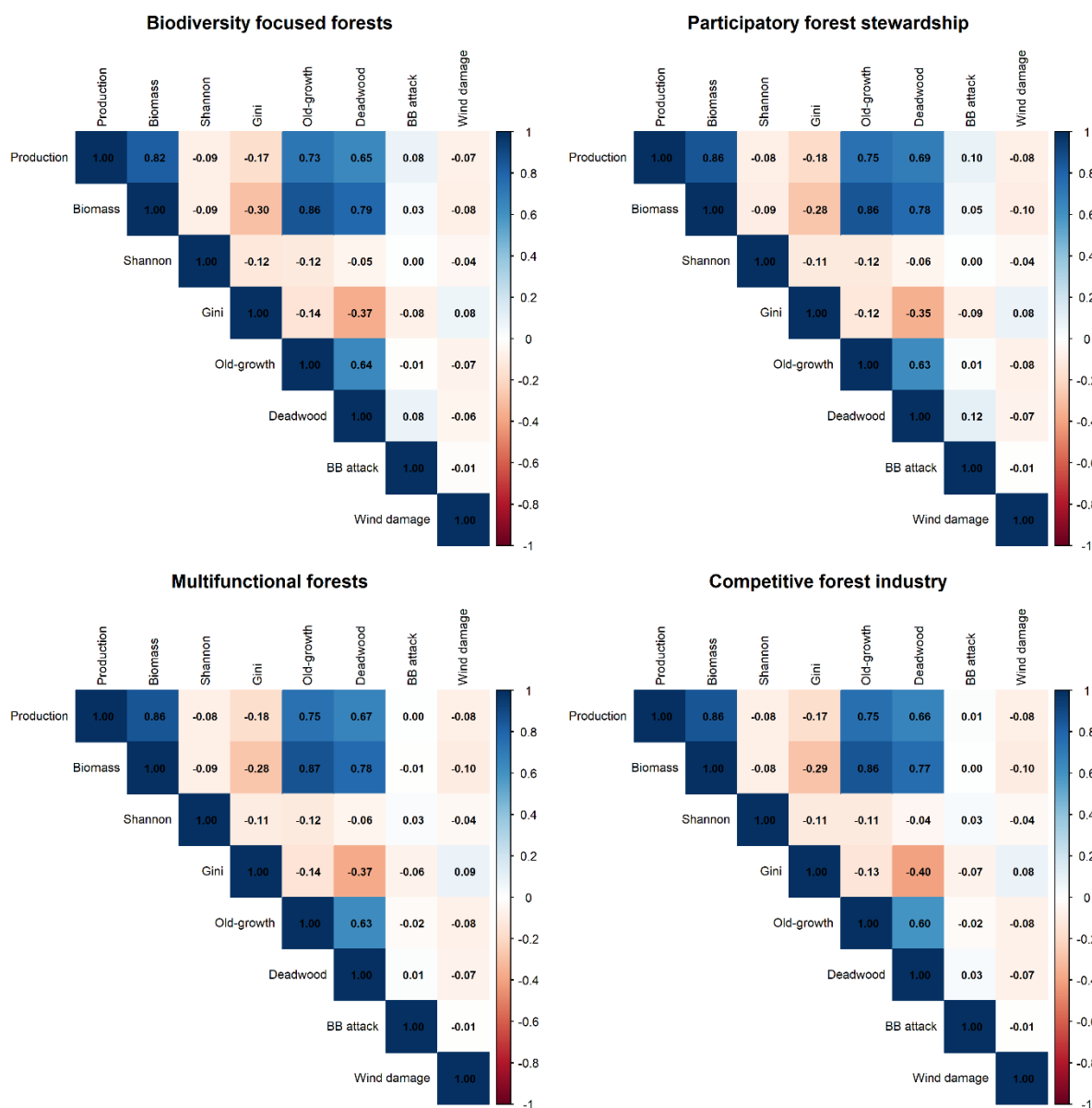


Figure C2. Pearson correlation matrix of the indicators evaluated across the four forest management scenarios for 2100. Blue denotes synergies (positive correlations) and red denotes trade-offs (negative correlations).

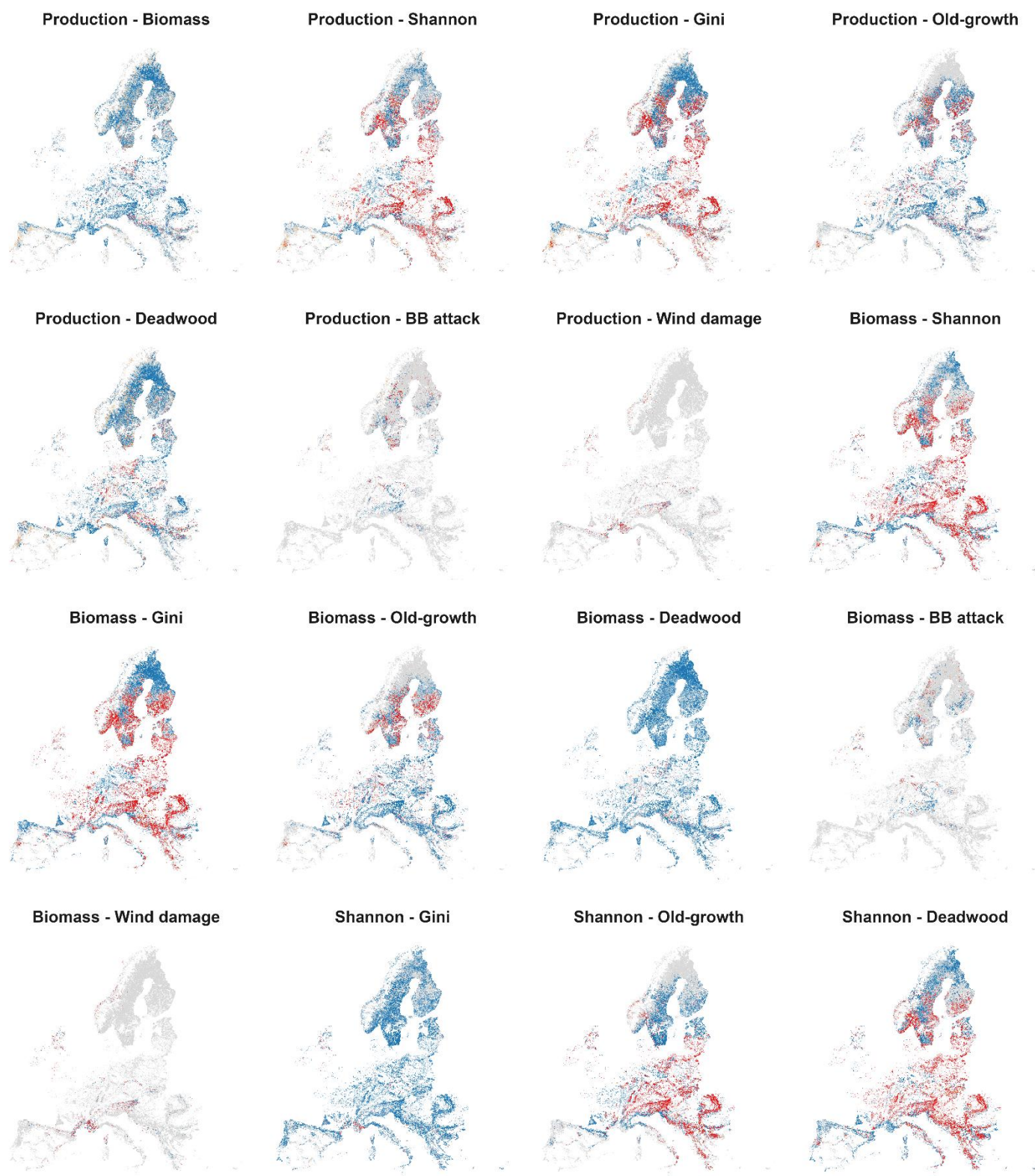


Figure C3. Spatial distribution maps of indicator pairs for the year 2030 across four forest management scenarios based on directional change thresholds. Interaction strength is classified by scenario consensus: strong synergy (same directional change in 3–4 scenarios; blue scale), weak synergy (same change in 1–2 scenarios; light blue), strong trade-off (opposite directional change in 3–4 scenarios; red), and weak trade-off (opposite change in 1–2 scenarios; orange). Panels show no interaction if results are mixed or if no interactions occurred in any scenario. (Figure continued on next page).

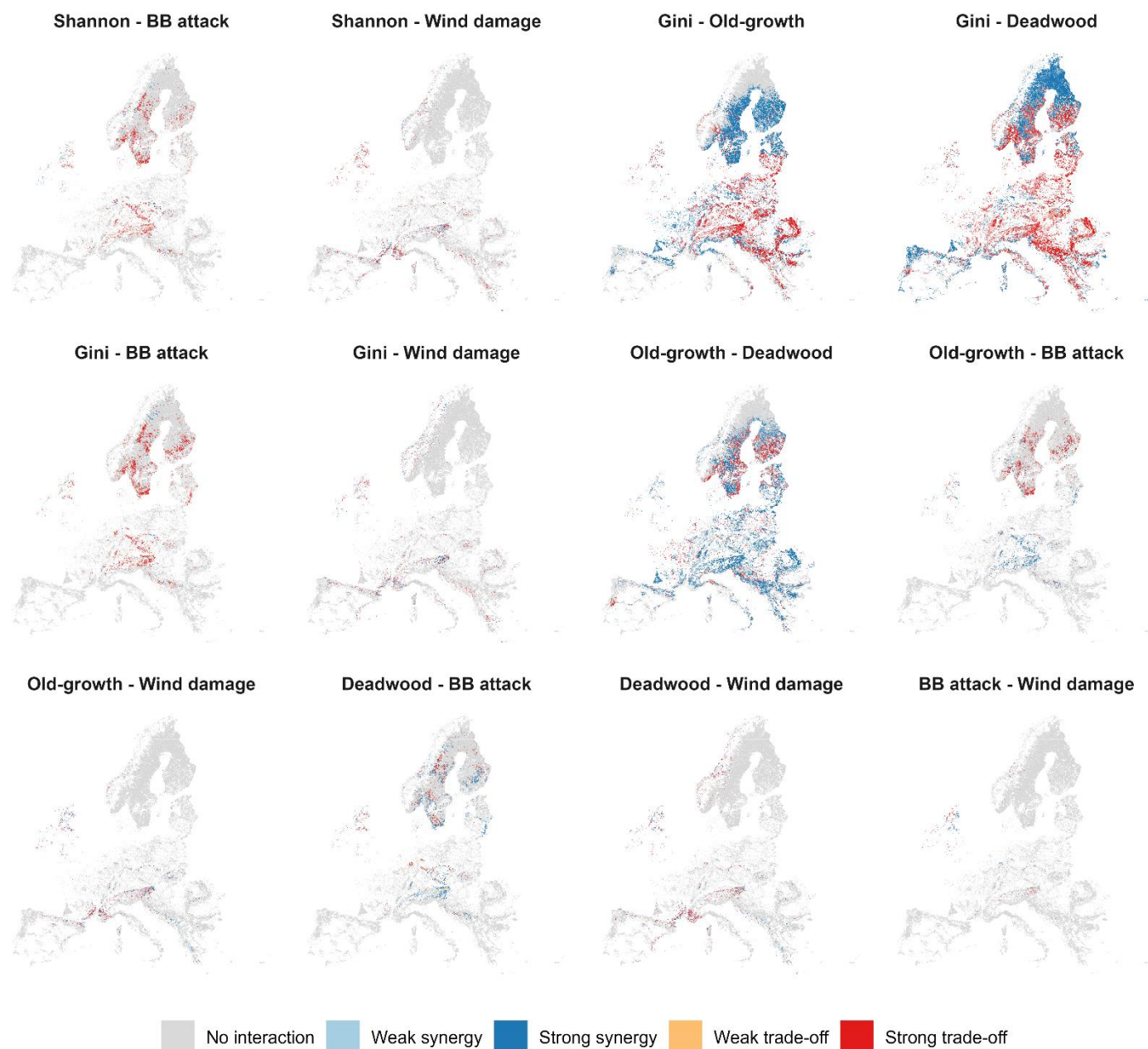


Figure C3. (Continued).

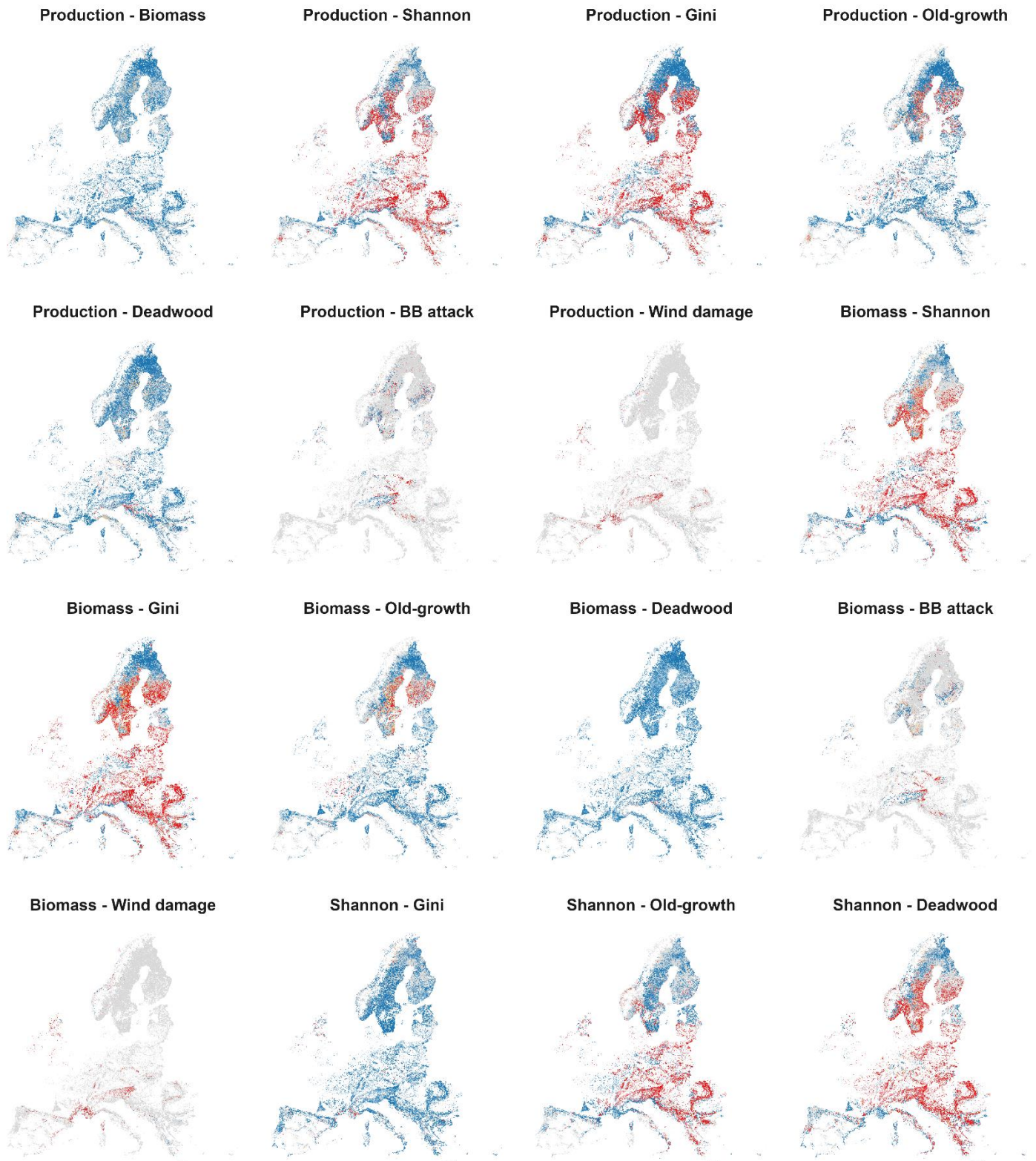


Figure C4. Spatial distribution maps of indicator pairs for the year 2100 across four forest management scenarios based on directional change thresholds. Interaction strength is classified by scenario consensus: strong synergy (same directional change in 3–4 scenarios; blue scale), weak synergy (same change in 1–2 scenarios; light blue), strong trade-off (opposite directional change in 3–4 scenarios; red), and weak trade-off (opposite change in 1–2 scenarios; orange). Panels show no interaction if results are mixed or if no interactions occurred in any scenario. (Figure continued on next page).

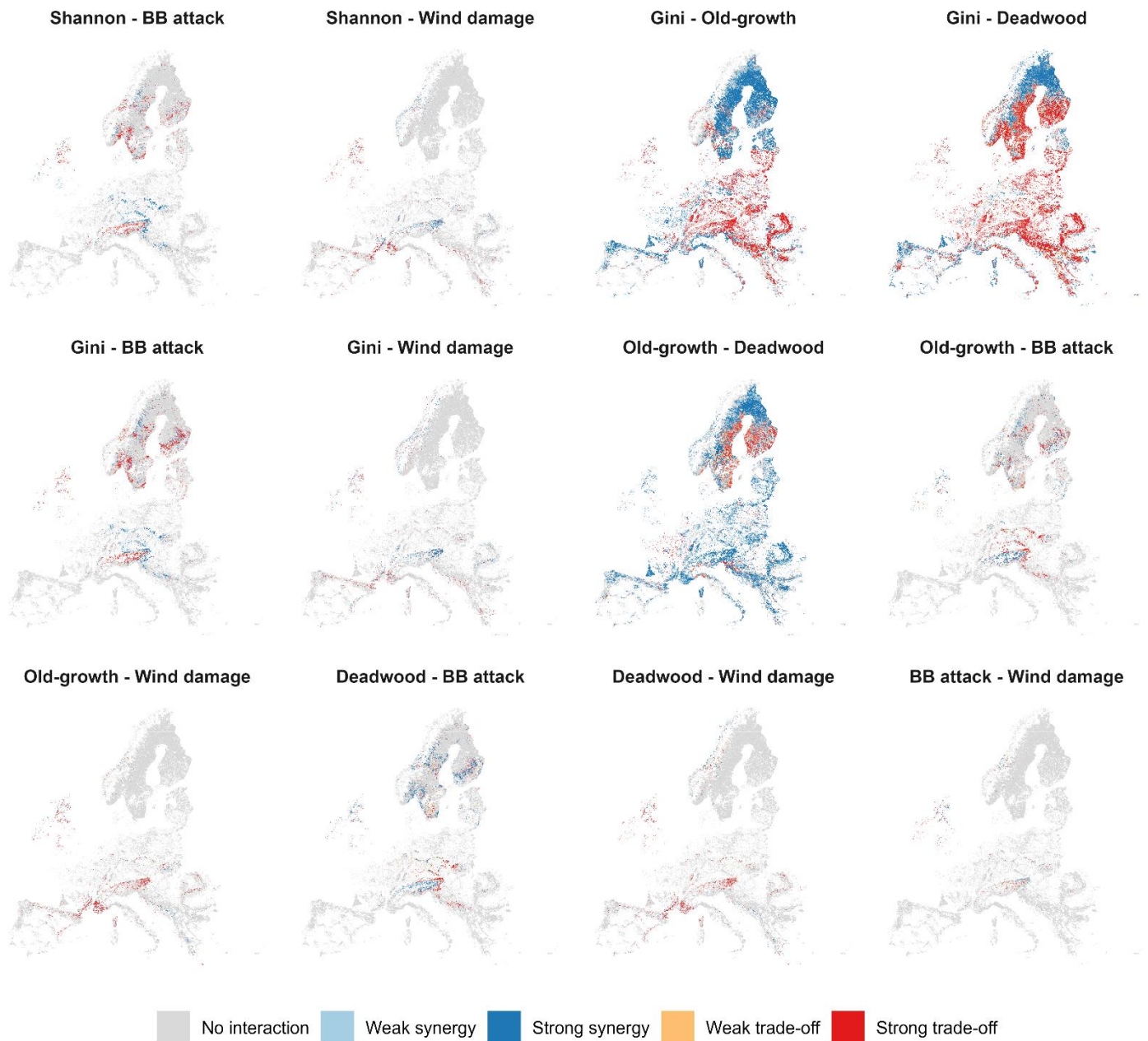


Figure C4. (Continued).