First iteration estimates of rewilding area and potential

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1. Table of Contents

1. Table of Contents ... 2
2. Executive Summary ... 4
3. Data availability ... 5
4. Keywords ... 5
5. Introduction ... 6
6. Land use scenarios framework ... 6
   6.1 IPCC Shared Socioeconomic Pathways ... 7
      6.1.1 SSP1 - Sustainability ("Taking the green road") ... 9
      6.1.2 SSP2 - Middle of the Road ... 10
      6.1.3 SSP3 - Regional Rivalry ("A road divided") ... 11
   6.2 IPBES Nature Futures Framework scenarios ... 12
      6.2.1 Nature for Nature (NfN) ... 13
      6.2.2 Nature for Society (NfS) ... 14
      6.2.3 Nature as Culture (NaC) ... 15
7. Modelling Approach ... 16
   7.1 Functionality ... 16
   7.2 Parametrisation and settings ... 17
8. Land use scenarios outcomes ... 21
   8.1 Agricultural abandonment and proforestation analysis ... 31
      8.1.1 Approach and method ... 31
      8.1.2 Results ... 34
9. Discussion ... 53
10. Limitations ... 56
11. Conclusion ... 58
12. References ... 60
13. Annex ... 66
   Technical documentation on common baseline development ... 66
   Technical documentation on scenarios storylines implementation ... 74
      SSP2 ... 74
      SSP2 – Technological innovation ... 88
      SSP2 - Planned rewilding scenario ... 91
      SSP1 ... 96
      IPBES NfN ... 107
      IPBES NfS ... 108

IPBES NaC 109
SSP3 110
Annex references 122

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2. Executive Summary

Background: This deliverable (D1.1) presents the first iteration of EU-scale estimates of potential rewilding areas, developed within Work Package 1 (WP1) of the WILDCARD project. It examines where, and to what extent, land in Europe could become available for rewilding as result of agricultural abandonment and reduced forest management (proforestation). This analysis provides the foundation for subsequent deliverables that will assess trade-offs, biodiversity outcomes, and policy implications, and is designed to incorporate new insights generated across WILDCARD's WPs. While the specific rewilding scenario will undergo further refinement and potential variations in light of findings from WP2, 3 and 4, the other scenarios presented here can be considered final. The next Deliverable 1.3 will therefore only present final versions of the rewilding scenario(s) after updating.

Objectives: The objective of this deliverable is to quantify and map the spatial probability of rewilding across Europe under multiple socioeconomic and environmental futures. The work aims to identify hotspots of forest regeneration and rewilding arising from set-aside forests (proforestation) and agricultural abandonment, thereby providing an initial, spatially explicit understanding of how rewilding opportunities vary across regions and scenarios.

Methods: Future land-use change scenarios were simulated using the CLUMondo model, a spatially explicit dynamic land system framework that allocates land-use transitions based on biophysical suitability, socioeconomic demand, and specific conversion rules. Eight scenarios were developed, drawing on the IPCC Shared Socioeconomic Pathways (SSPs) and the IPBES Nature Futures Framework (NFF), representing different combinations of technological development, governance structures, and policy ambition. The model projected land-use trajectories for the period 2020–2050 at a spatial resolution of 1 km². Rewilding-related processes were represented as three main categories of land-use transitions: **proforestation**, referring to the conversion of managed forests into close-to-nature forests; **agricultural abandonment and rewilding**, describing the conversion of croplands, grasslands, and mosaic systems into natural forests; and **agricultural abandonment**, indicating the shift from agricultural systems to combined-objective forests. Scenario-specific outputs were then aggregated to identify areas of agreement across scenarios, which were subsequently used to derive probability maps for each process and their combinations.

Summary of results: Across all scenarios, forest recovery emerges as a dominant land-use dynamic, with the strongest signals observed along major European mountain systems and upland regions, including the Alps, Pyrenees, Carpathians, and the Dinaric–Šar–Pindus mountain arc. Proforestation is most prevalent in areas with extensive managed forest cover, reflecting reduced management intensity and a shift toward near-natural forest structures. Agricultural abandonment and rewilding is most likely to occur in marginal farmland of southern and central Europe, where cropland and grassland retreat enables natural forest regeneration. Agricultural abandonment leading to combined-objective forests is more prominent in central and eastern Europe, where land is released from agriculture but remains partly managed for multifunctional purposes. When aggregated, these processes reveal a coherent spatial pattern of forest recovery concentrated in mountainous and less productive landscapes, while intensively farmed lowlands continue to be dominated by productive systems. The resulting rewilding probability map delineates Europe's main corridors of ecological regeneration and highlights the areas with the highest potential for near-natural forest expansion.

Key messages: Rewilding potential in Europe is largely concentrated in mountainous and upland regions, where biophysical suitability coincides with ongoing land abandonment and

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forest regrowth. Under the SSP2–Planned Rewilding scenario, spatially guided and policy-driven rewilding measures generate more coherent and connected patterns of forest recovery than would occur through spontaneous dynamics alone. Forest transitions are strongly influenced by gradients in land-use intensity and policy intervention, with natural regeneration thriving in areas where agricultural and management pressures decline. These initial results provide a continental baseline for assessing Europe's rewilding potential and lay the foundation for subsequent analyses of biodiversity and climate co-benefits within the WILDCARD project.

3. Data availability

Scenario results and documentation can be downloaded from the following public repositories:

- NFF scenarios: https://doi.org/10.5281/zenodo.17476213.
- SSP scenarios: https://doi.org/10.34894/GBDS5T.

Probability maps for proforestation and agricultural abandonment will be made available in the WILDCARD WebGIS following the publication of the related paper.

4. Keywords

Rewilding, agricultural abandonment, land-use change, spatial modelling, future scenarios, forest regeneration, proforestation, wilderness

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5. Introduction

Within Work Package 1 (WP1), Task 1.1 " Land use scenarios" focuses on iteratively refining scenarios of potentially available land for rewilding. Deliverable 1.1 (D1.1) presents the first iteration of EU-scale estimates and maps indicating where, and how much, land is likely to become available for rewilding, through agricultural abandonment and reduced forest management (proforestation). The Task relies on the CLUMondo land use modelling framework to generate plausible, spatially explicit estimates of the rewilding probability at high spatial and temporal resolution. Outputs are provided as EU-wide 1 km² raster maps and related analysis.

The CLUMondo framework is used to quantify trajectories that create rewilding opportunities, with results designed to directly inform Task 1.4 (policy recommendations). D1.1 represents the first step in WP1's role as the integrator of project findings. WP1 iteratively synthesizes new evidence from WPs 2–5 to refine estimates from rewilding potential, expanding from available area to contributions towards climate and biodiversity targets, as reflected in the project's workplan and milestones. This work directly connects to later WP1 deliverables: D1.2 (trade-off assessment, M48), D1.3 (final estimates and priority regions, M48), D1.4 (four policy briefs, M48), and D1.5 (White Paper, M40), with additional inputs and validation provided through the WILDCARD Rewilding Forum in WP5. Because WP1 is designed to incorporate new biophysical, socio-economic and stakeholder information as it becomes available, the specific rewilding scenario presented in D1.1 may be refined and expanded in subsequent deliverables and in routine project communication and data-management updates.

6. Land use scenarios framework

In this deliverable we adopt the climate-scenario setup used in recent IPCC assessments, pairing Shared Socioeconomic Pathways (SSPs) with Representative Concentration Pathways (RCP) to generate integrated futures scenarios. This approach follows the scenario matrix architecture, which positions socioeconomic development pathways on one axis and climate forcing targets on the other, enabling consistent analysis of impacts, adaptation and mitigation across models (van Vuuren et al., 2014; Lee et al., 2021). The SSPs provide policy-neutral socioeconomic worlds — defined through narratives and quantified drivers such as population, education, technology, institutions — and inequality, and are designed to span different challenges to mitigation and adaptation (O'Neill et al., 2017; Riahi et al., 2017). We use them as the baseline context for land-use demand and development patterns.

These socioeconomic worlds are then coupled to forcing pathways (RCPs). For this purpose, we used multi-model climate projections from CMIP6/ScenarioMIP (e.g., SSP1-2.6 and SSP3-7.0) as exogenous climatic drivers (temperature, precipitation, etc.) in our model (van Vuuren et al., 2011; O'Neill et al., 2016).

Alongside the climate/economy framing, we draw on the IPBES Nature Futures Framework (NFF) to include desirable, nature-positive futures built around diversified values of nature: Nature for Nature (NfN), Nature for Society (NfS), and Nature as Culture (NaC). The NFFs support the development of nature-centric scenarios that reflect the plurality of human-nature relationships to inform context- and place-specific policy options aimed at achieving a good quality of life in balance with nature (IPBES, 2023; Pereira et al., 2020). As these are inherently sustainable futures, we base the NFF scenarios on SSP1. In our framework, SSP1 is positioned at the centre of the NFFs triangle, representing a sustainability vision that gives

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balanced consideration to intrinsic (NfN), societal (NfS), and cultural (NaC) values of nature, without prioritising any single one.

Practically, the SSP+RCP combinations provide the macro-level context and climate signals that shape future pressures and opportunities (e.g., population, trade, technology, mitigation). The NFF then adds a finer-grained biodiversity goals and value orientations, specifying the conservation and restoration levers emphasized in each scenario. In Figure 1, we provide a visual representation of the scenario set, including two additional variants developed for this project: SSP2 Technological innovation (T.I) and SSP2 Planned rewilding (P.R).

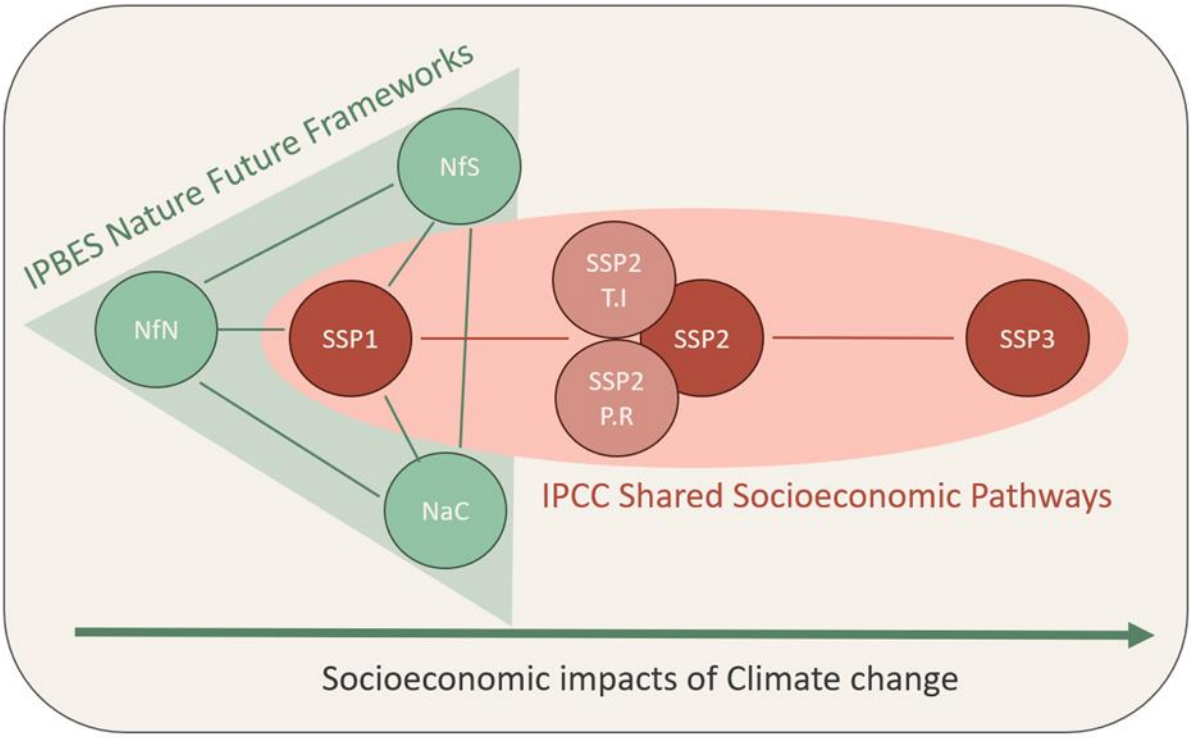

Figure 1: Visual representation of SSP and NFF scenarios (own interpretation, inspired by O'Neill et al., 2017; Pereira et al., 2020). SSP2 T.I = SSP2 Technological innovation. SSP2 P.R = SSP2 Planned rewilding.

6.1 IPCC Shared Socioeconomic Pathways

The IPCC defines five different scenarios, spanning a range of possible socio-economic futures from more sustainable pathways to more consumption-heavy possibilities:

- SSP1 - Sustainability ("Taking the green road")
- SSP2 - Middle of the road
- SSP3 - Regional rivalry ("A rocky road")
- SSP4 - Inequality ("A road divided")
- SSP5 - Fossil-fueled development ("Taking the highway")

In this deliverable, we focus on SSP1, SSP2, and SSP3. Building on O'Neill et al. (2017), Table 1 provides a summary of the main assumptions characterizing these scenarios along with our two SSP2 variants (SSP2 Technological Innovation and SSP2 Planned Rewilding).

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Table 1: Main assumptions that characterize our scenarios.

	SSP1	SSP2	SSP3	SSP2 – Technological innovation	SSP2 -Planned rewilding
Overall storyline	Inclusive, sustainable development; effective governance; cooperation and environmental stewardship.	Continuation of current trends; gradual progress; moderate sustainability.	Fragmented world; weak cooperation; inequality and high environmental pressure.	Continuation of current trends; gradual progress; moderate sustainability.	Continuation of current trends; gradual progress; moderate sustainability.
Climate pathway	RCP 2.6 – low emissions	RCP 4.5 – intermediate emissions	RCP 7.0 – high emissions	RCP 4.5 – intermediate emissions	RCP 4.5 – intermediate emissions
Population & Human development	Low population, high education & health, equitable development.	Medium population, moderate education & health progress.	High population, uneven education & health progress.	Same as SSP2.	Same as SSP2.
Economy & Inequality	Green, inclusive, less material-intensive growth.	Moderate growth, persistent but declining inequality.	Slow, unequal, regionally fragmented growth.	Same as SSP2.	Same as SSP2.
Energy & Technology	Clean energy, electrification, high efficiency.	Gradual efficiency improvements; fossil fuels remain relevant.	Fossil-fuel-dominated, low innovation.	Similar to SSP2, with greater impact or technological innovation on agriculture.	Same as SSP2.
Governance & Policy	Strong international cooperation, effective institutions, investment in public goods.	Moderate governance improvements; slow tightening of environmental regulation.	Weak, fragmented governance; nationalism and deregulation.	Same as SSP2.	Same as SSP2.
Land-use regulation	Strong regulation; deforestation reduced; restoration encouraged.	Existing protections maintained (e.g., Natura 2000); limited new expansion.	Weak regulation; small isolated protected areas vulnerable.	Same as SSP2.	Same as SSP2.
Agriculture	Intensification on existing land; dietary shifts toward less meat and less waste, subsidies to sustainable agriculture.	Intensification over expansion; diets still contain more meat.	Expansion due to stagnation in productivity; pressure on land; spatially limited intensification.	Similar to SSP2, with moderate projected increase of yield productivity.	Similar to SSP2, with spatially targeted agriculture subsidies outside of core high potential rewilding areas.
Forestry	Shift to close-to-nature and combined-objective management; existing natural	Mix of close-to-nature, combined, and intensive forestry.	Forest loss and management intensification.	Same as SSP2.	Similar to SSP2, with spatially planned forest rewilding/restoration concentrated in high potential areas.

	forests protected.				
Urbanisation	Compact and dense; minimize sprawl.	Densification (low-to-high density); no deurbanisation.	Uncoordinated, sprawling urban growth.	Same as SSP2.	Same as SSP2.
Restoration focus	Targeted restoration of forests and wetlands.	Limited to baseline protection; moderate intensification logic.	Limited restoration; weak enforcement.	Same as SSP2.	Similar to SSP2, with forest rewilding and restoration focused exclusively inside core high potential rewilding areas, leaving opportunities for intensification outside.
Spatial targeting & connectivity	Maintain natural cores and connect through restoration.	Maintain existing protected networks; moderate connectivity.	Fragmented protection; reduced connectivity.	Same as SSP2.	Similar to SSP2, but with rewilding efforts spatially concentrated to enhance connectivity among emerging natural areas.

6.1.1 SSP1 - Sustainability ("Taking the green road")

SSP1 – Sustainability ("Taking the Green Road") envisions a world steadily transitioning toward inclusive and sustainable development. In this scenario, institutions are effective and cooperative, inequality declines, and societies prioritize well-being and environmental stewardship. Consequently, SSP1 experiences low challenges to both mitigation and adaptation compared with other SSPs (O'Neill et al., 2017; Riahi et al., 2017).

Socio-demographically, rapid improvements in education and health accelerate the demographic transition, resulting in a lower global population by 2100 and higher human capital, particularly in today's lower-income regions (KC and Lutz, 2014). Economically, growth is broad-based but less material- and energy-intensive, driven by efficiency, circularity, and sustainability-oriented consumption and trade patterns (O'Neill et al., 2017).

In the energy system, technological innovation and rapid diffusion favour clean energy, electrification, and end-use efficiency, leading to lower overall energy demand and reduced carbon intensity relative to other futures (Riahi et al., 2017).

In land systems, stronger regulation, reduced deforestation, rising agricultural yields, dietary shifts toward lower meat consumption, and reduced food waste collectively reduce pressure on land, enabling both land-based mitigation and biodiversity co-benefits (Popp et al., 2017).

Governance is characterized by international cooperation, investment in public goods (education, health, ecosystem management), and improved management of global commons, underpinning SSP1's relatively favourable climate-risk profile (O'Neill et al., 2017).

Quantitatively, our implementation of SSP1 translates these into a reference world paired with lower emissions pathway (RCP 2.6), where climate change is projected to have limited impacts on human activities. For each land system type, the model is parametrized to reflect the key characteristics of SSP1 storyline. Natural forests and wetlands are safeguarded, with targeted restoration promoted; forestry is shifted toward close-to-nature and combined-objective management while avoiding conversion into productive areas; agricultural intensification is prioritized on existing land rather than expansion, with additional safeguards in high-biodiversity areas; and guide urban growth is guided toward compact development to limit sprawl.

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Collectively, these rules reduce land-use pressure and embody SSP1's sustainability narrative of lower material intensity, stronger environmental governance, and declining deforestation. Because the IPBES NFFs scenarios are also modelled using SSP1-driven demands (cf. section 2.2), this SSP1 scenario is designed to represent the centre of the NFFs triangle, assigning equal weight to the three different value perspectives of nature.

6.1.2 SSP2 - Middle of the Road

6.1.2.1 SSP2 – Baseline

SSP2 – Middle of the Road depicts a world broadly following historical trends, with intermediate challenges to mitigation and adaptation. Development progresses unevenly, institutions and international cooperation improve modestly, and sustainability ambitions rise only gradually, positioning SSP2 as a "middle" pathway between SSP1 and SSP3 (Fricko et al., 2017; O'Neill et al., 2017).

Socio-demographically, education and health advance at moderate rates, resulting in intermediate population outcomes (global population peaking mid-century and reaching around 9 billion by 2100 according to KC & Lutz (2014)), and human capital improves, though more slowly than in SSP1. Economically, SSP2 assumes moderate global growth with persistent, gradually declining inequalities across and within regions (Dellink et al., 2017).

Energy and technology evolve through incremental efficiency gains and a gradual shift toward cleaner systems, yet fossil fuels remain significant in the absence of strong climate policies (Fricko et al., 2017; Riahi et al., 2017). In land use and food systems, agricultural demand rises with population and income, deforestation declines more slowly than in SSP1, yields improve moderately, and dietary change/waste reductions are limited, resulting in intermediate land-use change and emissions relative to other SSPs (Popp et al., 2017).

Governance and policy progress gradually rather than transformatively: environmental regulation tightens slowly, trade remains partially open but uneven, and institutions are not consistently effective, contributing to the "middle-of-the-road" risk profile (O'Neill et al., 2017).

In our implementation of SSP2, these narratives are translated into a reference world paired with intermediate emissions projections (RCP 4.5), which remain relatively high compared to Paris Agreement target. The scenario is modelled as a Business as Usual (BAU) pathway: current land protection regulations are respected (e.g., Natura 2000 reserves) and conversion to productive systems is not allowed, while urban growth occurs through densification (ranging from low to medium to high density) without de-urbanization.

Wetlands remain largely static in the baseline, with limited conversions occurring only outside protected areas. Croplands and grasslands follow an intensification-over-expansion approach, with conversion resistance increasing with land use intensity, whereas mosaic ecosystems remain dynamic and convertible to neighbouring production or nature classes.

Forests are managed across close-to-nature, combined-objective, and intensive categories; management type switches are permitted, with rotation-length constraints applied to intensive systems. High-intensity agriculture, forestry and dense urban areas are encouraged to aggregate spatially.

Collectively, these rules produce a "middle-of-the-road" pattern characterized by moderate protection, compact urban growth, and productivity gains primarily achieved through intensification rather than expansion into new land.

6.1.2.2 SSP2 – Technological innovation

As an alternative to the BAU SSP2 scenario, we also parametrised a SSP2-driven scenario incorporating exogenous technological innovation in agricultural practices, as assumed within the GLOBIOM Partial Equilibrium Model and similar integrated assessment models (van Zeist et al., 2020). This scenario closely follows the structure of the baseline BAU SSP2 scenario, with innovations expected to increase crop yields under management intensity. Higher yields reduced agricultural land demand, creating new opportunities for land abandonment.

The technological innovation variant was applied exclusively to SSP2, as the assumptions underpinning SSP1 and SSP3 were considered unsuitable. In SSP1, high-intensity cropping systems are minimal, so technological improvements have little effect. In SSP3, the scenario envisions a fragmented, "rivalrous" world where technological progress, innovation, and diffusion are limited, preventing yield gains from technological change. The SSP2 – Technical innovation scenario is particularly relevant for rewilding studies, as increased yields free up agricultural land, potentially highlighting new locations suitable for rewilding implementation.

6.1.2.3 SSP2 – Planned rewilding

As a targeted "WildCard" scenario, we developed a SSP2-driven scenario (without technological innovation) designed to reflect a dedicated strategy for festering rewilding. In this scenario, agricultural abandonment and proforestation transitions are given a clearer spatial orientation.

In the baseline SSP futures—whether more or less sustainable—rewilding occurs largely passively, without explicit planning or targeted interventions. By contrast, the Planned Rewilding scenario envisions a future in which rewilding is purposefully targeted, spatially coordinated, and more actively implemented, prioritizing areas with the highest potential for success. Vegetation regrowth and forest-succession dynamics in selected locations are supported by active implementation measures. Within this exploratory scenario, such interventions are facilitated by a restructuring of agricultural subsidy distribution, redirecting support toward farming activities outside core areas of high rewilding potential (own data; Kloibhofer et al., 2025). This approach encourages land-use deintensification and abandonment within the core areas. Areas are defined as having "high rewilding potential" if they offer the greatest likelihood rewilding with minimal human intervention, considering factors such as ecological quality and practical feasibility.

6.1.3 SSP3 - Regional Rivalry ("A road divided")

SSP3 – Regional Rivalry ("A Rocky Road") depicts a fragmented world characterized by resurgent nationalism and security-first politics, where international cooperation is weak, institutions are often ineffective, and both climate mitigation and adaptation face high challenges (O'Neill et al., 2017). Human development advances unevenly: education and health investments lag in many regions, fertility declines more slowly, and population grows higher than in other SSPs, particularly in developing countries (KC and Lutz, 2014). Economically, growth is slower and regionally focused, trade barriers are elevated and inequalities persist (van Vuuren et al., 2017; Dellink et al., 2017). Technological change is limited, the energy system remains fossil-fuel-reliant with higher energy and carbon intensity, and efficiency gains are modest, resulting in higher emissions compared with sustainability-oriented pathways (Riahi et al., 2017).

In land systems, weak governance, limited environmental regulation, and low agricultural productivity growth — combined with rising demand — translate into greater pressure for agricultural expansion and higher land-use-dependent emissions, while deforestation is less constrained than in SSP1 (Popp et al., 2017).

In our implementation of SSP3 ("Regional Rivalry"), the scenario is paired with high emissions projections (RCP 7.0). The storyline of weak international cooperation and elevated land-use pressure is operationalized through rules tied to climate stress and protection strength. Agricultural intensification and expansion are constrained by increasing aridity: extremely dry areas deemed are considered unsuitable and areas projected to become drier are generally deprioritized (Zomer and Trabucco, 2024). To reflect weaker environmental governance, we relax certain protected-area regulations, allowing limited conversion within small protected sites (≤10 km²) to low-intensity uses, while maintaining stricter rules for larger sites, consistent with evidence that smaller, fragmented sites are more exposed to surrounding pressures (Li et al., 2024).

Finally, land use intensification is favoured in climatically suitable regions, and conversions leading to forest loss and intensified management are permitted. Combined with aridity constrains, these rules produce the patchy protection patterns and higher residual land-use pressure characteristic of SSP3.

6.2 IPBES Nature Futures Framework scenarios

The Nature Futures Framework (NFF) was developed as a heuristic tool to support the creation of transformative, multiscale scenarios aimed at achieving biodiversity conservation and sustainability goals (Pereira et al., 2020). The NFF captures a plurality of perspectives on desirable futures for nature using a triangular representation, with the corners representing three fundamental value perspectives on human-nature relationship (Kim et al., 2023, Pereira et al., 2020): Nature for Nature (NfN), Nature for Society (NfS), and Nature as Culture (NfC).

These three perspectives were further elaborated in the European context to align with EU policy objectives, plausible socio-economic developmental pathways (SSP1), and the global objectives of the Convention on Biological Diversity. The fully developed European NFF storylines are then translated into spatially explicit land-use change scenarios using the CLUMondo model (D'Alessio et al., 2025). Table 2 provides a summary of the main assumptions characterizing the NFF scenarios.

Table 2: Main assumptions that characterize our scenarios. NfN = Nature for Nature; NfS = Nature for Society; NfC = Nature as Culture.

	NfN	NfS	NaC
Overall storyline	Intrinsic value of nature; self-regulating ecosystems; land sparing.	Utilitarian value; nature managed for ecosystem services; multifunctional landscapes.	Cultural and relational values; land sharing; biocultural landscapes.
Climate pathway	RCP 2.6 – low emissions	RCP 2.6 – low emissions	RCP 2.6 – low emissions
Population & Human Development	Aligned with SSP1 (low population pressure).	Aligned with SSP1 (low population pressure).	Aligned with SSP1 (low population pressure).
Economy & Inequality	Economic activity secondary to conservation.	Economic activity tied to ecosystem service provision.	Economic activity embedded in local, cultural land practices.
Energy & Technology	Same clean-energy context as SSP1 baseline.	Same clean-energy context as SSP1 baseline.	Same clean-energy context as SSP1 baseline.

Governance & Policy	Strict protection and regulation; strong governance for nature.	Integrated governance balancing human and ecological goals.	Local, community-based stewardship; flexible governance.
Land-use regulation	Strict protection and restoration; minimal conversion.	Balanced protection and use; multifunctional land management.	Flexible transitions among low-intensity systems; cultural landscape preservation.
Agriculture	Human land use minimized; intensification in existing areas only.	Moderate-intensity, mosaic-type agriculture for ecosystem services.	Low-intensity, traditional farming integrated with nature.
Forestry	Restore/maintain natural forests; no new productive forestry.	Promote combined-objective and close-to-nature forests.	Promote selectively used forests; maintain cultural forests stable.
Urbanisation	Compact, dense urban growth.	Compact cities around multifunctional landscapes.	Promote low-density sprawl with nature-mixed settlements.
Restoration focus	Restoration in biodiversity and corridor areas; land-sparing.	Restoration along regulating-service corridors; connectivity focus.	Restoration in culturally significant corridors; community-based projects.
Spatial targeting & connectivity	Priority: Natura 2000 + large-mammal corridors + key biodiversity areas.	Priority: corridors + Natura 2000 + regulating-service areas.	Priority: Natura 2000 + corridors + cultural-service areas.

6.2.1 Nature for Nature (NfN)

Figure 2: Artist's impression of the Nature for Nature scenario

The "Nature for Nature" (NfN) perspective depicted in Figure 2 (Fornarini et al., 2024) centres on the intrinsic value of nature, recognizing its worth beyond benefits provided to humans. This storyline prioritizes the preservation of natural areas with minimal human intervention, allowing ecosystems to function autonomously. Key strategies include limiting infrastructure expansion and reducing land-intensive activities such as biofuel production, thereby creating more space for wilderness. The overarching objective is to foster self-regulating ecosystems, emphasizing rewilding, disturbance resilience, and the minimization of extractive activities.

In our scenario implementation, the NfN perspective is operationalized through a land-sparing approach that concentrates human land uses in already-modified areas, freeing up the lagest possible contiguous space for species and natural processes. Technically, the types of land-use conversions remain those permitted under SSP1, but spatial prioritization for protection and nature development is reinforced using a composite of Natura 2000 sites (EEA, 2022), large-mammal connectivity corridors (Dertien, 2021), and biodiversity-important areas (O'Connor et al., 2021). Where this priority network overlaps intact nature, it is kept undisturbed; where it intersect human-modified landscapes, it becomes a restoration target, guiding transitions towards more natural forests and wetlands.

Consistent with land sparing logic, mosaic systems are actively reduced in NfN, and urban land cover is steered toward compact, dense development rather than sprawl. Wetland

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restoration is supported by identifying potential wetland areas and prioritizing those currently used for agriculture for rewetting. Taken together, these measures implement NfN as a strategy of strict protection and ecological restoration where nature exists — or is expected to recover — and of efficiency and densification in areas already dominated by human activities.

6.2.2 Nature for Society (NfS)

Figure 3: Artist's impression of the Nature for Society scenario

The "Nature for Society" (NfS) perspective depicted in Figure 3 (Fornarini et al., 2024) emphasizes the utilitarian and instrumental values provided by nature, focusing on the enhancement of Nature's Contributions to People (NCP). In this storyline, landscapes are managed to maximize the services they provide, integrating natural and human land use through the creation of multifunctional landscapes — including mosaics and combined objective forests — that benefit both people and nature. The overarching goal is to sustainably manage these landscapes so they deliver essential services such as pollination, carbon sequestration, flood regulation, and recreation, ensuring that nature supports both environmental integrity and societal well-being.

In our scenario implementation, the NfS storyline operationalizes these principles by orienting land-use change toward enhancing regulating ecosystem contributions. We construct a spatial priority network by combining wildlife corridors and the Natura 2000 network with areas important for regulating ecosystem services (from O'Connor et al., 2021). Where this network overlaps existing natural cover, those areas remain stable; where it falls within human-modified landscapes, it becomes a restoration target. Restoration in NfS prioritizes close-to-nature and combined-objective forests, wetlands, and — distinctly from NfN — mosaic systems that support local regulating services.

Urban development follows a compact-city approach, favouring densification over sprawl. Agricultural areas move away from extremes of high input or high intensification, incorporating more mosaic and low-intensity configurations that jointly deliver production and regulating services. Overall, NfS yields more multifunctional landscapes around settlements while securing natural core areas and reconnecting them through restoration along key ecological corridors.

6.2.3 Nature as Culture (NaC)

Figure 4: Artist's impression of the Nature as Culture scenario

The "Nature as Culture" (NaC) perspective illustrated in Figure 4 (Fornarini et al., 2024), emphasizes the deep relational values between nature and people, focusing on the cultural, spiritual, and community connections that humans have with the environment. This storyline prioritizes traditional land-use practices and experiences that foster a strong personal bond with specific landscapes, such as Farm to Fork initiatives, biodiversity-friendly farming, and pilgrimage routes. By embedding nature within cultural and spiritual practices, the NaC perspective promotes a society where nature-centered education, stewardship, and lifestyles are fundamental. Key strategies include fostering the heterogeneity of cultural landscapes across Europe and promoting a land-sharing approach that integrates nature within human-managed systems. The overarching aim is to strengthen community-based management and transitions that deepen human-nature relationship.

Operationally, NaC prioritizes nature for its cultural significance, favouring integrated human–natural systems. As such, mosaic landscapes and selectively used forests are encouraged to maintain historically valued landscapes and culturally embedded land-use traditions. The NaC spatial priority network combines Natura 2000 areas, wildlife corridors, and regions important for cultural ecosystem services (O'Connor et al., 2021). Where this network overlaps existing natural cover, forests and wetlands are kept stable; where it intersects heavily modified landscapes, it becomes a restoration focus, particularly along culturally significant corridors and within protected-area contexts.

At the same time, the model allows flexible transitions among low-intensity systems, reflecting their cultural value and multifunctional character. Forests and wetlands remain largely unchanged, as they provide cultural benefits most effectively when conserved. Mosaics ecosystems are promoted extensively — in contrast to NfN, where they are suppressed, and more strongly than in NfS. For urban areas, NaC encourages low-density, nature-mixed settlements patterns, rather than densification promoted by NfN and NfS.

Overall, NaC cultivates biocultural, land-sharing landscapes, expanding mosaics and lower-density, nature-integrated settlements around production areas, while keeping culturally significant natural cores intact and reconnecting them through locally meaningful corridors that sustain people–nature relationships.

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7. Modelling Approach

Our set of eight scenarios, which explore alternative spatial configurations and extents of proforestation and agricultural abandonment across Europe, were made spatially explicit using the CLUMondo land-use model.

This section provides a general introduction to the CLUMondo framework and explains how it is used to implement our scenario specifications. The overview refers to the most recent implementation of CLUMondo, released in 2024 (version 5.1).

7.1 Functionality

CLUMondo is a dynamic, spatially-explicit model designed to optimize the allocation of land systems by simulating changes in land use in response to evolving demands for land-based goods and services (Van Asselen and Verburg, 2012, Van Asselen and Verburg, 2013, Eitelberg et al., 2015, Schulze et al., 2021). The model adopts a forward-looking approach, with land system allocation to meet demands driven by three key factors:

1. **Land System Suitability**: These are determined by spatial environmental and socio-economic factors, assessing the likelihood of a land system being suitable for a specific location. Suitability is calculated empirically as a logistic probability based on the initial land system map and may remain constant or adjust over time due to dynamic factors such as climate change.
2. **Conversion Rules**: These rules dictate which land system conversions are permissible, including their timing and location. For instance, certain policies might restrict the conversion of natural forests or grasslands to ensure their preservation.
3. **Competitive Advantage Rules**: These rules define how well each land system meets the demand for various goods and services, influencing its likelihood of being allocated to a particular area. For instance, the likelihood of land being allocated to forest could be increased in a scenario where carbon storage is enhanced.

The model operates iteratively, allocating land systems to pixels across the study region based on suitability and conversion rules (Figure 5). If the allocation plan meets the required demand for goods and services, the model advances to the next time step. If not, the process continues until the demand is satisfied. In this way, it is oriented toward meeting demands and baselines, rather than identifying an 'optimal' state according to criteria (CLUMondo is not an optimisation model). CLUMondo also incorporates policy scenarios, allowing for the simulation of different land management strategies. For example, in sustainability-oriented scenarios, conversion rules may prohibit the clearance of existing natural forests and grasslands, reflecting conservation efforts. Such restrictions can be applied selectively within certain regions, simulating the establishment or expansion of protected areas. The model captures changes in demand for land-based services due to factors like shifts in dietary preferences, population growth, or climate impacts. It also incorporates changes in land-system productivity, such as crop yields improvements resulting from technological innovation.

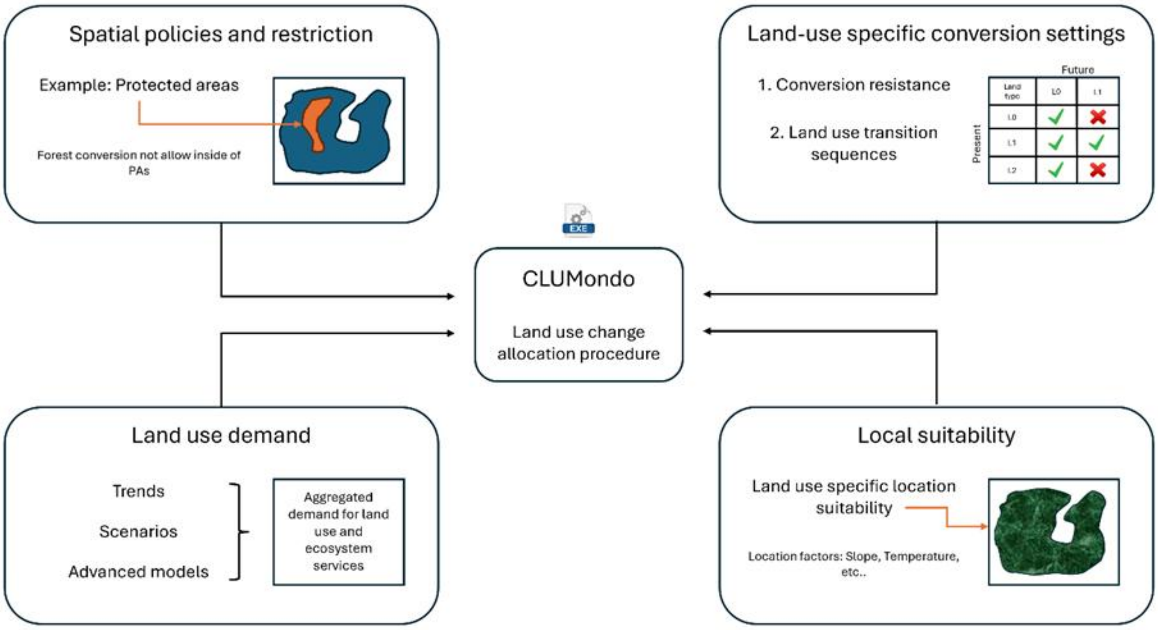

Figure 5: Structure of the land use allocation module

CLUMondo has been applied across a wide range of spatial scales in numerous studies, including recent and past simulations by Dou et al. (2023), Malek & Verburg (2018), Schulze et al. (2021), Venier-Cambron et al. (2024), and Wolff et al. (2018), among others.

7.2 Parametrisation and settings

In the CLUMondo model, suitability values are critical for guiding land system allocation by identifying the most likely locations for each land use. These values were calculated using binary logistic regression based on a balanced random sample of pixels representing the current land system distribution. Eighteen explanatory variables, chosen based on established literature, were included in the analysis. To maintain accuracy, all variables underwent rigorous multicollinearity testing, ensuring that only minimally correlated variables were used in the regression. Suitability values were calculated separately for each European region and kept consistent across all scenarios. Climate variables were averaged from five major climate models - GFDL-ESM4, IPSL-CM6A-LR, MPI-ESM1-2-HR, MRI-ESM2-0, and UKESM1-0-LL - to incorporate the influence of climate on land suitability.

The finalized baseline settings and parameters are shared by all the scenarios, but specific actions were implemented to meet each scenario's primary targets and objectives. The first big difference lies in the climatic suitability factors, derived from the RCP climate projections (as explained, SSP1 – NfN – NfS – NaC coupled with RCP 2.6 , SSP2 with RCP 4.5 , SSP3 with RCP 7.0). The modeling focused exclusively on the European mainland, intentionally excluding islands (e.g., Azores, Madeira, Canary Islands, Iceland) due to data constraints.

Under the different SSPs socio-economic scenarios, the model allocates land systems that provide five key goods and services: annual crop production, permanent crop production, livestock, wood production, and housing (population). The SSP1 scenario and the NFF scenarios build on this framework by incorporating two additional demand categories: tree number (an additional 3 billion trees by 2030, and 2 billion more by 2050) and wetland areas

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(a 17% increase by 2030). In addition, stable land-cover types — such as bare rock and shrubs, and water bodies — were omitted, as these are unlikely to undergo substantial change over time.

CLUMondo was calibrated to project land-use changes from 2020 to 2050, accounting a wide range of land systems and aligning these with demand forecasts derived from the Shared Socioeconomic Pathways (SSPs) in combination with the corresponding Representative Concentration Pathways (RCPs) for the climate variables (Sustainability). SSP1 paired with RCP2.6 was selected as the baseline for establishing macro-economic demands the NFF scenarios, as its sustainability focus provides the conditions under which positive futures envisioned for nature and people in the NFF framework become feasible.

Detailed internal documentation on model development and calibration for all eight scenarios is provided in the Annexes. A summary of the key model settings applied in each scenario is presented in Table 3. The technical documentation detailing how the scenarios were parametrised is also provided in the Annexes.

Table 3: Summary of the main model settings implemented in each scenario.

Scenario	Conversion rules	Elasticity to change	Demands	Location-specific rules
SSP1	• Block conversion of natural forests and wetlands. • Prevent any conversion to/within urban inside Protected Areas (e.g., Natura 2000). • In high-agrobiodiversity areas, low-intensity crops and grasslands cannot convert. • Prefer intensification on existing land. • PAs are prevented from land-use intensification/deforestation. • High elevation mosaic ecosystems in Northern Europe are kept stable for climatic reasons	• Stronger stability for forests, wetlands, and mosaics. • Higher stability for low-intensity agricultural systems.	• Standard CLUMondo demands (population, arable, permanent crops, livestock, wood). • Plus: Wetland restoration (+17% by 2030). • Plus: Trees (3B by 2030 + 2B by 2050).	• Emphasize restoration in potential wetland zones overlapping cropland/grassland (rewetting). • Emphasize restoration along Natura 2000 + large-mammal corridors. • Compact cities and intensification-over-expansion favored everywhere.
SSP2	• Agricultural and grassland intensification mostly on existing land. • Natural forest classes can convert into crops. • PAs prevented from land-use intensification/deforestation. • Urban densification promoted.	• Conversion resistance rises with land-use intensity for agriculture/grassland. • Natural forests and mosaics moderately dynamic.	• Standard CLUMondo demands (population, arable, permanent crops, livestock, wood).	• No location-specific adjustments applied.

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	• High elevation mosaic ecosystems in Northern Europe are kept stable for climatic reasons	• Wetlands more static than in SSP3.		
SSP2 – Technological innovation	Same as SSP2.	Same as SSP2.	• Standard CLUMondo demands (population, arable, permanent crops, livestock, wood). • The technologica l innovation factors are applied to the arable demand.	• No location-specific adjustments applied.
SSP2 – Planned rewilding	• Similar to SSP2. • Conversions from agriculture and grassland classes directly to natural forest is allowed only in high and moderate rewilding potential areas.	Same as SSP2.	Same as SSP2.	• Land use abandonment and proforestation are favoured in high rewilding potential areas, by increasing the preference for natural forest inside core areas and decreasing the preference outside.
SSP3	• High-intensity productive systems cannot fully de-intensify. • Natural forests can convert into crops. • Extremely dry areas limit high-intensity crops. • Small Natura 2000 areas can convert to low-intensity productive systems. • Urbanisation allowed from any land-use class; partial extensification of cities allowed. • High elevation mosaic ecosystems in Northern Europe are kept stable for climatic reasons	• Natural forests, wetlands, and mosaics convert more easily. • Cities and high-intensity systems are more resistant to change.	• Standard CLUMondo demands (population, arable, permanent crops, livestock, wood).	• Aridity Index maps (Zomer & Trabucco 2024) penalize high-intensity crops in dry areas. • Generalised increase in preference for high-intensity agriculture. • Generalised decrease in preference for low-intensity agriculture.
NfN	Same as SSP1.	Same as SSP1.	Same as SSP1.	• Composite of Natura 2000 + wildlife corridors + areas important for biodiversity favors natural forests; lowers preference for forest plantations. • Compact cities and intensification-over-expansion favored everywhere. • Mosaics suppressed everywhere. • Low-intensity crops lightly disfavored everywhere. • Emphasize rewetting where potential wetlands overlap cropland/grassland.

NfS	Same as SSP1.	Same as SSP1.	Same as SSP1.	• Composite of Natura 2000 + corridors + areas important for regulating ES favors natural forest and mosaics; lowers preference for forest plantations. • Multifunctional mosaics promoted, especially near settlements. • Compact cities and intensification-over-expansion favored everywhere. • Low-intensity crops lightly disfavored everywhere. • Emphasize rewetting where potential wetlands overlap cropland/grassland.
NaC	Same as SSP1.	Same as SSP1, except in the South region both natural and combined-objective forest types have maximum resistance.	Same as SSP1.	• Natura 2000 + corridors + areas important for cultural services in highly modified landscapes favor natural forest; lower preference for plantations and high-intensity ag/grass. • High-intensity crops disfavored everywhere. • Low-density settlement growth favored everywhere. • Emphasize rewetting where potential wetlands overlap cropland/grassland.

8. Land use scenarios outcomes

The model outputs are 1 km²-resolution maps covering most of continental Europe and providing 30-year land-use projections. The simulation period spans 2020–2050. Starting from the 2020 baseline land-use map (Figure 6), we ran CLUMondo with scenario-specific settings for the eight designed scenarios, generating the maps shown in Figure 7Figure 14.

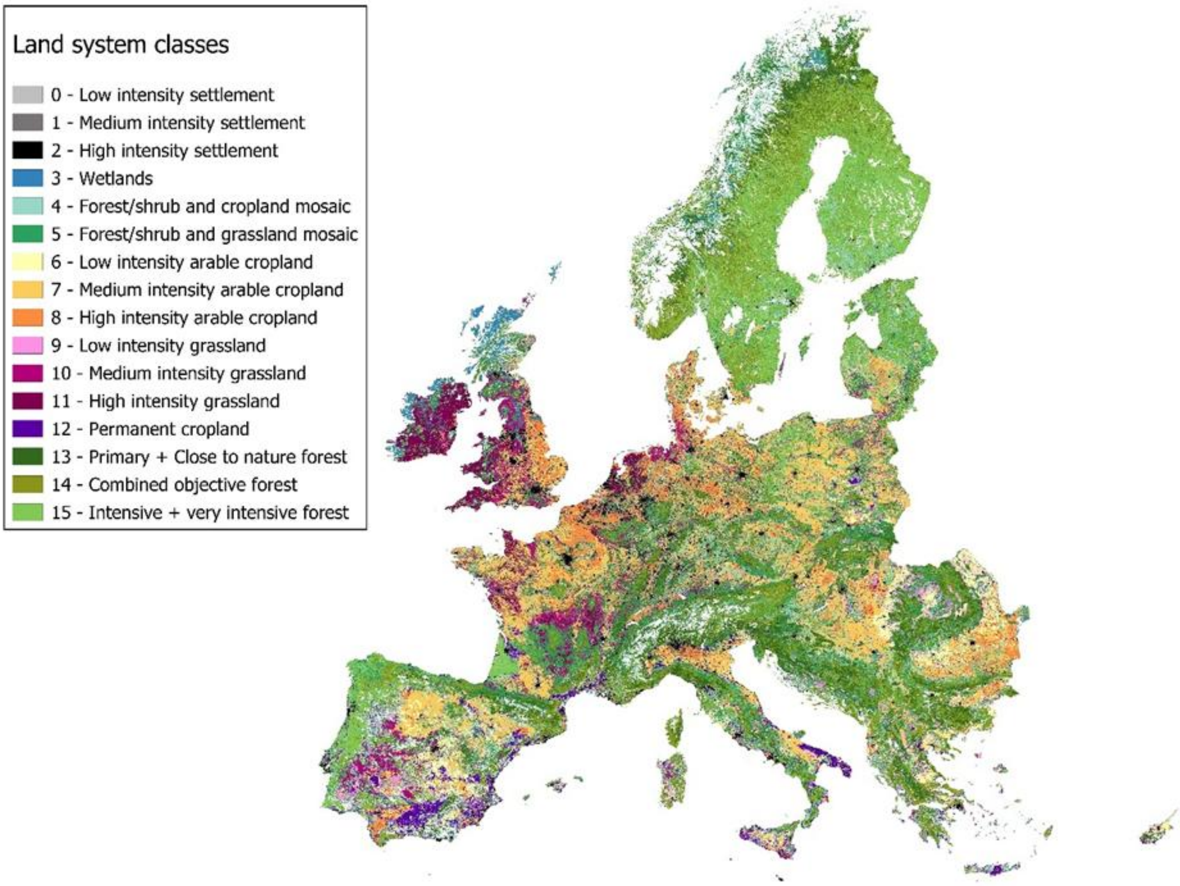

Figure 6: European land use management map representing the year 2020 (Sandström et al., 2023, v6)

The baseline 2020 land-use map for Europe (Figure 6) is based on Dou et al. (2021) and further refined by Sandström et al. (2023), who simplified mosaic categories and expanded forest-management classes. This version defined 20 land-use classes and served as the base map for Milestone 4. A subsequent update (version 6) by Sandström et al. (2023) and Scherpenhuijzen et al. (2025) refined agricultural intensity categories and forest management classes. The most up-to-date version of the basemap was used for the scenarios presented here.

For modelling purposes, we operationalized 16 classes by merging close-to-nature with primary forest, combining intensive with very intensive forestry and excluding the “Water and glacier” and “Bare, rock and shrub” classes.

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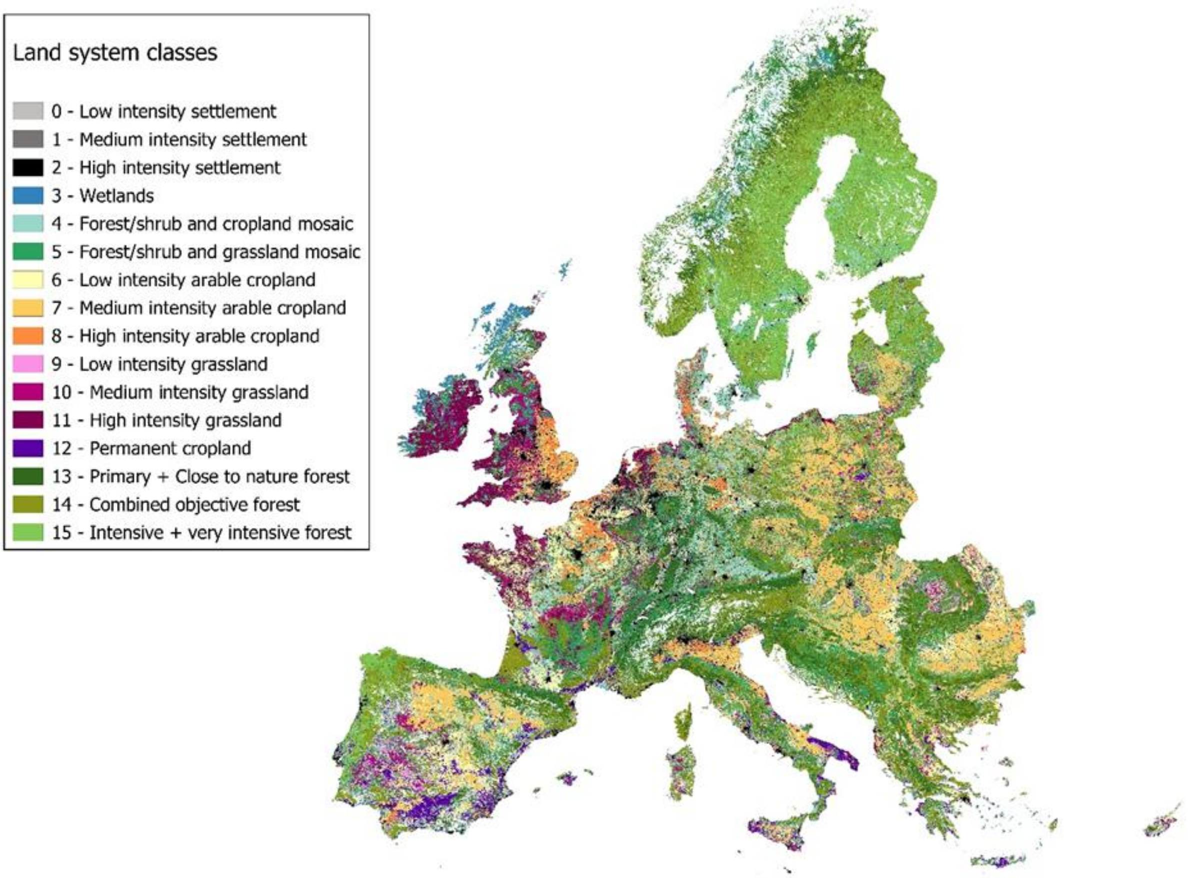

Figure 7: European land use management map representing the year 2050 under the SSP1-RCP2.6 scenario.

The SSP1 scenario projections to 2050 (Figure 7) indicate a clear shift towards more natural and semi-natural land systems. Close-to-nature forests increase by +19.4%, combined objective forests by +27.4%, and wetlands by +22.2%, reflecting substantial potential for ecosystem restoration. These gains are primarily enabled by strong contractions in high-intensity arable cropland (–53.8%) and medium-intensity arable cropland (–22.0%), together with declines in low- and medium-intensity grasslands (–41.8% and –17.4%, respectively) and forest–grassland mosaics (–10.2%).

The spatial pattern of agricultural abandonment leading to new forest is concentrated in:

- Austria (southern border with Hungary and Slovenia)
- Switzerland (large-scale abandonment in the northern region)
- Southern France (Atlantic Pyrenees)
- Carpathian Mountains in Romania
- The Dinaric Alps–Šar Mountains–Pindus Mountains corridor in Eastern Europe

Additional notable forest expansion occurs in the Alps, Italian Apennines and, to a lesser but widespread extent, in Czechia, Germany and Poland.

Regarding settlements, low-intensity urban areas decrease, while medium- and high-intensity settlement grow, indicating a trend towards more compact urban development rather than continued sprawl. At the same time, low-intensity arable cropland, forest-cropland mosaics and permanent cropland expand, suggesting that agricultural production is maintained through more extensive agriculture.

Notably, intensive and very intensive forest decreases (–14.5%), indicating a qualitative shift away from heavily managed stands towards more natural and multifunctional forest types. Overall, SSP1 projections illustrate a land-use pattern that balances natural conservation and multifunctional ecosystem services, lying between land-sparing and land-sharing approaches. Agricultural abandonment is not ubiquitous but is partially replaced by planned extensification of land use.

In summary, SSP1 depicts a sustainability-oriented world where integrated climate and biodiversity policies promote proforestation, wetland recovery, and rewilding across Europe. The results demonstrate the potential for large-scale agricultural extensification, with some opportunities for "pure" rewilding leading to wilderness formation.

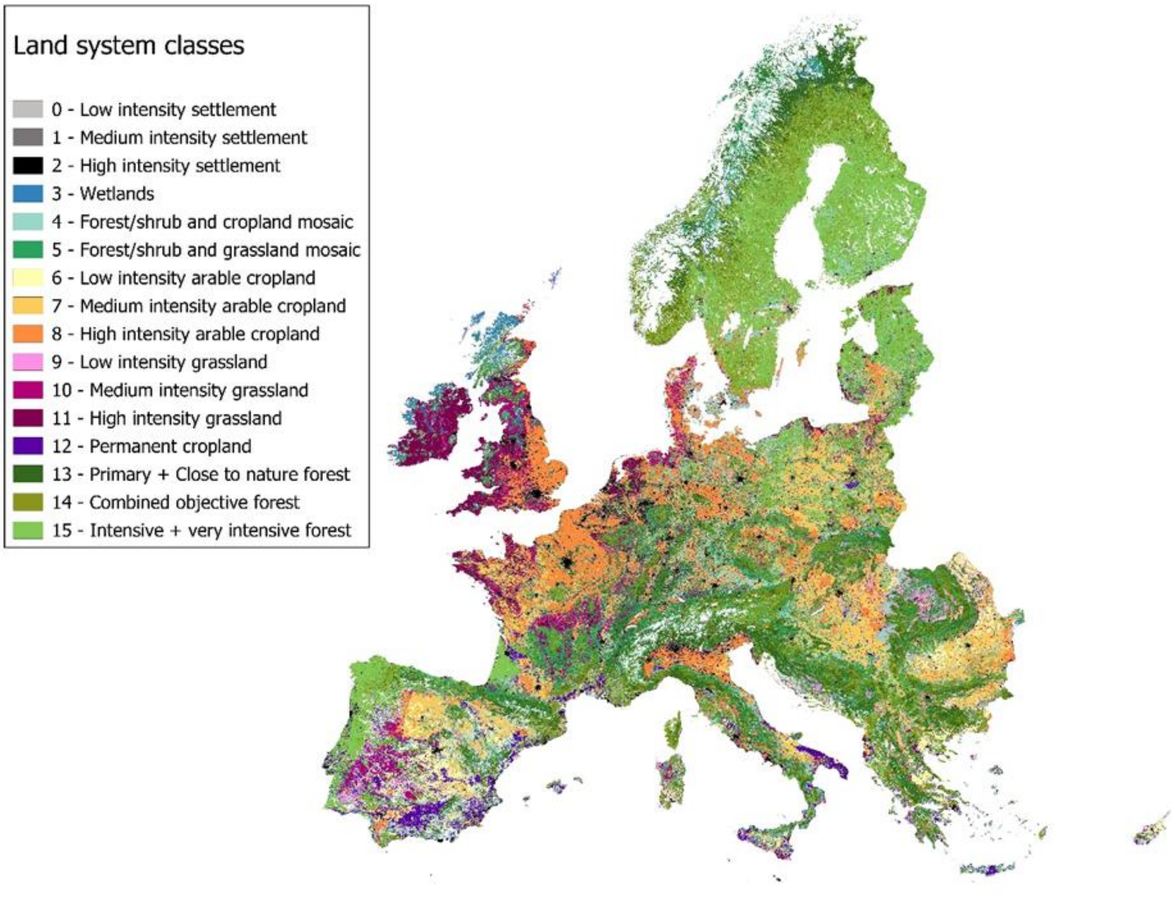

Figure 8: European land use management map representing the year 2050 under the SSP2-RCP4.5 scenario

The SSP2 scenario projections to 2050 (Figure 8) show a modest forest expansion signal embedded within a broader land-use intensification. Primary and close-to-nature forests increase by +38.8%, reflecting meaningful forest area growth, particularly on marginal lands and in upland zones, largely originating from previously existing multifunctional forest (–17.6%). At the same time, intensive and very-intensive forests expand by +22.6%, indicating that despite natural forest gains, there is still a strong push toward more managed forest types.

Forest growth is constrained by widespread demand for productive land: high-intensity arable cropland rises by +160.8%, high-intensity grassland by +70.7%, while semi-natural and less

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intensive systems — including forest–grassland mosaics (–47.6%), forest-cropland mosaics (–22.1%) and low-intensity grasslands and croplands (–5.7 %) — all decline sharply. Wetlands also decrease by –10.8%).

Spatially, forest gains are concentrated in mountainous foothills and less productive zones, such as the Alps, the Apennines, the Carpathians in Romania, and the Atlantic Pyrenees, whereas intensification dominates fertile lowlands. From a rewilding-perspective, SSP2 offers localized but significant potential: woodland regeneration occurs in peripheral and marginal regions, enabling passive ecosystem recovery driven mainly by land abandonment. However, the prevalence of intensification in agriculturally prime regions limits widespread rewilding. Consequently, forest expansion occurs within a productivity-driven context, rather than as a large-scale nature restoration wave.

Overall, SSP2 depicts a landscape where forests advance through localised abandonment dynamics, creating relatively large, isolated clusters of new forests, while the majority of the surrounding land remains dedicated to intenive productive uses.

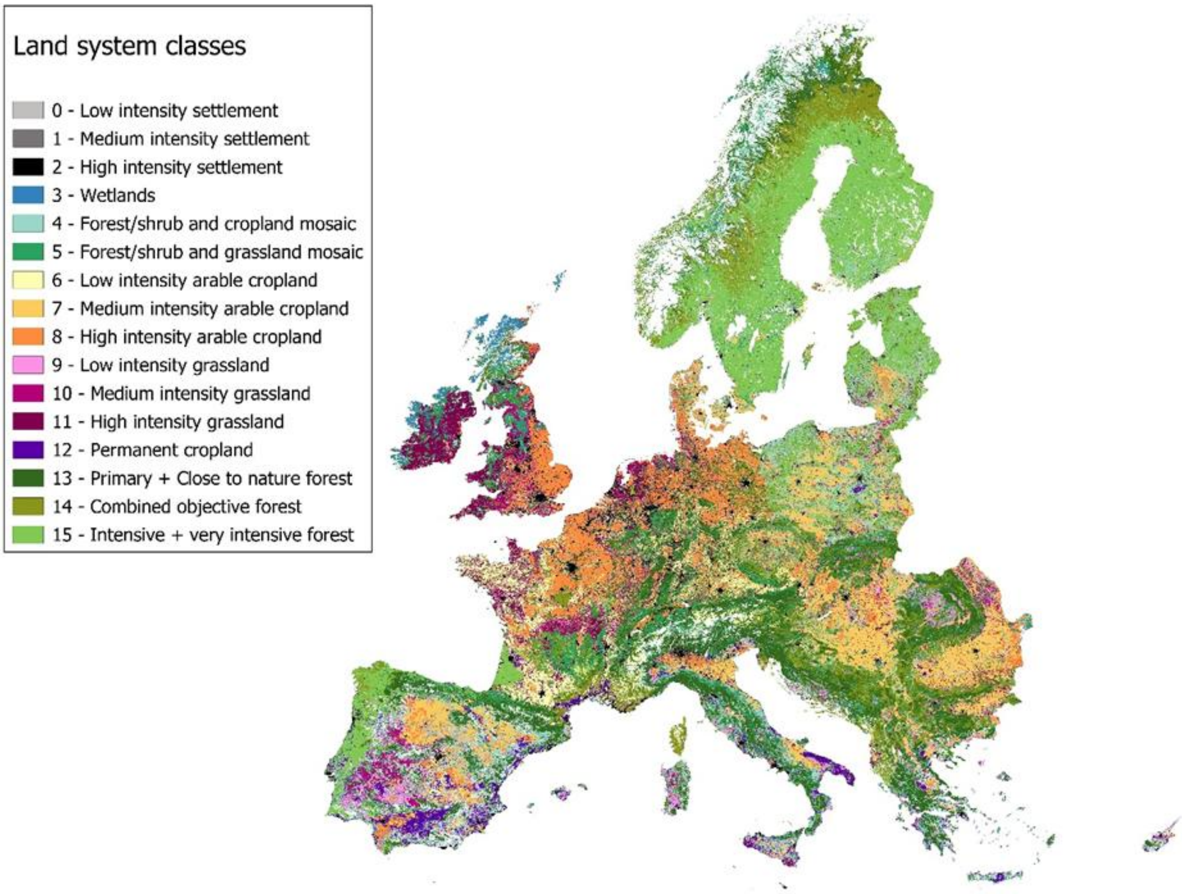

Figure 9: European land use management map representing the year 2050 under the SSP2 Technological innovation scenario.

In the SSP2 – Technical innovation scenario projections to 2050 (Figure 9), the spatial distribution of forest closely follows that of the baseline SSP2 scenario. The forest-recovery signal is apparent, but remains embedded within a broader trend of land-use intensification. Expansion and contraction trends are largely similar to the baseline SSP2, with close-to-nature forests increasing by +47.9%, combined-objective forests declining by –22.7%, and intensive forestry rising by +19.7%.

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The introduction of technological innovation in this scenario educes the pressure for productive intensification, leading to moderated growth in high-intensity systems (+75.4% for high-intensity crops and +55.2% for high-intensity grasslands), compared to the baseline SSP2. Notably, low-intensity arable crops increase substantially (+34.6%), contrasting with the decline observed in the baseline scenario.

Spatially, forest gains concentrated in mountainous foothills and less productive zones, while intensification continues to dominate the fertile lowlands. From a rewilding-perspective, this SSP2 variant offers similar localized potential as the SSP2 baseline: new forest clusters emerge in marginal areas, surrounded by less intensive productive systems, even without an explicit rewilding focus.

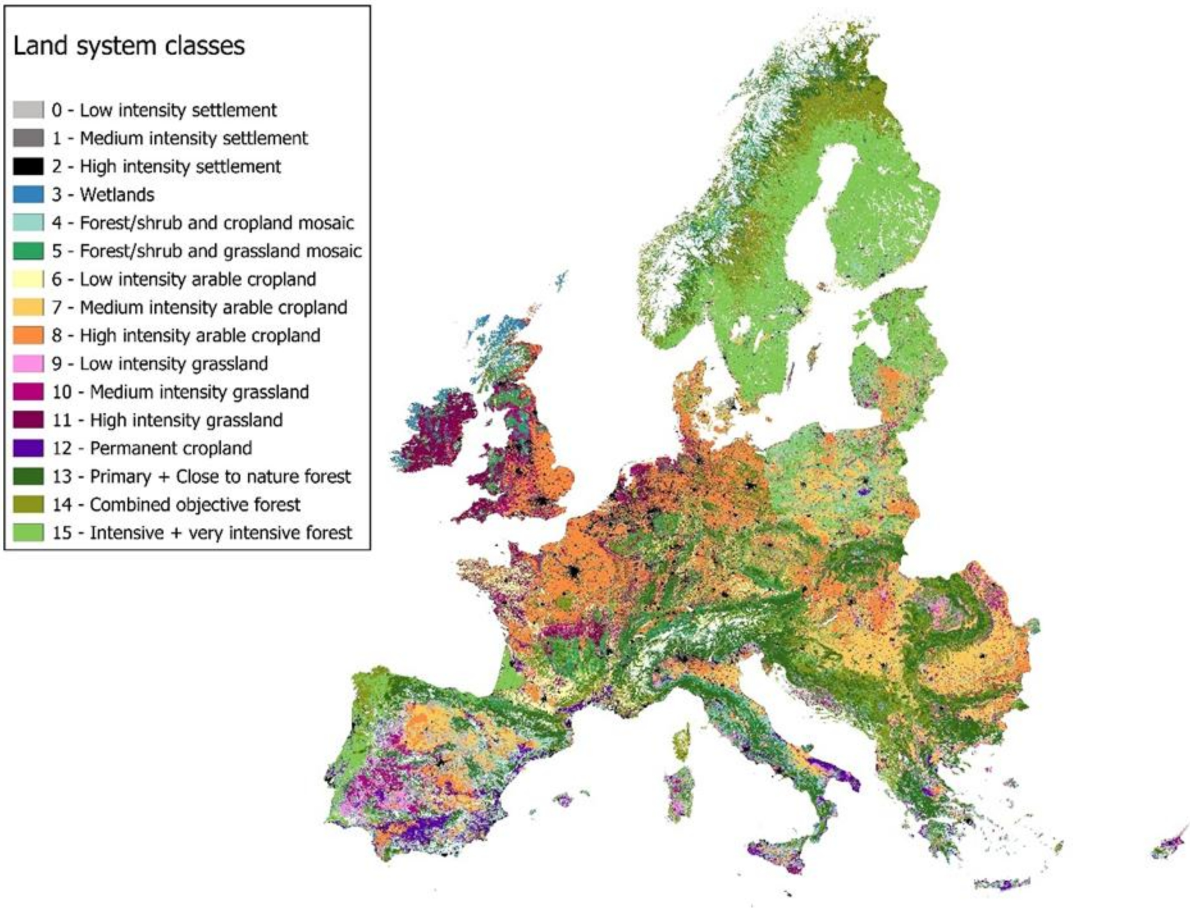

Figure 10: European land use management map representing the year 2050 under the SSP2 Planned rewilding scenario.

The SSP2 – Planned Rewilding scenario projections for 2050 (Figure 10) show a land-use configuration broadly similar to SSP2 baseline but with a stronger spatial concentration of forest expansion in areas of high rewilding potential. Primary and close-to-nature forests increase by +35.0%, while combined-objective forests decline by –13.3%, indicating available space for forest recovery. Intensive and very-intensive forests increase by +20.6%, suggesting that although ecological restoration is promoted in targeted zones, productive forestry remains part of the overall land management strategy.

Agricultural intensification continues, similarly to the baseline SSP2: high-intensity arable cropland increases by +163.3% and high-intensity grassland by +69.9%, while medium- and low-intensity croplands (–21.9% and –1.3%, respectively) and semi-natural mosaics (–48.1% for forest–grassland mosaics, –23.0% for forest–cropland mosaics) continue to decline.

Spatially, forest gains are clustered in mountainous and upland regions, notably the Alps, Pyrenees, Apennines, Carpathians, and the Dinaric–Šar–Pindus mountain arc, where rewilding measures and natural succession processes reinforce one another. Compared to SSP2, forest expansion in this scenario is more spatially coherent, creating larger, contiguous forest patches, reducing fragmentation. Fertile lowlands and high-value agricultural areas remain largely under intensive use, preserving Europe's productivity-driven landscape structure.

From a rewilding perspective, SSP2 – Planned Rewilding demonstrates the benefits of strategic ecological recovery, enabling improved forest connectivity and resilience in regions suited to rewilding, while maintaining agricultural productivity in key farming areas. This scenario highlights how planned interventions and spatial prioritization can enhance natural regeneration potential even within a moderately intensive socioeconomic pathway.

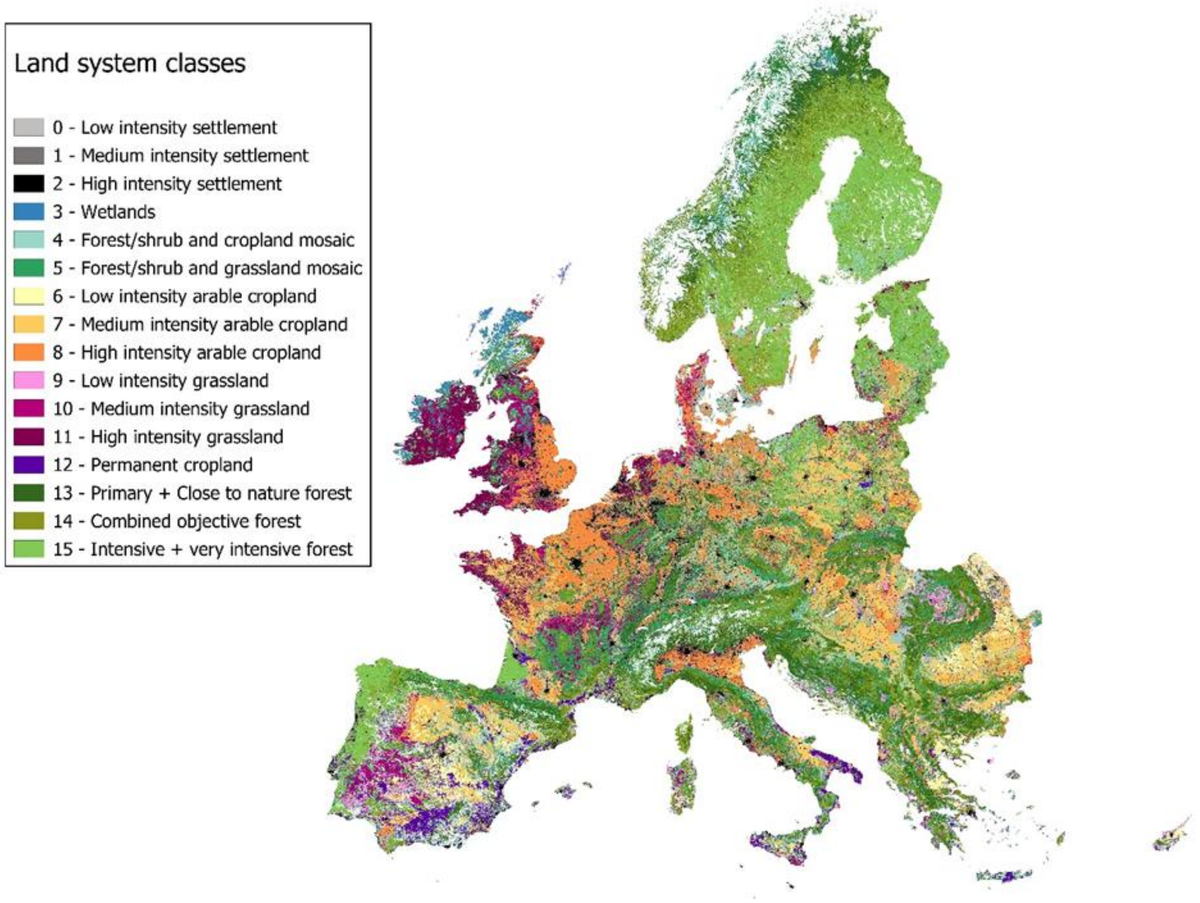

Figure 11: European land use management map representing the year 2050 under the SSP3-RCP7.0 scenario.

The SSP3 scenario projections to 2050 (Figure 11) indicate a modest forest expansion signal, accompanied by a notable increase of high-productivity systems (high intensity cropland and +124.8%, high intensity grasslands +54.5%). Primary and close-to-nature forests increase by +21.9%, reflecting some forest growth primarily on marginal land and upland zones. At the same time, intensive and very-intensive forests expand by +12.2%, suggesting a continued push toward managed forest forms similar to SSP2. Semi-natural and less intensive systems, including forest–grassland mosaics (–21.4%) and low-intensity grasslands and croplands (–

13.5% and –32.9%), decline sharply. Forest gains are concentrated in mountainous foothills and less productive areas — such as the Alps, Apennines, Carpathians in Romania, and the Atlantic Pyrenees — but the newly established forests are small, scattered, and fragmented.

From a rewilding-perspective, SSP3 offers limited potential: land abandonment occurs passively and unplanned, resulting in minimal woodland regeneration. These mixed outcomes reflect with fragmented governance and weaker environmental regulation, where land-use pressure is high in areas of opportunity, while protection and restoration efforts lag or occur unevenly across the landscape.

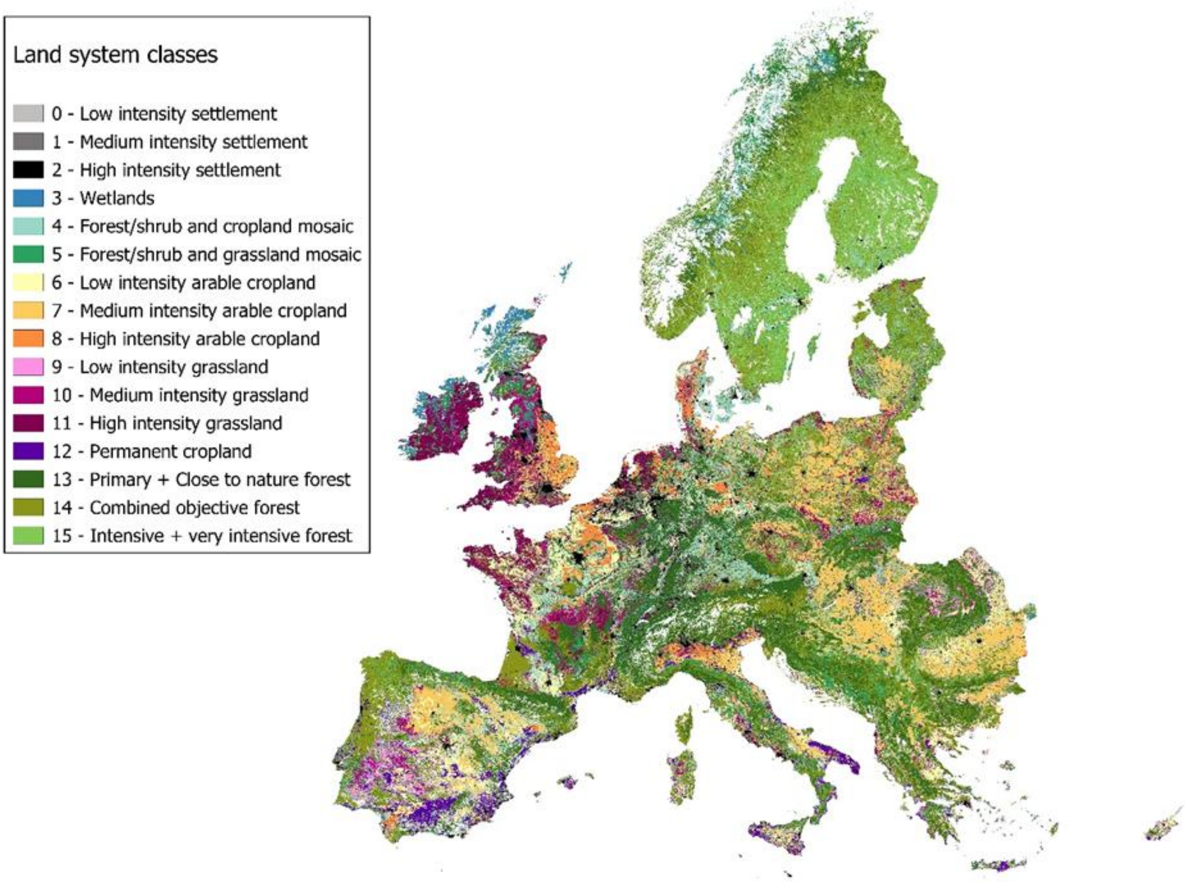

Figure 12: European land use management map representing the year 2050 under the Nature for Nature scenario

The Nature for Nature scenario (NfN) projections to 2050 (Figure 12) show a pronounced shift toward forest recovery and ecosystem restoration. Primary and close-to-nature forests increase by +96.7%, while combined objective forests rise by +35.8%, signalling major gains in natural forest cover. In contrast, intensive and very intensive forests decline by –28.2%, indicating a shift away from heavily managed stands toward more natural forest systems. These forest gains occur alongside marked contractions in low-intensity and semi-natural systems: forest/shrub–grassland mosaics decline by –54.9%, medium-intensity grasslands by –22.3%, and low-intensity grasslands by –30.0%. Low- and medium-intensity arable croplands also shrink (–53.8% and –23.9%, respectively), reflecting a rollback of agricultural extensification in favour of ecological space. Wetland systems increase by +22.1%, supporting broader natural-process restoration.

Spatially, forest regeneration is concentrated in mountainous and rural landscapes, including the foothills of the Alps, the Carpathians, the Dinaric–Šar–Pindus mountain corridors, and

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marginal agricultural zones where land abandonment is feasible. Additional new forest locations appear in Latvia, Estonia, and Lithuania, alongside substantial agricultural-to-forest transitions in Germany and France.

Overall, the NfN scenario represents a transformative trajectory for Europe, providing extensive space for rewilding, where coordinated policy, land-use change, and natural succession foster large-scale forest recovery and expansion of semi-natural ecosystems.

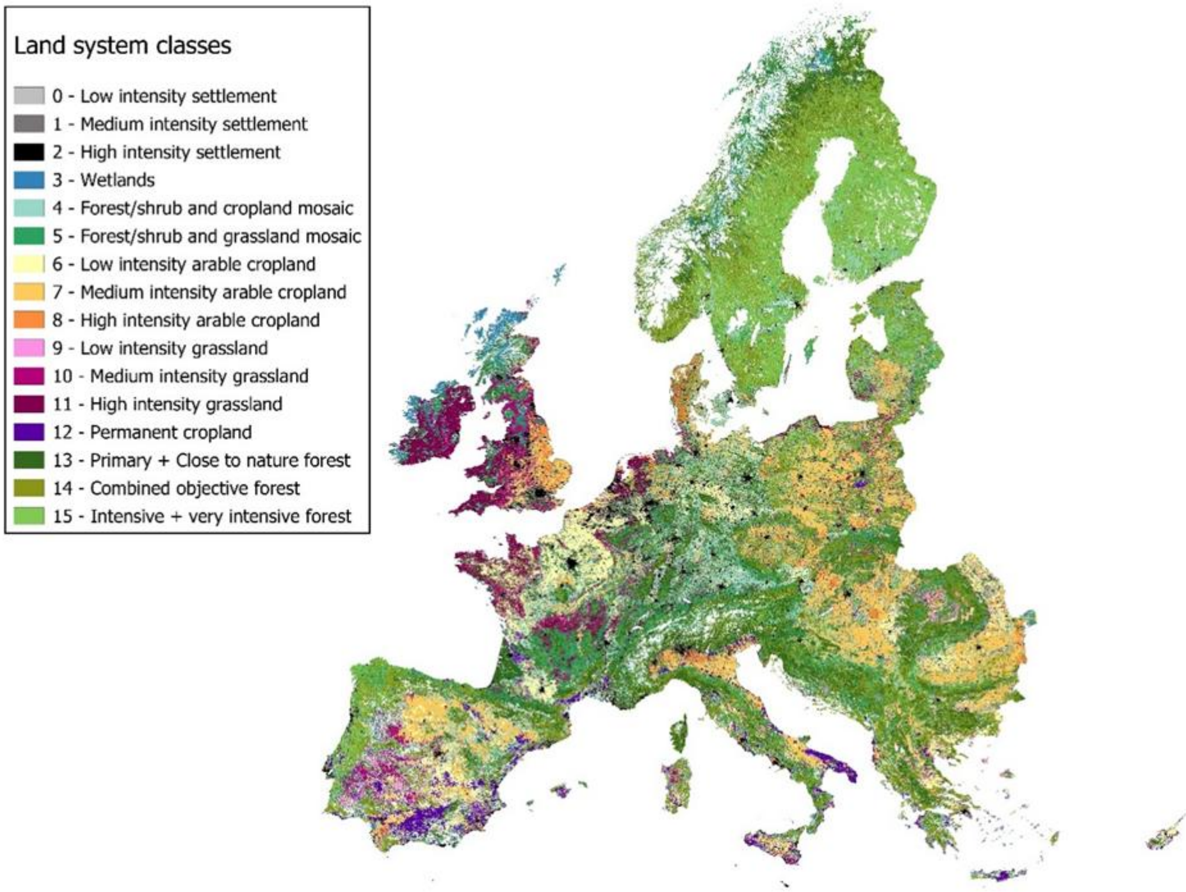

Figure 13: European land use management map representing the year 2050 under the Nature for Society scenario.

The Nature for Society (NfS) projections to 2050 (Figure 13) indicate a strong orientation toward forest recovery and nature-sensitive land systems. Primary and close-to-nature forests increase by +34.6%, and combined objective forests rise by +22.8%, reflecting substantial gains in forest extent and semi-natural forest structures. At the same time, intensive and very intensive forests decrease by –16.4%, signalling a shift away from heavily managed stands toward more natural forest types. Forest regeneration occurs alongside marked transitions in other land-use systems: high-intensity arable cropland contracts by –66.5%, while low-intensity arable cropland expands by +68.8%, indicating a shift from intensive production toward more extensive and nature-friendly agriculture. In parallel, forest/shrub–cropland mosaics increase by +11.2%, creating more heterogeneous landscapes that are less intensive and more natural, though not considered “pure” rewilding.

Spatially, new natural forests are concentrated in Austria, Germany, Switzerland, and France, with some expansion in the Carpathians. In Eastern and Southern Europe, land management tends to favour multifunctional forests rather than wilderness.

From a rewilding perspective, the NfS scenario envisions landscapes where integrated policies, moderate agriculture and forest expansion generate ecological space for nature. Gains in forest cover, especially in marginal and semi-abandoned areas, highlight the potential for structural land-use transformation. However, the scope for “pure” rewilding is limited, as management favours semi-natural, multifunctional systems rather than widespread rewilding trajectories.

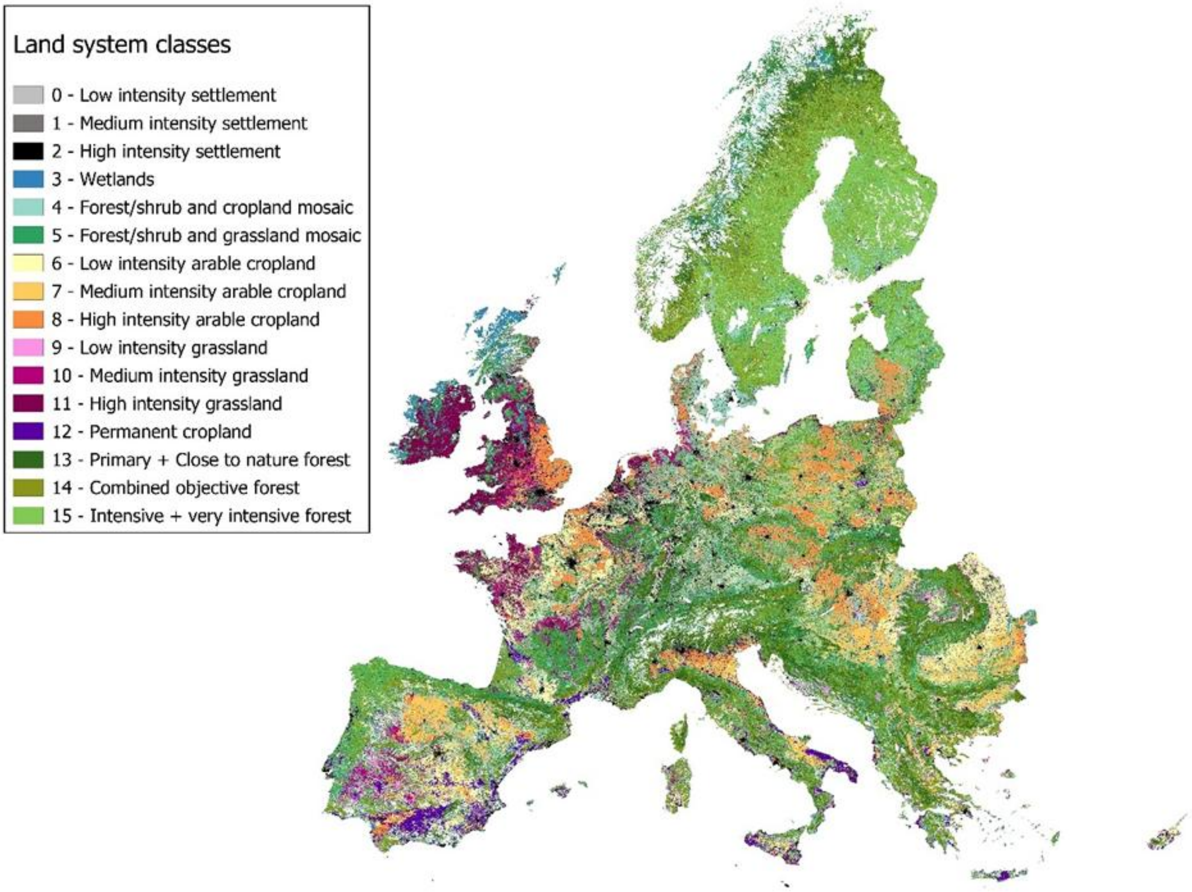

Figure 14: European land use management map representing the year 2050 under the Nature as Culture scenario.

The Nature as Culture (NaC) scenario projections to 2050 (Figure 14) depict a landscape where cultural-heritage and nature intertwine, resulting in strong semi-natural ecosystems expansion and good levels forest recovery. Combined-objective forests increase by +13.5%, reflecting modest but meaningful gains in woodland cover in areas aligned with traditional cultural land-use (e.g., forested landscapes in Greece, Italy and Spain). Primary and close-to-nature forests increase by +9.9%, while intensive and very intensive forests decline by –6.8%, indicating a moderate shift away from heavily managed, production-driven stands toward more natural forest types. Forest recovery occurs alongside diverse transitions in agricultural and semi-natural systems: high-intensity arable cropland rises by +34.9%, while low- and medium-intensity arable croplands change by +64.4% and –62.9%, respectively, reflecting nuanced shifts in cropland intensity. High-intensity grassland grow by +56.4%, whereas low- and medium-intensity grasslands decline by –18.0% and –45.4%, respectively, indicating consolidation of grazing onto more intensive grassland systems. At the same time, forest/shrub and cropland mosaic expands by +23.5%, and forest/shrub–grassland mosaics increase by +6.2%, supporting the re-weaving of mosaic landscapes aligned with cultural traditions.

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From a rewilding and forest-focus perspective, the NaC scenario emphasizes woodland regeneration embedded within historically cultivated and low-intensity managed landscapes, rather than through full abandonment. Forest gains in this scenario reflect a hybrid approach, where cultural landscapes, farmers, and forest-support policies combine to re-establish semi-natural woodlands, mosaics, and multifunctional ecosystems. In effect, NaC represents a middle ground: productive land systems remain but are recast in a nature-integrated form, enabling meaningful proforestation and mosaic-based naturalization without relying solely on full abandonment or agricultural intensification.

Across the eight futures, we could look at Europe's land system through the lens of three main trade-offs: compactness vs sprawl, intensification vs restoration, and land sparing vs sharing. We calculated the percentage change in land use class area by scenario compared to the baseline of 2020 (Table 4), and noticed the differences among scenarios. SSP2 (our BAU) concentrates growth through agriculture intensification (high increases in high-intensity arable and grasslands) combined with some urban densification, but this occurs partially at the expense of other systems, reflecting gradual, non-transformative policy.

SSP3 shows similar overall intensification, but with more uneven and patchy patterns, consistent with weak cooperation and fragmented governance.

Nature for Nature strongly expands natural areas (forests, wetlands), while suppressing mosaics, representing a classic land-sparing outcome.

Nature for Society balances core natural areas with multifunctional mosaics and compact cities, increasing wetlands and close-to-nature forests while moderating high-intensity arable croplands.

Nature as Culture emphasizes land-sharing, with large gains in low-density settlements and mosaic/cultural landscapes, while keeping natural cores broadly stable.

Finally, SSP1 reflects a central positions in the IPBES scenario triangle, achieving a balance among the three main values of nature — intrinsic, instrumental, and relational — and producing equilibrium-oriented future land-use patterns.

Table 4: Percent change (%) in land-use class area by scenario compared with the 2020 baseline (positive-green = expansion; negative-red = contraction).

	SSP1	SSP2	SSP2 Tech. Innovation	SSP2 Planned rewilding	SSP3	Nature for Nature	Nature for Society	Nature as Culture
Low intensity settlement	-14.8	3.5	3.1	3.6	-2.4	-3.4	-5.6	70.1
Medium intensity settlement	17.9	3.8	3.7	4.0	12.7	5.2	-4.3	0.0
High intensity settlement	4.8	5.3	5.3	5.2	0.9	8.7	8.6	0.0
Wetlands	22.2	-10.8	-11.7	-9.2	-0.2	22.1	22.6	22.1
Forest/shrub and cropland mosaic	18.8	-22.1	-9.7	-23.0	-0.3	-6.1	11.2	23.5
Forest/shrub and grassland mosaic	-10.2	-47.6	-32.9	-48.1	-21.4	-54.9	-12.3	6.2

Low intensity arable cropland	31.0	-5.7	34.6	-1.3	-32.9	57.0	68.8	64.4
Medium intensity arable cropland	-22.0	-21.3	-21.9	-22.9	-33.3	-23.9	-22.9	-62.9
High intensity arable cropland	-53.8	160.8	75.4	163.3	124.8	-53.8	-66.5	34.9
Low intensity grassland	-41.8	-5.7	-1.4	-4.2	-13.5	-26.0	-30.0	-18.0
Medium intensity grassland	-17.4	-12.3	-16.1	-12.1	-4.2	-4.8	-22.3	-45.4
High intensity grassland	37.9	70.7	55.2	69.9	54.5	45.0	40.5	56.4
Permanent cropland	7.6	7.8	-1.2	7.8	7.6	8.3	8.1	8.4
Primary + Close to nature forest	19.4	38.8	47.9	35.0	21.9	96.7	34.6	9.9
Combined objective forest	27.4	-17.6	-22.7	-13.3	-7.1	35.8	22.8	13.5
Intensive + very intensive forest	-14.5	22.6	19.7	20.6	12.2	-28.2	-16.4	-6.8

8.1 Agricultural abandonment and proforestation analysis

8.1.1 Approach and method

The projected land system maps for 2050 (Figure 7-Figure 14), along with the initial 2020 map (Figure 6) were used as the basis for all analyses. The first step consisted of generating change maps showing pixel-level transitions in land use and land cover from 2020 to 2050. This was performed using the QGIS plugin *MOLUSCE* (v. 5.0; NextGIS and Asia Air Survey Co., Ltd., n.d.), which compares two categorical rasters to compute a transition matrix and detect all class changes over time. For each scenario, the 2020 baseline and the corresponding 2050 projection were loaded, and the *Area Analysis / Change Detection* tool was used to produce a raster encoding the transitions between the two dates.

From these change maps, three specific subsets of transitions were extracted (Table 5):

1. **Proforestation transitions**, representing conversions from managed or mixed forest systems (e.g., intensive, very intensive, combined objective forests) to natural forest types (close-to-nature or primary forest).
2. **Agricultural abandonment transitions**, representing conversions from cropland and grassland classes (of varying intensities, including permanent cropland and mosaics) to the combined-objective forest class.

3. **Agricultural abandonment and rewilding transitions**, representing conversions from cropland and grassland classes (of varying intensities, including permanent cropland and mosaics) to natural forest types (close-to-nature or primary forest).

Table 5: Selected transitions relevant for proforestation and agricultural abandonment

Initial land systems (2020)	Projected land system (2050)	Type of process
Forestry-related • Intensive forestry and very intensive forestry • Combined objective forest	Close-to-nature / Primary forest	Proforestation
Croplands and grasslands • Low-intensity croplands • Medium-intensity croplands • High-intensity croplands • Low-intensity grasslands • Medium-intensity grasslands • High-intensity grasslands • Permanent croplands • Forest–shrub–grassland mosaic • Forest–shrub–agriculture mosaic	Close-to-nature / Primary forest	Agricultural abandonment and rewilding
Croplands and grasslands • Low-intensity croplands • Medium-intensity croplands • High-intensity croplands • Low-intensity grasslands • Medium-intensity grasslands • High-intensity grasslands • Permanent croplands • Forest–shrub–grassland mosaic • Forest–shrub–agriculture mosaic	Combined-objective forestry	Agricultural abandonment

As an additional type of transition relevant to rewilding probability, we included a set of maps highlighting transitions from agricultural land (low-, medium-, and high-intensity croplands, as well as permanent crops) and grasslands (low-, medium-, and high-intensity grasslands) to mosaic ecosystems. We define these transitions as partial abandonment, as they lead to ecosystems only partially covered by forest.

The resulting maps identify locations where these processes occur between 2020 and 2050. To assess cross-scenario consistency, individual scenario rasters were combined using a raster sum to produce several types of composite maps:

- **Composite map of agricultural abandonment and rewilding**: transition locations for agricultural abandonment and rewilding are summed across the eight scenarios to highlight areas where scenario agreement is strongest, representing the highest modelled rewilding probability.

- **Composite map of agricultural abandonment**: transition locations for agricultural abandonment are summed across all eight scenarios.
- **Composite map of proforestation**: transition locations for proforestation are summed across all eight scenarios.
- **Total rewilding probability map**: this combines the proforestation composite with the agricultural abandonment and rewilding composite, representing the complete rewilding hotspots map for Europe, as both processes lead to the growth of new close-to-nature forests.

This approach quantifies the frequency of agreement across scenarios, indicating how many times each process is projected to occur at a given location.

On the total rewilding probability map, we performed several additional calculations. We conducted a spatial analysis to quantify the probability for forest-regeneration and agricultural abandonment across Europe by integrating:

1. a 2020 baseline land-use raster, distinguishing forest and agricultural/grassland systems
2. a composite raster, where each pixel records the number of future land-use scenarios (out of eight) projecting conversion toward forest or close-to-nature systems.

For each rewilding category (proforestation, agricultural abandonment leading to close to nature forest), we calculated:

- the total area projected for conversion
- area corresponding to each scenario-agreement level (0 to 8).

Results were then summarised into three main groups:

- high-probability conversion (≥ 6 scenarios)
- moderate-probability conversion (≥ 3 scenarios)
- overall eligible area (at least one scenario).

Additionally, a country-level analysis was conducted by linking converted pixels to national boundaries. For each country, we calculated the area of high-probability rewilding and expressed it as a percentage of the country's total forest area, allowing for a comparative assessment of rewilding potential across Europe.

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8.1.2 Results

8.1.2.1 Individual scenario outcomes

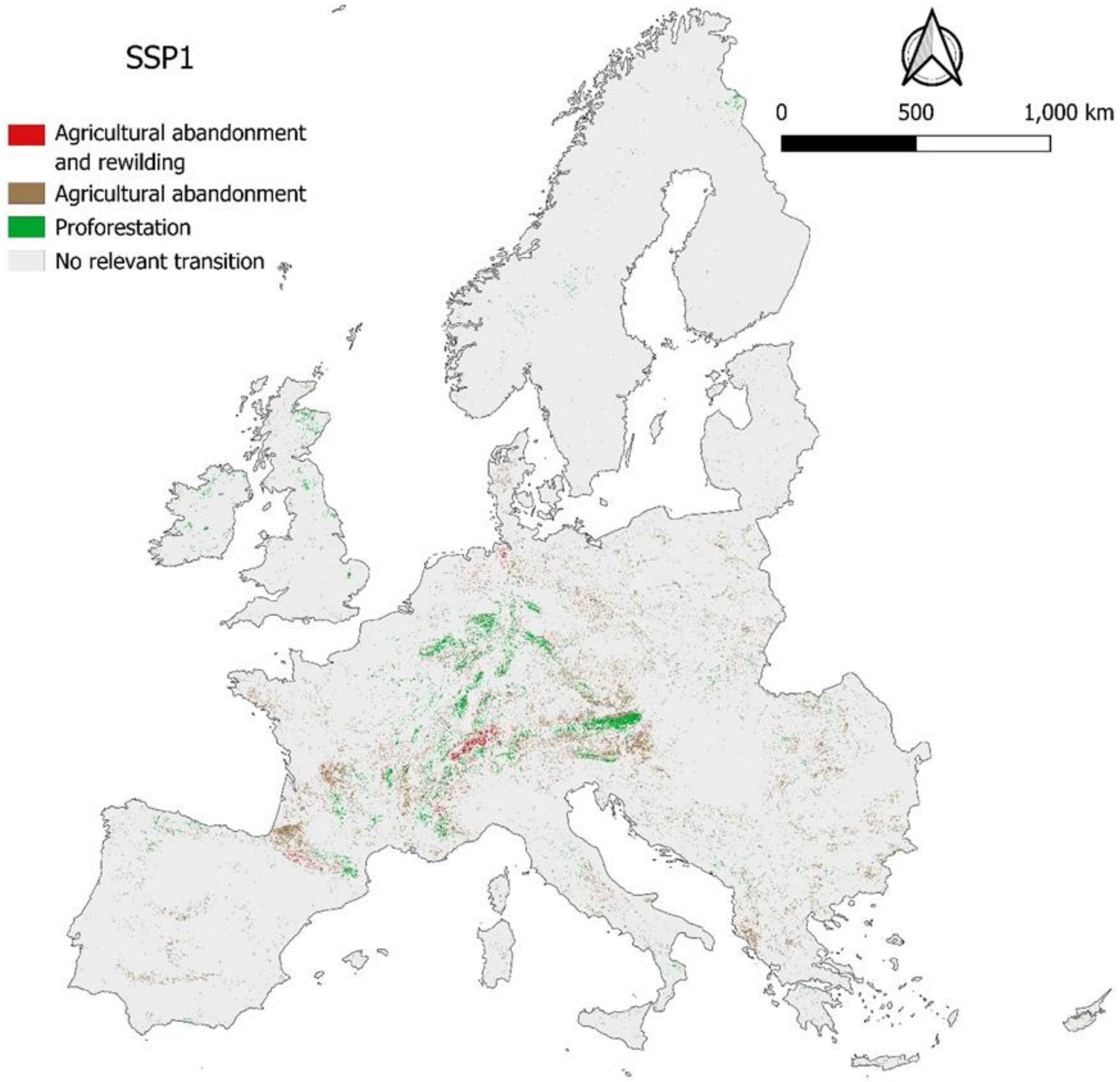

Figure 15: European land use change map representing transitions in the period 2020 - 2050 under the SSP1-RCP2.6 scenario. Agricultural abandonment and rewilding: transitions from cropland grassland and mosaics to close to nature forest; Agricultural abandonment: transitions from cropland grassland and mosaics to combined objective forest; Proforestation: transition from managed forest classes to close to nature forest.

The SSP1 scenario map (Figure 15) highlights extensive areas of proforestation, particularly in the alpine and sub-alpine zones of Austria and Switzerland, the northern Pyrenees in southern France, the upland sectors of the Dinaric Alps in Croatia/Bosnia and Germany. Additional proforestation is projected in Ireland and Scotland. At the same time, notable zones of agricultural abandonment and rewilding are evident in mid-altitude croplands and grasslands within those mountain regions as well as in parts of southern Spain. Areas where abandonment leads to combined-objective forestry are concentrated in moderate-slope zones such as the Italian Apennines and the Massif Central in France, where farmland is relinquished and forest systems are established under active management.

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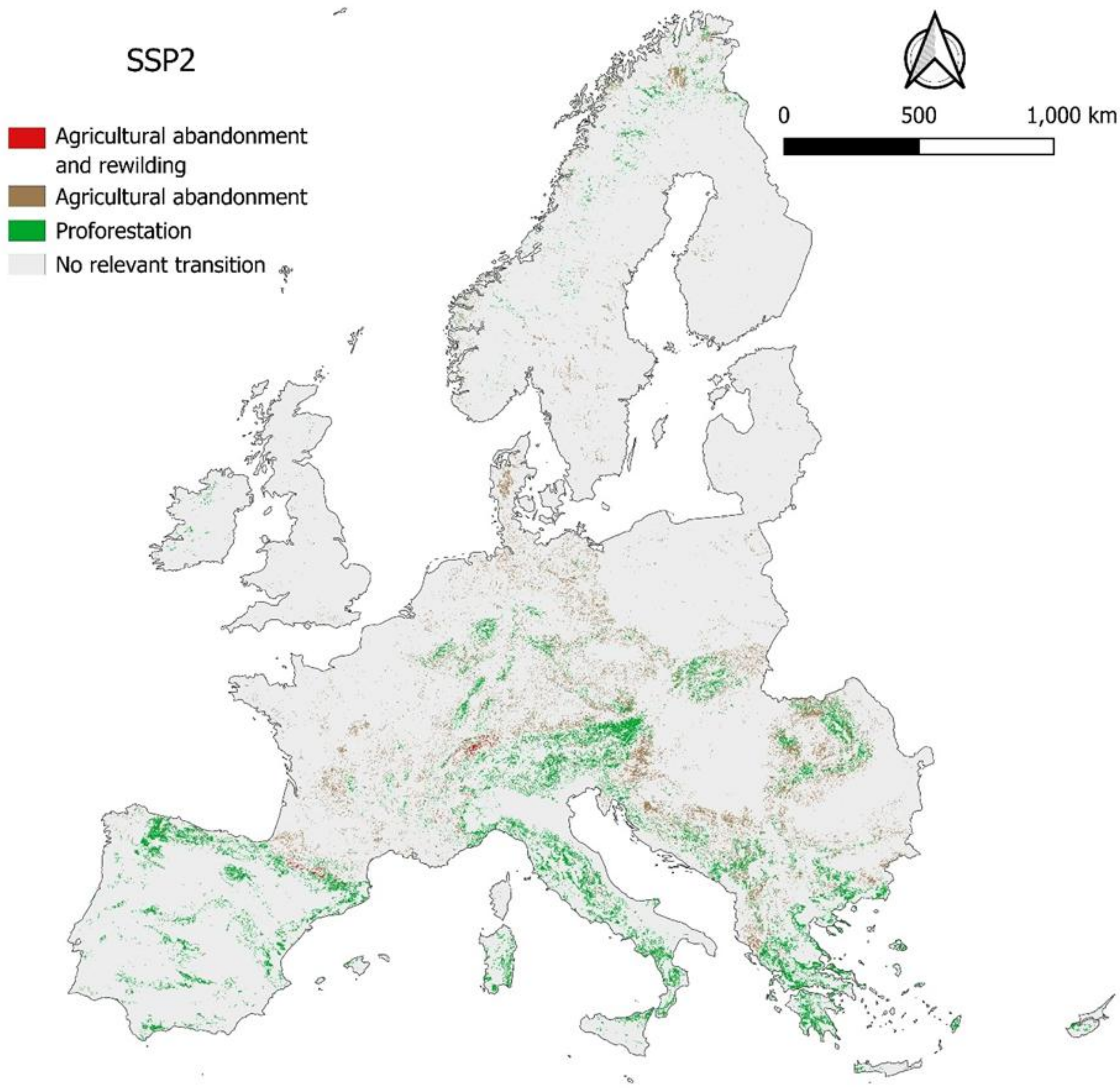

Figure 16: European land use change map representing transitions in the period 2020 - 2050 under the SSP2-RCP4.5 scenario. Agricultural abandonment and rewilding: transitions from cropland grassland and mosaics to close to nature forest; Agricultural abandonment: transitions from cropland grassland and mosaics to combined objective forest; Proforestation: transition from managed forest classes to close to nature forest.

Under SSP2 (Figure 16), proforestation becomes more spatially extensive, forming large corridors along the southern Alpine region, the Carpathians, Slovakia, southern Poland and northern Greece. Significant clusters are also visible in northern Spain and southern France, where forest regeneration extends into hilly and sub-mountainous terrain.

Agricultural abandonment and rewilding remain present but are less widespread than in SSP1, occurring mainly in localized uplands of the Pyrenees and Switzerland. More broadly, agricultural abandonment is observed across central and eastern Europe, particularly in France, Poland, and the Balkans, forming diffuse belts surrounding the main forest transition zones. Denmark also emerges as a potential hotspots for reduced management, favouring combined-objective forests.

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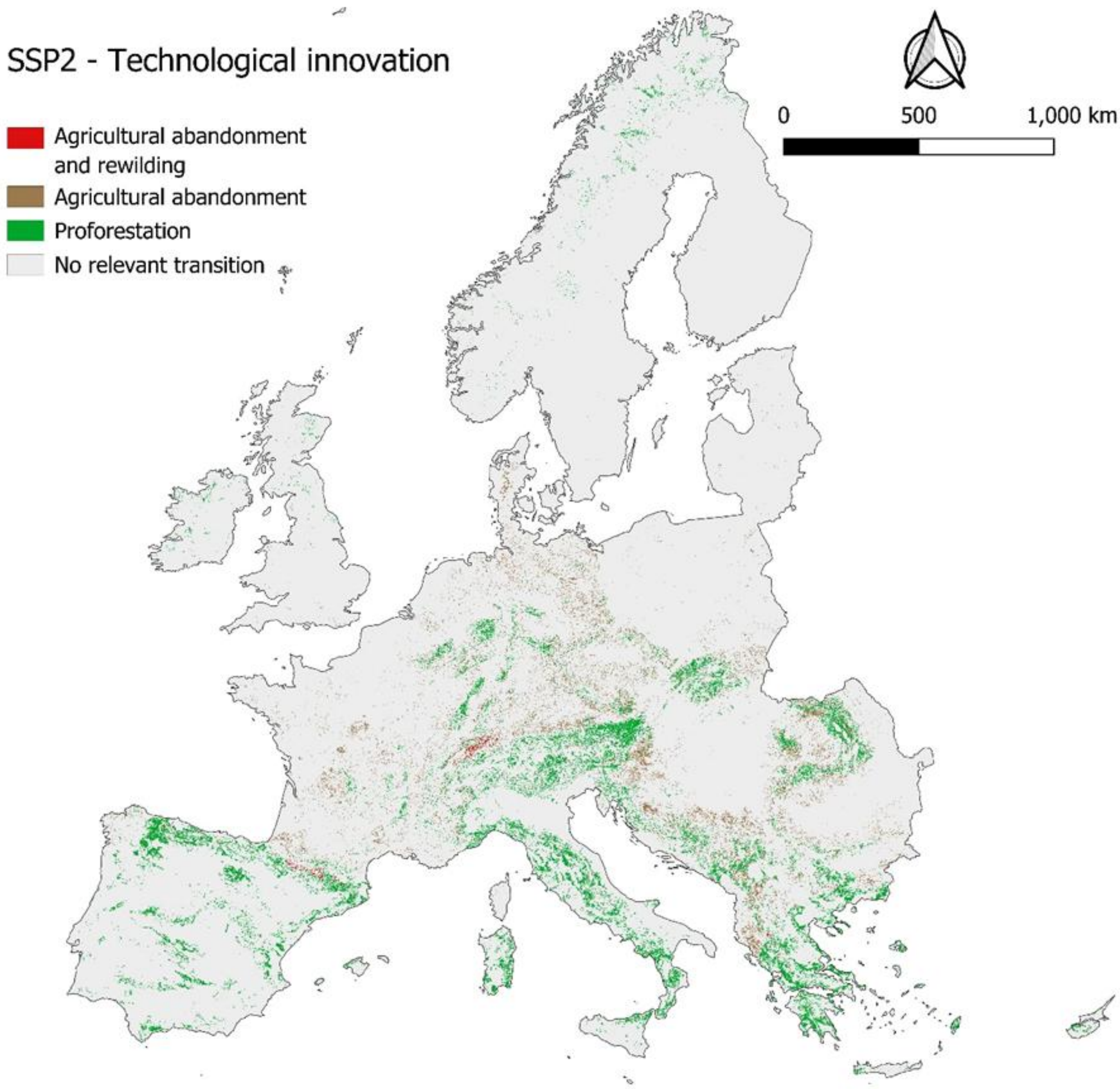

Figure 17: European land use change map representing transitions in the period 2020 - 2050 under the SSP2 – Technological innovation scenario. Agricultural abandonment and rewilding: transitions from cropland grassland and mosaics to close to nature forest; Agricultural abandonment: transitions from cropland grassland and mosaics to combined objective forest; Proforestation: transition from managed forest classes to close to nature forest.

The Technological Innovation variant (Figure 17) shows a pattern very similar to SSP2 baseline. Proforestation is widespread, particularly dense along the Alps, Carpathians, and northern Spain. Other notable areas include the Balkan uplands, the Apennines in central-southern Italy and several clusters of new forest in central Spain.

Agricultural abandonment and rewilding are sparse and localized, mainly occurring in southern France, northern Spain and Switzerland, indicating limited unmanaged regrowth of natural forest from agricultural areas. Agricultural abandonment is more evenly distributed across western and southern Europe, including central France, Bulgaria, Albania, Bosnia and Herzegovina and Serbia, often providing a buffer of multifunctional forest around proforestation areas. In these areas, land use shifts from agriculture toward multifunctional forests rather than full wilderness succession.

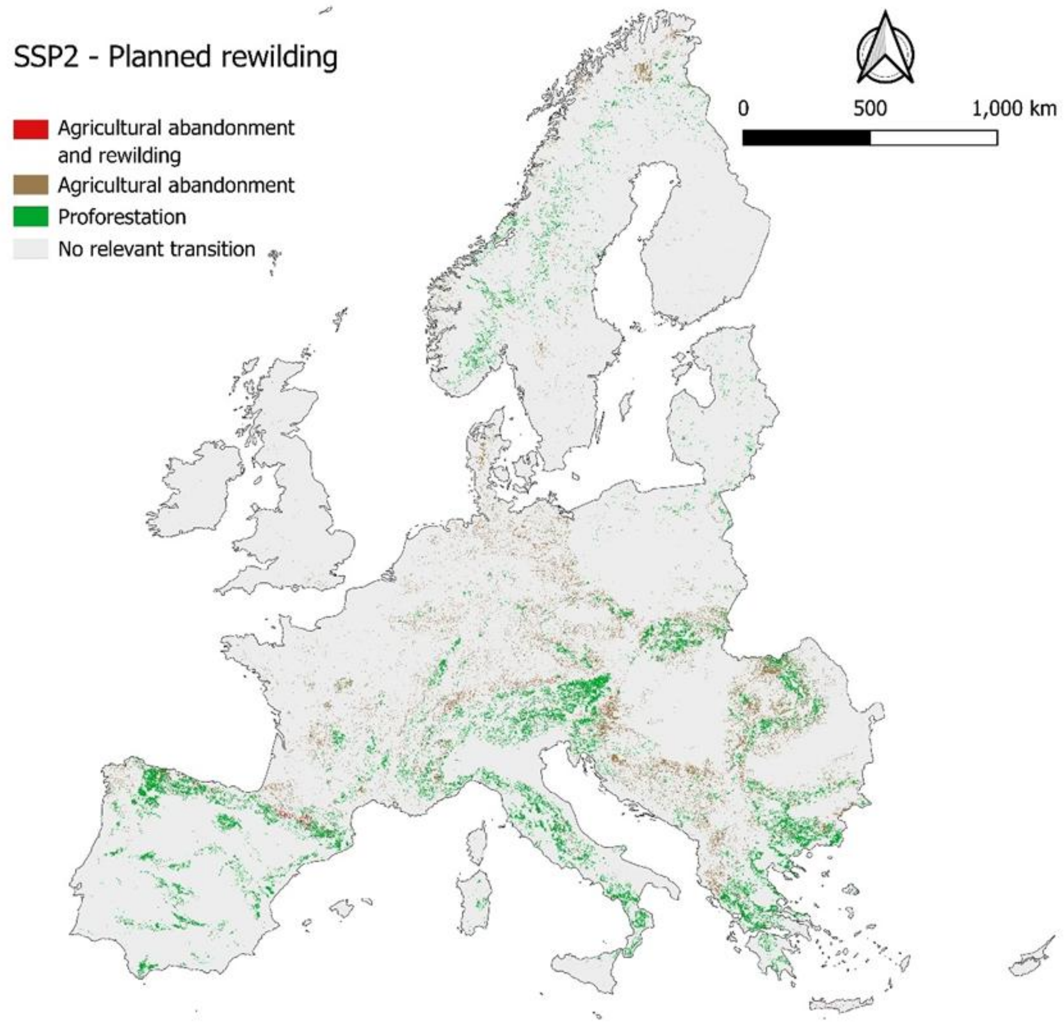

Figure 18: European land use change map representing transitions in the period 2020 - 2050 under the SSP2 – Planned rewilding scenario. Agricultural abandonment and rewilding: transitions from cropland grassland and mosaics to close to nature forest; Agricultural abandonment: transitions from cropland grassland and mosaics to combined objective forest; Proforestation: transition from managed forest classes to close to nature forest.

Under SSP2 – Planned Rewilding (Figure 18), proforestation hotspots are more consolidated along the Alps and Carpathians, forming continuous belts of forest recovery that connect upland ecosystems. Additional concentrated patches appear in northern Spain, southern France, and central Italy, where rewilding efforts align with hilly and sub-mountainous areas. Agricultural abandonment and rewilding are less scattered than in the baseline, increasingly confined to ecologically strategic zones near mountain foothills and less productive areas. In contrast, diffuse agricultural abandonment remains visible across central and eastern Europe, particularly in France, Poland, and the Balkans, but transitions there are less extensive. Proforestation dominates, reflecting a deliberate spatial focus on forest recovery in regions with high rewilding potential rather than spontaneous, widespread abandonment. Some clusters of new forest present in SSP2 – baseline are no longer visible due to lower suitability for rewilding, either from reduced ecological value or higher exposure to threats such as wildfires and invasive species pressure. This occurs in areas of Serbia, Montenegro, Bosnia and Herzegovina and Albania and much of Germany. In parallel, new dense clusters of natural forest are emerging in Bulgaria, northern and central Spain and southern Norway. Overall, SSP2 – Planned Rewilding depicts a Europe where forest regeneration is more targeted and contiguous, strengthening major ecological corridors while limiting diffuse land-use transitions in productive lowlands.

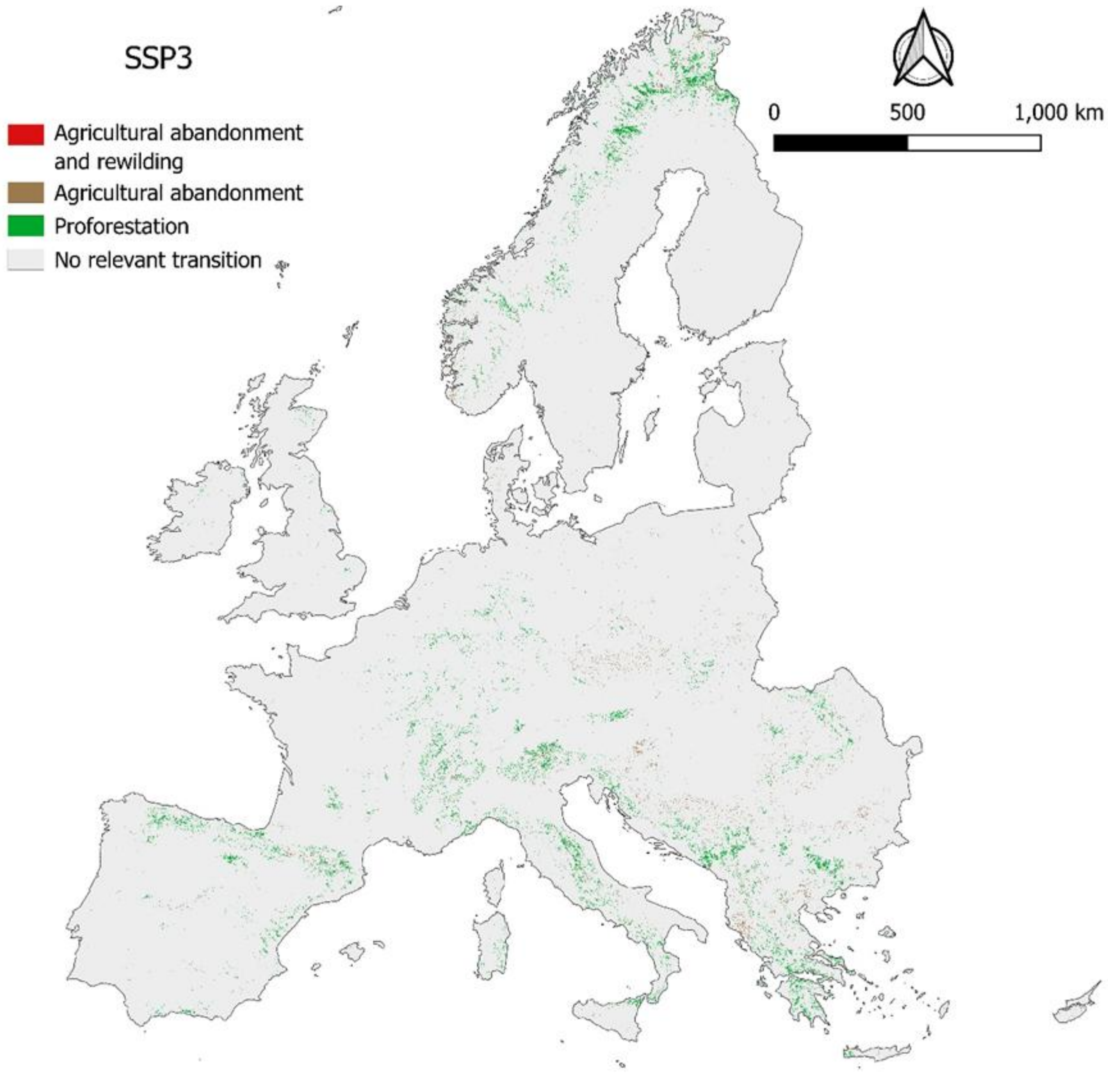

Figure 19: European land use change map representing transitions in the period 2020 - 2050 under the SSP3 – RCP 7.0 scenario. Agricultural abandonment and rewilding: transitions from cropland grassland and mosaics to close to nature forest; Agricultural abandonment: transitions from cropland grassland and mosaics to combined objective forest; Proforestation: transition from managed forest classes to close to nature forest.

The SSP3 scenario (Figure 19) shows limited proforestation, confined to a few larger hotspots in the Scandinavian uplands, Bulgaria, Bosnia and Herzegovina and Serbia, as well as smaller clusters in the northern Carpathians, Alps and Apennines. Some signals are also visible in Switzerland and central Germany. Agricultural abandonment and rewilding are scarce, appearing only in minor pockets in southern France and north-central Spain. The overall pattern is one of widespread stability, with only light agricultural abandonment scattered through eastern and southern Europe, indicating minimal forest transition or rewilding activity.

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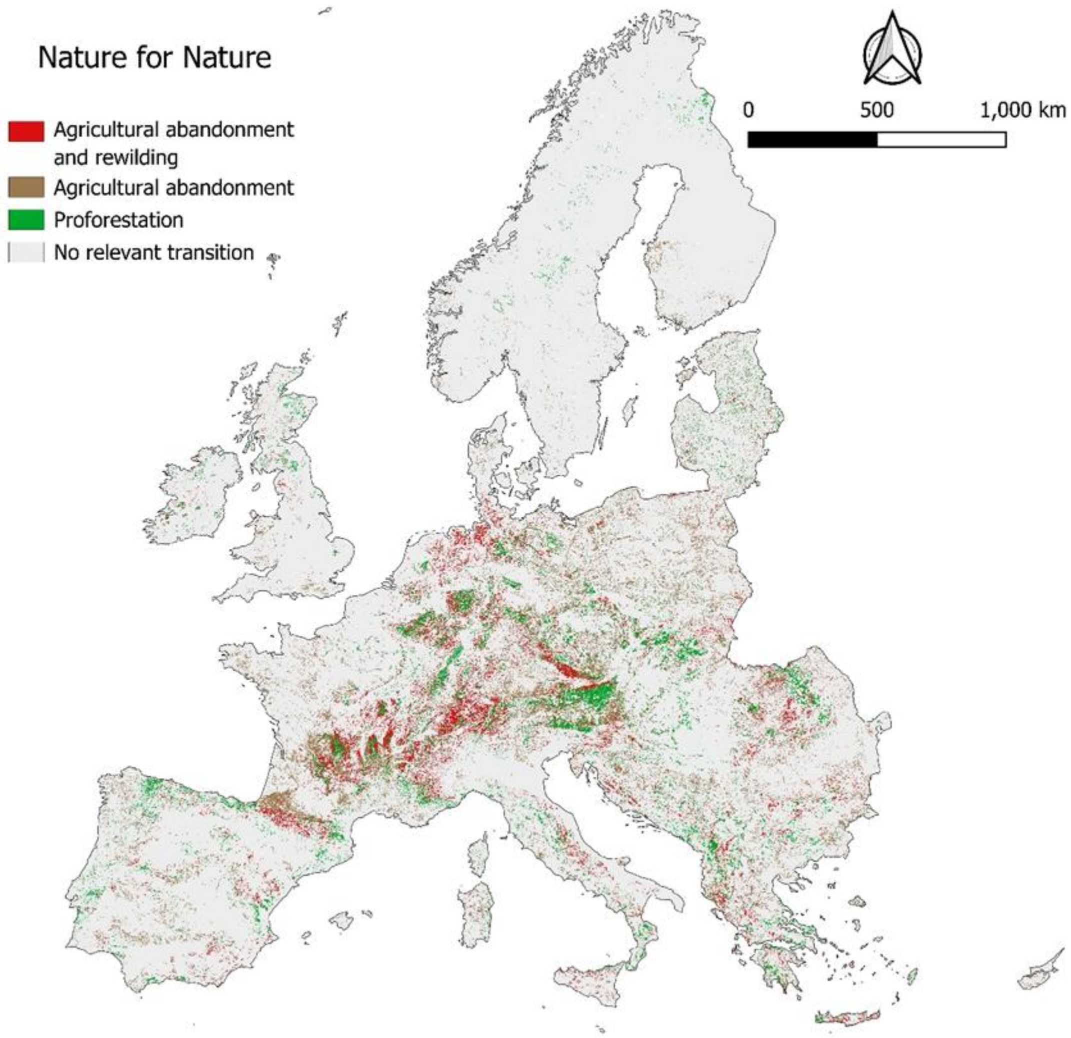

Figure 20: European land use change map representing transitions in the period 2020 - 2050 under the Nature for Nature scenario. Agricultural abandonment and rewilding: transitions from cropland grassland and mosaics to close to nature forest; Agricultural abandonment: transitions from cropland grassland and mosaics to combined objective forest; Proforestation: transition from managed forest classes to close to nature forest.

The Nature for Nature map (Figure 20) shows the most extensive forest transition among all scenarios. Proforestation is dense and continuous along the Alps, Carpathians, and Balkan mountain chains, extending into northern Greece, the Apennines and the Massif Central. Agricultural abandonment and rewilding are widespread in these regions, particularly in the Alps, northern and central Spain, southern France, and the western Balkans, reflecting large-scale release of farmland for natural succession. Additional agricultural abandonment occurs also in France, northern Italy, and central Europe, often surrounding areas of forest expansion and rewilding.

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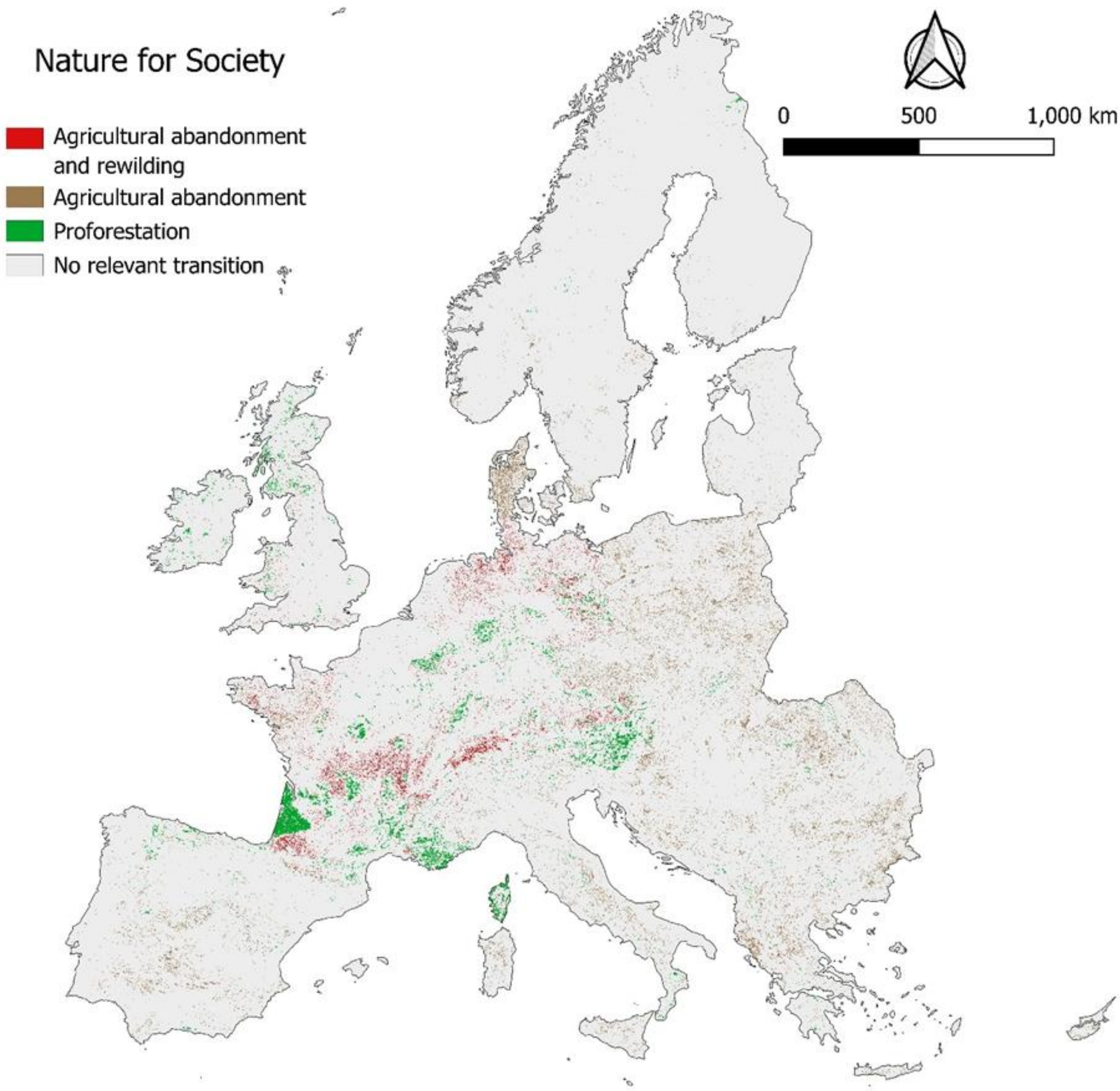

Figure 21: European land use change map representing transitions in the period 2020 - 2050 under the Nature for Society scenario. Agricultural abandonment and rewilding: transitions from cropland grassland and mosaics to close to nature forest; Agricultural abandonment: transitions from cropland grassland and mosaics to combined objective forest; Proforestation: transition from managed forest classes to close to nature forest.

The Nature for Society scenario (Figure 21) displays a heterogeneous pattern of forest-related transitions across Europe. Proforestation is concentrated in the western Pyrenees, the Massif Central and Jura Mountains in France, as well as along the northern and western Alpine arc extending into France and Austria. Smaller forest-gain clusters appear in southern Germany, the Carpathian foothills of Romania, and northern Spain, indicating localized expansion of close-to-nature forest systems. Agricultural abandonment and rewilding are mainly found in central and northern France, western Germany, and parts of southern England, with smaller pockets in northern Spain, often occurring adjacent to proforestation areas. More diffuse agricultural abandonment covers large parts of central and eastern Europe, including Poland, Hungary, Romania, and the Baltic region, where farmland contraction occurs without substantial forest establishment by 2050. Overall, the map indicates regionally limited but spatially coherent forest expansion, largely centred in western and southern Europe, alongside broad areas of agricultural release in the East.

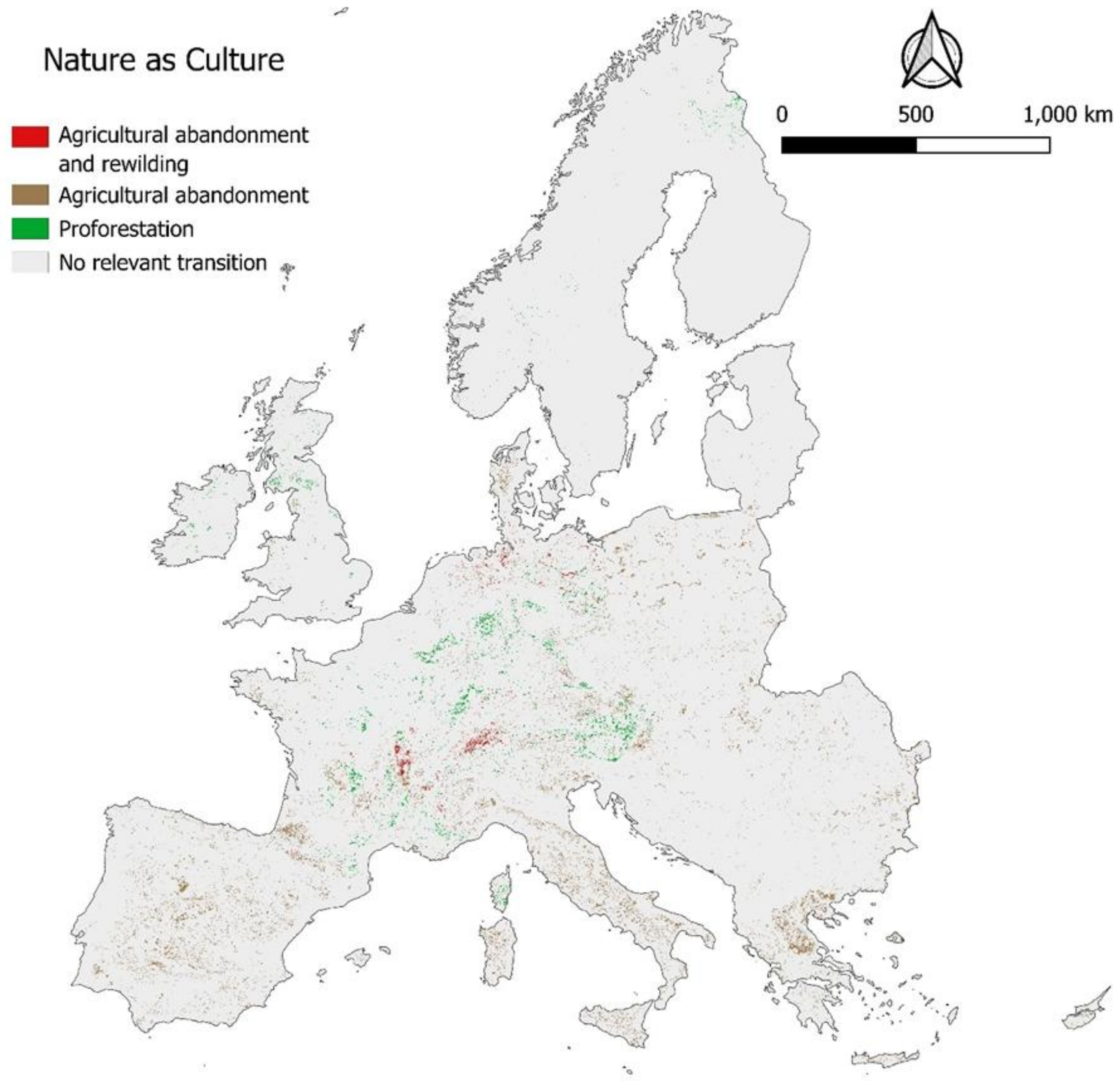

Figure 22: European land use change map representing transitions in the period 2020 - 2050 under the Nature as Culture scenario. Agricultural abandonment and rewilding: transitions from cropland grassland and mosaics to close to nature forest; Agricultural abandonment: transitions from cropland grassland and mosaics to combined objective forest; Proforestation: transition from managed forest classes to close to nature forest.

The Nature as Culture scenario (Figure 22) exhibits a sparse but spatially structured pattern of forest-related transitions. Proforestation is mainly concentrated in central Europe, particularly in southern Germany, Switzerland, and the Austrian Alpine foothills, with smaller clusters in southern France and parts of the Czech Republic. Additional scattered forest-gain areas appear in northern Italy and Slovenia, following existing forested uplands and cultural woodland landscapes. Agricultural abandonment and rewilding are more limited and mainly occurs in central France, southern Germany, and Switzerland, where patches of low-intensity cropland and mosaic landscapes transition towards semi-natural vegetation. More widespread agricultural abandonment is observed across southern and eastern Europe, including Spain, Greece, Romania, Bulgaria, and the Baltic region, often without full forest recovery by 2050. Overall, the scenario depicts modest, localized forest-related processes, concentrated in traditional agro-forest landscapes of central and western Europe, where managed woodlands and cultural land stewardship coexist with partial rewilding.

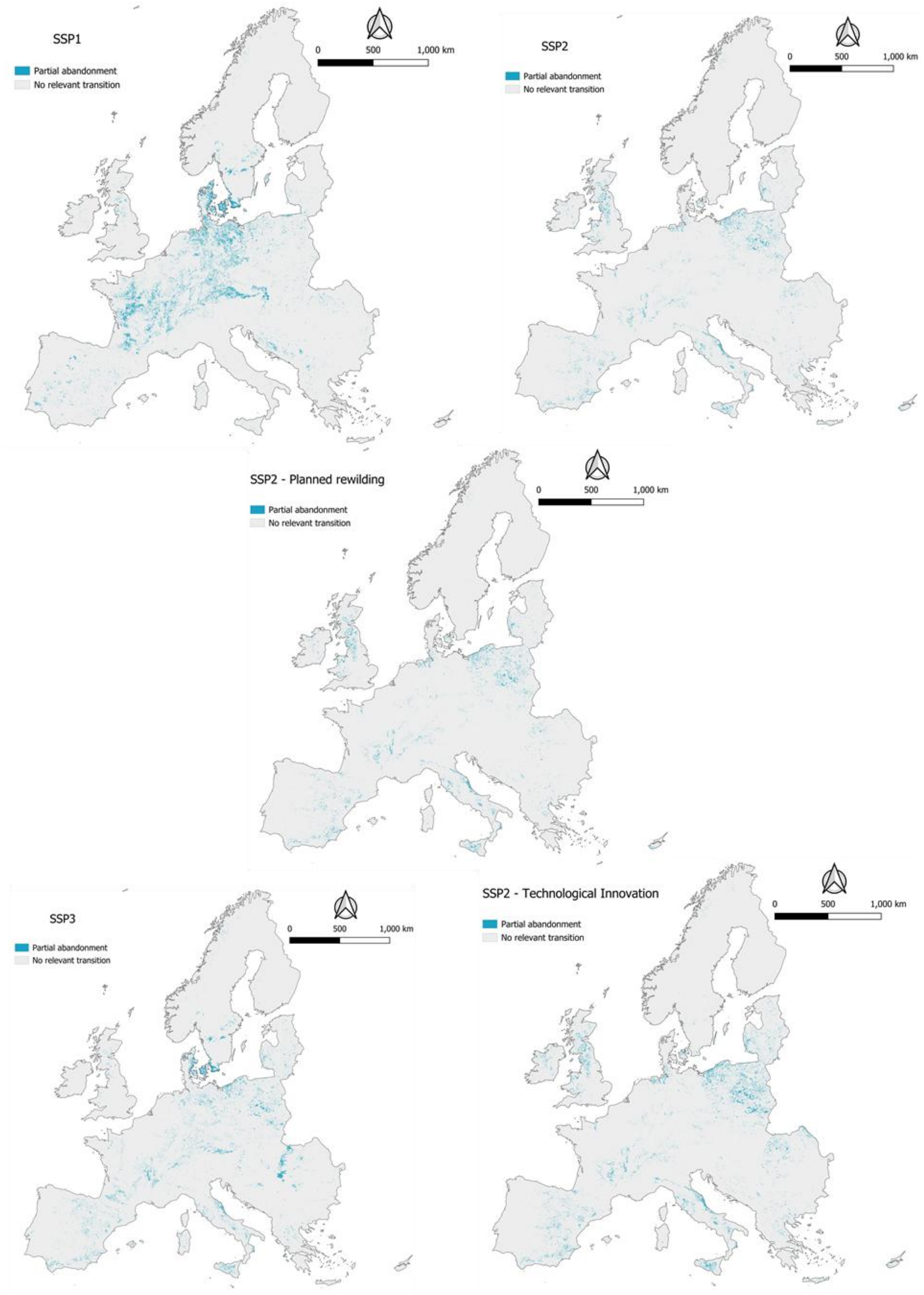

Figure 23: European land use change maps representing transitions in the period 2020 - 2050 under the SSP1, SSP2, SSP2-Technological innovation, SSP2 – Planned rewilding and SSP3 scenarios. Partial abandonment: transitions from cropland, grasslands and permanent crops into mosaics.

In addition to transitions directly related to rewilding, we also report ‘partial abandonment’ transitions, defined as the conversion of croplands, permanent crops, and grasslands into mosaic ecosystems (Figure 23). These transitions represent partial forest growth within the landscape, reflecting localized spontaneous vegetation succession or reforestation processes within our 1 km^2 mapping units.

Across all five IPCC SSP scenarios, partial abandonment is spatially concentrated in specific regions of Europe. Under SSP1, hotspots are clearly visible across central and western Europe, particularly in central France and Germany. Relevant are also the transitions in northern Europe, specifically in Denmark and southern Sweden. Additional clusters appear in central Spain, Switzerland and Northern Austria reflecting localised land-use relaxation in productive agricultural landscapes. The SSP2 scenario shows a quite dissimilar, more fragmented pattern, with concentrations of partial abandonment persisting in central France and Switzerland, and extending into central Italy. The two main hotspots regions in this case are Poland and central-northern UK. Patches also occur in Romania and Spain though at lower density. In the SSP2 – Technological Innovation variant, the overall extent of partial abandonment increase compared with SSP2 baseline. The main clusters remain comparable with SSP2, but their size increases visibly in Poland, France, Spain and Romania where some additional hotspots are visible where agricultural activity appears to retreat locally despite overall intensification trends. The SSP3 scenario presents the lowest overall extent of partial abandonment, with larger continuous hotspots restricted mainly to eastern Romania, Denmark and southern Sweden. Additional visible but more scattered locations of partial abandonment are spread across central and southern Italy, France, Germany, Poland and Spain. Overall, hotspots of partial abandonment are most consistently located within transitional agro-ecological zones in France, Poland, central Italy, and Spain—where cropland and grassland systems are interspersed with forested areas and therefore more susceptible to land-use de-intensification and partial vegetation succession.

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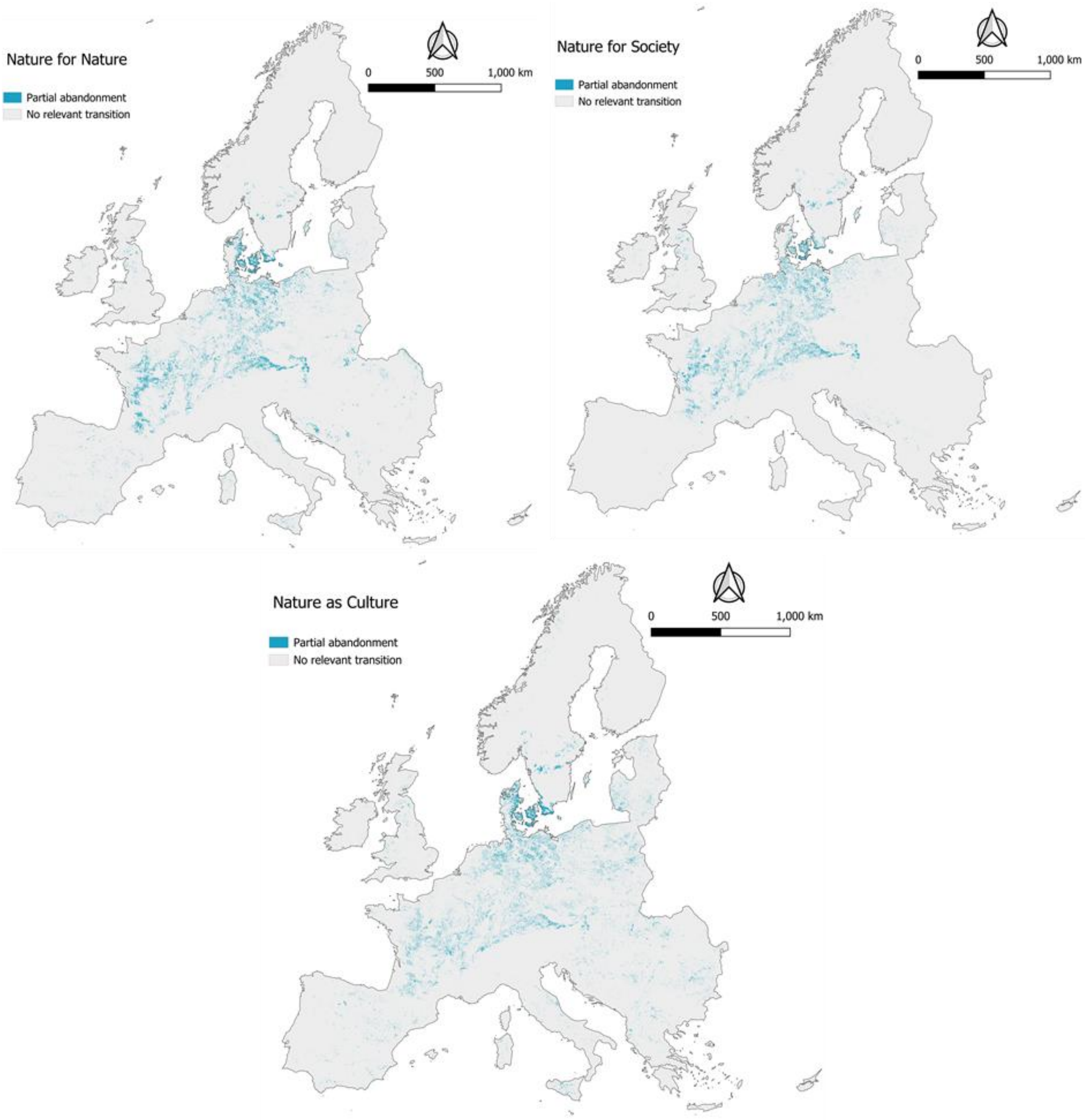

Figure 24: European land use change maps representing transitions in the period 2020 - 2050 under the Nature for Nature, Nature for Society, Nature as Culture scenarios. Partial abandonment: transitions from cropland, grasslands and permanent crops into mosaics.

Across the three IPBES NFF scenarios, partial abandonment exhibits quite similar hotspot regions within Europe (Figure 24). Notably, under the Nature for Nature scenario the densest clusters of this transition appear in the foothills of the Alps (southern Germany, eastern France, western Austria), along the Carpathian-Dinaric mountain belt (Slovakia, northern Romania, Bosnia and Herzegovina, Croatia), and more unevenly in the Iberian interior (north-central Spain). Similarly to the SSP1 scenario, also Denmark and southern Sweden represent important hotspots. In the Nature for Society scenario, the spatial pattern remains consistent with NfN but the size of the clusters decreases: strong concentrations are still observable in central and south-western France (Massif Central and adjacent terrain), Denmark, southern Sweden and Germany, but the partial abandonment locations in eastern Europe and in the Iberian peninsula are notably less dense than in NfN. Finally, the Nature as Culture scenario presents a more diffuse distribution of partial abandonment: identifiable but less dense hotspots lie in central France, northern Spain (Asturias–Cantabria uplands) and Germany,

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with more numerous patches in western Poland and eastern Europe in general. Denmark and southern Sweden remain consistent hotspots of partial abandonment. Overall, the most consistent zones of partial abandonment across scenarios coincide with transitional agro-ecological landscapes (for example in France, Germany, Poland), where agricultural and grassland systems border forested terrain, making them more susceptible to land-use de-intensification or mosaic re-structuring. More intensively managed landscape are also consistently transitioning to mosaics in Denmark.

8.1.2.2 Composite rewilding probability

The results of the three separate processes — proforestation, agricultural abandonment and agricultural abandonment leading to rewilding — were combined across all scenarios to identify hotspots for each category, highlighting areas of strong agreement across the scenarios.

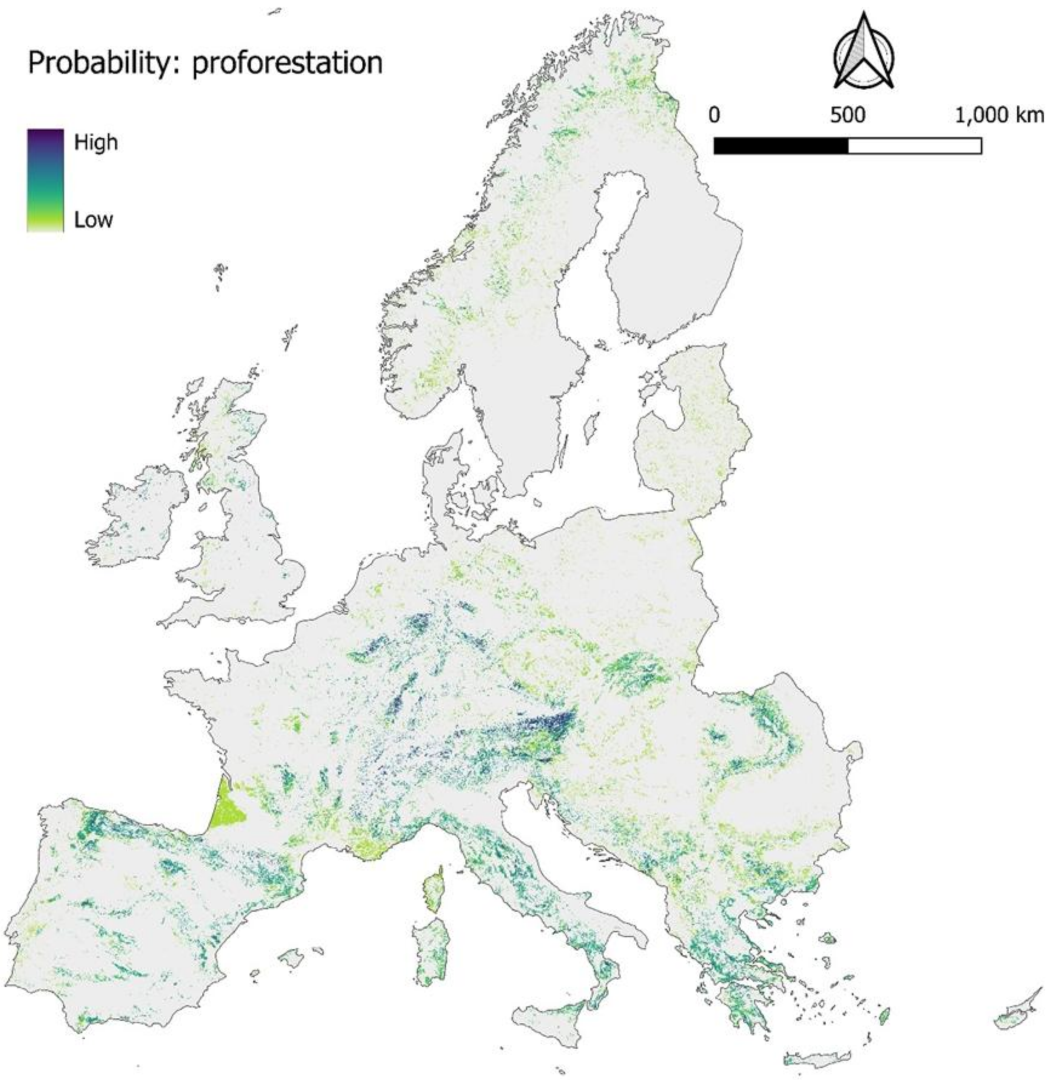

Figure 25: Proforestation probability map of Europe, representing areas with different levels of agreement across all eight land-use change scenarios. The maximum probability is reached when the conversion from managed forest to close-to-nature forest occurs in all eight scenarios.

In Figure 25 illustrates the probability of proforestation across Europe, highlighting regions where managed forests are most likely to transition toward close-to-nature forest conditions under consistent agreement across all eight land-use change scenarios. High-probability areas are concentrated along major mountain and hilly regions, including the Pyrenees, Alps, Massif Central, Carpathians, and Dinaric Alps, reflecting landscapes where forest management is often extensive and ecological conditions favour natural regeneration. In southern Europe, parts of northern Spain, central Italy, and Greece also show notable proforestation probability, while in northern Europe, southern Scandinavia and Scotland present smaller yet consistent clusters. Overall, the pattern reveals a strong alignment between topographic complexity, lower land-use pressure, and forest regeneration potential, suggesting that mountainous and semi-natural forested areas will play a central role in Europe's transition toward a more ecologically mature forest cover.

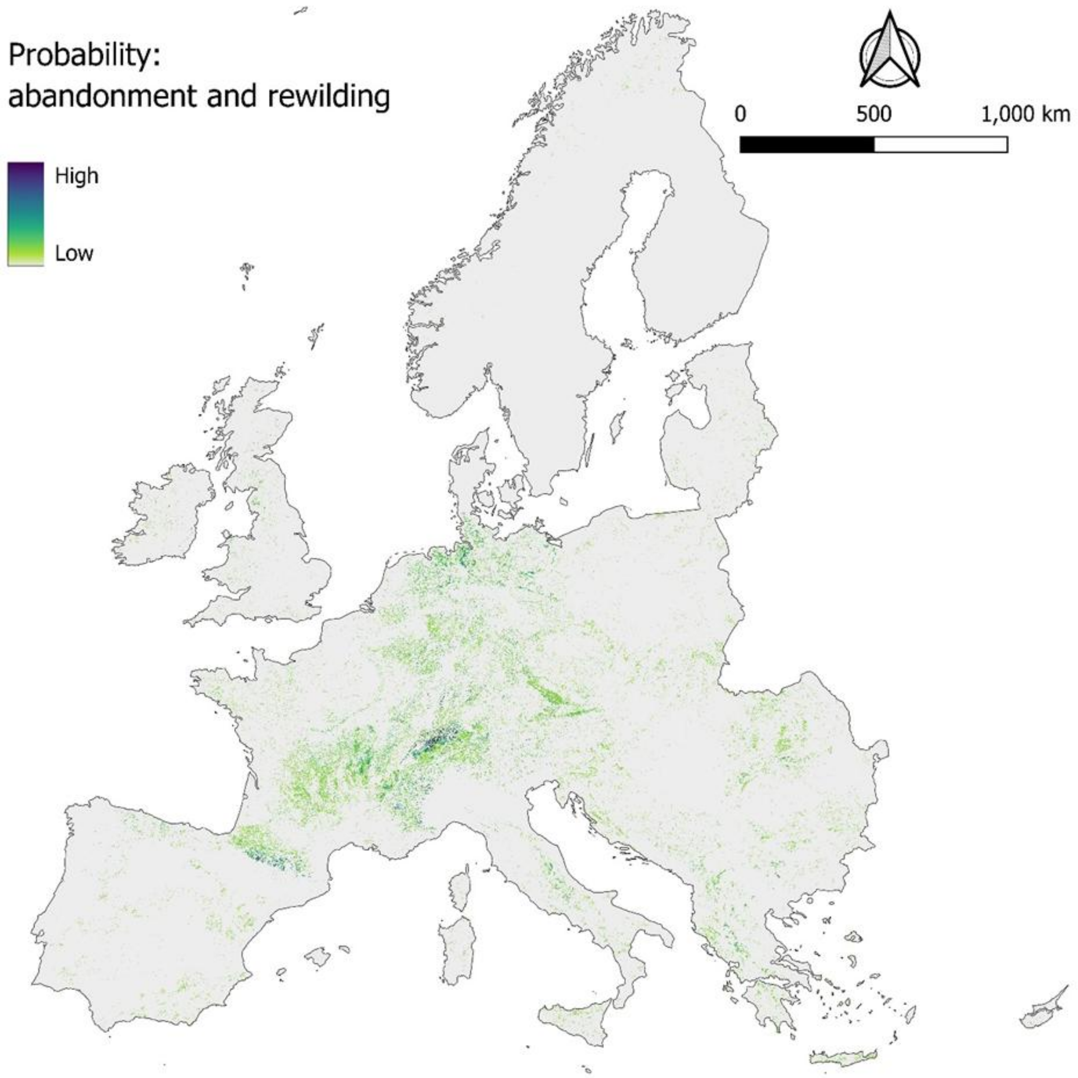

Figure 26: Agricultural abandonment and rewilding probability map of Europe, representing areas with different levels of agreement across all eight land-use change scenarios. The maximum probability is reached when the conversion from croplands (arable and permanent), grasslands and mosaics to close-to-nature forest occurs in all eight scenarios.

Figure 26 shows the probability of agricultural abandonment and rewilding across Europe, illustrating areas where croplands, grasslands, and mosaic systems are most likely to transition into close-to-nature forests under consistent agreement across eight land-use change scenarios. High-probability zones are relatively rare and prominently clustered along

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mountain foothills and upland valleys, especially across the Alps (France, Switzerland, Austria, Italy), and Pyrenees, where steep terrain and declining agricultural profitability favour natural forest regeneration. In southern France, northern Spain, central Italy, and parts of the Balkans, extensive patches indicate areas where farmland retreat could enable spontaneous woodland recovery, but the level of agreement among scenarios is lower. Large patches with lower probability are also evident in the Carpathians and Dinaric Alps. Smaller yet notable concentrations appear in northern Germany and northern Austria, reflecting ongoing processes of rural depopulation and low-intensity land use. Overall, the spatial pattern highlights a Europe where forest expansion is increasingly tied to the retreat of agriculture, usually where less intensive practices are currently in place, particularly in marginal and semi-natural landscapes, signalling the growing ecological potential for rewilding through passive succession.

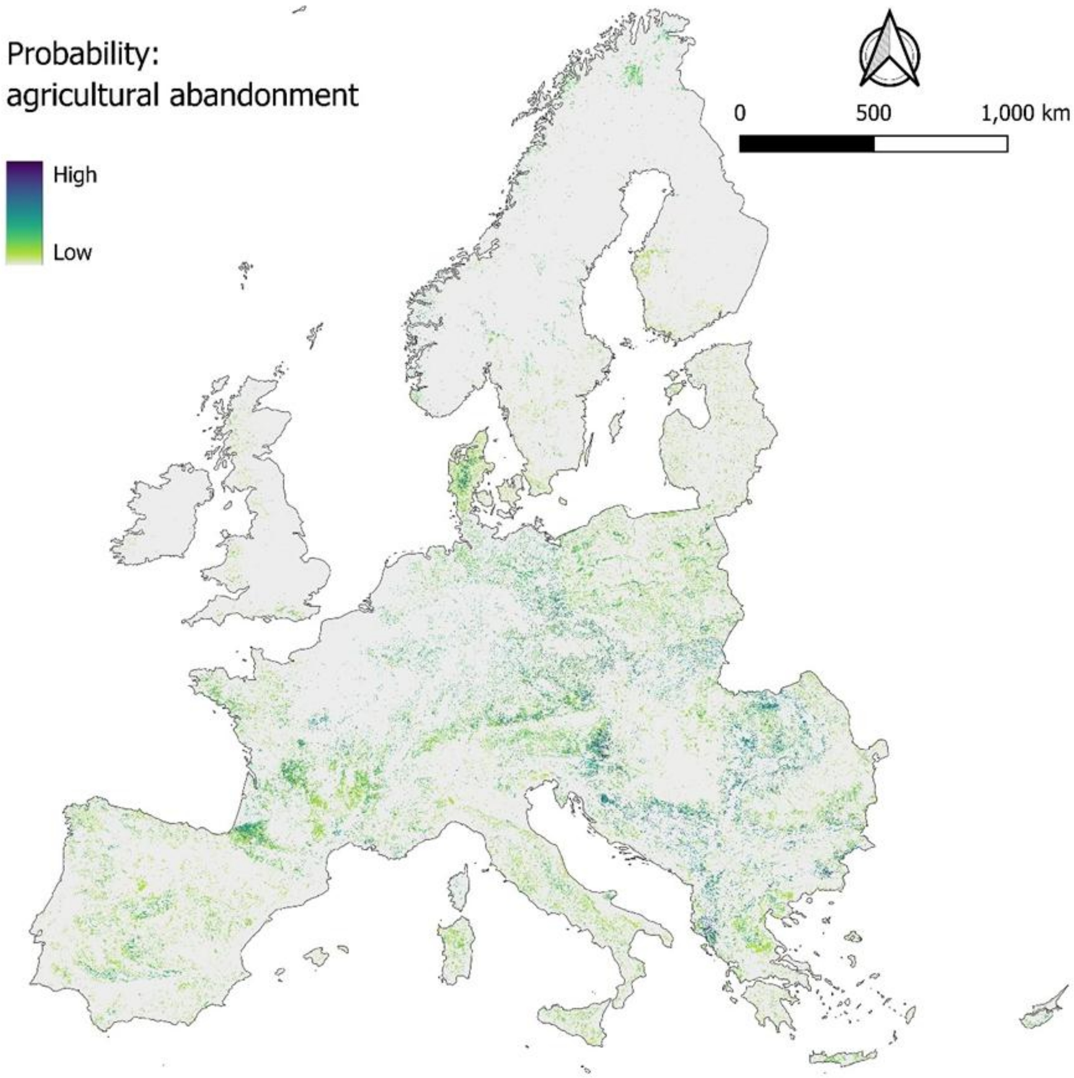

Figure 27: Agricultural abandonment probability map of Europe, representing areas with different levels of agreement across all eight land-use change scenarios. The maximum probability is reached when the conversion from croplands (arable and permanent), grasslands and mosaics to combined objective forest occurs in all eight scenarios.

Figure 27 illustrates the probability of agricultural abandonment leading to combined-objective forests across Europe, representing areas where farmland and grassland are most likely to transition into multifunctional forest systems under consistent agreement across eight scenarios. Unlike close-to-nature rewilding, these transitions imply a partial human role in forest recovery, balancing ecological and productive functions. The highest probabilities are found across central and eastern Europe, particularly in Poland, Czechia, Slovakia, Slovenia, the Carpathian foothills and the Dinaric–Šar–Pindus mountain system where large tracts of crops and mosaics are projected to revert to semi-managed woodland. Additional hotspots appear in southern and central France, Germany, and along the Apennines, marking zones where agricultural retreat meets forestry expansion policies. In the Nordic countries, especially in Denmark, southern Sweden and Finland and northern Norway, smaller clusters indicate potential shifts from marginal cropland and mosaics to mixed-use forests. Overall, the pattern points to a Europe where land abandonment increasingly fuels multifunctional afforestation, offering climate and resource benefits while still diverging from the fully self-regulated trajectories characteristic of pure rewilding.

Finally, the total rewilding probability map (Figure 28), the primary outcome of this deliverable, combines the proforestation and agricultural abandonment-rewilding maps. In this context, “pure” rewilding refers to land-use transitions reaching close-to-nature forest conditions. The resulting map highlights Europe’s main hotspots where new close-to-nature forests are most likely to emerge.

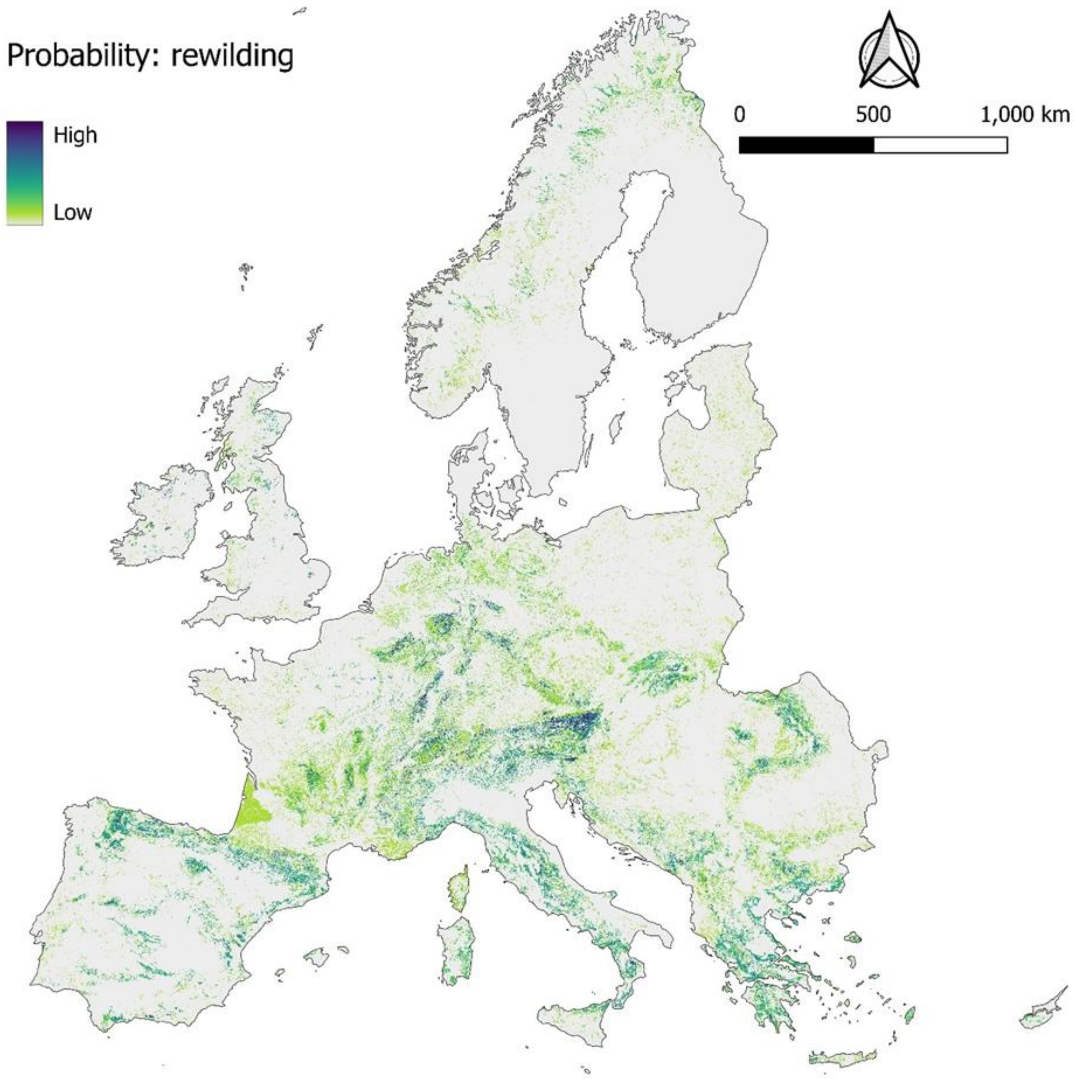

Figure 28: Total rewilding probability map of Europe, representing areas with different levels of agreement across all eight land-use change scenarios. The maximum probability is reached when the conversion from croplands (arable and permanent), grasslands, mosaics and managed forests to close-to-nature forest occurs in all eight scenarios.

High-probability rewilding hotspots are concentrated along Europe's major mountain systems, where topographic constraints, low agricultural profitability, and existing forest cover converge to favour ecological succession. Key region include the Alps, the Pyrenees, the Carpathians, and the Dinaric–Šar–Pindus mountain arc, all emerging as continental hotspots of rewilding potential. Additional concentrations are visible in northern Spain, southern France, central Italy, southern Germany, and across the Balkan Peninsula, where the mixture of cropland retreat and forest expansion suggests broad opportunities for habitat recovery and carbon storage. Outside mountainous areas, more fragmented but notable patterns appear in central and eastern Europe, especially in Poland, Czechia, and Romania, reflecting the interplay between land abandonment and forest succession in transitional rural landscapes. Overall, the results depicts a Europe where ecological recovery extends beyond protected areas, spreading through mosaic landscapes increasingly conductive to spontaneous forest regeneration and near-natural woodland expansion.

In Table 7, based on the total rewilding probability map (Figure 28), we summarise the distribution of modelled rewilding signals for both current forest and agricultural land (crops, grasslands, mosaics) across all eight scenarios. The table distinguishes eight levels of scenario agreement: 0 (no scenarios, low probability) through 8 (all scenarios, high probability). For each agreement level, the table lists the area (km²) and the proportion (%) of the total land in that category (forest or agriculture) undergoing transitions at exactly that level of scenario agreement. This detailed breakdown enables an assessment of both the scale of rewilding-eligible terrain and the degree of cross-scenario consensus supporting each probability class.

Table 6: Area (km²) and share (%) of Europe's current forest and agricultural land that, according to our composite map, are projected to undergo rewilding-related transitions at each level of scenario agreement (from 0 (no scenarios, low probability) to 8 (all scenarios, high probability)).

Level of agreement	Proforestation (km²)	Proforestation (% total forest)	Agricultural abandonment and rewilding (km²)	Agricultural abandonment and rewilding (% total forest)
0 (no scenarios)	1,276,528	73.74	2,209,884	90.64
1	171,356	9.90	187,716	7.70
2	74,064	4.28	26,514	1.09
3	103,872	6.00	8,435	0.35
4	61,198	3.54	2,957	0.12
5	23,978	1.39	1,395	0.06
6	12,823	0.74	1,147	0.05
7	6,679	0.39	104	0.00
8 (all scenarios)	527	0.03	1	0.00
Total current forest area : 1,731,025 km²				
Total current agricultural land area: 2,438,153 km²				

Outside the extensive areas where no rewilding is projected, the strongest cross-scenario consensus is concentrated in a relatively small fraction of the landscape. This limited spatial extent is largely driven by the small total area of rewilding projected under SSP3. Moderate levels of agreement (levels 3–5) occur more widely across upland and marginal land-use zones, whereas high-agreement areas (levels 6–8) are rare, highlighting the locations where the model most confidently identifies hotspots of forest regeneration or agricultural abandonment leading to rewilding.

To assess the distribution of rewilding probability across Europe, we computed country-level statistics, linking the total rewilding probability map to national boundaries (Table 7). This allows quantification of the area and share of each country's territory projected to undergo forest-regeneration or agricultural abandonment leading to close-to-nature forests, highlighting national-scale hotspots and enabling cross-country comparisons of rewilding potential.

Table 7: National forest cover and areas projected to undergo rewilding, showing generally eligible areas (≥ 1 scenario) and high (≥ 6 scenarios) probability locations, expressed as absolute area (km²) and percentage of total national forest cover.

Country	Total forest cover (km²)	Rewilding eligible area (≥ 1 scenarios) (km²)	Rewilding eligible area (≥ 1 scenarios) (% of total forest)	Rewilding high probability area (≥ 6 scenarios) (km²)	Rewilding high probability area (≥ 6 scenarios) (% of total forest)
Albania	10,206	4,308	42.21	183	1.79
Andorra	269	90	33.46	7	2.6
Austria	36,892	26,461	71.73	4392	11.91
Belarus	635	119	18.74	8	1.26
Belgium	4,435	3,309	74.61	532	12
Bosnia and Herzegovina	27,572	6,650	24.12	72	0.26
Bulgaria	41,840	14,985	35.82	192	0.46
Croatia	25,527	5,924	23.21	31	0.12
Cyprus	1,111	590	53.11	0	0
Czechia	20,908	11,231	53.72	72	0.34
Denmark	2,689	0	0	0	0
Estonia	25,997	2,373	9.13	7	0.03
Finland	264,925	12,869	4.86	173	0.07
France	120,474	60,083	49.87	2798	2.32
Germany	74,934	32,158	42.92	3222	4.3
Greece	49,287	33,362	67.69	538	1.09
Hungary	15,065	5,170	34.32	14	0.09
Ireland	3,080	2,375	77.11	384	12.47
Italy	89,055	49,016	55.04	1693	1.9
Kosovo	4,678	2,107	45.04	61	1.3
Latvia	34,840	4,462	12.81	2	0.01
Liechtenstein	57	15	26.32	0	0
Lithuania	17,825	3,656	20.51	5	0.03
Luxembourg	429	275	64.1	1	0.23
Malta	0	0	0	0	0
Monaco	3	3	100	0	0
Montenegro	8,001	4,054	50.67	185	2.31
Netherlands	2,127	1,370	64.41	2	0.09
North Macedonia	11,494	2,997	26.07	32	0.28
Northern Cyprus	110	95	86.36	0	0
Norway	114,586	18,873	16.47	532	0.46
Poland	78,785	11,114	14.11	50	0.06
Portugal	32,727	5,324	16.27	68	0.21
Republic of Serbia	28,483	6,692	23.49	25	0.09
Romania	67,929	22,901	33.71	805	1.19
San Marino	0	0	0	0	0
Slovakia	20,127	10,232	50.84	338	1.68

Slovenia	12,281	3,542	28.84	37	0.3
Spain	110,965	53,240	47.98	2137	1.93
Sweden	326,728	17,000	5.2	151	0.05
Switzerland	10,259	4,532	44.18	948	9.24
United Kingdom	17,202	9,101	52.91	222	1.29
Total current forest area in EU: 1,731,025 km²					
Total current agricultural land area in EU: 2,438,153 km²					

Rewilding probability is unevenly distributed across Europe. The largest areas eligible for rewilding (≥ 1 scenario) are found in already forest-rich countries such as France, Germany, Italy, Austria, Spain, Greece, and Romania. In relative terms, smaller countries with lower initial forest cover or historically strong abandonment trends — such as Ireland, Belgium, Czechia, and Cyprus — exhibit high proportions of forest with rewilding potential relative to their total forest area. Notably, some larger countries, including Austria and Greece, also show very high proportions. High-probability rewilding areas (≥ 6 scenarios) represent only a small fraction of national forests overall. This highlights that, while opportunities for natural forest regeneration are widespread, strong model agreement occurs primarily in well-defined upland and marginal landscapes. Nevertheless, Austria, Germany, Spain, Italy, and France maintain prominent trends even when considering the extent of high-probability rewilding areas..

9. Discussion

Across the proposed scenarios, we develop a composite picture of where rewilding is likely to occur. By modelling European land-use systems to 2050 and analysing two key processes, proforestation and agricultural abandonment, we identify areas where rewilding may proceed spontaneously (passive) as well as areas where it could require planned, active interventions, promoted by sustainability policies or changes in the distribution of existing subsidies (e.g., CAP and other agriculture targeted policies). Across scenarios, signals concentrate in familiar "edge" landscapes, uplands and montane forelands (Alpine/Carpathian arcs, Dinaric–Pindus), interior Iberia and northern Spain, and parts of southern Scandinavia, while highly productive Atlantic/Northern lowlands show thinner, more fragmented signals. This geography matches evidence that ecological "opportunity" for rewilding is highest where human pressure and profitability are lower, where remoteness and wilderness conditions are dominant (Ceausu et al., 2015; Araujo and Alagador, 2024).

In the SSP1 scenarios family, we see rising opportunities also in Western and Central Europe. In Western and Central Europe, specifically in countries like Germany, France, Austria and Czechia, farmland abandonment in sustainable futures may be elevated for several region-specific reasons. Firstly, rising environmental and production costs reduce the viability of smaller farms even in highly regulated, sustainability-oriented contexts; secondly, labour shortages and demographic pressures, especially in rural regions with ageing farmers, make farming less viable; thirdly, policy re-orientations from conventional production toward high-value ecosystem services reduce incentives for marginal land to remain under cultivation, thus increasing abandonment risk (Perpiña Castillo e al., 2021). Different studies on agricultural and land management abandonment confirm that within the EU, France and Germany are among the countries projected to contribute to the largest absolute losses of agricultural land despite their lower relative values compared to other regions (Perpiña Castillo e al., 2021). In our modelling, the SSP1 demands for wood and arable crops (strongly driving abandonment dynamics) are projected to strongly decrease and slightly increase, respectively, leaving space for nature to expand. In SSP1 we envision the introduction of strong nature-positive policies in Western Europe, that further enhance the likelihood of transition to natural forests.

Importantly, although the three variants of the Nature Futures Framework (NFF) built on SSP1 adopt identical demand assumptions, they produce noticeably different areas of future rewilding. This divergence highlights how different underlying value-orientations in the implementation of sustainability objectives can lead to very different outcomes for rewilding, even when current demands are held constant. Across the NFFs, hotspots line up with protected-area and corridor networks and extend toward places where different values of nature (intrinsic for NfN, regulating/utility for NfS, relational/cultural for NaC) converge (Pereira et al., 2020; Kim et al., 2023). Central and Western Europe is in general the area of highest agreement among the four SSP1-driven scenarios, with Switzerland, France, Germany and Austria consistently transitioning to forest in similar locations. In NfN, the Carpathians, Spain and Italy join the list of rewilding hotspots, while in NfS, the central European hotspots persist but become smaller in size and southern European agricultural abandonment dynamics generally shifts to multifunctional forestry rather than close to nature forest regrowth. In NaC, the multifunctional forests grow even more, leaving very small remaining hotspots of "pure" rewilding, mainly located in Switzerland and southern France.

By contrast, the SSP2 and SSP3-driven scenarios yields tighter, patchier agreement, with hotspots in Southern European countries (Italy, Greece, Spain) and the Carpathians, consistently happening in more remote areas. As in the SSP1-driven scenarios, high agreement is also found in Austria and central Germany.

Interpreting the patterns through a proforestation lens, places where natural and close-to-nature forests expand or where crop management intensity drops serve the purpose of rewilding quite well: letting existing forests keep growing (proforestation) delivers rapid, durable carbon uptake alongside structural and habitat co-benefits, particularly in mid- to late-successional stands. This is well-documented vegetation succession studies (Frei et al., 2022; Erdozain et al., 2025; Martín-Forés et al., 2020) and complements restoration approaches that plant new trees where appropriate (Moomaw et al., 2019). In practice, this means the broad NfN gains and the SSP1/SSP2-variant clusters in uplands and forelands might be strategic: they concentrate benefits where opportunity costs and risks tend to be lower, while leaving prime lowlands for production unless or until policy changes shift the boundary conditions. This second dynamic, though not dominant, is also evident in the more sustainability-oriented scenarios, where nuclei of new natural forests appear across Western and Central Europe driven by the assumption of rigorous implementation of nature and forest-positive policies.

Rewilding opportunities relay strongly also on agricultural abandonment (i.e., transitions from cropland or grassland or mosaics to seminatural or natural forest endpoints) and land use deintensification dynamics. Under SSP2 (baseline), we see moderate abandonment in Mediterranean and sub-alpine uplands (northern Iberia/interior Spain, parts of the Balkans), broadly continuous with 2000s–2010s trends (Quintas-Soriano et al., 2022; Lasanta et al., 2017); under SSP2-planned rewilding, an amplification of the same clusters; under SSP1, larger, more connected patches and a higher share reaching natural forest endpoints; under SSP3, more fragmented signals with greater recultivation pressure in fertile regions and a shift toward remote margins. All of these align with European syntheses showing that abandonment drivers and outcomes are context-dependent. Benefits (habitat recovery, carbon, regulating services) tend to rise in rugged or marginal zones, but risks (e.g., fuel build-up and fire where management ceases) can increase without control (Ustaoglu and Collier, 2018; Quintas-Soriano et al., 2022).

In addition, agricultural abandonment in our study often results in combined objective forest, where some use remains but is not intensive. Dedicated rewilding strategies could increase the amount of rewilding within these new forests and lead to much larger rewilded areas. However, our results indicate that, without appropriate incentives, some degree of management is likely to persist. Nevertheless, this management may remain at relatively low levels, still allowing for high nature values in the projected situation, as these forests typically arise from natural regrowth and are not primarily designed for wood production.

However, even when forest regrowth is facilitated, like in rewilding contexts, agricultural abandonment endpoints are not automatic: without governance or in areas where the climatic and ecological conditions in general slow the vegetation succession process, transitions can stall for a long time in shrub encroachment before reaching closed-canopy forest. In addition, in the Mediterranean region, shrubs and small trees-dominated landscapes (Mediterranean maquis) can constitute the climax state of vegetation succession. To not lose the nuances of the process and to include these less obvious abandonment cases, we studied also the transitions that we define as "partial abandonment": crops, grasslands and permanent crops transitioning to mosaic ecosystems. Partial abandonment emerges as a spatially consistent process concentrated in transitional agro-ecological zones of Europe. Hotspots recurrently occur in France, Poland, central Italy, Spain, Denmark, and southern Sweden—areas where cropland and grassland systems interface with forests, favouring land-use de-intensification. While SSP1 and Nature for Nature show the broadest and most connected hotspots, SSP3 and Nature as Culture display more fragmented and localized patterns. The persistence of partial abandonment is noticeable in productive yet structurally diverse landscapes and, even though they are not considered as priority areas for rewilding implementation, they hold some degree of potential, especially in landscapes that would benefit from the restoration of more open types of ecosystems.

The spatial patterns revealed by our modelling carry several implications for policy and practice. First, the identification of rewilding-ready zones offers actionable insights for policy-makers. Regions with high probability of natural forest transition can serve as priority areas for nature-based interventions and land-use incentives. The produced probability maps can support the spatial targeting of existing instruments (such as agri-environment schemes, forest and carbon payments, and restoration funds) by indicating where relatively small policy shifts could unlock substantial gains in forest recovery. They also provide an evidence base for integrating rewilding into national restoration strategies and EU-level planning, for example by aligning high-probability areas with zones where land-use extensification or set-aside is socially and economically feasible.

Our work contributes to filling a significant gap in the literature by clarifying the differences among rewilding typologies and emphasizing the need to study these processes separately. We distinguish between proforestation (forest regeneration from existing stands) and reforestation from agricultural abandonment; proforestation specifically, remains an area still largely under-explored in the literature. Most existing studies focus on current suitability (Ceaușu et al. 2015; Araujo and Alagador, 2024; Kloibhofer et al. 2025) or single-scenario outcomes (Thierry and Rogers, 2020), rather than quantifying projected future transitions across multiple land-use scenarios. Our rewilding suitability assessment (MCA – Multi Criteria Analysis) follows the general approach adopted in previous studies, but we extend it by coupling it with dynamic land-use change modelling within the WILDCARD-specific SSP2–Planned Rewilding scenario, enabling the exploration of both potential and realized spatial trajectories of forest regeneration (probability). Finally, by mapping pixel-level agreement across eight distinct scenarios, our study introduces a robust consensus metric, enabling the identification of zones where forest regeneration is consistently modelled.

In sum, our modelling results can help inform rewilding implementation efforts. To identify the most favourable locations for rewilding, we should give priority to standing and maturing forests in consensus-hotspots (proforestation) while building rewilding strategies in landscapes prone to abandonment that respect local values: land-sparing cores and corridors where the Nature for Nature logic dominates; multifunctional mosaics around settlements where the Nature for Society logic is strongest; and biocultural landscapes under Nature as Culture.

10. Limitations

The present study provides a first continental-scale assessment of rewilding potential and probability in Europe, yet it is subject to important limitations that must be acknowledged. Although eight distinct scenarios were employed, spanning multiple socioeconomic, technological and governance pathways, these still represent only a subset of all possible futures. The scenario set thus cannot capture the full range of plausible developments, including abrupt shifts such as major economic disruption, radical policy change or large-scale migration. As noted in land use modelling research, scenario diversity helps but does not eliminate uncertainty in future trajectories (Prestele et al., 2016; Hewitt et al., 2022).

Model uncertainty can arise from several sources. First, the translation of high-level narrative storylines into quantitative model parameters involves simplifications and assumptions, especially when applying generic conversion rules across the entire continent. Local institutional, cultural or policy contexts, which can differ substantially among European countries, are not explicitly reflected, making the spatial allocation of transitions somewhat idealised. Secondly, the overall accuracy of land use models such as CLUMondo is difficult to assess, as the unpredictability of human behaviour, land-manager decision-making and policy interventions is always a limitation (Gao et al., 2022). Thirdly, the spatial resolution (1 km^2) while suitable for continental coverage, masks fine-scale heterogeneity in land-use dynamics, forest succession pathways and local disturbances, meaning that some key processes (for example rapid shrub-invasion, local abandonment, patchy forest regeneration) may be under-represented.

Data limitations and structural model uncertainties also affect our results. As highlighted in comparative land-use change studies, model structure, parameterisation and input data quality contribute significantly to uncertainty in both quantity and spatial pattern of change (Bastos et al., 2021; Prestele et al., 2016). Moreover, key processes such as climate extremes, pest outbreaks, forest fires or other disturbance regimes, which can severely influence forest regeneration, tree mortality and succession trajectories (Langenbacher et al., 2025), are not explicitly included in this modelling exercise, even though they could materially alter rewilding probability. Furthermore, national policy mechanisms, subsidies, regional forest management strategies and local governance frameworks are not directly represented; instead, rules are applied uniformly across Europe, reducing sensitivity to national or sub-national policy variation.

An important limitation, specific to our modelling framework, lies in the representation of ecological succession after agricultural abandonment. Since no explicit “abandoned” or “transitional” land-use classes are available in our basemap, gradual regrowth cannot be directly simulated. To approximate this process, we allow agricultural areas to convert first into “combined objective forest” and then into “close-to-nature forest.” This approach avoids implausible direct conversions, yet it can still produce forest establishment within unrealistically short timeframes. Although the model generally retains pixels longer in the intermediate class, the final forest state remains uncertain in terms of successional maturity. Field studies show that natural forest regrowth from cropland or grassland usually takes several decades — around 20–40 years in temperate regions (Broughton et al., 2021; Řehounková et al., 2024) and up to 70–80 years in Mediterranean or boreal climates (Norden et al., 2021). Even under planned rewilding conditions with active interventions such as assisted natural regeneration or replanting (Qiu et al., 2025; De Lombaerde et al., 2020), full canopy closure would still require multiple decades. Despite this limitation, the model remains valuable in identifying spatial hotspots of potential forest recovery. These areas represent locations where forest succession is most likely to occur under favourable socio-ecological conditions, providing a valid spatial basis for targeting rewilding interventions, regardless of the specific successional stage reached by the end of the simulation.

Moreover, our simulations show that even under identical aggregate demand assumptions, the three Nature Futures variants produce markedly different spatial footprints of rewilding probability. This divergence highlights the structural uncertainty that arises when qualitative priorities are translated into spatially explicit projections. In addition, high relative probabilities or percentages at national or regional level can still correspond to modest absolute areas, particularly in countries with limited remaining forest cover, which further constrains the direct translation of our maps into quantitative policy targets.

Finally, the accuracy of land-use change modelling remains challenging because it deals with human and social systems as much as biophysical ones. The spatial allocation of rewilding probability is conditional on many interacting factors (economic, demographic, institutional) which carry deep uncertainty. The result is that the probability maps produced should be interpreted as indicative of possible patterns rather than prescriptive predictions of where rewilding will definitively occur. In the absence of comprehensive validation data, especially for future states, the modelled results require cautious interpretation.

11. Conclusion

This first continental-scale assessment of rewilding probability provides a spatially explicit baseline for identifying Europe's areas most likely to experience natural forest regeneration. Across all eight scenarios, the modeling shows that high-probability rewilding zones are concentrated in mountainous and upland regions, particularly the Alps, Apennines, Pyrenees, Carpathians (Eastern and Western), the Dinaric–Šar–Pindus mountain arc, Massif Central, and the Scandinavian Mountains.

The largest continuous clusters of high-probability rewilding land are located in Austria, especially the Eastern Alps, including the Alpine massifs in Salzburg, Tyrol, Carinthia, and Styria; Slovakia, in the Western Carpathians around the Fatra-Tatra mountain systems; Germany, in the German Central Uplands ("Mittelgebirge"), the southern Black Forest, and the eastern Bavarian-Bohemian Forest region; Spain, in the Pyrenees, the Cantabrian Mountains along the Atlantic coast, and the Sistema Ibérico in the eastern interior; and Italy, where the Apennines extend down the peninsula to Calabria in the South, along with the Dolomites in the North-East, the Ligurian Alps and Apennines in the North-West, and the Maritime, Cottian, Graian, and Pennine Alps in the North-West.

Notable clusters of mixed high and moderate rewilding probability are found in France (Massif Central), Greece (widespread across the territory), Romania (Carpathians), Scotland (Scottish Highlands), Bulgaria (south-west, including the Rhodope, Belasitsa, and Slavyanka Mountains), and Montenegro (following the Durmitor, Bjelasica, and Accursed Mountains). These regions combine steep terrain, low agricultural profitability, and extensive existing forest cover, making them structurally predisposed to natural regeneration under reduced management intensity.

High- and moderate-rewilding probability areas are also present, though more scattered or fragmented, in Slovenia, Croatia, Bosnia and Herzegovina, southern Serbia, Albania, Ireland, northern Finland, and northern-central Sweden.

The modelling indicates that over 1.16% (≈ 20,029 km^2) of Europe's current forest area (≈ 1,731,025 km^2) exhibits a proforestation signal in at least six of the scenarios, representing high-probability areas. Similarly, approximately 0.05% (≈ 1,252 km^2) of Europe's agricultural land, grasslands, and mosaics (≈ 2,438,153 km^2) shows a high probability — conversion in at least six scenarios — of abandonment leading toward close-to-nature forest systems.

Considering also locations with a lower likelihood of rewilding, around 10.92% (≈ 189,048 km^2) of Europe's current forest area exhibits a proforestation signal in at least three scenarios (excluding the ≥6 scenario agreement), while approximately 0.58% (≈ 14,039 km^2) of agricultural land demonstrates a moderate probability of conversion toward forested or close-to-nature systems (also in at least three scenarios, excluding ≥6 scenario agreement).

Overall, these results provide a tangible order of magnitude for the potential of forest-regeneration processes under future land-use evolution. The total proforestation-eligible forest area (conversion in at least one scenario) spans ≈ 454,497 km^2 (≈ 26.26% of existing forests), while agricultural-to-forest conversion-eligible cropland and grassland covers ≈ 228,269 km^2, representing roughly 9.36% of total agricultural land in Europe.

At the national level, countries with the largest identified proforestation probability — such as Spain, France, Italy, Romania, and Austria — show that high-probability areas range from a maximum of ≈ 4,300 km^2 in Austria (11.91% of current forest cover) to a minimum of 1,600 km^2 in Italy (1.9% of current forest cover). This indicates that even in the most promising territories, the scale of "proforestation-ready" terrain is substantial but remains a relatively small fraction of existing forest estates.

For the WILDCARD project, this spatially explicit modelling provides a robust decision-support layer: the maps highlight where field validation and biodiversity monitoring should be prioritized (Tasks 1.4, WP2, and WP3), and where forest-carbon modelling can focus on emergent forest-expansion zones. From a policy perspective, the mapping identifies priority regions for implementing incentives and ecosystem-restoration schemes under frameworks such as the EU Biodiversity Strategy 2030 and the forthcoming Nature Restoration Law.

In summary, while Europe's low-intensity agricultural lands and upland terrain contain substantial rewilding potential, forest-regeneration expansion is spatially concentrated, predominantly in structurally favourable mountain and upland regions rather than uniformly across the landscape. The next phases of WILDCARD will refine these insights through improved scenario-specific input data, enhanced socio-economic modelling, and targeted field validation, translating modelled probabilities into actionable trajectories for nature restoration.

By revealing the magnitude, distribution, and coherence of forest-regeneration potential, this deliverable lays the analytical groundwork for evaluating the climate and biodiversity co-benefits of rewilding. The resulting maps can guide upcoming project work packages (Tasks 1.4, WP2–WP5) and broader policy and management efforts, enabling conservation managers, communities, and the private sector to plan nature-based solutions at scale.

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13. Annex

Technical documentation on common baseline development

The data sources for building the 2020 basemap, common to all scenarios, are:

- **Forest management map**: Scherpenhuijzen, Niek; West, Thales; Debonne, Niels; Oostdijk, Saskia; Verburg, Peter, 2023, "A forest management map for Europe", https://doi.org/10.34894/HQIJN5, DataverseNL, V3
- **Land use map**: Sandström, Evelina; Namasivayam, Anandi; Oostdijk, Saskia; Scherpenhuijzen, Niek; Debonne, Niels; Verburg, Peter, 2023, "Land system map for Europe", https://doi.org/10.34894/THARMK, DataverseNL, V6

Land use drivers

The model incorporates the following land-use drivers, which were used in the regression analysis to produce the suitability and probability maps for each land-use class. Their original data sources are also indicated. All files have been clipped to Europe's boundaries, 1km resolution, projected to EPSG 3035 – ETRS89 extended LAEA Europa and aligned with the European reference grid.

DEM: European Commission – DG ENTR, 2012, EU-DEM Version 1, available from EU-DEM (LAEA) - GISCO - Eurostat (europa.eu)

Jarvis, A., H.I. Reuter, A. Nelson, E. Guevara, 2008, Hole-filled SRTM for the globe Version 4, available from the CGIAR-CSI SRTM 90m Database (http://srtm.csi.cgiar.org).

1km aggregation of srtm4.1dev median has been retrieved from https://www.earthenv.org/topography

The original dataset has a resolution of 25m. It was aggregated to 1 km using the *aggregate* function in R with the median as a summary statistic. For areas not covered by the EC dataset, we incorporated SRTM4.1dev data, originally at 90 m resolution and likewise aggregated to 1 km using the median. A few pixels remained without values and were manually filled with values obtained by the application of a nearest neighbour function. We chose the median because it ensures that at least 50% of the cell area has an elevation above or below the reported value. This approach prevents small high-elevation features within a predominantly low-elevation pixel from disproportionately increasing the aggregated elevation value, which could otherwise distort the subsequent assessment of land-use suitability.

Slope: European Commission – DG ENTR, 2012, EU-DEM Version 1, available from Slope - GISCO - Eurostat (europa.eu)

Jarvis, A., H.I. Reuter, A. Nelson, E. Guevara, 2008, Hole-filled SRTM for the globe Version 4, available from the CGIAR-CSI SRTM 90m Database (http://srtm.csi.cgiar.org).

1km aggregation of srtm4.1dev median has been retrieved from https://www.earthenv.org/topography

The original dataset was aggregated using the same procedure described above for the DEM. To generate the layer showing the percentage of slope below 5 degrees, the raw slope data were first converted into a binary classification. The data were then aggregated using the mean, producing the percentage of area within each grid cell with a slope below 5 degrees. The same procedure was applied to create the layer indicating the percentage of slope above

15 degrees. To fill data gaps, SRTM4.1 data at 90 m resolution were used, following the same methodology.

Soil data: clay content, silt content, sand content, coarse fragments, bulk density and available water content (AWC) were collected from Ballabio et al. (2016). The extrapolated data is used and extended with data of SoilGrids V2: https://doi.org/10.5194/soil-7-217-2021, downloadable at ISRIC - Index of /soilgrids/latest/data_aggregated/1000m/

The layers 0-5 cm, 5-15 cm and 15-30 cm were downloaded and the following formula was used to combine them into 0-30 cm depth layers: (0-5cm + 2* 5-15cm + 3*15-30cm) / 6.

AWC is not directly provided in SoilGrids. As described in Ballabio et al. (2016), AWC was calculated as the difference between water content at –33 kPa and –1500 kPa (expressed as volume fraction). SoilGrids V2 provides both layers, so AWC was derived by subtracting the –1500 kPa layer from the –33 kPa layer.

All SoilGrids data layers were converted from the SoilGrids V2 mapped units to the Ballabio et al. (2016) mapped units. The layers were then clipped to the study extent, aligned, and remaining gaps were filled with values obtained by the application of a nearest neighbour function. Finally, the two datasets were merged, giving priority to Ballabio et al. (2016) in overlapping regions.

Soil pH in H2O and cation exchange capacity (CEC) were taken from Ballabio et al. (2019). Because no extrapolated version was available, these layers only cover EU-26 (excl. Cyprus & Croatia). The same processing steps as above were applied for these layers.

A detailed inspection of SoilGrids V2 CEC revealed anomalously high values across Northern Europe, indicating a substantial upward bias. For this reason, the SoilGrids-based CEC layer was excluded from the modelling for Northern Europe.

Soil organic carbon content was collected from de Brogniez et al. (2015). It only covers EU-25, thus it is also extended by SoilGrids V2, using the same procedure, in unit g/kg.

We chose to prioritise European datasets because they are based exclusively on European observations rather than global data. These datasets were developed using measurements from the LUCAS database. We are aware that some variables in these products are predicted using land-cover information. However, no dataset currently exists that provides soil observations covering the whole of Europe. When using these datasets for modelling land cover, caution is warranted, as correlations between the soil layers and land-cover classes may be present due to the way the datasets were produced. Therefore, we recommend performing a correlation analysis — including both land-cover variables and the soil data layers — before using the data in predictive modelling.

Socio-economic data

Accessibility to cities: the dataset was aligned and gaps were filled with values obtained by the application of a nearest neighbour function.

Source: Weiss, D. J., Nelson, A., Gibson, H. S., Temperley, W., Peedell, S., Lieber, A., Hancher, M., Poyart, E., Belchior, S., Fullman, N., Mappin, B., Dalrymple, U., Rozier, J., Lucas, T. C. D., Howes, R. E., Tusting, L. S., Kang, S. Y., Cameron, E., Bisanzio, D., … Gething, P. W. (2018). A global map of travel time to cities to assess inequalities in accessibility in 2015. Nature, 553(7688), 333–336. https://doi.org/10.1038/nature25181

Motorized travel time to healthcare: the dataset was aligned and gaps were filled with NN.

Source: Weiss, D.J., Nelson, A., Vargas-Ruiz, C.A. et al. Global maps of travel time to healthcare facilities. Nat Med 26, 1835–1838 (2020). https://doi.org/10.1038/s41591-020-1059-1

Total road density (grip4): the dataset has an original resolution of 5 arcminute. The data was upscaled using values obtained by the application of a nearest neighbour function.

Source: Meijer, J. R., Huijbregts, M. A. J., Schotten, K. C. G. J., & Schipper, A. M. (2018). Global patterns of current and future road infrastructure. Environmental Research Letters, 13(6). https://doi.org/10.1088/1748-9326/aabd42

Climate data: climate data was taken from Chelsa cmip 6 package. The chosen bioclimatic variables are summarized in Table 8. Data is available for RCP2.6, RCP 4.5 and RCP7.0.

Protected areas: Natura2000, Emerald network and IUCN data is available. Also Natura2000 combined with Emerald and IUCN data is available. Natura 2000 data was taken from European Environmental Agency.

Source: Natura 2000 (vector) - version 2021 revision 1,Oct. 2022SHPGeopackageMicrosoft Access (.mdb, .accdb)ascii (.csv, .txt, .sql)ESRI:RESTOGC:WMS https://www.eea.europa.eu/en/datahub/datahubitem-view/6fc8ad2d-195d-40f4-bdec-576e7d1268e4

Emerald network data was taken from Emerald Network data - the Pan-European network of protected sites (europa.eu) (2023). Natura2000 only covers the European Union, Emerald network is the equivalent to Natura2000 outside of the European Union.

IUCN protected areas. This data was taken from The World Database on Protected Areas (WDPA; https://www.protectedplanet.net/en/thematic-areas/wdpa?tab=WDPA). Only PAs with IUCN category, were selected:

- Category Ia: Strict Nature Reserve/Wilderness Area
- Category Ib: Wilderness Area
- Category II: National Park
- Category III: Natural Monument or Feature
- Category IV: Habitat/Species Management Area
- Category V: Protected Landscape/Seascape
- Category VI: Protected Area with Sustainable Use of Natural Resources

Table 8: Explanatory variables and data sources.

Category	Explanatory variable	Original resolution	Description (Unit)	Source	File name in CLUMondo
Biophysical	DEM	25m	Elevation (m)	(EC, 2012a)	sc1gr0.fil.asc
	Slope	25m	Slope (degrees)		sc1gr1.fil.asc
	Slope under 5 degree	25m	Flat slope (%)	(EC, 2012b)	sc1gr2.fil.asc
	Slope above 15 degree	25m	Steep slope (%)		sc1gr3.fil.asc

	AWC	500m	Available Water Capacity (AWC) (difference of volume water content at 33kPa and 1500kPa (volume fraction))	(EC, 2012b)	sc1gr4.fil.asc
	Bulk density	500m	Bulk density (t m−3 (g cm−3))	(EC, 2012b)	sc1gr5.fil.asc
	Clay	500m	Topsoil (0–20 cm) clay content (%)	(Ballabio et al., 2016)	sc1gr6.fil.asc
	Sand	500m	Topsoil (0–20 cm) sand content (%)	(Ballabio et al., 2016)	sc1gr7.fil.asc
	Silt	500m	Topsoil (0–20 cm) silt content (%)	(Ballabio et al., 2016)	sc1gr8.fil.asc
	Coarse fragments	500m	Topsoil (0–20 cm) coarse fragments (%)	(Ballabio et al., 2016)	sc1gr9.fil.asc
	pH in water	500m	Topsoil (0-20cm) pH of water in soil (pH)	(Ballabio et al., 2019)	sc1gr10.fil.asc
	Organic carbon concentration	500m	Topsoil (0-20cm) soil organic carbon concentration (g/kg)	(de Brogniez et al., 2015)	sc1gr11.fil.asc
	Cation exchange capacity	500m	Topsoil (0-20cm) cation exchange capacity (cmol(c)/kg)	(Ballabio et al., 2019)	sc1gr12.fil.asc
Socio-economic	Road density	5’	Densities summed across the five road types (m/km2)	(Meijer et al., 2018)	sc1gr13.fil.asc
	Accessibility	1km	Travel time to cities (h)	(Weiss et al., 2018)	sc1gr14.fil.asc
	Travel time healthcare	1km	Motorized travel time to	(Weiss et al., 2020)	sc1gr15.fil.asc

			healthcare (min)		
Climatic	Bioclimatic variable 01	1km	Annual Mean Temperature (°C)	(Karger et al., 2017)	sc1gr16.fil.asc
	Bioclimatic variable 02	1km	Mean Diurnal Range (°C)	(Karger et al., 2017)	sc1gr17.fil.asc
	Bioclimatic variable 04	1km	Temperature Seasonality (standard deviation)	(Karger et al., 2017)	sc1gr18.fil.asc
	Bioclimatic variable 07	1km	Annual range of air temperature (°C)	(Karger et al., 2017)	sc1gr19.fil.asc
	Bioclimatic variable 12	1km	Annual precipitation amount (kg m-2)	(Karger et al., 2017)	sc1gr20.fil.asc
	Bioclimatic variable 15	1km	Precipitation seasonality (kg m-2)	(Karger et al., 2017)	sc1gr21.fil.asc
Protected areas	Natura2000 + Emerald Network	1km	Natura2000 and Emerald Network areas (polygon)	(EEA, 2022) & (EEA, 2023)	sc1gr22.fil.asc

Land use systems used in CLUMondo

Table 9: Land use systems used in CLUMondo

Land system	Value in Basemap	Code CLUMondo
Low-density rural settlement	210	0
Medium-density peri-urban settlement	220	1
High-density urban settlement	230	2
Wetlands	300	3
Forest, shrub and cropland mosaics	410	4
Forest, shrub and grassland mosaic	420	5
Low-intensity arable cropland	510	6
Medium-intensity arable cropland	520	7
High-intensity arable cropland	530	8
Low-intensity grasslands	610	9
Medium-intensity grasslands	620	10
High-intensity grasslands	630	11
Permanent cropland	700	12

Close-to-nature forestry + Primary forest	820	13
Combined objective forestry	830	14
Intensive forestry + Very intensive forestry	840	15
KEPT STABLE:		
Water bodies		16
Bare, rock and shrubs		17

Region polygons

In order to obtain a final map covering all Europe, 4 different simulations were run separately, inside four region polygons that divide Europe into: East, West, South, North. The region polygons define which pixels is considered by the model for the simulation. The valid pixels were included in the simulation while the nodata pixels were excluded. All region files had nodata gaps, as we decided to classify bare, rock and shrubs and water bodies as no data because they are not dynamic land use systems. All input files included in the simulation had the same nodata mask. Iceland and Canary islands/Azores were excluded, to decrease the size of the polygons, hence the running time. In addition, the number of pixels in these areas was very low and especially Iceland was mainly covered by wetlands, which were not driven by demand.

Sampling / regression

The local suitability for each land use class was estimated via a logistic regression model (for each land system separately), in which:

- the dependent variable indicates whether a cell is observed to belong to that land system (in the base year) or whether it converts to that land system during the training period,
- the independent variables consist of spatial suitability layers (driving factors), including elevation, proximity to roads, management intensity, soil characteristics, and other relevant biophysical or socio-economic variables.

The logistic regression formula typically used in CLUMondo is:

$$P_{\mathrm{loc},i,LS} = \frac{1}{1 + e^{-(b_0 + b_1 f_1 + b_2 f_2 + \cdots + b_n f_n)}}$$

where f1…fn are the suitability factors at cell i, and the b_s are regression coefficients.

Convert.exe (2010 version) was used as sampling tool. A minimum sampling distance was applied to reduce spatial autocorrelation. To address multicollinearity, a correlation matrix was computed for all driving factors used in each region, and highly correlated variables were excluded or treated accordingly. The coefficients from the logistic regression analysis were then used as suitability factors in the alloc1 file. The climate files included in the regression were taken from the historical climate dataset for the period 1981-2010.

Demands

Five baseline demands were considered:

1. Population (number of people)

2. Arable crops (tons of DM)
3. Permanent crops (tons of DM)
4. Livestock (LSU)
5. Wood production (m^3)

Demands were projected under the reference SSP1, SSP2 and SSP3 scenarios, based on the GLOBIOM model for 2100, including AGLINK. AGLINK aggregates various categories in one single demand. Arable crops were taken from AGLINK. AGLINK does not include ROWE (rest of Western Europe) and RCEU (rest of Central Europe), in contrast to the standard GLOBIOM output. Demand of permanent crops was delivered by CAPRI, as GLOBIOM does not include permanent crops. However only a standard scenario was included, which corresponded most to SSP 2. Because CAPRI was only working with this scenario, CAPRI data was not used for other demands. Population data were taken from projections of KC et al. (2024).

The starting values of the demands (year 2020) were derived from the following calculation: the provision values detailed in the lusmatrix file (containing how much of each demand is satisfied by a single pixel of each land use class) multiplied by the number of pixels of the corresponding land system (in the 2020 basemap). In order to get the demands for the following years, the yearly percentage change from GLOBIOM/CAPRI outputs and KC et al. (2024) were applied.

Units and aggregations of the demands

Population: Population captures the amount of people, aggregated over the whole region. Demand was taken from KC et al. (2024). All categories were added, so no distinction was made between rural/urban, gender or education.

Arable crops: Arable crops were specified as crops that grow annually. Subcategories that were included in this aggregation contain:

Barley
Dry beans
Cassava
Chickpeas
Corn
Cotton
Ground nuts
Millet
Oil palm
Potatoes
Rapeseed
Rice
Soy beans
Sorghum
Sugar cane
Sunflower
Sweet potato

Wheat
Miscanthus
Switch grass

The unit chosen was tons of dry matter (DM). Although the analysis included different crop types, their demand was aggregated into a single category. Using a common unit is essential to ensure comparability across crops, and DM provides a consistent basis because it reflects the nutrient content of a crop while eliminating differences in water content between crop types.

Permanent crops: Permanent crops are crops that grow again every year. Output from CAPRI was taken, aggregate CRP|PRM. CAPRI results were available for only one scenario, which closely corresponds to SSP2. As with arable crops, dry matter (DM) was chosen as the unit, to ensure consistency and comparability across crop types by removing differences related to water content.

Livestock: Livestock includes all grazing animals. In GLOBIOM, the unit is TLU, but this does not affect the analysis of trends. The final output is expressed in LSU, as the lusmatrix is based on this unit. One LSU represents the grazing equivalent of one adult dairy cow producing 3,000 kg of milk per year, without additional concentrated feed. LSU is calculated only for grazing cattle, sheep, and goats. The GLOBIOM output uses the following abbreviations: BOVD (bovine dairy), BOVO (bovine others), BOVF (bovine followers), SGTD (sheep and goats dairy), SGTO (sheep and goats others), SGTF (sheep and goats followers).

Wood production: wood production refers to total roundwood production. The specific GLOBIOM categories included are listed in Table 10.

Table 10: Selection of GLOBIOM items for wood production (m^3)as the volume of logs is measured here.

Acronym	Definition
SW_BIOMASS	sawnwood biomass
PW_BIOMASS	pulpwood biomass
IP_BIOMASS	industrial plantations biomass
OW_BIOMASS	other wood biomass
FW_BIOMASS	fuelwood biomass

Technical documentation on scenarios storylines implementation

SSP2

The SSP2 scenario, combined with RCP 4.5, is considered our business-as-usual scenario (BAU). Therefore, the general settings implemented for this scenario serve as the baseline from which all the subsequent scenarios were developed.

Allow matrix

The allow matrix is one of the input files for CLUMondo, and it defines which land use conversion are permitted and which are prohibited. Additionally, it allows specifying the time steps necessary for a conversion to happen (using the code 100 + n. years), and/or restrict a certain type of conversion to a limited area by linking a dedicated file to the matrix (e.g., file *n*. *). The matrix is structured with land-use classes at the initial year of the simulation represented in rows, and land-use classes in subsequent years represented in columns. For example, in Table 11, a value of 0 in row 2, column 5 indicates that low density rural settlement in 2020 cannot be converted into high density rural settlements.

Table 11: Allow Matrix of the SSP2 that includes NATURA2000 area protection. This version acts as baselines for the subsequent scenarios. 1= conversion allowed ; 2= conversion not allowed ; 23= restriction file for Natura2000 areas (conversions to the land use class is allowed only outside Protected Areas) ; 24= restriction file with Nat2000 reserves and high elevation mosaics blocked; 25= restriction file with high elevation mosaics blocked; 100 + n. years = the initial land use class can convert into the next land use class when it's at least n. years old.

Land system	Code	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Low-density rural settlement	0	1	23	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Medium-density peri-urban settlement	1	0	1	23	0	0	0	0	0	0	0	0	0	0	0	0	0
High-density urban settlement	2	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0
Wetlands	3	23	0	0	1	23	23	23	23	23	23	23	23	23	23	23	23
Forest, shrub and cropland mosaics (North/all regions)	4	23	0	0	0	1	1	24/23	24/23	24/23	24/23	24/23	24/23	24/23	0	25/1	24/23
Forest, shrub and grassland mosaic (North/all regions)	5	23	0	0	0	1	1	24/23	24/23	24/23	24/23	24/23	24/23	24/23	0	25/1	24/23
Low-intensity arable cropland	6	23	0	0	0	1	1	1	1	1	1	1	1	23	0	1	23
Medium-intensity arable cropland	7	23	0	0	0	1	1	1	1	1	1	1	1	23	0	1	23
High-intensity arable cropland	8	23	0	0	0	1	1	1	1	1	1	1	1	1	0	1	1
Low-intensity grasslands	9	23	0	0	0	1	1	1	23	23	1	23	23	23	0	1	23
Medium-intensity grasslands	10	23	0	0	0	1	1	1	1	1	1	1	23	23	0	1	23
High-intensity grasslands	11	23	0	0	0	1	1	1	1	1	1	1	1	1	0	1	1
Permanent crops	12	23	0	0	0	105	105	105	105	105	105	105	105	1	0	105	105
Close-to-nature forestry + Primary forest	13	23	0	0	0	23	23	23	23	23	23	23	23	23	1	23	23
Combined objective forestry	14	23	0	0	0	23	23	23	23	23	23	23	23	23	1	1	23
Intensive forestry + very intensive forestry (North/West/South/East)	15	23	23	0	0	130/130/110/120	130/130/110/120	130/130/110/120	130/130/110/120	130/130/110/120	130/130/110/120	130/130/110/120	130/130/110/120	130/130/110/12(	130/130/110/120	130/130/110/120	1

The protection priority within Natura2000 reserves is listed below and is based on the intensity of land use, where 1 indicates the highest level of protection and 10 the lowest:

1. Wetlands
2. Close-to-nature forestry and primary forest
3. Combined objective forestry
4. Forest, shrub and cropland/grassland mosaics
5. Low-intensity arable cropland / grasslands
6. Medium-intensity arable cropland / grasslands
7. High-intensity arable cropland / grasslands, intensive and very intensive forestry and permanent crops
8. Low-density rural settlements
9. Medium-density peri-urban settlement

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10. High-density urban settlement

Low-density rural settlements in SSP2 allow matrix

Low-density rural settlements can transition into medium-density peri-urban settlements, but not directly into high-density urban areas, as infrastructure cannot develop rapidly enough to support such a change. Conversion to low-density rural settlements is possible from all land-use types except medium-density peri-urban and high-density urban settlements, provided the area is outside Natura2000 reserves. Conversion from other urban classes is not allowed, as this would require a transition from urban infrastructure back to rural land, which is highly unlikely. Built-up areas remain unchanged. All other land uses can convert into low-density rural settlements, as this typically requires only a minor increase in infrastructure.

Medium-density peri-urban settlements in SSP2 allow matrix

Medium-density peri-urban settlements can only convert towards high-density urban settlements, because of the reason mentioned above: urban infrastructure/built-up area does not change. Conversion towards medium-density peri-urban settlements is possible for all land uses, except for high-density urban settlements. Same reasoning here as for low-density rural settlements.

High-density urban settlements in SSP2 allow matrix

Due to high levels of infrastructure and economic importance, high-density urban settlements are static and only medium-density peri-urban settlements can change into high-density urban settlements. To facilitate depopulation, a decreasing output in the lusmatrix is considered. See lusmatrix documentation.

Wetlands in SSP2 allow matrix

Wetlands can convert into low-density rural settlements and medium-density peri-urban settlements (outside of Natura2000 areas), because wetlands can change into built-up area. However, it cannot change into high-density urban settlements due to an unrealistic change in infrastructure and economic importance. Besides, conversion to arable cropland, grassland and forest is allowed outside of Natura2000 areas. No class can convert into wetlands, as there is no demand driving conversion to wetlands in the baseline scenario. When adding a demand that drives wetland restoration, this needs to be revised.

Forest, shrub and cropland mosaics in SSP2 allow matrix

Forest, shrub, and cropland mosaics can transition into residential land uses, but not directly into high-density urban settlements, as such a change would require an impractical upgrade in infrastructure and economic significance. They can also convert into forest, shrub, and grassland mosaics, as well as homogeneous cropland, grassland, or forest classes. This is because the mosaic already partly contains these classes, and conversion to grassland from these classes is a common land-use change. Within Natura 2000 areas, this mosaic can only convert into primary forest, combined-objective forestry, or forest, shrub, and grassland mosaics, as these classes receive equal or higher protection than the forest, shrub, and cropland mosaic. All land systems can transition into this mosaic except urban areas and wetlands, due to the constraints mentioned above. Conversely, most classes can convert into forest, shrub, and cropland mosaics; however, primary forest and combined-objective forestry can only transition outside Natura 2000 areas, as they are subject to stricter protection. For this class, the restriction file 24 and 25 are used in the North region, in order to keep the high elevation mosaics from converting. These are stable ecosystems that persist due to climatic reasons.

Low-intensity arable cropland in SSP2 allow matrix

Low-intensity arable cropland can convert into all land classes except high-density urban settlements and wetlands, due to infrastructure and economic growth limitations and the absence of baseline demand for wetlands. All other conversions are possible, including within-cropland changes, cropland–grassland conversion, afforestation, and the expansion of rural and peri-urban settlements. Low-intensity arable cropland receives greater protection than higher-intensity cropland and grassland, so conversions are only allowed outside Natura 2000 areas. This restriction also applies to conversions into low-density rural settlements, medium-density peri-urban settlements, and intensive or very intensive forestry.

Wetlands, due to their protection, and urban classes, due to the loss of infrastructure, built-up area, and economic value, can convert into low-intensity arable cropland, but only outside Natura 2000 areas. All other conversions, including within-cropland changes, cropland–grassland conversion, and deforestation, are permitted. Both mosaics, primary forest, and combined-objective forestry receive higher protection than low-intensity arable cropland and therefore can only convert into it outside Natura 2000 areas.

Medium-intensity arable cropland in SSP2 allow matrix

Medium-intensity arable cropland can convert into all land classes except high-density urban settlements and wetlands. The former is restricted due to infrastructure and economic growth limitations, while the latter reflects the lack of baseline demand for wetland expansion. All other conversions are possible, including within-cropland changes, cropland–grassland conversion, afforestation, and the expansion of rural and peri-urban settlements.

Medium-intensity arable cropland receives higher protection than high-intensity cropland and grassland, so conversions are only possible outside Natura 2000 areas. The same applies to conversions into low-density rural settlements, medium-density peri-urban settlements, and intensive or very intensive forestry. Wetlands, due to their protection, and urban classes, due to the loss of infrastructure, built-up area, and economic value, cannot convert into medium-intensity arable cropland. All other conversions, including within-cropland changes, cropland–grassland conversion, and deforestation, are possible.

Both mosaics, primary forest, combined-objective forestry, and low-intensity cropland and grassland classes receive higher protection than medium-intensity arable cropland. Therefore, they can only convert into medium-intensity arable cropland outside Natura 2000 areas.

High-intensity arable cropland in SSP2 allow matrix

High-intensity arable cropland can convert into all land classes except high-density urban settlements, due to infrastructure and economic growth limitations in the baseline scenario. All other conversions are possible, including within-cropland changes, cropland–grassland conversion, afforestation, and the expansion of rural and peri-urban settlements. High-intensity arable cropland receives relatively little protection compared to other land systems, making conversions possible even within Natura 2000 areas. Only low-density rural settlements and medium-density peri-urban settlements are less protected.

Wetlands, due to their protection, and urban classes, due to the loss of infrastructure, built-up area, and economic value, cannot convert into high-intensity arable cropland. All other conversions, including within-cropland changes, cropland–grassland conversion, and deforestation, are possible. Most land systems, except low-density rural settlements and medium-density peri-urban settlements, receive more protection than high-intensity arable cropland and therefore can only convert into it outside Natura 2000 areas.

Low-intensity grasslands in SSP2 allow matrix

For low-intensity grasslands, the same rules apply as for low-intensity arable cropland. The same conversions are allowed, and they receive the same level of protection within Natura 2000 areas. The only exception is that wetlands can convert into low-intensity grasslands outside Natura 2000 areas.

Medium-intensity grasslands in SSP2 allow matrix

For medium-intensity grasslands, the same rules apply as for medium-intensity arable cropland. The same conversions are allowed, and they receive the same level of protection within Natura 2000 areas. The only exception is that wetlands can convert into medium-intensity grasslands outside Natura 2000 areas.

High-intensity grasslands in SSP2 allow matrix

For high-intensity grasslands, the same rules apply as for high-intensity arable cropland. The same conversions are allowed, and they receive the same level of protection within Natura 2000 areas. The only exception is that wetlands can convert into high-intensity grasslands outside Natura 2000 areas.

Permanent cropland in SSP2 allow matrix

For permanent cropland, the same rules as for high-intensity arable cropland apply. However, a minimum period of five years is required before permanent cropland can be converted into another land system. This reflects the fact that permanent cropland represents a long-term investment that typically only becomes profitable after about five years. Additionally, observations from European landscapes, particularly in the western and southern regions, indicate that permanent cropland areas often contain low-density settlements. As a result, outside Natura 2000 areas, permanent cropland can also be converted into low-density rural settlements.

Close-to-nature forestry + primary forest in SSP2 allow matrix

Primary forests are strictly protected and generally cannot be converted to other land systems, with only a few specific exceptions. Conversion to high-density urban settlements is permitted in rare cases, reflecting exceptional infrastructure requirements and overriding economic importance. Conversion to wetlands is allowed, but only outside Natura 2000 protected areas. Conversion to forestry systems is also possible under certain conditions. Transition to combined-objective forestry is allowed because it involves a change in management rather than land cover, and no minimum time steps are required, provided it occurs outside Natura 2000 areas.

Conversion from intensive or very intensive forestry is permitted, but it is subject to regional constraints based on forest composition and investment cycles. In the North and West, where older trees predominate and investment recovery times are estimated at around 30 years, a minimum of 130 time steps is required. In the East, with moderately fast-growing species, the minimum is 120 time steps, corresponding to approximately 20 years. In the South, where faster-growing species such as Eucalyptus spp. are present, the minimum is reduced to 110 time steps, or roughly 10 years.

Combined objective forestry in SSP2 allow matrix

Combined-objective forestry can be converted into all land systems except urban areas of any density, due to infrastructure and economic limitations. The land can be deforested and converted into other land systems. Conversion from combined-objective forestry to combined close-to-nature forestry, primary forest, or intensive and very intensive forestry is possible, as these changes involve only a modification of management type. No minimum time steps are required for these conversions. However, combined-objective forestry is highly protected, so conversions are only allowed outside Natura 2000 areas, with the exception of conversion to primary forest, which receives even greater protection.

Conversely, low-density rural settlements, medium-density peri-urban settlements, and high-density urban settlements cannot convert into combined-objective forestry, reflecting the loss of infrastructure and economic value. All other land systems can convert into combined-objective forestry through afforestation. Within forests, close-to-nature forestry and primary forests can convert into combined-objective forestry only outside Natura 2000 areas. Intensive and very intensive forestry can also convert into combined-objective forestry, but only after completion of the rotation cycle. Accordingly, the allowed conversion matrix includes a minimum number of time steps for these conversions, as described in the previous paragraph.

Intensive forestry + very intensive forestry in SSP2 allow matrix:

Intensive and very intensive forestry can only be converted into other land systems after completion of the rotation length, which varies by region. In Northern Europe, *Pinus sylvestris* and *Picea spp.* dominate intensive forestry areas, with a minimum rotation length of 30 years, which may be extended to 40 years for simulations approaching the end of the century. Although Aszlos et al. (2021) report rotation lengths of 90–100 years, for modeling purposes these durations are shortened to allow the model to explore mid- and long-term alternatives, including conversion of intensive forestry to close-to-nature forestry. In Western Europe, where tree species patterns are more diverse, the minimum rotation length is set at 30 years. In Southern Europe, the average felling age is lowest, with *Eucalyptus* plantations exhibiting a minimum rotation length of 10 years, representing approximately 11% of the region (Xu et al., 2020). For Eastern Europe, similar patterns to Northern Europe are observed, but shorter-rotation species such as *Alnus spp.* are more common, leading to a proposed minimum rotation length of 20 years (Daugaviete et al., 2022). After completion of the rotation length, clear-cutting occurs, and a new management type may be applied. Conversion to high-density urban settlements is not allowed due to infeasible infrastructure and economic demands, nor is conversion to wetlands, which are assumed to be stable systems.

Conversion to intensive or very intensive forestry is possible from all land systems except low-density rural settlements, medium-density peri-urban settlements, and high-density urban settlements, due to the associated infrastructure and economic losses. Intensive and very intensive forestry receives limited protection. Only high-intensity grasslands and high-intensity arable cropland are permitted to convert into intensive or very intensive forestry within Natura 2000 areas.

Restriction files 24 and 25 in North region

Restriction file 24 includes both Natura 2000 protected areas and high-elevation mosaics as blocked (assigned a value of 0), whereas restriction file 25 only blocks high-elevation mosaics. To create the high-elevation mask, the Digital Elevation Model (DEM) aggregated at a 1 km resolution — the elevation factor used for regression calculations— was overlapped with the 2020 base map (Sandström et al., 2023 v6) in QGIS, retaining only mosaic pixels. Pixels with elevations above 500 meters above sea level were assigned a value of 0, while the remaining pixels were reclassified to 1, resulting in a binary map with 0 for high-elevation pixels and 1 for all others. After applying the nodata mask from the North region file, this produced restriction file 25. To generate restriction file 24, this high-elevation map was multiplied by the

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existing sc1gr23 file representing protected areas, thereby creating a map in which both Natura 2000 areas and high-elevation mosaics are blocked.

Demands

Table 12: Demands for East region, SSP2 scenario

Population (# people)	arable crops (tons)	permanent crops (tons)	livestock (LSU)	Wood production (m^3)
119212769.00	221962538.71	1670390.95	10369564.97	213039877.60
119212769.00	223672399.82	1677946.98	10373801.45	214689192.96
119212769.00	225395432.62	1685537.19	10378039.66	216351277.00
119212769.00	227131738.60	1693161.74	10382279.60	218026228.60
119212769.00	228881420.00	1700820.78	10386521.28	219714147.36
119212769.00	230644579.85	1708514.46	10390764.69	221415133.68
119212769.00	232421321.99	1716242.95	10395009.83	223129288.72
119212769.00	234211751.04	1724006.39	10399256.70	224856714.43
119212769.00	236015972.44	1731804.95	10403505.32	226597513.55
119212769.00	237834092.44	1739638.79	10407755.66	228351789.62
119212769.00	239666218.10	1747508.07	10412007.75	230119646.96
119212769.00	240147437.45	1754964.79	10427207.40	231168958.56
119212769.00	240629623.02	1762453.33	10442429.24	232223054.86
119212769.00	241112776.76	1769973.83	10457673.30	233281957.68
119212769.00	241596900.61	1777526.41	10472939.61	234345688.95
119212769.00	242081996.51	1785111.23	10488228.21	235414270.67

Table 13: Demands for North region, SSP2 scenario

Population (# people)	arable crops (tons)	permanent crops (tons)	livestock (LSU)	Wood production (m^3)
25563958.46	46649781.33	3252.15	2277446.81	207074325.41
25656460.06	47000868.23	3252.15	2275165.12	207405587.71
25749296.38	47354597.43	3252.15	2272885.72	207737379.93
25842468.62	47710988.79	3252.15	2270608.60	208069702.93

25935978.00	48070062.36	3252.15	2268333.76	208402557.55
26029825.73	48431838.33	3252.15	2266061.20	208735944.66
26097447.53	48796337.02	3252.15	2263790.92	209069865.09
26165245.00	49163578.94	3252.15	2261522.91	209404319.70
26233218.60	49533584.72	3252.15	2259257.17	209739309.35
26301368.79	49906375.18	3252.15	2256993.71	210074834.88
26369696.01	50281971.26	3252.15	2254732.51	210410897.17
26434344.27	50414783.70	3252.15	2252473.58	210747497.07
26499151.02	50547946.95	3252.15	2255306.65	211245280.50
26564116.65	50681461.93	3252.15	2258143.29	211744239.69
26629241.55	50815329.57	3252.15	2260983.49	212244377.42
26694526.11	50949550.80	3252.15	2263827.27	212745696.47

Table 14: Demands for South region, SSP2 scenario

Population (# people)	arable crops (tons)	permanent crops (tons)	livestock (LSU)	Wood production (m^3)
123697438.96	76917899.31	7684074.90	2082619.45	42551146.00
123697438.96	77934139.95	7708358.74	2092448.61	42660180.43
123697438.96	78963807.18	7732719.32	2102324.16	42769494.26
123697438.96	80007078.39	7757156.89	2112246.32	42879088.19
123697438.96	81064133.32	7781671.68	2122215.31	42988962.95
123697438.96	82135154.08	7806263.95	2132231.35	43099119.26
123697438.96	83220325.18	7830933.94	2142294.66	43209557.84
123697438.96	84319833.58	7855681.90	2152405.46	43320279.40
123697438.96	85433868.71	7880508.06	2162563.98	43431284.69
123697438.96	86562622.49	7905412.68	2172770.45	43542574.42
123697438.96	87706289.38	7930396.01	2183025.09	43654149.32
123697438.96	87963759.97	7958120.59	2165135.24	43336393.91
123697438.96	88221986.39	7985942.10	2147392.01	43020951.42
123697438.96	88480970.86	8013860.87	2129794.17	42707805.01
123697438.96	88740715.60	8041877.25	2112340.56	42396937.97
123697438.96	89001222.85	8069991.57	2095029.97	42088333.71

Table 15: Demands for West region, SSP2 scenario

Population (# people)	arable crops (tons)	permanent crops (tons)	livestock (LSU)	Wood production (m^3)
263686655.00	288671053.64	1694067.50	42495514.27	145410237.71
264243159.08	291105353.15	1687020.80	42609617.46	145073187.01
264800837.65	293560180.57	1680003.42	42724027.03	144736917.56
265359693.18	296035709.02	1673015.22	42838743.79	144401427.57
265919728.17	298532113.05	1666056.10	42953768.57	144066715.22
266480945.09	301049568.70	1659125.92	43069102.21	143732778.71
266796881.27	303588253.51	1652224.56	43184745.52	143399616.24
267113192.02	306148346.49	1645351.92	43300699.34	143067226.02
267429877.79	308730028.17	1638507.86	43416964.50	142735606.25
267746939.01	311333480.60	1631692.27	43533541.85	142404755.16
268064376.14	313958887.38	1624905.03	43650432.21	142074670.95
268386752.65	316159791.13	1617260.97	43744636.23	142186498.53
268709516.85	318376123.58	1609652.87	43839043.55	142298414.13
269032669.21	320607992.89	1602080.56	43933654.62	142410417.83
269356210.19	322855507.98	1594543.88	44028469.87	142522509.68
269680140.27	325118778.51	1587042.65	44123489.75	142634689.75

Lusconv

Lusconv values are defined based on the ratios in the *lusmatrix* (Table 16). The highest value in the *lusmatrix* is assigned a score of 3, and the scores for the other contributing land systems are calculated proportionally and then rounded. Land systems that do not contribute to demand provisioning in the *lusmatrix* are assigned a value of -1. For the columns corresponding to arable crops and livestock, the highest value was set to 4, as mosaics also contribute to meeting the demand for these land uses.

Table 16: Lusconv table SSP2 scenario, all regions

Population (# people)	arable crops (tons)	permanent crops (tons)	livestock (LSU)	Wood production (m3)
1	-1	-1	-1	-1
2	-1	-1	-1	-1
3	-1	-1	-1	-1
-1	-1	-1	-1	-1

0	1	0	0	-1
0	0	0	1	-1
0	2	0	0	-1
0	3	0	0	-1
0	4	0	0	-1
0	0	0	2	-1
0	0	0	3	-1
0	0	0	4	-1
0	0	1	0	-1
0	0	0	0	1
0	0	0	0	2
0	0	0	0	3

Main file

Elasticities / conversion resistance (Table 17)

Urban areas are dynamic to facilitate land-use conversions, with the exception of high-density urban settlements, which are considered static and assigned a value of 1. Low-density rural settlements can convert into medium-density peri-urban settlements, and medium-density peri-urban settlements can convert into high-density urban areas, with corresponding values of 0.5 and 0.6, respectively. Low-density settlements are slightly more dynamic than medium-density due to differences in infrastructure between the two classes.

Wetlands are minimally dynamic. In the baseline scenario, wetlands can convert into a limited number of other land systems, but there is no demand driving their change. Wetlands are therefore assigned a value of 0.9, although this could be adjusted for scenarios in which wetlands are intended to be more dynamic.

Both mosaics — forest, shrub, and grassland mosaic, and forest, shrub, and cropland mosaic — are considered dynamic because they represent a mixture of land systems. They are assigned a value of 0.4, consistent with the medium values for cropland, grassland, and forest.

Cropland, grassland, and forest exhibit similar patterns of dynamics, with conversion resistance increasing with investment intensity. Low-intensity systems are the easiest to convert, followed by medium-intensity, and finally high-intensity systems. This results in conversion resistance values of 0.3 for low-intensity arable cropland, 0.4 for both low-intensity grassland and medium-intensity cropland, 0.5 for high-intensity cropland, 0.6 for high-intensity grassland, 0.7 for close-to-nature forestry, 0.4 for combined-objective forestry, and 0.5 for intensive forestry.

Permanent cropland is relatively static due to the high investment required to establish it, resulting in a higher conversion resistance of 0.6.

Table 17: Conversion elasticities for SSP2, all regions

0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
0.5	0.6	1	0.9	0.4	0.4	0.3	0.4	0.5	0.4	0.5	0.6	0.6	0.7	0.4	0.5

Age0 file

This file defines the initial ages of land-use systems at the start of the simulation. Due to limited data availability, a random age between 0 and 10 years is assigned to each pixel for all land-use classes, except forests. For forest pixels, age is assigned using a reference map containing information on the individual age of trees in each pixel (Besnard et al., 2025). The original forest age map had a resolution of 100 meters and was upscaled to 1 km by taking the median value within each aggregation unit. Gaps in the data were filled using the nearest-neighbor method. The forest age map was then overlaid with the 2020 basemap, and forest ages were recorded for pixels where forest was present.

After running CLUMondo, a random age file was generated for all land-use classes. This file was then merged with the forest age data, ensuring that the actual forest ages were retained in pixels where forest was present, while random ages were assigned to all other land-use classes.

Lusmatrix

The lusmatrix represents the average productivity of each land system for each type of demand.

Population is primarily associated with urban land systems, although other land systems also provide housing. For this reason, all land systems were overlaid with the population grid from Batista e Silva et al. (2021). This overlay was performed with the 2020 baseline map produced by Sandström et al. (2024). In some areas, artifacts were observed where urban presence was detected within agricultural areas more frequently than expected. To correct for this, the number of households per km^2 was averaged by pixel count. The resulting values, summarized in Table 18, are applied to each land-class intensity to prevent the removal of urban areas and avoid unrealistic conversions**.**

Table 18: Average population count per arable land, grassland and natural areas.

	West	East	North	South
Arable land	44.74010737	43.92286551	33.11109128	22.85739753
Grassland	47.07465297	62.24501898	32.36787743	23.7835392
Forest	15.268147	12.79251707	4.729890768	18.65416561

Arable crop production is driven by arable cropland land systems and the forest, shrub, and cropland mosaic. Other land systems do not produce arable crops and are therefore assigned a value of 0. Medium-intensity cropland was overlaid with the GlobalWheatYield4km dataset (Luo et al., 2022). There are too few observations for low-intensity cropland in the current land-use map, so directly overlaying low-intensity cropland would have produced biased estimates. Additionally, the resulting difference between medium- and high-intensity cropland was unrealistic due to the use of different data sources in creating the land-use map. To harmonize the results, ratios between low and medium intensity, and medium and high intensity, were calculated based on nitrogen inputs in the land-use map. Ratios differed by region, with Southern and Eastern Europe providing the most representative results across all intensity classes. Because the relationship between nitrogen input and crop yield is non-linear, the ratio between high and medium intensity was adjusted downward using a Michaelis-Menten curve and considering natural nitrogen uptake by arable crops. The final ratios used for low, medium, and high intensity were 0.75, 1, and 1.2, respectively (Table 19). These ratios were then multiplied by the value obtained for medium-intensity cropland to produce the productivity estimates for all intensity classes (Table 20).

Table 19: Nitrogen ratio of the different arable land classes

	West	East	North	South	EU	ratio
Low	0.635	0.456	0.739	0.566	0.454	0.75
Medium	1	1	1	1	1	1
High	1.414	1.001	1.337	1.541	1.444	1.2

Table 20: Production of arable crops per intensity class

	West	East	North	South
Low	544.683	416.319	658.074135	199.4662057
Medium	726.244	555.092	877.43218	398.9324114
High	871.4928	666.1104	1052.918616	797.8648229

For the forest, shrub, and cropland mosaic, the share of arable cropland within the mosaic is calculated and multiplied by the productivity of low-intensity cropland. This approach reflects the relatively low nitrogen inputs typical of cropland within mosaics. Validation was performed by overlaying the GlobalWheatYield4km dataset with the mosaics. Wheat was chosen as an indicator of arable crop productivity because it is widely cultivated across Europe and represents the highest cereal production. For modelling purposes, the percentage of cropland within each mosaic is multiplied by the productivity of low-intensity agriculture. Using medium-intensity cropland instead would result in productivity values that are not substantially different from low-intensity cropland and, in some cases, even higher, which would rarely reflect the realistic production levels in these pixels (Table 21).

Table 21: Final production in mosaics

	West	East	North	South
CROPLAND IN 4	0.3781328	0.389632375	0.442488785	0.228240941
Final Production in Mosaics	205.962542	162.2113607	291.1904245	45.5263544

Permanent crops are solely driven by the land system permanent crops, so all other land systems receive value 0. As permanent crops have no distinction between classes, the start value of permanent crop production from CAPRI is divided by the area of permanent crops.

Livestock production is driven by grassland systems and the forest, shrub, and grassland mosaic. Other land systems do not support livestock and are therefore assigned a value of 0. Grassland classes were overlaid with data from Žiga Malek et al. (2024). Because there are few grasslands in Northern Europe, livestock values from Western Europe were applied to the North (see also Table 22). Cattle grazing density and sheep and goat density were used as indicators of grassland productivity, with sheep and goat densities converted into Livestock Units (LSU) to standardize the measurements.

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Table 22: Ratio of livestock

	West		East		North		South		EU level	Ratio EU
	Obs	**ratio**	**Obs**	**ratio**	**Obs**	**ratio**	**Obs**	**ratio**	**Obs**	
Low	2642	0.71	26721	0.58	16	0.75	21245	0.22	50621	**0.47**
Medium	102507	1.00	14050	1.00	1534	1.00	25402	1.00	133887	**1.00**
High	82577	1.21	1	0.83	5	0.93	472	1.22	72395	**1.62**

For **grasslands**, a ratio between intensity classes was calculated based on the livestock data layer from Žiga Malek et al. (2024), which includes three intensity classes. This ratio was then applied across all of Europe, with values for low-, medium-, and high-intensity grasslands set to 0.4, 1, and 1.6, respectively (Table 23).

Table 23: The final outcomes of the livestock production in terms of LSU/km²

	West	East	North	South
Low	62.220525	51.51932	62.220525	12.047859
Medium	133.43873	110.4888	133.43873	25.837955
High	215.64661	178.5579	215.64661	41.755997

For the **forest, shrub, and grassland mosaic**, the same procedure as for the arable cropland mosaic is applied. The only difference is that, instead of using nitrogen input for validation, the livestock data layer from Žiga Malek et al. (2024) is used to evaluate the proportion of reference livestock counts within the mosaic (Table 24).

Table 24: Final outcomes of livestock production for the mosaic

	West	East	North	South
Grassland in 5	0.3809481	0.379354971	0.382377936	0.335190732
Final Production in Mosaics	23.702791	19.54410879	23.79175593	4.038330826

Wood production occurs in forest classes and both forest-related mosaics, while all other land-use classes are assigned a value of 0. The production ratios were derived from National Forest Inventory (NFI) data from ten countries: Norway, Sweden, Germany, Austria, Poland, Slovenia, Spain, Belgium, Czechia, and Ireland. The NFI data included volume observations for each plot (vol0 and vol1). For each plot, the percentage change in volume was calculated, and plots were assigned to corresponding 20% volume-change intervals. Plot locations were then overlaid with the forest management map, and for each forest management class, the final distribution of plots across the volume-change intervals was derived. This distribution was corrected to account for the average time span between vol0 and vol1 for each forest management class. To calculate the wood production ratios, only the intervals indicating a decrease in volume were considered. The distribution of yearly occurrences within these volume-decrease intervals per forest management class was then used to determine the final ratios (Table 25).

Table 25: Ratios for each volume for all forestry classes

% ALL	Unmanaged forest	Close-to-nature forestry	Combined objective forestry	Intensive forestry	Very intensive forestry
0-0.2	0.202179	0.068952	0.242565	0.387237	0.637008
0.2-0.4	0	0.09124	0.183592	0.204773	0.360605
0.4-0.6	0	0.185266	0.285743	0.306762	0.388062
0.6-0.8	0.404357	0.504953	0.587633	0.635833	0.56745
0.8-1	2.830502	1.714751	1.634421	1.695555	1.123917

To calculate the wood production ratios, a formula was applied in which the annual occurrence of a volume decrease per 20% interval was multiplied by the average value of that interval. The interval values were defined as follows: 0.9 for an 80–100% decrease, 0.7 for 60–80%, 0.5 for 40–60%, 0.3 for 20–40%, and 0.1 for 0–20% decrease in volume. The results obtained after applying the formula are presented for the five forest management classes (Table 26). These ratios were then normalized so that the medium value equals 1.

Table 26: Ratio of the five forest management classes.

Unmanaged forest	Close-to-nature forestry	Combined objective forestry	Intensive forestry	Very intensive forestry
0.586318	0.541519	0.829426	1.00554	1.302389
0.706896	0.652884	1	1.212332	1.570229

Unmanaged forest contained very few plots and is protected in any case; therefore, its data were ignored. Low-intensity forestry corresponds to close-to-nature forestry, medium-intensity forestry corresponds to combined objective forestry, and high-intensity forestry is represented by the average of intensive and very intensive forestry (Table 27).

Table 27: Final ratio for each of the forest class

Low	Medium	High
0.652884	1	1.391281

These ratios were then multiplied by the average wood production (m^3/km^2) for each class (Table 28). The average production was calculated by dividing the total regional roundwood production, as estimated by FAOSTAT, by the total forest area in the region.

Table 28: Final production with the ratio applied

Region	Low	Medium	High
North	154.7734855	237.0612322	329.8187882
East	252.6579594	386.9875191	538.4083826
South	84.63626801	129.6344649	180.357968
West	285.3333569	437.0353032	608.0389136

For the mosaics, the same procedure applied to arable crops and grasslands was used. FAOSTAT production data were utilized, as values from Verkerk et al. (2015) were considered potentially outdated. The production within the mosaics was derived by multiplying the values from the low-intensity forest class by the percentage of forest contained in each mosaic. The resulting values are summarized in Table 29.

Table 29: Final production of the forest for the mosaic 4 and 5

	West	**East**	**North**	**South**
Forest in 4	0.40209297	0.426534034	0.476157995	0.283383562
Forest in 5	0.38546385	0.443411319	0.350353273	0.27485199
Final Production in Mosaic 4	114.730536	107.7672185	73.696633	23.98452712
Final Production in Mosaic 5	109.985695	112.0313992	54.22539729	23.26244673

Neighbourhood settings

For the neighbourhood settings, we aimed to simulate a typical Business-As-Usual (BAU) scenario under SSP2. In this context, we enhanced the aggregation of high-density urban areas, high-intensity agriculture, and high-intensity forestry to reflect their clustering patterns under current development trajectories (Table 30). Additionally, when generating the alloc2.reg file, we included a weighting for high-intensity grasslands as well (see Table 31).

Table 30: Current Neighmat.txt file

0		0	0.4	0	0	0	0	0	0.4	0	0	0	0	0	0	0.4	
16		0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
1																	
1		1	1														
1		1	1														
1		1	1														
16		0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
1																	
1		1	1														
1		1	1														
1		1	1														
16		0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
1																	
1		1	1														
1		1	1														
1		1	1														

Table 31: Example of weights for high intensity agriculture and high intensity grasslands

8	
0	
2	
0.5	8
0.3	11

Location specific rules

In CLUMondo, it is possible to define a spatially explicit preference for a specific land use class in certain locations, giving that class a competitive advantage in the allocation procedure. For SSP2, we used *locspec* files for the urban classes to balance intensification with urban sprawl. Without these weights, the model produced only urban sprawl, which did not realistically reflect current trends.

The *locspec* for the urban classes, a value of 1 is assigned to the entire region and the following weights are applied to the main file (low/medium/high):

- North: -0.3 / 0 / 0.3
- West: -0.5 / 0 / 0.5
- East: -0.5 / 0 / 0.5
- South: -0.2 / 0 / 0.2

SSP2 – Technological innovation

The parameterization of the SSP2 scenario with technological innovation closely follows the structure of the baseline BAU SSP2 scenario. The only difference in this variant is the introduction of technological advances in agriculture and farming, which alter the demand for arable crops, permanent crops, and grasslands. These innovations are expected to free up land by increasing crop yields, thereby reducing the overall demand for agricultural land and creating greater opportunities for land abandonment.

Arable crops and permanent crops

The demand was reduced by applying the technological coefficients derived from GLOBIOM. To refine their implementation, we applied an additional step: a linear interpolation that gradually adjusted the coefficients at 10-year intervals up to 2050, ensuring a smoother transition over time. An example of the interpolation results is presented in Table 33.

Grassland

We followed the same approach with the exception that we used the coefficient of grassland technology change from GLOBIOM instead of the arable crops. An example of the interpolation results is presented in Table 34.

In the following Table 32, a summary of the applied technological coefficients is presented.

Table 32: GLOBIOM technological coefficients.

Region	Land-use system	Base year (2020)	2030	2040	2050
West	Arable cropland Permanent crops	0	0.0288	0.0630	0.0971
	Grasslands	1.00	0.0077	0.0157	0.0236
Central Europe	Arable cropland	1.00	0.0540	0.1016	0.1381

	Permanent crops				
	Grasslands	1.00	0.0112	0.0226	0.0336
Southern Europe	Arable cropland Permanent crops	1.00	0.0264	0.0585	0.0925
	Grasslands	1.00	0.0129	0.0259	0.0383
Northern Europe	Arable cropland Permanent crops	1.00	0.0145	0.0309	0.0482
	Grasslands	1.00	0.0086	0.0174	0.0261

Table 33: Example from the West region showing the interpolation of arable and permanent crop coefficients.

Year	Tech factor	Interpolated
2020	0	0
2021		0.001659213
2022		0.004915083
2023		0.008170953
2024		0.011426823
2025		0.014682693
2026		0.017938563
2027		0.021194434
2028		0.024450304
2029		0.027706174
2030	0.028834039	0.030962044
2031		0.034217914
2032		0.037473784
2033		0.040729654
2034		0.043985524
2035		0.047241394
2036		0.050497264
2037		0.053753134
2038		0.057009004
2039		0.060264874
2040	0.062986783	0.063520744
2041		0.066776614
2042		0.070032484

2043		0.073288354
2044		0.076544225
2045		0.079800095
2046		0.083055965
2047		0.086311835
2048		0.089567705
2049		0.092823575
2050	0.097144754	0.096079445

Table 34: Example from the West region showing the interpolation of grassland coefficients

Year	tech factor	Interpolated
2020	0	0
2021		0.000728087
2022		0.001515369
2023		0.00230265
2024		0.003089932
2025		0.003877213
2026		0.004664495
2027		0.005451776
2028		0.006239058
2029		0.007026339
2030	0.007724833	0.007813621
2031		0.008600902
2032		0.009388184
2033		0.010175465
2034		0.010962747
2035		0.011750029
2036		0.01253731
2037		0.013324592
2038		0.014111873
2039		0.014899155
2040	0.015686429	0.015686436

2041		0.016473718
2042		0.017260999
2043		0.018048281
2044		0.018835562
2045		0.019622844
2046		0.020410125
2047		0.021197407
2048		0.021984688
2049		0.02277197
2050	0.023588852	0.023559251

We applied the following equation to the original SSP2 demands (see Section 1.2.1.2) to incorporate the technological changes.

$$Demand_{tech}=(1-\text{tech factor})\times Demand_{no\ tech}$$

SSP2 - Planned rewilding scenario

The parameterization of the SSP2 scenario with technological innovation closely follows the structure of the baseline BAU SSP2 scenario. In this variant, the differences lie in the introduction of specific conversion restrictions and land-use preference parameters that reflect a scenario in which rewilding efforts are spatially planned. The main changes concern the combined objective and the close-to-nature forest dynamics.

Allow matrix

Table 35: Allow Matrix of the SSP2 – Planned rewilding scenario

Land system	Code	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Low-density rural settlement	0	1	23	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Medium-density peri-urban settlement	1	0	1	23	0	0	0	0	0	0	0	0	0	0	0	0	0
High-density urban settlement	2	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0
Wetlands	3	23	23	0	1	23	23	23	23	23	23	23	23	23	23	23	23
Forest, shrub and cropland mosaics (North/other regions)	4	23	23	0	0	1	1	25/23	25/23	25/23	25/23	25/23	25/23	25/23	0	27/1	25/23
Forest, shrub and grassland mosaic (North/other regions)	5	23	23	0	0	1	1	25/23	25/23	25/23	25/23	25/23	25/23	25/23	0	27/1	25/23
Low-intensity arable cropland	6	23	23	0	0	1	1	1	1	1	1	1	1	23	0	1	23
Medium-intensity arable cropland	7	23	23	0	0	1	1	1	1	1	1	1	1	23	0	1	23
High-intensity arable cropland	8	23	23	0	0	1	1	1	1	1	1	1	1	1	0	1	23
Low-intensity grasslands	9	23	23	0	0	1	1	1	23	23	1	23	23	23	0	1	23
Medium-intensity grasslands	10	23	23	0	0	1	1	1	1	1	1	1	23	23	0	1	23
High-intensity grasslands	11	23	23	0	0	1	1	1	1	1	1	1	1	1	0	1	23
Permanent crops	12	23	23	0	0	105	105	105	105	105	105	105	105	1	0	105	23
Close-to-nature forestry + Primary forest	13	23	23	0	0	23	23	23	23	23	23	23	23	23	1	23	23
Combined objective forestry	14	23	23	0	0	23	23	23	23	23	23	23	23	23	24	1	23
Intensive forestry + very intensive forestry (North/West/South/East)	15	23	23	0	0	130/130/110/120	130/130/110/120	130/130/110/120	130/130/110/120	130/130/110/120	130/130/110/120	130/130/110/120	130/130/110/120	130/130/110/120	26/25/25/25	130/130/110/120	23

The structure of the allow matrix largely reflects the main characteristics of the SSP2 baseline, with several important modifications (Table 35). Direct conversion of agricultural classes to close-to-nature forests remains impossible; therefore, arable land, permanent crops, and grasslands must first transition through the combined-objective forest class before eventually converting to close-to-nature forests. Consequently, conversions from land-use systems 14 and 15 (combined-objective and intensive forestry) to close-to-nature forest are permitted only in areas with high or moderate rewilding potential (based on our proforestation dataset and agricultural abandonment data from Kloibhofer et al. 2025). This rule is implemented through restriction file 24 (all regions) for combined-objective forests.

For the conversion of plantation forests to close-to-nature forests, the same spatial restrictions apply, while also respecting the 100 + n-year forestry-management rotation rule (implemented through file 26 in the North and file 25 in the other regions).

In the North region, the same conversion block for mosaics above 500 m was applied. Accordingly, file 25 includes restrictions for both protected areas and high-elevation mosaics, while file 27 blocks only the high-elevation mosaics.

Summary of restriction files:

- File 24 (all regions): Conversions of land-use system 14 (combined-objective forests) to close-to-nature forests are restricted to areas with high or moderate rewilding potential.
- File 25 (26 in North): Conversions of plantations to close-to-nature forests are restricted to areas with high or moderate rewilding potential, while maintaining the 100 + n-year forestry-management rotation rule.
- File 25 (North): Blocks conversions in protected areas and high-elevation mosaics.
- File 27 (North): Blocks conversions in high-elevation mosaics only.

Restriction file 24

The restriction file sc1gr24 was developed to spatially guide the conversion of combined-objective forests into close-to-nature forests. Its primary purpose is to confine rewilding dynamics to areas exhibiting high environmental suitability and suitable land-use conditions, while excluding regions with low potential or limited relevance. The process adhered to the main steps outlined below:

1. **Preparation of base inputs**: Two primary rewilding potential layers were utilized:

   - Proforestation potential map (own data), covering forest and mosaic systems.
   - Kloibhofer rewilding potential map (Kloibhofer et al., 2025), representing rewilding potential for agricultural systems, including arable land, grasslands, and permanent crops.

   Both datasets were spatially aligned and referenced to our baseline land-use map (cov0, 2020), which defined the spatial extent and class boundaries for subsequent masking operations.

2. **Mask creation and application**. Using the cov0 map, two masks were generated in QGIS:

   1. Agricultural and grassland systems: covering three cropland classes, three grassland classes, and permanent crop classes,
   2. Forest and mosaic systems: covering three forest types and the mosaic class.

   Each rewilding potential map was then multiplied by its corresponding mask, setting all non-relevant pixels to zero. This ensured that each potential layer retained information only within its applicable land-system classes.

3. **Reclassification of rewilding potential**. The masked maps were reclassified to emphasize areas of moderate to high potential::

    1. Pixels with values ≥ 0.5 (on a 0–1 scale) were assigned a value of 1,

    2. all remaining pixels were set to 0.

    The resulting binary rasters delineate zones where proforestation or agricultural abandonment could lead to successful rewilding.

4. **Combination of potentials**. The two reclassified rasters were summed to generate a single map representing combined rewilding potential across all land systems. The resulting raster was then divided into four regional rasters using the region files as masks. These were exported as sc1gr24 and incorporated into the "allow" configuration for the scenario run.

This restriction file ensures that transitions to close-to-nature forest are simulated only within areas pre-identified as having high ecological and management suitability.

Although the dataset from Kloibhofer et al. (2025) covers only part of our study region — excluding Norway, Croatia, Bosnia and Herzegovina, Serbia, Montenegro, North Macedonia, and Albania — we opted to use it. The MCA-driven methodology employed by Kloibhofer et al. aligns with our proforestation assessment approach, ensuring consistency and comparability between the two datasets.

Restriction file 25 (26 in North)

Pixels with a value of 1 (representing areas of moderate to high rewilding potential) in the sc1gr24 file were reclassified by region as follows:

- 130 – West and North
- 120 – East
- 110 – South

Restriction file 25 (North)

The sc1gr23 raster, with protected areas blocked, was multiplied by sc1gr25 North from the baseline scenario, in which only high-elevation mosaics were blocked (see Section 1.2.1.1 for details on its creation).

Restriction file 27 (North)

This file is simply a renamed version of the sc1gr25 file used for the baseline SSP2 North, in which only high-elevation mosaics were blocked.

Location specific preferences

Locspec 13 (close to nature forest)

Building upon the same spatial datasets used for sc1gr24, locspec 13 was created as a subset of the restriction file 24, enhancing the preference for close-to-nature forests within the top 20% of highest-scoring pixels in the rewilding potential maps. This approach prioritizes conversions in the most suitable areas. The file was created through the following steps:

1. **Preparation and masking**. The same two base potential maps — Kloibhofer for agricultural systems and proforestation MCA for forest and mosaic systems — were

used, with each masked according to the respective cov0 land-system selection. Non-relevant land systems were set to 0.

2. **Selection of top-potential areas**. From the continuous potential surfaces, the top 20% highest-scoring pixels in each dataset were identified and assigned a value of 1, while all other pixels were set to 0. This step isolates areas with the greatest potential for rewilding and ecological restoration.

3. **Integration of agricultural and forest potentials**. The two binary maps were summed to produce a combined rewilding potential surface. This surface was then divided into four regional subsets (North, South, East, and West) using regional nodata masks, generating region-specific locspec base layers.

4. **Suitability scaling for model integration**. The binary potential maps were reclassified following a land-use class–specific approach:
    - −0.1 for areas of low suitability (not in the top 20% scoring pixels),
    - 0.5 for areas of high suitability (top 20% scoring) overlapping forest systems (codes 13–15),
    - 0.15 for areas of high suitability (top 20% scoring) overlapping agricultural and grassland systems (codes 4–12).

Proforestation potential assessment

The following paragraphs summarize the steps taken to produce the Proforestation Potential Map, which served as the basis for generating the restriction and locspec files. This map was developed to identify European forest and mosaic areas with the highest ecological and management potential to evolve toward self-sustaining, mature ecosystems. Thirteen spatial metrics were combined to capture key ecological, physical, and anthropogenic factors influencing forest regeneration and the feasibility of long-term protection (Table 36).

Table 36: Spatial metrics used to capture ecological, physical and anthropogenic factors influencing forest regeneration and the feasibility of long-term protection.

Metric	Description	Datasets
Area	Size of continuous forest–mosaic patches; larger patches are more suitable for long-term, self-sustaining ecosystems.	European land-system basemap (Sandström et al. 2023).
Elevation	Variation in elevation within each 1 km cell.	ESA 2022, Copernicus DEM GLO-30
Slope	Distribution of slope classes within each 1 km pixel, favouring gentle to moderate slopes and downweighting very steep areas.	European Commission – DG ENTR, 2012b, EU-DEM Version 1
Connectivity	How well each forest–mosaic pixel is connected to other similar pixels at local (1 km) and broader (5 km) scales.	Sandström et al. (2023)
Seed bank availability	Potential for forests to regenerate naturally based on soil seed density/diversity and proximity to natural forest.	Yang et al. (2021) global soil seed density and diversity rasters + land-system map (Sandström et al. 2023) for management and distance to natural forests.

Cover of buildup areas	Amount of built-up / impervious surface (urban structures, sealed surfaces) in each pixel, as a negative pressure on rewilding.	Copernicus Impervious Surface 2018 (100 m).
Road density	Density of road infrastructure (m of road per km²), used as a proxy for disturbance and accessibility pressure.	Meijer et al. (2018) global road density dataset.
Diversity soil types	Variety of soil types (Shannon Diversity) inside and in the neighbourhood of each 1 km cell, representing edaphic heterogeneity and potential for diverse plant communities.	European Soil Database (ESDB) / European Soil Database v2 (1 km raster)
Diversity habitat types	Diversity of habitat types (Shannon diversity) inside and in the neighbourhood of forest–mosaic pixels, capturing structural and ecological heterogeneity at landscape scale.	EUNIS habitat map
Potential for RedListed species	Potential presence of forest specific IUCN Red Listed species in forest–mosaic areas, as an indicator of conservation value and biodiversity.	IUCN Red List species range vector maps (latest release)
Presence large fauna	Presence of large-bodied fauna (>5 kg), used as a proxy for trophic complexity and functioning ecological interactions.	*PHYLACINE v1.2* – current mammal range data (10 km).
Wildfire regime	Combined information on fire danger / anomaly and vulnerability, highlighting where fire regimes are particularly relevant for rewilding.	WDTA wildfire dataset + wildfire vulnerability layer from EFFIS Copernicus.
Invasive species pressure	Pressure from invasive alien species that may disrupt natural regeneration and native biodiversity.	Invasive species data from Polce et al. (2023) / EASIN (processed to fill gaps).

All metrics were normalized using a min–max approach to a common 0–1 scale, with 1 representing the highest suitability. The 13 metrics were grouped into three main conceptual components:

- **Ecological value**: factors that make a location environmentally relevant for proforestation, including soil type diversity, habitat diversity, presence of endangered species, and presence of large fauna.
- **Feasibility**: factors influencing the practicality of allowing proforestation under current conditions, such as area, elevation, slope, connectivity, seed bank availability, built-up area cover, and road density.
- **Threat exposure**: pressures that may undermine long-term success, including wildfire regime and invasive species pressure.

For each component, the metrics were averaged, producing three intermediate maps: Ecological Value Map, Feasibility Map, and Threat Exposure Map (where higher values indicate lower exposure or safer conditions).

Before combining the components, a “deal-breaker” mask was applied to exclude areas clearly unsuitable for proforestation, even if some metrics appeared favourable. Deal-breaker criteria included: forest/mosaic fragments smaller than 10 km^2; very high road density (>1,000 m/km^2); very high impervious cover (>30%). Areas meeting these criteria were set to 0.

The three component maps were then averaged to produce the final Proforestation Potential Map. For ease of interpretation and use in scenario modelling, the final values were grouped into low, medium, and high potential classes.

In the final map, high-potential areas are defined by the following conditions:

- rich ecological conditions: diverse soils and habitats, presence of threatened species, and presence of large fauna,
- feasibility of forest growth: sufficient area, good connectivity, and favourable accessibility and management context,
- low external pressures: minimal impact from fire, invasive species, or infrastructure that could impede natural processes.

These high-potential areas serve as key inputs for identifying priority zones for proforestation and rewilding in the scenario analyses.

SSP1

Allow matrix

As previously said, the allow matrix is one of the input files for CLUMondo and specifies which land use conversions are permitted and which are prohibited. It is also possible to define additional constraints, such as the time required for a conversion to occur, using the code 100 + n, where n represents the number of years, or to restrict a specific type of conversion to a limited area by linking a corresponding file (e.g., file n). The matrix is structured with land use classes at the initial year of the simulation in rows, and land use classes in subsequent years in columns. For example, in the East region, a value of 0 in the cell corresponding to row code 1 and column code 3 indicates that medium-density rural settlements in 2020 cannot convert into wetlands in subsequent years. The allow Matrix for the SSP1 scenario is reported in Table 37).

Table 37: Allow Matrix of the SSP1 that includes NATURA2000 area protection. 1= conversion allowed; 2= conversion not allowed; the numerical restriction files are explained below; 100 + n. years = the initial land use class can convert into the next land use class when it's at least n. years old.

East

Land syst	Code	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Low-densi	0	1	23	0	0	0	0	0	0	0	0	0	0	1	0	0	0
Medium-d	1	0	1	23	0	0	0	0	0	0	0	0	0	0	0	0	0
High-densi	2	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0
Wetlands	3	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0
Forest, shr	4	23	23	0	1	1	1	1	1	1	1	1	1	1	0	1	1
Forest, shr	5	23	23	0	1	1	1	1	1	1	1	1	1	1	0	1	1
Low-intens	6	23	23	0	1	22	22	1	22	22	22	22	22	22	0	22	22
Medium-in	7	23	23	0	1	1	1	1	1	1	1	1	1	1	0	1	1
High-inten	8	23	23	0	1	1	1	1	1	1	1	1	1	1	0	1	1
Low-intens	9	23	23	0	1	22	22	22	22	22	1	22	22	22	0	22	22
Medium-in	10	23	23	0	1	1	1	1	1	1	1	1	1	1	0	1	1
High-inten	11	23	23	0	1	1	1	1	1	1	1	1	1	1	0	1	1
Permanen	12	23	23	0	0	105	105	105	105	105	105	105	105	1	0	105	105
Close-to-n	13	23	23	0	0	0	0	0	0	0	0	0	0	0	1	0	0
Combined	14	23	23	0	0	24	24	24	24	24	24	24	24	24	1	1	24
Intensive fores	15	23	23	0	0	115	115	115	115	115	115	115	115	115	115	115	1

North

Land syst	Code	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Low-densi	0	1	24	0	0	0	0	0	0	0	0	0	0	1	0	0	0
Medium-d	1	0	1	24	0	0	0	0	0	0	0	0	0	0	0	0	0
High-densi	2	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0
Wetlands	3	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0
Forest, shr	4	24	0	0	23	1	23	23	23	23	23	23	23	23	0	23	23
Forest, shr	5	24	0	0	23	23	1	23	23	23	23	23	23	23	0	23	23
Low-intens	6	24	0	0	1	22	22	1	22	22	22	22	22	22	0	22	22
Medium-in	7	24	0	0	1	1	1	1	1	1	1	1	1	1	0	1	1
High-inten	8	24	0	0	1	1	1	1	1	1	1	1	1	1	0	1	1
Low-intens	9	24	0	0	1	22	22	22	22	22	1	22	22	22	0	22	22
Medium-in	10	24	0	0	1	1	1	1	1	1	1	1	1	1	0	1	1
High-inten	11	24	0	0	1	1	1	1	1	1	1	1	1	1	0	1	1
Permanen	12	24	0	0	0	105	105	105	105	105	105	105	105	1	0	105	105
Close-to-n	13	24	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0
Combined	14	24	0	0	0	25	25	25	25	25	25	25	25	25	25	1	25
Intensive fores	15	24	0	0	0	130	130	130	130	130	130	130	130	130	130	130	1

South

Land syst	Code	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Low-densi	0	1	23	0	0	0	0	0	0	0	0	0	0	1	0	0	0
Medium-d	1	0	1	23	0	0	0	0	0	0	0	0	0	0	0	0	0
High-densi	2	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0
Wetlands	3	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0
Forest, shr	4	23	0	0	1	1	1	1	1	1	1	1	1	1	0	1	1
Forest, shr	5	23	0	0	1	1	1	1	1	1	1	1	1	1	0	1	1
Low-intens	6	23	0	0	1	22	22	1	22	22	22	22	22	22	0	22	22
Medium-in	7	23	0	0	1	1	1	1	1	1	1	1	1	1	0	1	1
High-inten	8	23	0	0	1	1	1	1	1	1	1	1	1	1	0	1	1
Low-intens	9	23	0	0	1	22	22	22	22	22	1	22	22	22	0	22	22
Medium-in	10	23	0	0	1	1	1	1	1	1	1	1	1	1	0	1	1
High-inten	11	23	0	0	1	1	1	1	1	1	1	1	1	1	0	1	1
Permanen	12	23	0	0	0	105	105	105	105	105	105	105	105	1	0	105	105
Close-to-n	13	23	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0
Combined	14	23	0	0	0	24	24	24	24	24	24	24	24	24	1	1	24
Intensive fores	15	23	0	0	0	110	110	110	110	110	110	110	110	110	110	110	1

West

Land syst	Code	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Low-densi	0	1	23	0	0	0	0	0	0	0	0	0	0	1	0	0	0
Medium-d	1	0	1	23	0	0	0	0	0	0	0	0	0	0	0	0	0
High-densi	2	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0
Wetlands	3	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0
Forest, shr	4	23	23	0	1	1	1	1	1	1	1	1	1	1	0	1	1
Forest, shr	5	23	23	0	1	1	1	1	1	1	1	1	1	1	0	1	1
Low-intens	6	23	23	0	1	22	22	1	22	22	22	22	22	22	0	22	22
Medium-in	7	23	23	0	1	1	1	1	1	1	1	1	1	1	0	1	1
High-inten	8	23	23	0	1	1	1	1	1	1	1	1	1	1	0	1	1
Low-intens	9	23	23	0	1	22	22	22	22	22	1	22	22	22	0	22	22
Medium-in	10	23	23	0	1	1	1	1	1	1	1	1	1	1	0	1	1
High-inten	11	23	23	0	1	1	1	1	1	1	1	1	1	1	0	1	1
Permanen	12	23	23	0	0	105	105	105	105	105	105	105	105	1	0	105	105
Close-to-n	13	23	23	0	0	0	0	0	0	0	0	0	0	0	1	0	0
Combined	14	23	23	0	0	24	24	24	24	24	24	24	24	24	1	1	24
Intensive fores	15	23	23	0	0	110	110	110	110	110	110	110	110	110	110	110	1

The restriction files used in the allow matrix are as follows:

- Sc1gr22.fil.asc prevents the conversion of low-intensity cropland or grassland in areas of high agrobiodiversity (Matthies et al., 2023).
- Sc1gr23.fil.asc (sc1gr24.fil.asc in North) prevents the conversion of any land system to urban areas and the intensification of urban areas within the Natura 2000 and Emerald network reserves (EEA, 2022; EEA, 2023).

- Sc1gr23.fil.asc (in North) prevents the conversion of mosaics in high-elevation areas. Northern grass–forest mosaics are climatically and edaphically determined rather than management-driven; without this restriction, they would incorrectly convert to closed forest. Specifically: North of Bergen: above 500 m altitude; North of Trondheim: all mosaics excluded; South of Bergen: above 1000 m altitude.
- Sc1gr24.fil.asc (sc1gr25.fil.asc in North): Ensures that combined-objective forests located in Natura 2000 areas (EEA, 2022) or important wildlife corridors (Dertien, 2021) can only retain their current identity or convert to close-to-nature forests.

Low-density rural settlement (0). As in SSP2, can transition to peri-urban, but not directly to high-density urban. Inflows from non-urban areas are allowed, while urban → rural conversions are prohibited.

Medium-density peri-urban (1). As in SSP2, can densify to high-density urban. Broad inflows from non-urban areas are allowed.

High-density urban (2). As in SSP2, generally static, except for densification inflows from peri-urban areas.

Wetlands (3). Unlike SSP2, wetlands are static and preserved in all locations. Inflows are allowed from mosaics, grasslands, and croplands.

Forest, shrub & cropland mosaic (4). As in SSP2, can convert to other mosaics, cropland, grassland, forest, and low/medium-density settlements, but not directly to high-density urban. In the North, high-elevation mosaics are blocked (23) to prevent conversion above altitude thresholds.

Forest, shrub & grassland mosaic (5). Same allow set as mosaics with cropland.

Low-intensity arable cropland (6). Same family of conversions as SSP2 (within arable; to grassland/forest; to low/medium-density settlements); cannot convert to high-density urban or wetlands. SSP1 introduces code 22 to protect low-intensity agriculture in high-agrobiodiversity areas.

Medium-intensity arable cropland (7). Matches SSP2 for allowed conversions.

High-intensity arable cropland (8). Core pattern as in SSP2. SSP1 regional matrices restrict inflows toward high-intensity arable using codes 23/24 (and 25/1 in the North).

Low-intensity grassland (9). Same behavior as SSP2; SSP1 adds code 22 to protect high-agrobiodiversity grasslands.

Medium-intensity grassland (10). Same as in SSP2.

High-intensity grassland (11). Same as in SSP2.

Permanent cropland (12). Same as SSP2, including minimum residence time and notes on low-density settlement pockets outside protected areas. SSP1 expresses PA rules regionally (23/24) instead of SSP2's single 23.

Close-to-nature + primary forest (13). Same as SSP2, with strict protection and management switches. Regional matrices largely mirror SSP2; codes 24/25 appear only where corridor/Natura 2000 rules apply, which is rare for this class.

Combined-objective forestry (14). Follows SSP2 for convertibility and management switching, with rotation logic unchanged. In SSP1, codes 24 (and 25 in the North) are applied to ensure that combined-objective forests located within Natura 2000 sites or key wildlife corridors may only persist or convert to close-to-nature forests — a nuance that was not implemented in the SSP2 matrix.

Intensive + very intensive forestry (15). As in SSP2, with regional rotation-length constraints and allowances for post-rotation conversions to non-urban classes; wetlands remain excluded. Regional SSP1 matrices introduce additional 23/24 overlays not present in SSP2, while rotation-timing annotations remain unchanged.

Demands

Table 38: Demands for East region, SSP1 scenario

Population (# people)	arable crops (tons)	permanent crops (tons)	livestock (LSU)	Wood production (m^3)	Wetlands (km^2)	Trees (n. Trees)
119212769	221962539	1670391	10369565	213039878	3354	27388206062
119212769	221925411.7	1678600.92	10369262.52	215026880	3623	27463206062
119212769	221851170.1	1686851.242	10368657.66	217032414.9	3893	27538206062
119212769	221739845	1695142.115	10367750.42	219056655.2	4162	27613206062
119212769	221591485.9	1703473.737	10366540.86	221099775.5	4431	27688206062
119212769	221406161.2	1711846.309	10365029.1	223161951.7	4701	27763206062
119212769	221183957.5	1720260.032	10363215.24	225243361.7	4970	27838206062
119212769	220924980	1728715.109	10361099.45	227344184.7	5239	27913206062
119212769	220629352.3	1737211.742	10358681.89	229464602	5508	27988206062
119212769	220297216.2	1745750.137	10355962.78	231604796.2	5778	28063206062
119212769	219928731.6	1754330.497	10352942.33	233764951.7	6047	28138206062
119212769	219524076.6	1762074.618	10349620.81	233764951.7	6316	28171539395
119212769	219083446.9	1769852.923	10345998.49	233764951.7	6586	28204872728
119212769	218607056.3	1777665.564	10342075.69	233764951.7	6855	28238206062
119212769	218095135.8	1785512.692	10337852.73	233764951.7	7124	28271539395
119212769	217547933.9	1793394.46	10333329.99	233764951.7	7394	28304872728

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Table 39: Demands for North region, SSP1 scenario

Population (# people)	arable crops (tons)	permanent crops (tons)	livestock (LSU)	Wood production (m^3)	Wetlands (km^2)	Trees (n. Trees)
25563958	46649781	3252	2277447	206837789	20931	55611846893
25659629.29	45456481.23	3252	2274779.212	206922789	20948	55686846893
25755658.16	44293705.73	3252	2272114.737	207007824.2	20966	55761846893
25852046.41	43160673.99	3252	2269453.382	207092894.3	20983	55836846893
25948795.38	42056625.17	3252	2266795.145	207177999.4	21001	55911846893
26045906.43	40980817.88	3252	2264140.021	207263139.4	21018	55986846893
26118993.35	39932529.72	3252	2261488.008	207348314.4	21036	56061846893
26192285.36	38911056.74	3252	2258839.1	207433524.4	21053	56136846893
26265783.03	37915713	3252	2256193.296	207518769.5	21071	56211846893
26339486.94	36945830.14	3252	2253550.59	207604049.6	21088	56286846893
26413397.67	36000756.85	3252	2250910.98	207689364.7	21106	56361846893
26483514.63	35679234.35	3252	2242653.238	207689364.7	21123	56361846893
26553817.72	35360583.36	3252	2234425.79	207689364.7	21141	56361846893
26624307.44	35044778.24	3252	2226228.526	207689364.7	21158	56361846893
26694984.28	34731793.58	3252	2218061.334	207689364.7	21176	56361846893
26765848.74	34421604.18	3252	2209924.104	207689364.7	21193	56361846893

Table 40: Demands for South region, SSP1 scenario

Population (# people)	arable crops (tons)	permanent crops (tons)	livestock (LSU)	Wood production (m^3)	Wetlands (km^2)	Trees (n. Trees)
123697439	76917899	7684075	2082619	42551146	1512	19660950739
123697439	76913141.94	7708358.741	2081437.599	42713218.54	1533	19735950739
123697439	76908384.87	7732719.322	2080256.414	42875908.39	1554	19810950739
123697439	76903628.09	7757156.889	2079075.899	43039217.91	1575	19885950739
123697439	76898871.61	7781671.685	2077896.054	43203149.46	1596	19960950739
123697439	76894115.42	7806263.956	2076716.879	43367705.4	1617	20035950739
123697439	76889359.52	7830933.944	2075538.373	43532888.12	1638	20110950739
123697439	76884603.92	7855681.897	2074360.536	43698700.01	1659	20185950739
123697439	76879848.62	7880508.061	2073183.367	43865143.45	1680	20260950739
123697439	76875093.61	7905412.682	2072006.867	44032220.85	1701	20335950739
123697439	76870338.89	7930396.008	2070831.033	44199934.64	1722	20410950739
123697439	76396677.35	7958120.592	2051876.514	44199934.64	1743	20444284073
123697439	75925934.44	7985942.1	2033095.486	44199934.64	1764	20477617406
123697439	75458092.16	8013860.871	2014486.364	44199934.64	1785	20510950739
123697439	74993132.64	8041877.247	1996047.572	44199934.64	1806	20544284073
123697439	74531038.12	8069991.568	1977777.553	44199934.64	1827	20577617406

Table 41: Demands for West region, SSP1 scenario

Population (# people)	arable crops (tons)	permanent crops (tons)	livestock (LSU)	Wood production (m³)	Wetlands (km²)	Trees (n. Trees)
263686655	288671054	1694068	42495514	145410238	31098	23067403379
264271802.4	283917505.7	1687020.805	42506397	146204796	31220	23142403379
264858248.3	279242234.5	1680003.42	42517280	147003696	31342	23217403379
265445995.5	274643951.1	1673015.224	42528162	147806961	31464	23292403379
266035047.1	270121387.6	1666056.096	42539045	148614616	31586	23367403379
266625405.7	265673297.1	1659125.916	42549928	149426684	31707	23442403379
266999438.4	261298453.4	1652224.563	42560810	150243189	31829	23517403379
267373995.7	256995650.3	1645351.917	42571693	151064155	31951	23592403379
267749078.5	252763701.4	1638507.859	42582575	151889608	32073	23667403379
268124687.4	248601440.1	1631692.269	42593458	152719571	32195	23742403379
268500823.3	244507718.8	1624905.03	42604341	153554070	32317	23817403379
268876849.5	241068249.3	1617260.971	42615223	153554070	32439	23850736713
269253402.2	237677162.5	1609652.873	42626106	153554070	32561	23884070046
269630482.3	234333777.9	1602080.565	42636989	153554070	32683	23917403379
270008090.5	231037424.4	1594543.879	42647871	153554070	32804	23950736713
270386227.5	227787440.4	1587042.649	42658754	153554070	32926	23984070046

Two new demand categories were introduced for SSP1:

Wetlands. The demand in 2020 (time step 0) equals the number of wetland pixels in the cov0 (2020 basemap). The 2030 demand is defined as the initial demand plus 17% of the wetland locspec area (see Section 1.2.4.8). Demand values between 2020 and 2030 are linearly interpolated and then held constant for the remainder of the scenario.

Trees. The average number of trees per land system (Crowther et al., 2015) was calculated and used to determine baseline provisioning. The 2030 demand for each region equals baseline provisioning plus 3 billion / 4 (i.e., the 3-billion-tree target is divided evenly across the four regions). A further 2 billion trees are added by 2050, divided only among the East, South, and West regions; the North is assumed to be at capacity. Intermediate values are linearly interpolated. The tree-provision estimate for wetlands was revised relative to the original source data. The Crowther et al. (2015) values for wetlands were considered overestimates, as wetlands are typically dominated by tall shrub-like vegetation rather than standing trees. This matters because the 3 Billion Trees target — on which this ad hoc demand category is based — explicitly refers to standing trees. To correct this, the wetland tree-provision estimate was reduced by 50%, under the assumption that only half of wetland vegetation consists of tree forms relevant to the target. This adjustment is reflected in the revised provision column of the lusmatrix (only the tree-demand column is shown in the table below). The 2020 tree provision was updated accordingly. The stepwise increase in tree demand is implemented in the following way: an additional 75,000,000 trees per year from 2020 to 2030, reaching the 3-billion-tree target shared among the four regions. From 2030 to 2050, demand increases by 33,000,000 trees per year, totalling 2 billion trees, distributed across the South, East, and West; tree demand in the North remains constant after 2030.

Finally, the original crop and livestock demands for the East region, and the livestock demand for the West region, were smoothed to avoid abrupt year-to-year changes that were causing instability in the simulations.

Lusconv

Lusconv values (Table 42) are derived from the ratios provided in the lusmatrix. The land-use class with the highest provisioning value in each demand column is assigned a lusconv value of 3, and the other contributing land systems receive values proportional to this ratio, rounded to the nearest integer. Land systems that do not contribute to a given demand (i.e., have no provisioning value in the lusmatrix) are assigned a value of –1.

For the arable crops and livestock demand columns, the highest value was set to 4 rather than 3, because mosaics also contribute to these two demand types, requiring an expanded scale to preserve proportional differences.

The priorities assigned to the different land-use classes in SSP1 follow those used in the SSP2 BAU scenario, with the addition of the two newly introduced demand columns. Only wetlands contribute to satisfying the wetlands demand, whereas the trees demand is met equally by the mosaics and the three forest classes

Table 42: Lusconv table SSP1 scenario, all regions

Population (# people)	arable crops (tons)	permanent crops (tons)	livestock (LSU)	Wood production (m^3)	Wetlands (km^2)	Trees (n. Trees)
1	-1	-1	-1	-1	-1	-1
2	-1	-1	-1	-1	-1	-1
3	-1	-1	-1	-1	-1	-1
-1	-1	-1	-1	-1	1	-1
0	1	0	0	-1	-1	1
0	0	0	1	-1	-1	1
0	2	0	0	-1	-1	-1
0	3	0	0	-1	-1	-1
0	4	0	0	-1	-1	-1
0	0	0	2	-1	-1	-1
0	0	0	3	-1	-1	-1
0	0	0	4	-1	-1	-1
0	0	1	0	-1	-1	-1
0	0	0	0	1	-1	1
0	0	0	0	2	-1	1

0	0	0	0	3	-1	1

Main file

Table 43: Conversion elasticities for SSP1, North East South

0	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**
0.5	0.6	1	0.9	0.7	0.7	0.4	0.5	0.6	0.4	0.5	0.6	0.8	0.9	0.9	0.6

Table 44: Conversion elasticities for SSP1, West

0	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**
0.5	0.6	1	0.9	0.7	0.7	0.4	0.5	0.6	0.4	0.6	0.8	0.8	0.9	0.9	0.6

Elasticities / conversion resistance (Table 43 and Table 44)

Urban areas are dynamic to facilitate conversion. High-density urban is the exception and remains largely static, with an elasticity value of 1. The elasticities of all urban classes follow those defined in SSP2.

Wetlands are also only minimally dynamic, with elasticity values identical to those in SSP2.

Both **mosaic classes** exhibit low dynamism because they represent mixed land-system types. In SSP1, mosaics are made less convertible than in SSP2 to reflect their ecological value and the higher priority placed on nature protection in this scenario.

Cropland, grassland and forest follow similar dynamic patterns: low-intensity systems are easiest to convert due to lower investment levels, followed by medium-intensity and then high-intensity systems. Compared with SSP2, close-to-nature forests and combined-objective forestry are made substantially less dynamic—almost static—because of their high ecological value. The three arable crop classes are made slightly more resistant to conversion than in SSP2 to ensure consistency with the behaviour of grasslands.

Permanent cropland is relatively static. The investment required to establish permanent crops increases resistance to conversion. This resistance is set higher than in SSP2, reflecting the greater appreciation of cultural and traditional landscape values in an SSP1 future.

In the West region, to prevent the low-intensity expansion of productive systems and to maintain space for nature restoration, the conversion resistance of high-intensity grassland is increased to 0.8, and that of medium-intensity grassland to 0.6.

Adjustments in the main file relevant for the demand's settings

We allowed overshooting of the tree demand by treating it as a minimum rather than an exact requirement. This adjustment resolves the issue observed in earlier tests, where the model began resisting land abandonment once the tree target had been reached. Defining the target as a minimum provides greater flexibility and ensures that meeting the tree objective does not inadvertently constrain broader land-use dynamics.

In addition, the stronger de-intensification trend in the West region created greater potential for forest restoration. Because natural forests also contribute some wood provisioning in the *lusmatrix*, we wanted to avoid a situation where wood-product demand would restrict reforestation or the expansion of close-to-nature forests. To prevent this, we activated the dynamic *lusmatrix* option in the main configuration file.

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<u>Locspec weights in the main file</u>

East:	-0.5	0	0.5	0.6	0.4	0.4	-0.5	0	0	-0.5	0	0	0	0.6	0.6	-0.4
North:	-0.3	0	0.3	0.6	0.1	0.1	-0.5	0	0	-0.5	0	0	0	0.6	0.6	-0.4
South:	-0.2	0	0.2	0.6	0.4	0.4	-0.5	0	0	-0.5	0	0	0	0.6	0.6	-0.4
West:	-0.5	0	0.5	0.6	0.4	0.4	-0.2	0	0	-0.2	0	0.2	0	0.6	0.6	-0.4

Age0 file

This file defines the age of each land-use system at the initial year of the simulation. Due to data limitations, a random age between 0 and 10 years is assigned to most land-use classes at the pixel level. The only exception is forest. For forest pixels, age is assigned using a reference map containing information on the estimated age of individual trees for each pixel (Besnard et al., 2025).

Lusmatrix

The *lusmatrix* provides the average productivity of each land system per demand category. Below is a summary of the procedures used to obtain the values included in the *lusmatrix*. Note that SSP1 uses the same provisioning values as SSP2 for the five baseline demands. For SSP1, two additional demands were included (wetlands and trees), and their provisioning values were calculated accordingly. In the West region of SSP1, a dynamic *lusmatrix* was implemented. The dynamic component affected only the wood demand: the wood provision from close-to-nature forests was gradually reduced by 25% by 2050. This ensured that wood demand could still be met while preventing close-to-nature forests from being constrained by wood production requirements, thereby allowing greater expansion of this class.

Population is primarily associated with urban land systems, although several non-urban land systems also host population. For this reason, all land systems were overlaid with the population grid from Batista e Silva et al. (2021). This dataset was intersected with the baseline land-use map from Sandström et al. (2024).

Arable crops. Arable crop production is provided by the three arable cropland classes as well as by the forest–shrub–cropland mosaic. All other land systems receive a value of 0. Data sources include GlobalWheatYield4km (Luo et al., 2022) and nitrogen input data from Sandström et al. (2024).

For **mosaic systems**, the share of arable cropland within each mosaic pixel was calculated and multiplied by the productivity value of low-intensity cropland. This approach reflects the lower nitrogen inputs typically found in mosaics. Validation was performed by overlaying GlobalWheatYield4km with mosaic areas, using wheat yields as a proxy because wheat is widely grown in Europe and represents the highest-producing cereal.

Permanent crops Permanent crop production is provided exclusively by the permanent crop land system; all other systems receive a provision value of 0. Since no intensity classes exist for permanent crops, the CAPRI baseline production value was divided by the area of permanent crops to obtain a per-pixel productivity estimate.

Livestock is provided by the three grassland classes and by the forest–shrub–grassland mosaic. All other land systems receive a value of 0. Grasslands were overlaid with livestock data from Malek et al. (2024). Because Northern Europe contains relatively few grassland areas, livestock productivity values from Western Europe were transferred to the North. Cattle,

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sheep, and goat densities were used as indicators, and values for sheep and goats were converted into Livestock Units (LSU).

For **mosaic systems with grasslands**, an approach parallel to that used for arable mosaics was applied, but using the livestock data from Malek et al. (2024) rather than nitrogen inputs.

Wood. Wood production occurs in all forest classes and in both mosaic classes. All other systems receive a value of 0. Production ratios were derived from National Forest Inventory (NFI) data from ten countries: Norway, Sweden, Germany, Austria, Poland, Slovenia, Spain, Belgium, Czechia, and Ireland.

For **mosaics containing forest**, FAOSTAT forest production data were used to scale the productivity of low-intensity forest by the percentage of forest cover within the mosaic tile.

Neighbourhood settings

For the neighbourhood settings, our objective was to simulate a high-sustainability pathway consistent with SSP1. To achieve this, we applied aggregation effects to high-density urban areas, high-intensity agriculture, and high-intensity forestry (Table 45). The neighbourhood configuration follows the same structure and parameterisation used in SSP2. In addition, as in SSP2, the *alloc2.reg* file was generated with a specific weighting that encourages clustering of high-intensity grasslands together with high-intensity croplands. This ensures spatial coherence among highly managed productive systems under the SSP1 scenario.

Table 45: Current Neighmat.txt file

0	0	0.4	0	0	0	0	0	0.4	0	0	0	0	0	0	0.4	
16	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
1																
1	1	1														
1	1	1														
1	1	1														
16	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
1																
1	1	1														
1	1	1														
1	1	1														
16	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
1																
1	1	1														
1	1	1														
1	1	1														

Location specific rules

As mentioned before, in CLUMondo, it is possible to specify a spatially explicit preference for certain land-use classes at given locations, providing those classes with a competitive advantage during the allocation process. The number embedded in each locspec filename corresponds to the land-use class code it influences. For SSP1, the use of these files was combined with adjustments to the regional files.

For SSP1, *locspec* files were applied to the urban classes to balance urban intensification with urban sprawl. Without these additional weights, the model produced almost exclusively sprawl, which did not realistically reflect the SSP1 storyline.

The *locspec* files for the urban classes assign a uniform base value of 1 across the entire region. The following weights were then applied in the main configuration file (low / medium / high density):

- North: -0.3 / 0 / 0.3
- West: -0.5 / 0 / 0.5
- East: -0.5 / 0 / 0.5
- South: -0.2 / 0 / 0.2

Terrestrial conservation/restoration preferences (Region3.fil and locspecs4,5,12-15)

Important wildlife corridors (Dertien, 2021) were combined with the Natura2000 network (EEA, 2022) to produce the *region3.fil* file and the restoration oriented *locspecs* layers.

The following inputs from Dertien (2021) were used:

- **Large Predator Raster** - lg_predator_normal_currmap.tif
- **Large Herbivore Raster** - lg_herbivore2_normal_currmap.tif

The Natura 2000 network was added as a separate binary raster layer.

Starting from the connectivity rasters, we applied the following transformations: subtracted 0.8 from each pixel value; set all resulting negative values to 0; set all values still > 0.8 to 0.8. After this normalization, the predator and herbivore rasters were averaged into a single connectivity surface, which was then multiplied by 1.25 so that the rescaled maximum reached 1. The threshold choices follow the interpretation provided by Dertien.

Normalized current density.

This raster is designed to identify restricted areas and pinchpoints in wildlife movement. For clarity, it may be useful to categorize the values or adjust the scale so that blocked areas have negative values. General interpretation of the raster values (note: numeric thresholds may vary slightly depending on the source):

- 0.0–0.8: Movement blocked by human infrastructure, topography, or other barriers.
- 0.8–1.2: Diffuse movement; wildlife can move freely across large, unrestricted habitat areas.
- 1.2–1.6: Restricted movement; connections begin to narrow and movement is increasingly constrained.
- >1.6: Channelized movement; these are the highest-priority corridor zones for conservation, where connectivity is critical.

We excluded areas with normalized current density values below 0.8. A threshold of 1.6 was used to define maximum connectivity, as all areas above this value are highly important for wildlife movement. Capping at 1.6 also mitigates the effect of a few extreme outliers (values up to 7), which would otherwise skew the distribution and make it unsuitable for use in a *locspec* file.

The binary rasterized Natura 2000 layer was then added to the above raster, with all values greater than 1 set to 1. This ensured that the resulting layer captured both existing protected areas and key wildlife corridors.

Overlaying this with the baseline land system map (timestep 0), the raster was split by initial land cover. For the SSP1 baseline and the N4N scenario, areas overlapping wetlands or close-to-nature forests (LS 3, 13) were “frozen” in the region file (represented as -9998) and excluded from allocation calculations. For the N4S and NaC scenarios, wetlands, close-to-nature forests, and combined-objective forests (LS 3, 13, 14) were frozen similarly. Areas in modified land systems (all others) were instead captured by location-specific preference files (locspecs 12–15) to guide targeted restoration.

In the West region, reduced agricultural demands could lead to extensive deintensification of grassland and cropland. To balance this with restoration objectives, we adjusted *locspec* parameters to allow abandonment to favour expansion of natural systems. Specifically, *locspecs* 4, 5, and 12–15 were divided by 2 and then added to a blanket *locspec* with a value of 1: (restoration priorities / 2) + 1. This modified *locspec* was applied to LS 13 and 14 (locspec13.fil.asc and locspec14.fil.asc), promoting close-to-nature forests and combined-objective forests across the region, particularly in priority wildlife corridors and protected areas.

Wetland restoration preferences (locspec3)

Likely areas for potential wetland restoration were identified using the categorical raster of potential vegetation types, specifically extracting areas classified as wetlands. Areas that overlapped with agricultural land systems (LS 6–11) in cov0 were included in *locspec3.fil* as preferred locations for rewetting.

Location specific preferences for agricultural patterns

A uniform *locspec* with a base value of 1 was created for low-density cropland and grasslands. This *locspec* was coupled with a negative weight in the allow matrix, thereby encouraging intensification of these areas, in line with a land-sparing strategy.

IPBES NfN

The Nature for Nature (NfN) scenario builds upon the SSP1 scenario. The core parameters of NfN, as well as its differences compared to SSP1, are summarized below.

Allow matrix

Same as baseline, inclusive of sc1gr# conversion restriction files.

Main

Same as in the SSP1 scenario, with the tree demand allowed to overshoot as in SSP1. The *locspec* weights are:

East:	-0.5	0	0.5	0.6	-0.5	-0.5	-0.6	0	0	-0.6	0	0	0	0.6	0.6	-0.4
North:	-0.3	0	0.3	0.6	-0.5	-0.5	-0.4	0	0	-0.4	0	0	0	0.6	0.6	-0.4
South:	-0.3	0	0.3	0.6	-0.5	-0.5	-0.4	0	0	-0.4	0	0	0	0.6	0.6	-0.4

West: -0.5 0 0.5 0.6 -0.2 -0.2 -0.2 0 0 -0.3 0 0.3 0 0.6 0.6 -0.4

Region and *locspecs*

In each of the NFF scenarios, the region files and restoration *locspecs* are enhanced with scenario-specific priorities. Specifically, O'Connor et al. (2021) provides a map of areas important for biodiversity, which is incorporated into both the restoration *locspecs* and the region files for NfN. For NfN, a composite map is created combining: important wildlife corridors (Dertien, 2021), Natura 2000 protected areas (EEA, 2022), and areas important for species (O'Connor et al., 2021). This composite is then divided based on land cover in the starting year:

- Areas with natural land cover (specifically wetlands or close-to-nature forests, as in the SSP1 baseline) are frozen in the region file (region4.fil.asc).
- Areas in modified landscapes (all LS except wetlands, close-to-nature forests, or combined-objective forests) are targeted for restoration via locspecs 12–15.
- Priority areas covered by combined-objective forests are allowed to convert only to close-to-nature forests, and no other classes.

Additionally, in the N4N scenario:

- A blank locspec with a negative weight is applied to mosaics everywhere, promoting land-sparing.
- Blank locspecs are also used for urban systems, encouraging urban densification across all scenarios

IPBES NfS

The Nature for Society (NfS) scenario builds upon the SSP1 scenario. The core parameters of NfS, as well as its differences compared to SSP1, are summarized below.

Allow matrix

Same as the baseline SSP1 scenario, except that the sc1gr24.fil.asc (and sc1gr25.fil.asc in the North) is removed. This is because combined-objective forestry (COF) is included in the region file for these scenarios, meaning that priority areas (Natura 2000, important wildlife corridors, and scenario-specific priorities) that are currently wetlands, close-to-nature forests, or COF are frozen in the region file. For the NfS and NaC scenarios, COF is assumed to play a critical role and should therefore be maintained in these management areas, rather than being converted to close-to-nature forests as in the NfN scenario. As a result, there is no sc1gr file linked to the allow matrix to enforce COF conversion to close-to-nature; instead, COF is preserved in place.

Main

Same as in the baseline SSP1 scenario, with the tree demand allowed to overshoot as in SSP1. The *locspec* weights are:

East: -0.5 0 0.5 0.6 0.4 0.4 -0.4 0 0 -0.4 0 0 0 0.6 0.6 -0.4
North: -0.3 0 0.3 0.6 0.1 0.1 -0.4 0 0 -0.4 0 0 0 0.6 0.6 -0.4
South: -0.2 0 0.2 0.6 0.4 0.4 -0.4 0 0 -0.4 0 0 0 0.6 0.6 -0.4
West: -0.5 0 0.5 0.6 0.4 0.4 -0.2 0 0 -0.2 0 0.2 0 0.6 0.6 -0.4

Region and locspec

For NfS, a composite map of important wildlife corridors (Dertien, 2021), the Natura 2000 network (EEA, 2022), and areas important for regulating ecosystem services (O'Connor et al., 2021) is divided into areas currently in natural landcover — this time inclusive of combined-objective forests, which likely provide key ecosystem services (region3.fil.asc) — and areas in modified landscapes (*locspecs 4, 5, 12–15*). This approach allows the scenario to promote natural systems, and, to a lesser extent, mosaic systems, as these also contribute a degree of regulating services to the surrounding landscape.

Blank *locspecs* are used for urban systems across all scenarios to encourage urban densification in N4N and N4S (consistent with the baseline), while low-density urban sprawl is promoted in NaC.

IPBES NaC

The Nature for Culture (NaC) scenario builds upon the SSP1 scenario. The core parameters of NaC, as well as its differences compared to SSP1, are summarized below.

Allow matrix

The NaC scenario is the same as the baseline, except that sc1gr24.fil.asc (and sc1gr25.fil.asc in the North) is removed. This is because combined-objective forests are included in the region file for these scenarios, meaning that priority areas (Natura 2000, important wildlife corridors, and scenario-specific priorities) currently in wetlands, close-to-nature forests, or combined-objective forests — whereas in the SSP1 baseline and NfN only wetlands and close-to-nature forests were frozen — are now preserved. We assume that in NfS and NaC, combined-objective forests play important ecological and cultural roles and should be maintained in these management areas, rather than converted to close-to-nature forests as in the NfN narrative. Consequently, no sc1gr file is linked to the allow matrix to enforce conversion of combined-objective forests to close-to-nature; instead, these forests are retained.

Main

The NaC scenario is the same as the SSP1 baseline, except that in NaC South, both close-to-nature forests and combined-objective forests are assigned the maximum conversion resistance of 1. As in SSP1, the tree demand is allowed to overshoot. The *locspec* weights are:

East:	0.5	0	-0.5	0.6	0.4	0.4	0	0	-0.5	0	0	-0.5	0	0.6	0.6	-0.4
North:	0.1	0	-0.1	0.3	0.1	0.1	0	0	-0.1	0	0	-0.1	0	0.3	0.3	-0.3
South:	0.2	0	-0.2	0.6	0.5	0.5	0	0	-0.5	0	0	-0.5	0	0.6	0.6	-0.4
West:	0.5	0	-0.5	0.6	0.5	0.5	0	0	-0.3	0	0	-0.3	0	0.6	0.6	-0.4

Region and locspec

For the NaC scenario, a composite map of important wildlife corridors (Dertien, 2021), the Natura 2000 network (EEA, 2022), and areas important for cultural services (O'Connor et al., 2021) is divided into areas currently in natural land cover (including combined-objective forests, as these likely provide key cultural services; stored in region3.fil.asc) and areas in highly modified landscapes (locspecs 6–15).

While low-intensity agriculture, permanent crops, and peri-urban systems also contribute to cultural services, only natural land-cover areas are frozen in the model to avoid locking too much of the landscape and making solutions infeasible. This approach also maintains the possibility of restoration in wildlife corridors and Natura 2000 areas, which provide a specific type of cultural service. Some flexibility is therefore allowed for transitions among low-intensity agriculture, peri-urban, and permanent crops, whereas forests and wetlands are prioritized for stability due to their high cultural value.

In highly modified landscapes (urban areas and medium/high-intensity crops and grasslands), restoration priorities are applied. Additionally, a blank *locspec* with a positive weight is used to promote mosaics everywhere, supporting a land-sharing approach. Blank *locspecs* are also used for urban systems: to push for densification in NfN and NfS (consistent with baseline), while low-density urban sprawl is promoted in NaC.

SSP3

Allow matrix

As previously recalled, the allow matrix is a core CLUMondo input file that specifies which land use conversions are allowed and which are not. It is also possible to define time steps required for a conversion (using codes of the form 100 + n, where n is the number of years) or restrict a conversion to a specific area by linking a file to the matrix (e.g., file n.*). The matrix is structured with initial-year land use classes in the rows and future-year land use classes in the columns (Table 46). For example, if the matrix value in row 2, column 5 is 0, it indicates that low-density rural settlement in 2020 cannot convert into high-density rural settlement.

Table 46: Allow Matrix of the SSP3. This version acts as baselines for the subsequent scenarios. 1= conversion allowed ; 2= conversion not allowed ; 23= restriction file for Natura2000 areas (conversions to the land use class is allowed only outside Protected Areas) ; 24,25 (South) = restriction file for very dry areas (conversions to high intensity crops is not allowed in those areas and existing fields need to convert in 5 years); 24,25 (North) = restriction files for high elevation mosaics (24) and high elevation mosaics combined with Pas (25); 100 + n. years = the initial land use class can convert into the next land use class when it's at least n. years old.

Land system	Code	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Low-density rural settlement	0	1	23	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Medium-density peri-urban settlement	1	0	1	23	0	0	0	0	0	0	0	0	0	0	0	0	0
High-density urban settlement	2	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0
Wetlands (South/other regions)	3	23	23	0	1	23	23	23	23	24/23	23	23	23	23	23	23	23
Forest, shrub and cropland mosaics (South/North/other regions)	4	23	23	0	0	1	1	23/25/23	23/25/23	24/25/23	23/25/23	23/25/23	23/25/23	23/25/23	0	1/24/1	23/25/23
Forest, shrub and grassland mosaic (South/North/other regions)	5	23	23	0	0	1	1	23/25/23	23/25/23	24/25/23	23/25/23	23/25/23	23/25/23	23/25/23	0	1/24/1	23/25/23
Low-intensity arable cropland (South/other regions)	6	23	23	0	0	1	1	1	1	24/23	1	1	23	23	0	1	23
Medium-intensity arable cropland (South/other regions)	7	23	23	0	0	1	1	1	1	24/23	1	1	23	23	0	1	23
High-intensity arable cropland (South/other regions)	8	23	23	0	0	1	1	0	1	25/1	1	1	1	1	0	1	1
Low-intensity grasslands (South/other regions)	9	23	23	0	0	1	1	1	23	24/23	1	23	23	23	0	1	23
Medium-intensity grasslands (South/other regions)	10	23	23	0	0	1	1	1	1	24/23	1	1	23	23	0	1	23
High-intensity grasslands	11	23	23	0	0	1	1	1	1	1	0	1	1	1	0	1	1
Permanent crops	12	23	23	0	0	105	105	0	105	105	0	105	105	1	0	105	105
Close-to-nature forestry + Primary forest (South/other regions)	13	23	23	0	0	23	23	23	23	24/23	23	23	23	23	1	23	23
Combined objective forestry (South/other regions)	14	23	23	0	0	23	23	23	23	24/23	23	23	23	23	1	1	23
Intensive forestry + very intensive forestry (North/West/South/East	15	23	23	0	0	130/130/110/12	130/130/110/12	130/130/110/12	130/130/110/12	130/130/110/120	130/130/110/12	130/130/110/12	130/130/110/12	130/130/110/120	130/130/110/120	130/130/110/12	1

Low-density rural settlement (code 0). The behaviour is the same as in SSP2: conversion to medium-density peri-urban is allowed, whereas direct conversion to high-density urban is not. Conversions from non-urban classes into medium-density peri-urban remain permitted, while urban classes cannot convert into it. Urban intensification is allowed only outside Natura2000 areas (restriction file 23).

Medium-density peri-urban settlement (code 1). The behaviour is as in SSP2. Conversion to high-density urban is permitted, and inflows from most non-urban classes are allowed outside Natura2000 protected areas (restriction file 23).

High-density urban settlement (code 2). The behaviour is as in SSP2. The class is static except for densification from peri-urban. No differences from SSP2.

Wetlands (code 3). As in SSP2, outflows to low-/medium-density settlements and other land systems occur outside protected areas (restriction files 23, 24). No baseline inflows to wetlands are present.

Forest, shrub and cropland mosaic (code 4). The behaviour mirrors SSP2. Conversion to the other mosaic, cropland/grassland/forest classes, and low-/medium-density settlements is permitted, while direct conversion to high-density urban is not.

Forest, shrub and grassland mosaic (code 5). The set of allowed conversions is the same as in SSP2.

Low-intensity arable cropland (code 6). The behaviour is as in SSP2. A broad set of conversions is allowed (within arable, to grassland/forestry, to low-/medium-density settlements), while conversion to high-density urban or wetlands is not permitted.

Medium-intensity arable cropland (code 7). The behaviour follows SSP2 for allowed conversions.

High-intensity arable cropland (code 8). Core allowed/blocked conversions correspond to SSP2 (Section 1.2.1.1). In SSP3, inflows to high-intensity arable and transitions toward this class are flagged with restriction files 24/25, indicating added constraints. The creation and rationale for files 24 and 25 are explained at the end of the section**.**

Low-intensity grassland (code 9). The behaviour is the same as in SSP2.

Medium-intensity grassland (code 10). The behaviour is the same as in SSP2.

High-intensity grassland (code 11). The behaviour is the same as in SSP2.

Permanent cropland (code 12). The behaviour is as in SSP2, including the minimum time requirement before conversion and the note on low-density settlement pockets outside protected areas.

Close-to-nature forestry + primary forest (code 13). The behaviour is as in SSP2, with strict protection and the same permitted management switches.

Combined-objective forestry (code 14). The behaviour is as in SSP2 for general convertibility and management switching; rotation-length logic remains unchanged. In SSP3, some cells include restriction files 24/23, adding file 24 on top of the base 23 rule**.**

Intensive + very intensive forestry (code 15). The behaviour is as in SSP2. Regional rotation-length constraints apply, and post-rotation non-urban conversions are allowed while wetlands remain excluded. SSP3 includes a small number of cells with restriction files 24/23 applied; timing and rotation annotations mirror SSP2.

<u>Restriction file 23 in SSP3</u>

In SSP3, small Natura2000 areas are considered capable of conversion into productive systems, while large natural reserves remain strictly protected. In the modified protected area map, small Natura2000 sites are assigned a value of 1, whereas large reserves are assigned 0. This approach reflects empirical evidence showing that smaller protected areas are more vulnerable to anthropogenic habitat loss due to land use conversions (Li et al., 2024). Their higher perimeter-to-area ratio increases exposure to edge effects, encroachment, and external land use pressures, which limits their effectiveness in preventing habitat degradation in human-dominated landscapes (Maiorano et al., 2008). Under a low sustainability scenario such as SSP3, protected areas generally receive low priority, with weak environmental policies and limited international cooperation resulting in fragmented and poorly enforced conservation (O'Neill et al., 2017). In land use modelling, natural protected areas are typically represented as spatial constraints. Common modelling frameworks, such as CLUMondo and IMAGE, implement this by applying conversion restrictions — prohibiting land use changes within reserve boundaries — or by assigning differentiated suitability scores, such as lower suitability for urban or intensive agricultural uses (Krumins and Klavins, 2025; FIREURISK D3.2; Molina Bacca et al., 2025; Bayer et al., 2021; Petz et al., 2016). The types of conversions allowed in small reserves are informed by the literature on the main anthropogenic drivers of habitat loss in protected areas, with deforestation and conversion to cropland, pastureland, and built-up land accounting for the majority of observed changes (Li et al., 2024). Consequently, these limited productive conversions are permitted in small protected areas to realistically reflect human pressures:

- From close-to-nature forest (code 13) to low-intensity grasslands (code 9), low-intensity cropland (code 6), combined-objective forest (code 14), permanent crops (code 12)
- From low-intensity grasslands (code 9) to low-intensity cropland (code 6), combined-objective forest (code 14), permanent crops (code 12)
- From low-intensity cropland (code 6) to low-intensity grasslands (code 9), combined-objective forest (code 14), permanent crops (code 12).

In SSP3, conversions in small Natura2000 areas are limited to low-intensity systems, as allowing transitions to medium or high-intensity land use would be considered too extreme. In this context, "small PAs" are defined as protected areas with a size of 10 km^2 or less. This threshold was chosen based on the available literature on size-class divisions among European protected areas. Although there is substantial variability in the size of terrestrial PAs across Europe, the majority of them fall below 10 km^2, making this a representative cut-off for identifying areas most vulnerable to anthropogenic pressures (European Commission, n.d. ; Table 47).

Table 47: Class sizes commonly referenced for terrestrial protected areas in Europe (European Commission, n.d).

Size class	Area (km²)	Proportion of sites
Very small	<1	~60–69%
Small	1-10	15–20% (varies by country)
Medium	10-100	10–15% (varies by country)
Large	100-1000	<5%

In our SSP3 implementation, we used the same protected areas as in SSP2. For implementation, the scr1gr22 raster, which serves as the location factor for protected areas, was used as the base layer. Isolated protected areas smaller than 10 km^2 were identified using a flood-fill algorithm implemented in Python. This process generated the sc1gr23 factor, which specifically flags these small, vulnerable PAs for the SSP3 scenario.

Restriction file 24 and 25 in South SSP3

To implement the exclusion of high-productivity agriculture in excessively arid environments under SSP3, we used an Aridity Index (AI)-based approach combined with preference adjustments, following Malek & Verburg (2023) and using projected AI maps from Zomer and Trabucco (2024) specific to SSP3 RCP 7.0. This method constrains land-use transitions toward intensive agriculture based on future aridity conditions.

Areas with very high drought (AI ≤ 0.2) were fully excluded from conversion to high-intensity crops. These restrictions were applied through exclusion maps for each relevant land-use class, referenced directly in the allow matrix. In other words, in regions with AI below 0.2, no land-use class was allowed to convert to high-intensity agriculture. For regions with medium to high aridity (AI 0.21–0.5), the suitability for high-intensity crops and grasslands was reduced using *locspec* files. Continuous maps were derived from the projected AI maps, keeping only the areas with AI > 0.2. In the model, a negative coefficient was applied to these high-intensity land uses to reflect lower preference, rather than fully prohibiting conversion. This combined approach ensured that both absolute exclusion in very dry areas and gradual discouragement in moderately dry regions were implemented, aligning agricultural expansion with realistic environmental constraints.

The numerical thresholds cited here are based on literature defining critical AI thresholds for agriculture (Orshoven et al., 2013; UNCCD, 2024):

1. **AI ≤ 0.5 (Severe Limitation)**. According to the European Commission's bio-physical criteria, this threshold marks the point at which dryness constitutes a severe natural constraint for general agriculture. Areas with AI ≤ 0.5 (P/PET ≤ 0.5) are characterized by insufficient soil moisture to reliably support rainfed crop production.
2. **AI ≤ 0.2 (Arid/Hyper-arid: Near-Impossible Rainfed Agriculture)**. Regions with AI values in the arid (0.03–0.2) or hyper-arid (<0.03) ranges are generally unsuitable for rainfed agriculture due to extreme water deficits.

For our analysis, we used AI maps from Zomer and Trabucco (2024), which provide high-resolution (30 arc-seconds) global estimates of the average annual aridity index for 22 CMIP6 Earth System Models over two future periods (2021–2041 and 2041–2060). We selected projections corresponding to SSP3 RCP 7.0 and used the "all models" multi-model ensemble average.

Since our simulation period spans 2020–2050, the AI rasters for the two periods were averaged to produce a single raster representing the 2021–2060 period (Raster Calculator, QGIS). The resulting raster was then reprojected and clipped to match our study area's resolution and coordinate reference system (Warp Reproject, QGIS).

The reprojected AI raster was reclassified into a binary format, assigning a value of 0 to pixels with AI ≤ 0.2 and a value of 1 to all other pixels. Region-specific .fil files were used as masks to generate four distinct .asc files for the regions of interest. This processing was performed in Python.

These region-specific files were then combined with small protected area exclusion files to create unified exclusion layers, which were incorporated into the allowance matrix. In practice, these exclusion files prevent land conversion in both major natural reserves and arid areas.

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A separate exclusion file was created (Exclusion File 25) to manage high-intensity crop areas. Pixels where 2020 high-intensity crops overlap with AI ≤ 0.2 were assigned a value of -105, indicating forced conversion, while all other areas were assigned a value of 1 (allowing crops to remain). To enforce immediate conversion, the same locations were assigned a value of 5 in the age.0 file.

Restriction file 24 and 25 in North SSP3

We implemented a restriction on the conversion of mosaic landscapes in the northern regions above a fixed altitude. This decision is based on ecological reasoning: the grass/forest mosaics in the North are not the result of management decisions but are climatically determined, as the environment is too cold to support continuous closed forest. In our classification, these mosaics are grouped together, but without this restriction, the model could erroneously convert them into closed forest. Since their composition is determined by climate and soil rather than demand, we fixed them in the system by preventing their conversion.

Restriction file 24 was designed to block only high-elevation mosaics, while restriction file 25 blocks both Natura 2000 protected areas and high-elevation mosaics. To create these files, the Digital Elevation Model (DEM), aggregated at 1 km resolution and used as the elevation factor for regression calculations, was overlapped with the 2020 base map (Sandstrom et al., 2023 v6) in QGIS. Only mosaic pixels were retained, and among these, pixels above 500 m a.s.l. were assigned a value of 0 to indicate they were blocked, while all other pixels were set to 1. This produced a binary map in which high-elevation mosaics are blocked and all other mosaics are allowed. After applying the NoData mask from the North region file, this binary map became restriction file 24. To produce restriction file 25, the binary map was multiplied with the existing sc1gr23 file, which represents protected areas, resulting in a combined mask that prevents conversions in both protected areas and high-elevation mosaics.

Demands

Table 48: Demands for East region, SSP3 scenario

Population (# people)	arable crops (tons)	permanent crops (tons)	livestock (LSU)	Wood production (m^3)
119212769.00	221962538.71	1670390.95	10369564.97	213039877.60
119212769.00	222202721.05	1678600.92	10448332.18	214315453.87
119212769.00	222443163.28	1686851.24	10527697.71	215598667.65
119212769.00	222683865.69	1695142.11	10607666.11	216889564.67
119212769.00	222924828.56	1703473.74	10688241.94	218188190.94
119212769.00	223166052.17	1711846.31	10769429.82	219494592.73
119212769.00	223407536.81	1720260.03	10851234.41	220808816.61
119212769.00	223649282.76	1728715.11	10933660.39	222130909.40
119212769.00	223891290.29	1737211.74	11016712.47	223460918.22

119212769.00	224133559.70	1745750.13	11100395.42	224798890.46
119212769.00	224376091.26	1754330.49	11184714.02	226144873.82
119212769.00	223773109.91	1762074.61	11231667.45	227154452.38
119212769.00	223171748.99	1769852.92	11278817.99	228168538.00
119212769.00	222572004.15	1777665.56	11326166.47	229187150.81
119212769.00	221973871.05	1785512.69	11373713.72	230210311.00
119212769.00	221377345.35	1793394.45	11421460.57	231238038.90

Table 49: Demands for North region, SSP3 scenario

Population (# people)	arable crops (tons)	permanent crops (tons)	livestock (LSU)	Wood production (m^3)
25563958.46	46649781.33	3252.15	2277446.81	207074325.41
25635541.22	46910383.14	3252.15	2281336.69	207003940.85
25707324.43	47172440.78	3252.15	2285233.21	206933580.21
25779308.64	47435962.35	3252.15	2289136.39	206863243.49
25851494.42	47700956.05	3252.15	2293046.24	206792930.67
25923882.33	47967430.10	3252.15	2296962.76	206722641.75
25970556.10	48235392.76	3252.15	2300885.97	206652376.73
26017313.90	48504852.35	3252.15	2304815.89	206582135.58
26064155.89	48775817.24	3252.15	2308752.51	206511918.32
26111082.21	49048295.83	3252.15	2312695.86	206441724.91
26158093.02	49322296.58	3252.15	2316645.95	206371555.37
26204355.02	49384337.27	3252.15	2324543.39	206387569.81
26250698.84	49446456.00	3252.15	2332467.76	206403585.48
26297124.62	49508652.87	3252.15	2340419.14	206419602.40
26343632.50	49570927.97	3252.15	2348397.63	206435620.56
26390222.64	49633281.41	3252.15	2356403.32	206451639.96

Table 50: Demands for South region, SSP3 scenario

Population (# people)	arable crops (tons)	permanent crops (tons)	livestock (LSU)	Wood production (m^3)
123697438.96	76917899.31	7684074.90	2082619.45	42551146.00
123697438.96	77466294.24	7708358.74	2084631.26	42578999.98
123697438.96	78018599.02	7732719.32	2086645.02	42606872.19
123697438.96	78574841.51	7757156.88	2088660.72	42634762.65
123697438.96	79135049.80	7781671.68	2090678.36	42662671.37
123697438.96	79699252.16	7806263.95	2092697.96	42690598.35
123697438.96	80267477.06	7830933.94	2094719.51	42718543.62
123697438.96	80839753.19	7855681.89	2096743.00	42746507.18
123697438.96	81416109.43	7880508.05	2098768.46	42774489.04
123697438.96	81996574.86	7905412.67	2100795.87	42802489.22
123697438.96	82581178.79	7930396.00	2102825.24	42830507.73
123697438.96	82971611.62	7958120.58	2104459.13	42846976.06
123697438.96	83363890.36	7985942.09	2106094.30	42863450.72
123697438.96	83758023.75	8013860.86	2107730.73	42879931.72
123697438.96	84154020.55	8041877.24	2109368.44	42896419.05
123697438.96	84551889.56	8069991.56	2111007.42	42912912.73

Table 51: Demands for West region, SSP3 scenario

Population (# people)	arable crops (tons)	permanent crops (tons)	livestock (LSU)	Wood production (m^3)
263686655.00	288671053.64	1694067.50	42495514.27	145410237.71
264093113.21	290485057.34	1687020.80	42579782.88	145613623.01
264500197.96	292310460.21	1680003.42	42664218.59	145817292.78
264907910.20	294147333.88	1673015.22	42748821.73	146021247.43
265316250.91	295995750.43	1666056.10	42833592.65	146225487.35
265725221.05	297855782.40	1659125.92	42918531.66	146430012.94
265878305.35	299727502.78	1652224.56	43003639.11	146634824.60
266031477.84	301610985.01	1645351.92	43088915.33	146839922.73
266184738.58	303506303.01	1638507.86	43174360.64	147045307.73

266338087.61	305413531.15	1631692.27	43259975.40	147250980.00
266491524.98	307332744.29	1624905.03	43345759.93	147456939.94
266682717.72	307013444.01	1617260.97	43608218.51	147617668.01
266874047.64	306694475.46	1609652.87	43872266.27	147778571.27
267065514.82	306375838.30	1602080.56	44137912.85	147939649.91
267257119.37	306057532.19	1594543.88	44405167.91	148100904.13
267448861.39	305739556.77	1587042.65	44674041.20	148262334.11

Lusconv

The lusconv values are derived from the ratios in the lusmatrix (Table 52). The highest value in the lusmatrix is assigned a value of 3, and the ratios of the remaining contributing land systems are calculated relative to this maximum and then rounded. Land systems that do not contribute to meeting the demand in the lusmatrix are assigned a value of -1. Notably, in the columns corresponding to arable crops and livestock, the highest value is set to 4, as mosaics are also considered contributors to satisfying land demand.

In SSP3, unlike SSP2, medium- and high-density urban settlements are assigned the same priority value of 2. This decision is based on the assumption that urban planning in a SSP3 future will be weak and disorganized (O'Neill et al., 2017), leading to less compact cities and increased urban sprawl. With this configuration of lusconv, the model interprets medium- and high-density urban settlements as equally suitable for meeting population-driven land demand, which results in a wider spread of medium-density urban areas.

Table 52: Lusconv table SSP3 scenario, all regions

Population (# people)	arable crops (tons)	permanent crops (tons)	livestock (LSU)	Wood production (m3)
1	-1	-1	-1	-1
2	-1	-1	-1	-1
2	-1	-1	-1	-1
-1	-1	-1	-1	-1
0	1	0	0	-1
0	0	0	1	-1
0	2	0	0	-1
0	3	0	0	-1
0	4	0	0	-1
0	0	0	2	-1
0	0	0	3	-1

0	0	0	4	-1
0	0	1	0	-1
0	0	0	0	1
0	0	0	0	2
0	0	0	0	3

Main file

Table 53: Conversion elasticities for SSP3, all regions

0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
0.5	0.6	1	0.8	0.3	0.3	0.3	0.4	0.5	0.4	0.5	0.6	0.6	0.6	0.4	0.5

Elasticities / conversion resistance (Table 53)

Urban areas are treated as dynamic to facilitate land conversion. The exception is high-density urban areas, which are relatively static and assigned a value of 1. The elasticities of the urban classes are the same as in SSP2.

Wetlands are generally less dynamic. In the baseline model, wetlands can convert into a limited set of other land systems, but there is no active demand driving these conversions. In SSP3, wetlands are slightly more dynamic than in SSP2, reflecting the scenario narrative of low priority for nature and ongoing environmental degradation.

Both types of mosaics are considered dynamic because they represent mixtures of land systems. A conversion resistance value of 0.3 is assigned to both the forest–shrub–grassland mosaic and the forest–shrub–cropland mosaic. These mosaics are easier to convert compared to SSP2, though they retain some ecological value. The lower protection aligns with SSP3's assumption of minimal environmental prioritization.

Cropland, grassland, and forest follow similar patterns in terms of conversion dynamics. Low-intensity land uses are easiest to convert due to lower investments, followed by medium-intensity, and then high-intensity land uses. This results in a conversion resistance of 0.3 for low-intensity arable cropland, 0.4 for both low-intensity grassland and medium-intensity cropland, 0.5 for high-intensity cropland, and 0.6 for high-intensity grassland. Compared to SSP2, close-to-nature forests are made easier to convert to align with SSP3's narrative of low priority for nature and ongoing environmental degradation.

Permanent cropland is relatively static because establishing such land requires significant investment, resulting in a higher conversion resistance of 0.6.

Age0 file

This file defines the age of land use systems at the initial year of the simulation. Due to data limitations, a random age between 0 and 10 years is assigned to each pixel for most land use classes. Forests are treated differently: the age of each forest pixel is determined using a reference map that provides information on the age of individual trees within each pixel (Besnard et al., 2025).

Lusmatrix

The lusmatrix provides the average productivity of each land system per demand. Summaries of the procedure used to obtain these values are presented here, while a complete description is provided in Section 1.2.1.6. Note that the same provisions calculated for SSP2 are applied to SSP3.

Population demand is primarily driven by urban land systems, though other land systems also contribute to housing. To account for this, all land systems were overlaid with the population grid from Batista e Silva et al. (2021). This overlay was combined with the baseline map produced by Sandstrom et al. (2024).

Arable crop production is driven by arable cropland land systems and the forest–shrub–cropland mosaic. Other land systems do not produce arable crops and are assigned a value of 0. Data for estimating arable crop productivity come from GlobalWheatYield4km (Luo et al., 2022) and nitrogen input data used in Sandstrom et al. (2024).

For the mosaics, the share of arable cropland within the mosaic is multiplied by low-intensity cropland productivity, reflecting the relatively low nitrogen inputs in mosaic cropland. Validation was performed by overlaying GlobalWheatYield4km with the mosaics. Wheat was chosen as a representative indicator of arable crop productivity, as it is widely produced across Europe and represents the highest cereal production. For modelling purposes, mosaic productivity is thus calculated as the crop cover percentage multiplied by the low-intensity agriculture production.

Permanent crop production is solely driven by the permanent crop land system, with all other land systems assigned a value of 0. Because permanent crops have no intensity classes, the starting value of permanent crop production from CAPRI is divided by the total area of permanent crops.

Livestock production is driven by grassland systems and the forest–shrub–grassland mosaic. All other land systems have a value of 0. Grassland classes were overlaid with data from Žiga Malek et al. (2024). Due to the scarcity of grasslands in Northern Europe, livestock densities from Western Europe were used as a reference. Cattle, sheep, and goat densities were used as indicators of grassland productivity, with sheep and goat numbers converted to Livestock Units (LSU).

For **mosaics containing grasslands**, the same procedure as for arable cropland mosaics was applied. The difference is that nitrogen input was not used; instead, the Malek et al. (2024) data layer was used to assess the share of reference livestock counts within the mosaic.

Wood production is driven by forest classes and both forest-containing mosaics, with all other classes assigned a value of 0. Wood production ratios were derived from National Forest Inventory (NFI) data for ten countries: Norway, Sweden, Germany, Austria, Poland, Slovenia, Spain, Belgium, Czechia, and Ireland. For the mosaics, the procedure applied to arable crops and grasslands was repeated, using FAOSTAT production data.

Mosaic productivity was calculated by multiplying the production values of low-intensity forest classes by the proportion of forest within the mosaics.

Neighbourhood settings

For the neighbourhood settings, we aimed to simulate a low-sustainability scenario consistent with SSP3. To achieve this, we increased the aggregation of high-density urban areas, high-intensity agriculture, and high-intensity forestry, reflecting SSP3's assumptions. Additional adjustments were also made to better align the model with SSP3 narratives (Table 54).

Table 54: Current Neighmat.txt file

0	**0.2**	**0.5**	**0**	**0**	**0**	**0**	**0**	**0.5**	**0**	**0**	**0**	**0**	**0**	**0**	**0.5**	
16	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
1																
1	1	1														
1	1	1														
1	1	1														
16	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
1																
1	1	1														
1	1	1														
1	1	1														
16	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
1																
1	1	1														
1	1	1														
1	1	1														
16	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
1																
1	1	1														
1	1	1														
1	1	1														

For SSP3, we increased the neighbourhood effect for high-density urban areas, arable crops, and plantations to maintain greater spatial clustering of these land use classes. A neighbourhood effect was also applied to medium-density urban areas to guide the spread of medium-density urbanization promoted in the *lusconv*. In the alloc2.reg file, arable crops were defined to cluster not only with themselves but also with high-intensity grasslands. All other land use classes subject to neighbourhood effects were set to cluster exclusively with their own class.

Location specific rules

As previously said, in CLUMondo, it is possible to set spatially explicit preferences for specific land use classes, giving them a competitive advantage during the allocation process. For

SSP3, as in SSP2, we applied *locspec* files to urban classes to balance intensification with urban sprawl. Since SSP3 emphasizes urban sprawl, the weights applied are lower than in SSP2. The *locspec* for urban classes assigns a baseline value of 1 across the entire region, with the following regional adjustments for low-, medium-, and high-density urban areas:

- North: -0.2 / 0 / 0.2
- West: -0.4 / 0 / 0.4
- East: -0.4 / 0 / 0.4
- South: -0.1 / 0 / 0.1

For SSP3, farming systems are stimulated, while subsidies for sustainable, less-intensive agriculture decrease, leading to rapid agricultural expansion (O'Neill et al., 2017). However, yield productivity is expected to decline due to challenging climatic conditions (O'Neill et al., 2017). As a result, agricultural intensification — defined as the ability of crops to produce more — is localized to areas where climatic conditions still allow higher yields. This spatial heterogeneity is accounted for by applying *locspec* files to projected drought conditions, specifically targeting high-intensity agriculture.

The overall tendency toward high-intensity systems, where feasible, is implemented by adding a uniform positive adjustment to increase the preference for high-intensity agriculture across all areas in the previously created drought-focused *locspec* files. Additionally, a *locspec* for decreasing the preference for low-intensity agriculture is applied. Consequently, the complete locspec file for high-intensity agriculture reduces preference in pixels experiencing medium-to-high drought and increases it elsewhere, whereas the *locspec* for low-intensity agriculture reduces preference generally, with no additional changes in medium-to-high drought areas.

Final list of *locspec* files:

- The *locspec6.fil* file corresponds to low-intensity agriculture and assigns a value of -0.3 across the entire region, except in pixels experiencing medium to very high aridity, which are assigned a value of 0 (with a weight of 1 in the main file).
- The *locspec8.fil* file corresponds to high-intensity agriculture and assigns a value of 0.3 across the region, except in pixels under drought stress. Pixels with an aridity index (AI) below 0.2 are assigned a value of 0, while pixels with AI between 0.21 and 0.5 receive a negative value ranging from -0.2 to -0.5, depending on the AI. In this scaling, higher AI indicates less arid conditions, which corresponds to a higher suitability for high-intensity agriculture. The weight in the main file for high-intensity agriculture is 1.

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