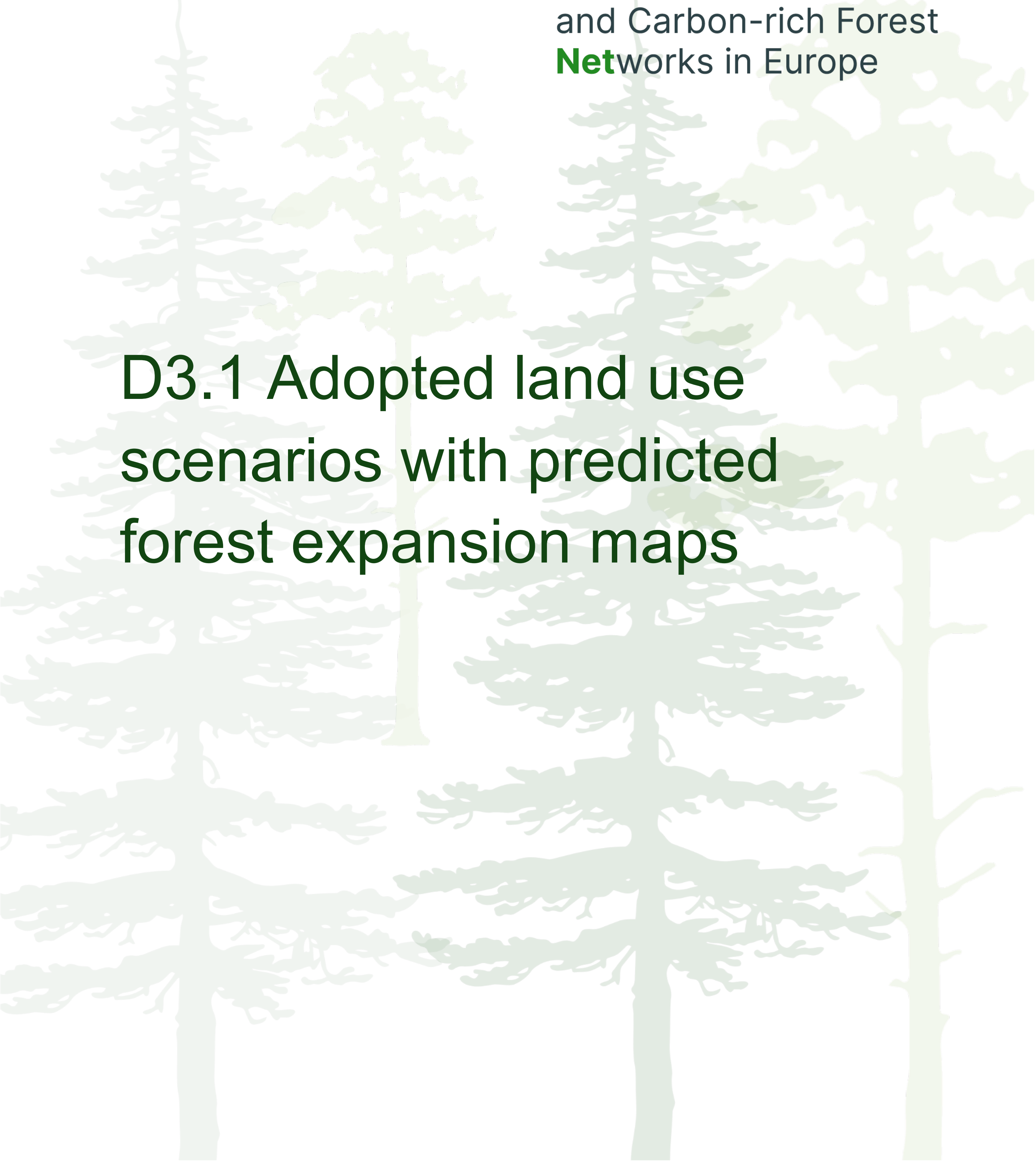
SafeNet

Safeguarding Biodiversity
and Carbon-rich Forest
Networks in Europe



D3.1 Adopted land use scenarios with predicted forest expansion maps

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Funded by the European Union under the Horizon Europe Programme, Grant Agreement No. 101181981 (SafeNet). Views and opinions expressed are, however, those of the author(s) only and do not necessarily reflect those of the European Union or European Research Executive Agency (REA). Neither the European Union nor the granting authority can be held responsible for them.

Document information

Grant agreement	**101181981**
Project Acronym	SafeNet
Project Title	Safeguarding Biodiversity and Carbon-rich Forest Networks in Europe
Deliverable number	D3.1
Work Package Number	WP3
Deliverable Title	Adopted land use scenarios with predicted forest expansion maps
Lead Partner	International Institute for Applied Systems Analysis (IIASA)
Author(s)	Mahdi (André) Nakhavali, Fulvio Di Fulvio, IIASA William Kunin, University of Leeds
Due Date	31.01.2026
Submission Date	31.01.2026
Dissemination Level	PU[1]
Type of Deliverable	R[2]

Version	Date	Institution	Reviewer	Summary of Changes
1.0	16/01/2026	Vrije Universiteit Amsterdam	Sebastiaan Luyssaert	Clarified ORCHIDEE-specific compatibility assumptions and refined wording to avoid overstatement, with minor edits to improve precision and consistency.
2.0	20/01/2026	Natural Resources Institute Finland	Anna Repo	Tightened clarity and terminology, improving flow, and expanding the stakeholder workshop description and referencing.
3.0	23/01/2026	Natural Resources Institute Finland	Mikko Peltoniemi	Clarified and refined for consistency, including reference adjustments and brief additions on scenario forcing and model compatibility.

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[1] Dissemination level: PU: Public
[2] Type of deliverable: R: Document, Report

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Acronyms and Abbreviations

AWC	Available Water Capacity
CF	Climate and Forecast (metadata conventions)
CHELSA	Climatologies at High resolution for the Earth's Land Surface Areas
CMIP6	Coupled Model Intercomparison Project Phase 6
CORDEX	Coordinated Regional Climate Downscaling Experiment
DGVM	Dynamic Global Vegetation Model
ESA-CCI	European Space Agency Climate Change Initiative
ESGF	Earth System Grid Federation
EURO-CORDEX	European branch of CORDEX
EUR-11 EURO-CORDEX	European domain at ~0.11° resolution
EU27+UK	European Union (27 Member States) plus the United Kingdom
G4M	Global Forest Model
GCM	Global Climate Model
GHG	Greenhouse gas
GLOBIOM	Global Biosphere Management Model
HWSD2	Harmonized World Soil Database v2.0
IAM	Integrated Assessment Model
ICP Forests	International Co-operative Programme on Assessment and Monitoring of Air Pollution Effects on Forests
ISRIC	International Soil Reference and Information Centre
LUH2	Land-Use Harmonization v2
LUCAS-LUC	LUCAS Land Use and land Cover change (Europe)
NetCDF	Network Common Data Form
ORCHIDEE	Organising Carbon and Hydrology in Dynamic Ecosystems
PFT	Plant Functional Type
ppm	parts per million
PR	Precipitation
QC	Quality control
RCM	Regional Climate Model
RCP	Representative Concentration Pathway
SOC	Soil Organic Carbon
SSP	Shared Socioeconomic Pathway
TAS	Near-surface air temperature
WP	Work Package

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1. Introduction

Future conservation and management strategies for Europe's carbon and biodiversity-rich forests must be evaluated under co-evolving boundary conditions, notably (i) climate forcing that modifies constraints on productivity, water balance, and disturbance regimes(Reichstein et al., 2013; Seidl et al., 2017), and (ii) socioeconomic land-use dynamics that determine forest extent, age structure, management intensity, and competition with agriculture and urban development (Hurtt et al., 2020; Riahi et al., 2017). Land-use decisions alter surface biophysics and carbon stocks (Bonan, 2008; Lawrence & Vandecar, 2015). Climate-driven changes in growth, mortality, and disturbance can in turn reshape management, harvesting patterns, and protection priorities (Patacca et al., 2023; Wessely et al., 2024). Robust scenario analysis therefore requires a modelling framework in which human-system trajectories (land use and management) and biophysical trajectories (climate and soils) are represented consistently, at appropriate spatiotemporal resolution, and with traceable provenance.

A widely adopted framework for exploring plausible socioeconomic futures is the set of Shared Socioeconomic Pathways (SSPs), which describe alternative global development narratives (demography, economic growth, inequality, technological change, and institutional capacity), and the associated challenges to mitigation and adaptation (O'Neill et al., 2014). In parallel, climate forcing is commonly expressed through pathways of atmospheric composition and associated end of century radiative forcing. Historically, these have been communicated as Representative Concentration Pathways (RCPs), while Coupled Model Intercomparison Project Phase 6 (CMIP6) applications frequently use SSP-consistent forcing pathways (van Vuuren et al., 2011). In practical impact and ecosystem-modelling workflows, SSP-based land-use trajectories and climate forcing pathways are operationalised through spatially explicit datasets: (i) gridded land-use states and transitions produced by integrated assessment models (IAMs) and harmonisation protocols (Hurtt et al., 2020); and (ii) climate projections derived from global climate model (GCM) / regional climate model (RCM) ensembles or statistically downscaled products (Jacob et al., 2020).

For land use, the CMIP6 community standard is the Land-Use Harmonization dataset (LUH2), which provides annual global land-use states and transitions (1850–2100) at 0.25° resolution and is internally consistent with the SSP narratives and scenario-specific integrated assessment model outputs (Hurtt et al., 2020). LUH2 was developed primarily to harmonise historical land-use reconstructions with integrated assessment model (IAM) projections into a continuous, internally consistent forcing for Earth System Models (ESMs) within CMIP6. Moreover, LUH2 is widely used because it provides a traceable, scenario-consistent representation of land-use change, including transitions among cropland, pasture, primary and secondary vegetation, and other classes. However, many European regional applications require (i) higher spatial resolution, (ii) land-cover/ plant functional type (PFT) representations compatible with land-surface schemes, and (iii) explicit representation of land-cover classes that are regionally important (e.g., forest type and management fractions, urban land, heterogeneous mosaics).

To address these European regional modelling requirements, Hoffmann et al. developed the LUCAS Land Use and Land Cover Change (LUCAS-LUC) dataset for Europe (Hoffmann et al., 2023). It provides annual gridded land-cover and land-use information for 1950–2100 at 0.1° resolution and was constructed by translating LUH2 transitions onto a European baseline derived from ESA-CCI land cover using a dedicated land-use translator.

The resulting product is explicitly designed to support regional climate modelling and land-surface modelling by supplying harmonised, scenario-consistent trajectories in a form closer to land-surface model requirements than global LUH2 alone. Consistent with this approach, the plant functional type (PFT) structure underlying the European land-cover representation leverages the LANDMATE PFT workflow, which converts ESA-CCI land-cover classes into PFT fractions using climate-informed cross-walking guided by the Holdridge life-zone concept and provides evaluation against ground-truth datasets (Reinhart et al., 2022).

For climate forcing, European impact assessments increasingly rely on the European branch of the Coordinated Regional Climate Downscaling Experiment (EURO-CORDEX) dynamical downscaling ensembles, including the EUR-11 (~0.11°, ~12.5 km) domain widely used in climate-services production and sectoral impact studies (Jacob et al., 2014). EURO-CORDEX provides multi-model projections (RCM–GCM chains) primarily under Representative Concentration Pathway (RCP) scenarios (notably RCP2.6, RCP4.5, RCP6.0, and RCP8.5), enabling explicit exploration of uncertainty linked to driving GCMs, RCM formulations, and internal variability. Evaluation studies document systematic, spatially and seasonally varying biases in temperature and precipitation across Europe and provide an empirical basis for ensemble interpretation and, where appropriate, bias-adjustment strategies (Kotlarski et al., 2014; Vautard et al., 2021). For historical baseline characterisation and high-resolution climatological constraints, CHELSA (Climatologies at High resolution for the Earth’s Land Surface Areas) provides daily kilometre-scale temperature and precipitation estimates derived from reanalysis downscaling that explicitly accounts for orographic and wind-related precipitation effects (Karger et al., 2017).

Finally, translating land-use and climate forcing into terrestrial ecosystem responses requires a coherent representation of soil properties, which modulate hydrology, plant water stress, nutrient constraints, and carbon cycling. Soil boundary conditions are commonly characterised using complementary sources, including (i) SoilGrids-type gridded products that provide spatially continuous predictions of key soil attributes with quantified uncertainty (Poggio et al., 2021), and (ii) inventory-based products such as the Harmonized World Soil Database v2.0 (HWSD2), developed for modelling applications at kilometre-scale resolution (Nachtergaele et al., 2023).

2. Objectives

This deliverable operationalises WP3 – Task 3.1 (Adapting and adopting future European forest expansion scenarios) by adopting and documenting the scenario boundary conditions and workflows required to produce contrasting future forest distribution/expansion templates to 2100, selected in consultation with stakeholders and provided in a model-ready form for downstream tasks and models (notably ORCHIDEE and G4M-X/GLOBIOM). Specifically, it aims to:

1. **Define the scenario framing:** Set out the scenario logic linking SSPs to land-use trajectories and climate forcing pathways and specify the scenario combinations adopted for project analyses.
2. **Specify land-use and land-cover change inputs relevant to forest dynamics:** Document the adopted land-use/land-cover datasets and their intended role in representing annual historical and future area trajectories over Europe (e.g., forest, cropland, grassland, urban), including the relationship between global harmonised land-use products and higher-resolution regional datasets. This deliverable does not cover land-management practices such as fertilisation, irrigation, or mowing/grazing.
3. **Define the plant functional type representation associated with land cover:** Describe the adopted PFT class structure and its relationship to land-cover information, enabling consistent interpretation of changes in vegetation composition alongside changes in forest extent.
4. **Characterise climate forcing datasets for baseline and future periods:** Document the climate forcing sources used to represent the historical baseline and scenario-based projections over Europe and justify the use of downscaled regional ensembles alongside high-resolution baseline datasets for impact and ecosystem modelling.
5. **Characterise soil boundary conditions relevant for hydrology and carbon cycling:** Document the soil data sources used to represent key soil properties controlling water availability, plant stress, and carbon dynamics, supporting consistent interpretation of spatial heterogeneity in ecosystem responses.
6. **Provide scenario-based diagnostics and illustrative outputs supporting interpretation:** Deliver scenario-relevant maps and summary indicators that highlight differences in forest relevant land-use fractions, PFT distributions, climate signals, and soil constraints across the selected scenarios.
7. **Ensure interoperability of inputs across the SafeNet modelling suite:** Define a harmonised workflow including consistent conventions, formats, and metadata to support downstream use across ORCHIDEE and the G4M-X-GLOBIOM modelling chain and to ensure that scenario differences can be attributed to defined land-use and climate drivers rather than inconsistencies in inputs. It is acknowledged that achieving full interoperability also requires addressing conceptual differences

between the models and will be carefully managed in the downstream integration phase.

Collectively, these objectives establish a consistent scenario workflow for SafeNet simulations across ORCHIDEE (a Dynamic Global Vegetation Model (DGVM), i.e., a process-based vegetation model that simulates vegetation dynamics and carbon–water fluxes as a function of climate, CO_2 and land cover/PFT forcing), G4M-X (age-class dynamic forest sector optimization model), and GLOBIOM (global land use optimization model), enabling attribution of scenario differences to define drivers rather than input inconsistencies.

3. Methods

3.1. Selection of land use and climate scenarios

We considered the set of SSP-RCP scenario combinations supported by the LUH2 land-use harmonisation framework and by the available climate-scenario archives and selected three representative pathways for detailed simulation and analysis (Hurtt et al., 2020; O'Neill et al., 2014). The selection was designed to balance (i) the need to bracket a wide range of plausible end of century conditions relevant for European forests with (ii) the practical requirements of running an integrated multi-model workflow with sufficient replication and consistent inputs. This required prioritising a small number of scenarios that are maximally informative (in terms of forcing and land-use divergence) and operationally feasible (in terms of repeated runs and data completeness).

Three constraints shaped the final choice. First, we explicitly aimed to span a wide forcing gradient by 2100, from a strongly mitigated pathway with limited radiative forcing to a high-emissions pathway with very large forcing, because many forest responses (growth limitation, drought stress, mortality, and disturbance exposure) are nonlinear and can differ qualitatively between low and high-warming futures (Pilli et al., 2022; Vangi et al., 2024) (Figure 1). Second, the number of scenario combinations that can be simulated is constrained by the need for repeated model experiments across the workflow (e.g., baseline establishment, stabilisation/spin-up, sensitivity checks, and iterative runs across the workflow), which prioritises a small number of informative pathways over a broad but shallow scenario matrix (Pilli et al., 2022). Third, scenario choice is constrained by the availability and completeness of spatially explicit, high-frequency climate forcing data across scenarios and GCM-RCM model chains. In practice, downscaled products do not provide uniform coverage across all forcing pathways and model realisations, and variable availability, temporal coverage, and consistency of required fields can differ across GCM–RCM chains, which would otherwise undermine comparability of model experiments (Thrasher et al., 2024).

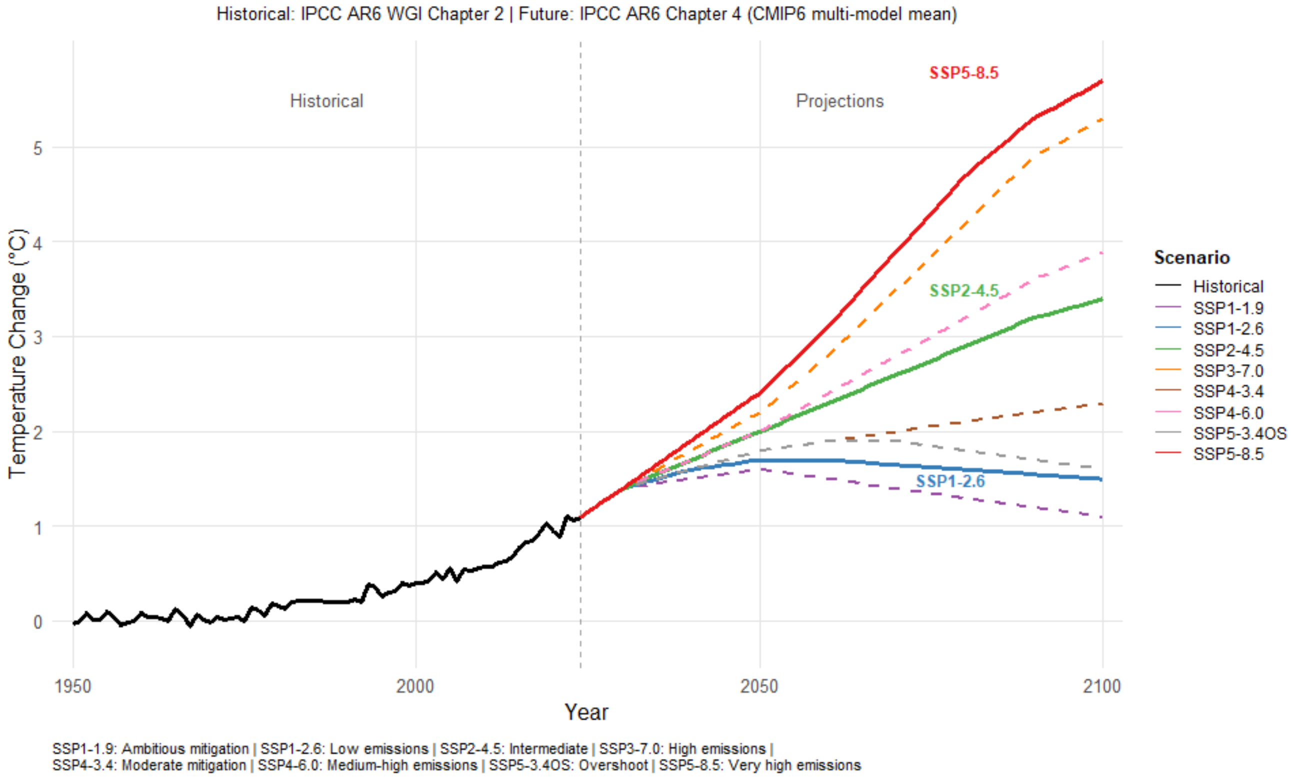
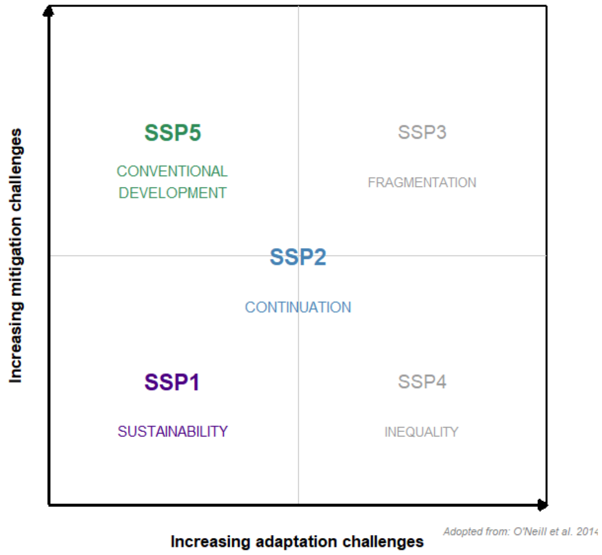


Figure 1. Historical and CMIP6 multi-model Global Mean Surface Temperature Change

Within these constraints, we adopted a three-scenario design that is widely used as an illustrative bracket in impact and ecosystem-modelling applications. The scenarios combine SSP narratives (which structure land-use pathways through integrated assessment modelling and LUH2 harmonisation) with radiative forcing pathways expressed in the RCP framework (Hurtt et al., 2020; van Vuuren et al., 2011). We recognise that SSP and RCP elements are not intrinsically one-to-one and that land-use outcomes can vary across integrated assessment models even within the same SSP group, but pairing SSP narratives with low/intermediate/high forcing levels provides an operational and interpretable design for constructing internally consistent land-use and climate boundary conditions under tractable computational budgets (Hurtt et al., 2020; O’Neill et al., 2014). In this study, pairings are used to represent comparable forcing levels for interpretability across low-, medium-, and high-end futures. SSP3 (Regional Rivalry) was considered, but was not selected for the core three-scenario set because the objective here is a compact low–mid–high bracket that maximises forcing contrast and (critically) maintains climate-forcing data completeness across the required EURO-CORDEX GCM–RCM chains; SSP3 remains available in the processed LUCAS-LUC archive for optional extended sensitivity/diagnostic analyses. The selected scenarios (Figure 2) are:

- **SSP1-RCP2.6 (Sustainability)**: a pathway with relatively low challenges to mitigation and adaptation, characterised by shifts toward sustainable development, relatively low population growth, improved resource efficiency, and accelerated deployment of low-carbon technologies (O'Neill et al., 2014). It is paired with a low radiative forcing outcome (~2.6 W/m² by 2100), representing a future with limited climate forcing and comparatively lower climate-driven stress. In land-use terms, this narrative is commonly associated with strengthened environmental governance and a stronger emphasis on conservation and restoration, implying comparatively favourable conditions for maintaining or expanding forest area in many regions(Hurtt et al., 2020). From a biophysical perspective, the lower-warming pathway is also consistent with reduced poleward shifts of forest suitability (i.e., less expansion into (sub-)Arctic zones) and comparatively greater potential for forest retention at climate-sensitive southern margins (e.g., the Mediterranean) than under higher-warming pathways.

- **SSP2-RCP4.5 (Middle of the Road / Continuation)**: a pathway in which broad historical trends in socioeconomic development persist without major discontinuities in institutions, technology, or policy ambition. It is paired with an intermediate forcing trajectory (~4.5 W/m² by 2100), providing a mid-range climate outcome and a useful reference point for attribution. As a central pathway, SSP2-RCP4.5 supports interpretation of results against a median future in which both land-use pressures and climate impacts are material but not extreme, strengthening comparative interpretation across the low- and high-forcing cases (Riahi et al., 2017).
- **SSP5-RCP8.5 (Fossil-fuelled / Conventional Development)**: a pathway with high economic growth and rapid technological development alongside sustained reliance on fossil fuels and energy-intensive lifestyles, paired with a high forcing outcome (~8.5 W/m² by 2100) consistent with severe climate change. Under this storyline, land-use pressures can be amplified by high demand for food, materials, and energy (including potential bioenergy expansion), increasing competition for land and raising the likelihood of adverse outcomes for natural ecosystems under high warming and heightened disturbance exposure (Riahi et al., 2017).



Adopted from: O'Neill et al. 2014

Figure 2. SSP framework Visualisation

Together, these scenarios provide a structured lower–middle–upper bracket of plausible futures in terms of both climate forcing and land-use pressure, while remaining feasible within SafeNet's computational and data constraints. Restricting the design to three pathways enables deeper replication within the modelling workflow and tighter control over input harmonisation, which is essential for attributing differences in model outcomes to scenario drivers rather than to avoidable differences in forcing availability or processing choices. Differences in simulated forest outcomes can therefore be linked to well-defined contrasts in forcing intensity and socioeconomic land-use narratives while maintaining a consistent and repeatable experimental design across the integrated modelling workflow. Each scenario's narrative assumptions and end of century forcing level guide downstream selection and harmonisation of land-use and climate inputs, maintaining internal consistency in the boundary conditions used throughout the SafeNet modelling exercise.

3.2. Data preparation

All boundary condition datasets (climate, land use, plant functional types, and soils) were prepared through a harmonised routine to ensure consistency in spatial reference, temporal coverage, variable definitions, and downstream interoperability across the SafeNet modelling suite.

3.2.1. Climate data

Climate forcing data for the historical period and future scenarios were derived from a combination of observationally constrained high-resolution products and regional climate model projections, with future forcing centred on outputs from the EURO-CORDEX initiative. The two sources serve complementary purposes: CHELSA provides kilometre-scale baseline climatological constraints that better resolve topographic gradients and sharp spatial heterogeneity, whereas EURO-CORDEX provides dynamically consistent scenario projections at coarser resolution (~0.11°, ~12.5 km) required to represent end of century forcing contrasts under alternative emissions pathways. The full set of climate variables prepared from each source is summarised in Table 1:

- **Historical climate (baseline):**
  As a baseline for present climate, we used the CHELSA dataset, which provides gridded climate information at ~1 km resolution for the late 20th century (1979–2017) (Karger et al., 2017). CHELSA integrates station information with downscaled reanalysis to capture fine-scale temperature and precipitation patterns across complex terrain, including orographic precipitation enhancement and elevation-driven temperature gradients. In SafeNet, CHELSA is used to represent high-resolution historical climatological constraints over Europe and to support baseline diagnostics and spatial pattern fidelity in regions where topography strongly structures climate.

- **EURO-CORDEX regional climate simulations and scenario projections:**
  EURO-CORDEX provides regional climate model simulations for Europe that span both a historical segment and scenario extensions (Jacob et al., 2014; Vautard et al., 2021). In SafeNet, EURO-CORDEX data were processed from 1950 onward to

ensure a continuous, internally consistent forcing archive covering historical conditions and scenario projections. Scenario data were extracted for RCP2.6, RCP4.5, and RCP8.5 from the EURO-CORDEX domain (0.11° ~12.5 km grid). These simulations are produced by RCMs driven by GCMs under the respective forcing pathways and provide spatially explicit time series suitable for impact and ecosystem modelling. Consistent with the scenario framework adopted in previous section, RCP2.6/4.5/8.5 projections are used to represent low, intermediate, and high-end forcing levels, respectively, supporting attribution across the scenario set. The meteorological forcing fields compiled from EURO-CORDEX are provided in Table 1.

- **Atmospheric CO_2 concentrations:**
  Alongside meteorological variables, atmospheric CO_2 concentrations were prescribed using CMIP6-recommended SSP greenhouse gas concentration pathways (Meinshausen et al., 2020). These pathways provide annually resolved, globally averaged CO_2 concentrations (ppm) for historical and future periods that are consistent with the SSP scenario framework. As context, atmospheric CO_2 was ~285 ppm in the mid-19th century and reached ~413 ppm by 2020. Under SSP1-2.6, CO_2 typically peaks around mid-century and declines slightly thereafter, reaching ~446 ppm by 2100; under SSP2-4.5, CO_2 increases through the century to ~603 ppm by 2100; and under SSP5-8.5, CO_2 rises strongly to ~1135 ppm by 2100 (Meinshausen et al., 2020). These trajectories were supplied as an external CO_2 forcing using annual global-mean values, applied uniformly over the modelling domain and interpolated to the model time step where required by the forcing interface. Interannual (and higher-frequency) variability in temperature and precipitation is represented explicitly through the time-resolved EURO-CORDEX meteorological forcing, not through the CO_2 series.

- **Data processing and quality control:**
  Climate data preparation followed a standardised routine to ensure consistent organisation, spatial coverage, metadata, and direct usability for model integration. Processing consisted of: (i) sourcing raw CHELSA and EURO-CORDEX data from the relevant repositories and verifying file integrity (e.g., checksum validation where available); (ii) sorting and organising variables into a consistent directory structure by scenario, model chain, variable, and period; (iii) standardising units and variable conventions where required (including verification against expected physical units and CF conventions); (iv) extracting all fields to the SafeNet European domain using a common EU mask; and (v) compiling outputs into variable-specific NetCDF files with an explicit time dimension, delivered as CF-compliant NetCDF with consistent spatial referencing and time-axis definitions (including calendar handling). Quality control was implemented through structured checks on completeness (expected variables and time steps), time-coordinate integrity (monotonicity, missing steps, calendar consistency), missing-value patterns, and plausibility screening of value ranges, supplemented by test reads to confirm that compiled NetCDF outputs are ingested correctly by downstream tooling. For efficient reuse across work packages and repeated model runs, the processed archives were organised as a consolidated,

model-ready IIASA-ACCELERATOR project repository (archived footprint on the order of ~650 GB for EURO-CORDEX and ~250 GB for CHELSA).

Table 1. Climate Forcing Datasets and Variables prepared for SafeNet

Data source	**Citation**	**Native spatial resolution**	**Temporal coverage and resolution**	**Scenarios / forcing**	**Variables prepared**	**Intended use in SafeNet**	**Delivered format**
CHELSA	Karger et al., 2017	~1 km	1979–2017 (baseline climatological period)- Daily	Historical (reanalysis-based downscaling)	pr, rad, tas, tasmax, tasmin	High-resolution baseline climatological constraints; spatial gradients and baseline diagnostics	CF-compliant NetCDF (per variable, EU-domain extracted)
EURO-CORDEX (EUR-11)	Jacob et al., 2014; Vautard et al., 2021	~0.11° (~12.5 km)	1950–2100- **Daily**	Historical, RCP2.6, RCP4.5, RCP8.5	hurs, huss, pr, ps, rlds, rsds, sfcwind, tas, tasmax, tasmin, uas, vas, wsgsmax	Continuous historical + scenario meteorological forcing for land-surface/DGVM simulations and scenario attribution	CF-compliant NetCDF (time-stacked per variable, EU-domain extracted) GCM–RCM chains used: MPI-M-MPI-ESM-LR → MPI-CSC-REMO2009; ICHEC-EC-EARTH → DMI-HIRHAM5 (r1i1p1). Data sourced via ESGF (EUR-11 domain).
SSP CO_2 concentration pathways	Meinshausen et al., 2020	N/A (global mean)	Historical + future Annual	SSP-consistent trajectories aligned to scenario set	CO_2 (ppm; annual series)	External forcing for modelling: CO_2 fertilisation and carbon-cycle responses	Annual tabular/NetCDF time series; applied uniformly over domain

3.2.2. Land use data

For land-use and land-cover boundary conditions, we adopted the LUCAS-LUC dataset (Land Use and Land Cover change) developed by Hoffmann et al. (2023) for the European modelling domain. LUCAS-LUC provides annual land-cover/land-use information from 1950 to 2100 at 0.1° (~10 km) resolution and was explicitly designed to support regional climate, land-surface, and ecosystem modelling by providing SSP-consistent land dynamics at spatial and temporal granularity suitable for impact assessment and vegetation/forest applications. In SafeNet, LUCAS-LUC is treated as the native land-use/land-cover boundary-condition archive at 0.1°, and an additional model-ready land-use product at 0.5° resolution is provided in parallel. The 0.5° product is used as the common “integration grid” across the modelling chain, as it is the target resolution for ORCHIDEE and is also optimal for interoperability with G4M-X and GLOBIOM workflows. This dual-resolution strategy preserves the full spatial detail of the original product for high-resolution analyses and diagnostics, while ensuring direct usability and cross-model consistency in the integrated modelling workflow simulations.

Methodologically, LUCAS-LUC is constructed by combining: (i) coarse-resolution, SSP-based land-use states and transitions from LUH2 (Hurtt et al., 2020), produced via integrated assessment modelling and land-use harmonisation; (ii) a higher-resolution baseline land-cover map for Europe derived from satellite land-cover products (notably ESA-CCI land cover); and (iii) a dedicated land-use translator that applies LUH2 transition information onto the European baseline while preserving fine-scale spatial structure (Hoffmann et al., 2023). This approach yields a continuous annual time series of land-use/land-cover maps that typically provides greater spatial realism than LUH2 alone, while maintaining a direct link to SSP-consistent global land-use change signals embedded in the LUH2 harmonised transitions.

Key features of the land-use forcing used in SafeNet are as follows:

- **Land-cover classes and modelling-oriented representation:**
  LUCAS-LUC provides a land-cover classification designed for Earth system and land-surface modelling contexts. Relative to global harmonised products, the European translation supports improved interpretability of land-cover composition changes, including distinctions among forest-related land-cover components and other major classes (e.g., cropland, grassland, urban, bare), which is important for representing spatially heterogeneous land-surface conditions and for diagnosing land-cover-driven biophysical feedbacks in coupled model experiments (Hoffmann et al., 2023; Hurtt et al., 2020).
- **Historical baseline (1950–2015):**
  For the historical period, LUCAS-LUC provides annually resolved land-cover trajectories anchored to a European baseline map and constructed by translating LUH2 historical reconstructions onto that baseline. This yields a continuous historical time series intended to provide coherent continuity into scenario projections and to capture multi-decadal European land-use/land-cover developments within a consistent modelling framework.
- **Scenario projections (2016–2100):**
  From 2016 onward, LUCAS-LUC provides prescribed SSP-aligned land-use and land-cover trajectories as annual gridded maps. In SafeNet, these trajectories are used as external boundary-condition forcing (i.e., they do not evolve dynamically in response to simulated climate–ecosystem feedbacks within ORCHIDEE/G4M-X). For the core SafeNet simulations (Section 3.1), land-use forcing is applied for SSP1-2.6, SSP2-4.5, and SSP5-8.5, enabling scenario attribution via time-explicit land-cover fraction changes under contrasting socioeconomic narratives. The underlying LUCAS-LUC scenario archive available to the SafeNet preparation routines also includes SSP1-1.9 and SSP3-7.0 for optional diagnostic comparisons and

completeness checks, but these are not required inputs for the core modelling chain. Conservation and restoration signals are therefore represented to the extent they are encoded in the SSP-consistent LUCAS-LUC trajectories, rather than emerging endogenously from the ecosystem simulations. Any modified policy-adjusted scenarios would need to be defined as separate scenario products, because post hoc changes to baseline SSP pathways would break alignment with the harmonised SSP/IAM framing.

- **Spatial resolution and coverage:**
  At 0.1° resolution, the dataset captures heterogeneity across Europe at scales relevant for regional analyses, including strong gradients across biogeographic regions, coastlines, mountainous terrain, and fragmented land-use mosaics. The domain provides consistent pan-European spatial support suitable for gridded modelling and scenario diagnostics.

- **Data format, accessibility, and model integration readiness:**
  LUCAS-LUC is distributed as gridded and provided as annual fields by scenario and land-cover fraction type. For SafeNet, the datasets were retrieved from the distribution associated with Hoffmann et al. (2023) and organised to ensure consistent file structure and grid definitions across scenarios and the historical segment. Standard integrity checks were applied to confirm that annual coverage is complete, that land-cover fractions remain within expected bounds, and that historical and scenario segments form a continuous annual record for 1950-2100 without discontinuities introduced by file handling.

- **SafeNet land-use preparation routine and derived products:**

  SafeNet land-use boundary conditions were prepared through a standardised routine that organises the distributed LUCAS-LUC NetCDF archive by historical period and SSP branch to enable unambiguous retrieval of annual land-cover fraction fields for 1950–2100; extracts annual fraction layers and writes year-specific CF-compliant NetCDF outputs (units: fraction; bounded 0-1) for consistent downstream ingestion; delivers two interoperable products, namely a native-resolution 0.1° annual archive for high-resolution diagnostics and mapping and an ORCHIDEE-resolution 0.5° annual archive generated via area-weighted aggregation to preserve fractional cover; applies operational integrity checks (coverage completeness, expected layers present, physical bounds, and continuity across the historical–scenario boundary); and generates scenario diagnostics to support the deliverable, including Δ forest fraction (%) maps relative to a 2020 baseline for 2021–2100 plus 2100 snapshots and animations (Figure 3).

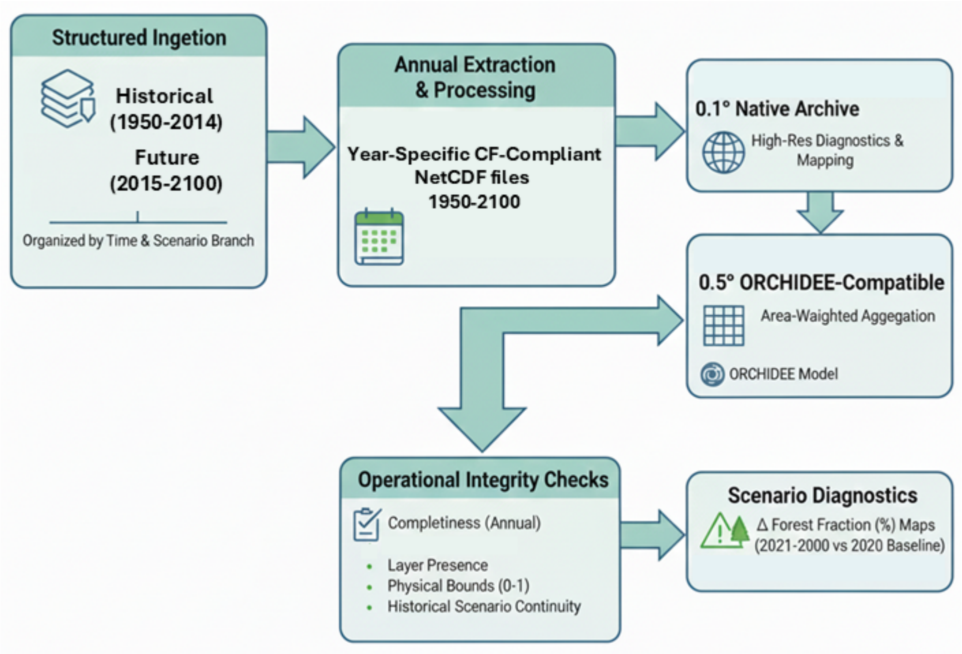


Figure 3. SafeNet land-use preparation routine and derived products

By using LUCAS-LUC, SafeNet leverages a state-of-the-art, Europe-specific representation of land-use/land-cover change that balances regional detail (~10 km resolution) with scenario consistency (SSP-traceable via LUH2). This supports precise quantification of forest extent changes and competing land uses under contrasting socioeconomic futures, and provides land-cover composition information directly relevant to land–atmosphere feedbacks, surface biophysics, and coupled ecosystem modelling (Hoffmann et al., 2023; Hurtt et al., 2020).

3.2.3. Plant Functional Types data

Plant Functional Types (PFTs) are standardised vegetation classes defined by shared physiological and phenological traits (e.g., broadleaf versus needleleaf trees, deciduous versus evergreen strategies, C3 versus C4 grasses).They provide a functional representation of vegetation composition that is widely used in land-surface and ecosystem-modelling contexts to link land cover and land-use change to biophysical and biogeochemical behaviour (Fisher et al., 2018; Wullschleger et al., 2014). In SafeNet, PFT information is therefore treated as a scenario-aligned vegetation boundary-condition layer, derived consistently from the adopted land-use/land-cover scenario archive and provided as annually resolved gridded products suitable for model forcing and for scenario diagnostics. PFTs are critical for modelling future forest distributions because they provide the functional link between prescribed land cover and modelled ecosystem processes and they provide the model-compatible interface (e.g., for ORCHIDEE) between prescribed land cover and simulated vegetation dynamics. Different tree functional types have distinct phenology, carbon allocation, water use, and climate sensitivity, which determine productivity, mortality risk, and the spatial pattern of forest persistence or change under evolving climate and CO_2. Representing forests as PFT fractions therefore allows the modelling chain to translate scenario land-cover change into mechanistically meaningful differences in forest composition and response, rather than treating forest as a single homogeneous class (Poulter et al., 2015). The PFT class set, indexing, and interpretations adopted in SafeNet are summarised in Table 2.

PFT definition and encoding: The SafeNet PFT scheme uses a 16-class structure (including non-vegetated and anthropogenic categories), consistent with the modelling-oriented European land-cover translation lineage underpinning the LUCAS-LUC product (Hoffmann et al., 2023). A fixed integer index (1–16) is retained consistently across all years and scenario branches, and the index-to-name mapping is embedded in NetCDF metadata (flag values/meanings) to ensure stable interpretation across the workflow and across derived products. The full class list, functional grouping, and land-cover archetype interpretation are provided in Table 2.

Derivation from land-use/land-cover boundary conditions: PFT layers were derived from the annual fractional land-cover information provided by the European land-use/land-cover scenario archive. This archive is constructed by translating SSP-consistent LUH2 land-use states and transitions onto a European satellite-based baseline using a dedicated land-use translator (Hoffmann et al., 2023), yielding annual gridded land-cover fractions suitable for modelling and diagnostics. SafeNet uses these annually resolved fraction layers as the basis for PFT fraction delivery, ensuring that the PFT time series remains directly linked to the selected socioeconomic pathway branches and their harmonised land-use transitions. Forest composition change (e.g., conifer to deciduous) is represented through time-varying prescribed PFT fractions in the scenario archive, not through alternative PFT options chosen per land-use class at runtime.

Annual extraction (1950–2100): To generate a complete, year-by-year forcing time series, an automated extraction routine (implemented in R using terra) was used to: (i) organise and index the distributed NetCDF archives by historical period and by scenario branch; (ii) identify the correct source file group for each requested year; (iii) extract the annual PFT fraction layers for that year in stable index order; (iv) apply consistent layer naming (per Table 2); and (v) write year-specific, CF-compliant NetCDF outputs. Each yearly output contains the full 16-layer PFT fraction stack (units: fraction; bounded 0–1), enabling unambiguous retrieval, reproducible downstream ingestion, and modular post-processing (e.g., targeted diagnostics of forests, croplands, grasslands). The extraction was performed for the historical period (1950–2015) and for the scenario period (2016–2100) for each scenario branch supported in the SafeNet land-use preparation workflow (including SSP1-1.9, SSP1-2.6, SSP2-4.5, SSP3-7.0, SSP5-8.5), ensuring a continuous annual series across 1950–2100 within each branch.

Dominant PFT per grid cell: In addition to absolute fractional cover fields, SafeNet provides a categorical “dominant PFT” product for each year and scenario branch. The dominant PFT is defined as the PFT index with the maximum fractional cover in a grid cell (with explicit handling of fill values and non-land cells under the adopted masking conventions). This representation supports rapid spatial diagnostics, categorical change detection, and map-based communication of shifts in prevailing vegetation/land-cover type, complementing the fractional products used for quantitative analysis.

Resolution delivery for modelling and diagnostics: To serve both high-resolution spatial interpretation and model-ready applications, SafeNet delivers the PFT products in two consistent spatial resolutions: (i) a native-resolution archive aligned with the source European land-use/land-cover product, preserving fine-scale spatial heterogeneity for diagnostics, mapping, and interpretation; and (ii) a coarser aggregated archive produced via area-weighted aggregation and/or dominant-class-to-fraction mapping (depending on the source representation), designed to preserve fractional-cover consistency during resolution transitions. Both archives retain the same PFT indexing and metadata conventions (Table 2), enabling direct comparability of diagnostics across resolutions and stable interpretation over time and across scenario branches.

Operational integrity checks and consistency controls: Across all PFT products (fractions and dominant PFT) and across both spatial resolutions, operational checks were applied to ensure: (i) completeness of annual coverage for each scenario branch across 1950–2100; (ii) presence of the expected 16 PFT layers in stable order (Table 2); (iii) physical bounds and numerical consistency of fractional values (0–1), including expected closure behaviour under the adopted masking conventions; (iv) continuity across the historical-to-scenario transition (i.e., no artefacts introduced by archive segmentation or file handling); and (v) consistency of index metadata (flag values/meanings) across outputs to prevent downstream misinterpretation. These controls ensure that changes in PFT composition observed in subsequent analyses reflect scenario-driven land-use dynamics rather than processing artefacts.

Scenario-relevant interpretability: The resulting PFT time series provides an explicit, annually resolved description of how vegetation functional composition and land-cover allocation evolve under contrasting socioeconomic narratives. Because the products are delivered as both fractional and dominant-class representations, and at both native and aggregated resolutions, they support complementary use cases that is, quantitative accounting of compositional change (fractions), categorical mapping and communication (dominant PFT), and multi-scale spatial interpretation across Europe.

Table 2. PFT scheme adopted from the LANDMATE Europe 2015 PFT mapping and the LUCAS-LUC land-cover translation framework (Hoffmann et al., 2023).

index	PFT short name	Group	Phenology	Land-cover represented
1	TropBroadEvergreen	Tree	Tropical broadleaf Evergreen strategy; year-round leaf area; warm-climate physiology	Tropical evergreen broadleaf forest
2	TropDeciduous	Tree	Tropical broadleaf deciduous strategy; seasonal leaf-off period	Tropical deciduous forest / woodland
3	TempBroadEvergreen	Tree	Temperate broadleaf evergreen strategy; mild-winter adaptation	Temperate evergreen broadleaf forest
4	TempDeciduous	Tree	Temperate broadleaf deciduous (“summergreen”); strong seasonality	Temperate deciduous broadleaf forest
5	EvergreenConifer	Tree	Needleleaf evergreen strategy; cold-tolerant; year-round foliage	Boreal/temperate evergreen needleleaf forest
6	DeciduousConifer	Tree	Needleleaf deciduous strategy (e.g., larch-type); strong cold-season phenology	Boreal deciduous needleleaf forest
7	ConiferShrubs	Shrub	Woody shrub functional strategy with conifer-type traits	Coniferous shrublands / heath
8	DeciduousShrubs	Shrub	Woody shrub deciduous strategy	Temperate/boreal shrublands
9	C3Grass	Herbaceous	C3 photosynthetic pathway; cooler/moister preference	Natural/managed grasslands represented as C3
10	C4Grass	Herbaceous	C4 photosynthetic pathway; warm/dry adaptation	Warm-season grasslands / Mediterranean dry grass dominance
11	Tundra	Herbaceous	Cold-region low-stature vegetation; short growing season	Tundra / alpine herbaceous cover
12	Swamp	Wetland	Wetland vegetation associated with high soil moisture / inundation	Swamps / wetlands
13	NonIrrCrops	Crops	Managed cropland, rainfed	Rainfed cropland
14	IrrCrops	Crops	Managed cropland, irrigated	Irrigated cropland
15	Urban	Anthropogenic	Built environment / impervious; non-vegetated	Urban / settlements
16	Bare	Non-vegetated	Bare ground / sparse cover	Bare soil / rock / sparsely vegetated

Note: In the European domain, the tropical forest classes (PFT1–2) are expected to be zero (or near-zero) everywhere. Forest diagnostics therefore focus on the temperate/boreal forest PFTs (PFT3–6), noting that some classes (e.g., deciduous conifer, PFT6) may be negligible depending on the land-cover-to-PFT translation.

3.2.4. Soil data

Accurate soil information is essential for modelling forest growth and carbon dynamics because soil properties regulate plant-available water, rooting constraints, nutrient status, and the magnitude and spatial variability of initial soil carbon stocks (Fan et al., 2017). For SafeNet, we compiled and harmonised soil boundary conditions for Europe from two complementary sources, International Soil Reference and Information Centre (ISRIC) SoilGrids and the Harmonized World Soil Database v2.0 (HWSD2) and integrated their strengths into a consistent soil parameter baseline while retaining each dataset at its native spatial resolution (Table 3). ISRIC provides spatially continuous, high-resolution predictions (typically 250 m - 1 km) derived from large soil profile compilations using statistical learning, offering strong within-region spatial detail for key properties (Poggio et al., 2021). HWSD2 provides a curated, harmonised compilation of soil attributes at ~1 km resolution, delivered in standardised depth layers and widely used in modelling applications (Nachtergaele et al., 2023). Using both datasets supports a ‘detail plus benchmark’ strategy as ISRIC supplies the primary spatial heterogeneity, while HWSD2 supports plausibility screening, depth-structure interpretation, and cross-checking in settings where predictive products may be uncertain (e.g., organic soils, complex terrain, data-sparse regions).

Data sources, depth structure, and extracted properties: From ISRIC, we extracted key variables relevant for forest ecosystem processes, including texture fractions (clay, silt, sand), soil organic carbon (SOC), total nitrogen (N), pH (where available; pH in H_2O and/or KCl depending on the layer set), and the water-retention quantities required to derive available water capacity (AWC) (Table 3). ISRIC provides depth resolved variables in standard intervals, enabling consistent construction of topsoil and subsoil representations for diagnostics and subsequent modelling steps. From HWSD2, we extracted comparable attributes (notably texture and organic carbon) and used its depth-explicit structure, seven standard depth layers (0–20, 20–40, …, 150–200 cm), to support profile consistency checks and interpretation. HWSD2-derived attributes such as bulk density and soil-depth descriptors were used to support stock-consistent handling of SOC and to screen depth plausibility (e.g., avoiding unrealistic deep organic-layer behaviour in peatland-dominated cells).

Variable harmonisation and cross-dataset integration: A unified SafeNet soil baseline was produced through a structured harmonisation procedure, designed to retain spatial realism while limiting cross-dataset inconsistencies. ISRIC fields were used as the default (“primary”) representation because they provide continuous coverage and fine-scale spatial heterogeneity. HWSD2 was used as an independent reference for discrepancy detection and plausibility screening, particularly for variables with known sensitivity to mapping/upscaling approaches (notably SOC and texture). Harmonisation focused on: (i) consistent unit handling and depth conventions (topsoil/subsoil summaries derived from the native depth layers); (ii) systematic identification of grid cells/regions where ISRIC and HWSD2 diverge beyond expected uncertainty; and (iii) conservative statistical reconciliation in value space (e.g., regional offset correction and variance scaling where warranted) that preserves the ISRIC spatial pattern while avoiding implausible domain-wide biases in critical variables such as SOC (Nakhavali et al., 2025).

Validation against ICP Forests observations: The resulting gridded soil information was evaluated against independent ground-based measurements from the International Co-operative Programme (ICP) Forests monitoring network to ensure realism for European forest conditions (Ferretti et al., 2020). Validation was performed for clay, silt, sand, and SOC in both topsoil and subsoil, using depth-consistent comparisons between plot observations and collocated grid values. In addition, AWC was validated at the whole-soil/profile level, reflecting the integrated nature of plant-available water storage across the rooting zone. Additional soil products such as HoliSoils derived layers were not included in the baseline compilation for this deliverable and can be considered in follow on benchmark or sensitivity analyses once variable definitions and depth conventions are aligned.

Delivered soil parameters: The final SafeNet soil baseline includes (Table 3):

- **Texture:** percent clay, silt, and sand (topsoil and subsoil). Texture controls soil hydrology, plant water availability, and percolation behaviour.
- **SOC:** topsoil and subsoil SOC, delivered in forms suitable for interpretation and downstream use (e.g., concentration and/or stock-consistent representations depending on the target workflow).
- **Total N:** retained as a nutrient-status indicator for interpretation and optional nutrient-related sensitivity analyses.
- **pH (H_2O and/or KCl where available):** retained primarily for descriptive purposes and optional screening, recognising not all model configurations use pH explicitly.
- **AWC:** derived from water-retention quantities as the field-capacity minus wilting-point water storage over the representative soil/rooting zone; AWC is central for drought stress assessment.

All soil layers are provided at their native spatial resolution in standard geospatial raster formats (NetCDF/GeoTIFF), with accompanying documentation of units, depth conventions, and provenance. Where needed for non-raster workflows, grid-cell value extracts are additionally provided as tabular outputs (CSV), and summary map products are generated to support rapid inspection and reporting. Delivering a consistent soil baseline in this manner supports coherent interpretation of spatial heterogeneity in forest responses and reduces the risk of discrepancies arising from inconsistent soil assumptions across the SafeNet workflow components.

Table 3. SafeNet soil datasets, variables and structure

Dataset	Resolution	Coverage	Depth	Variables used in SafeNet	Derived variables	Role in SafeNet
ISRIC (Poggio et al., 2021)	250 m – 1 km	Pan-Europe (global product subset)	Depth-resolved standard intervals (SoilGrids depth layers)	Clay, silt, sand; SOC; total N; pH (H_2O and/or KCl where available); AWC	Topsoil and subsoil summaries derived from native depth layers	Soil input dataset provided for SafeNet simulations and diagnostics
HWSD v2.0 **(Nachtergaele et al., 2023)**	~1 km / 30 arc-sec)	Pan-Europe (global product subset)	Seven layers: 0–20, 20–40, 40–60, 60–80, 80–100, 100–150, 150–200 cm	Texture and organic carbon attributes; bulk density; AWC	Depth-profile interpretation and plausibility screening; support stock-consistent SOC handling and depth plausibility checks	Soil input dataset provided for SafeNet simulations and diagnostics (parallel/alternative source to ISRIC)
ICP Forests observations	Point data	Europe-wide forest monitoring plots	Plot depth layers (top/sub) + profile metrics	Observed clay/silt/sand and SOC (top + sub); AWC (whole soil/profile)	Collocated comparisons to gridded layers for evaluation	Independent field observations used for evaluation of gridded soil products.

4. Scenarios data illustration

After assembling the harmonised boundary-condition dataset, here we present a set of scenario-input diagnostics to illustrate the magnitude and spatial structure of forcing differences relevant to European forests. The figures compare climate forcing, land-use/land-cover change, and PFT distributions under SSP1-RCP2.6, SSP2-RCP4.5, and SSP5–RCP8.5 (scenarios selected for SafeNet) and include soil baseline maps together with validation against ICP Forests observations. All results are derived from the processed, quality-controlled inputs documented above.

4.1. Climate

The climate illustration here serves two purposes: (i) to document that the processed baseline fields preserve physically expected European-scale gradients and mesoscale structure, and (ii) to demonstrate that the scenario forcing contrasts used in SafeNet are clearly separable in both magnitude and spatial pattern for the key forest relevant variables (e.g. temperature and precipitation) (Jacob et al., 2014; Karger et al., 2017; Vautard et al., 2021). This provides an explicit traceable workflow record from the harmonised processing workflow (Section 3.2.1) to the boundary-condition products used in downstream analyses.

The historical baseline maps confirm the expected zonal temperature gradient across Europe and the strong topographic imprint in mountainous regions, while precipitation fields highlight pronounced orographic enhancement that is particularly relevant for mountain forest systems (Karger et al., 2017). As anticipated from their construction, CHELSA exhibits sharper local gradients consistent with its kilometre scale statistical mechanistic downscaling, whereas EUROCORDEX fields are smoother at approximately 0.11° resolution, reflecting the effective scale of dynamical regional simulations and their gridded output (Jacob et al., 2014; Vautard et al., 2021). This qualitative agreement is supported by the processed historical diagnostics based on pan-European (domain-wide) area averages. Specifically, the domain-mean annual near-surface air temperature, averaged over the full European modelling mask, is closely aligned between products (CHELSA: 7.50 °C; EURO-CORDEX: 7.59 °C), and their realised grid-cell ranges over the baseline period are comparable (CHELSA: -18.18 to 25.23 °C; EURO-CORDEX: -16.91 to 24.66 °C). For precipitation, the pan-European mean annual total precipitation, averaged over the same domain, is likewise very similar (CHELSA: 766.1 mm yr^{-1}; EURO-CORDEX: 759.0 mm yr^{-1}). Both products reproduce the expected large-scale gradient from wetter Atlantic and Alpine regions to drier Mediterranean sectors, while CHELSA retains finer orographic structure that is intentionally preserved for baseline diagnostics (Figure 4).

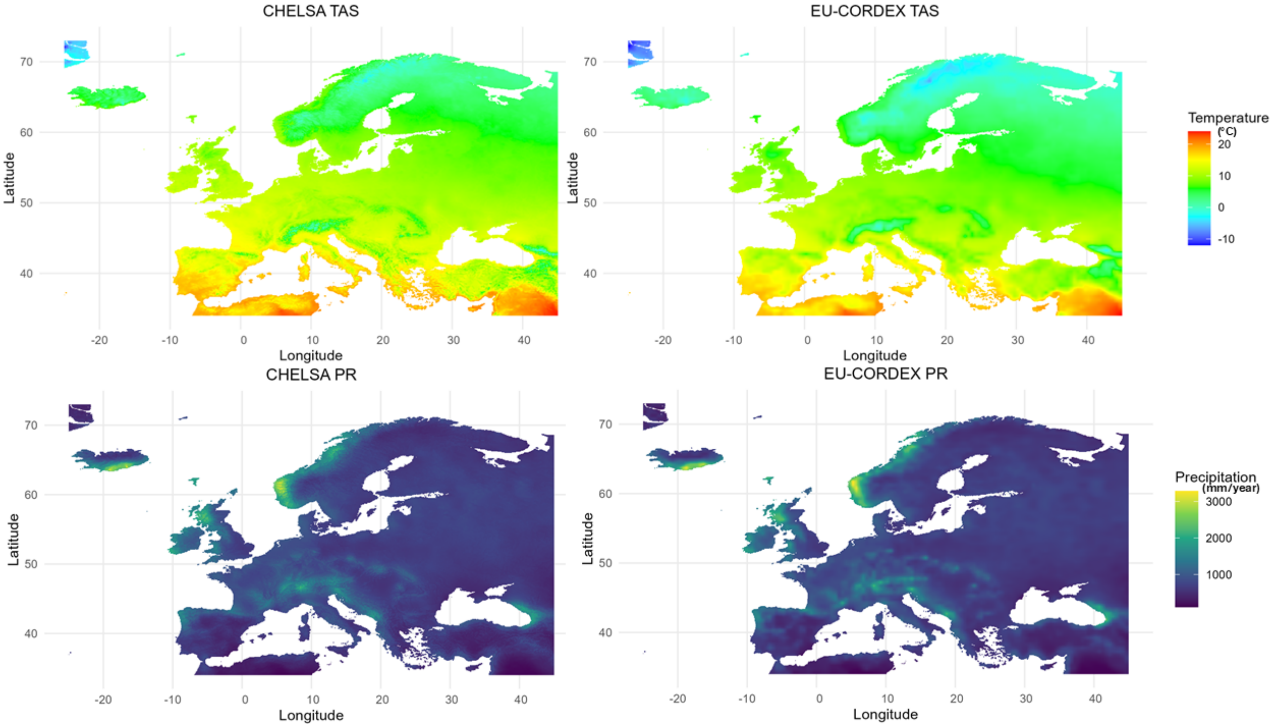


Figure 4. CHELSA and EURO-CORDEX historical (1980-2015) temperature and precipitation changes

Across the shared historical period, the processed European area mean time series indicate close alignment between products in both central tendency and interannual variability. Mean annual temperature (TAS) is 7.54 ± 0.59 °C for CHELSA and 7.48 ± 0.63 °C for EUROCORDEX, where the ± values denote the interannual standard deviation of annual means. Mean annual precipitation (PR) is 766.1 ± 26.5 mm yr-1 (2.10 ± 0.07 mm day-1) for CHELSA and 759.0 ± 21.4 mm yr-1 (2.08 ± 0.06 mm day-1) for EURO-CORDEX. Despite these small offsets, temporal coverability remains high (r = 0.98 for TAS and r = 0.87 for PR), indicating that both products track coherent large scale European variability while retaining expected discrepancies arising from differing downscaling methodologies and the spatially and seasonally varying RCM biases reported in the European evaluation literature (Kotlarski et al., 2014; Vautard et al., 2021) (Figure 5).

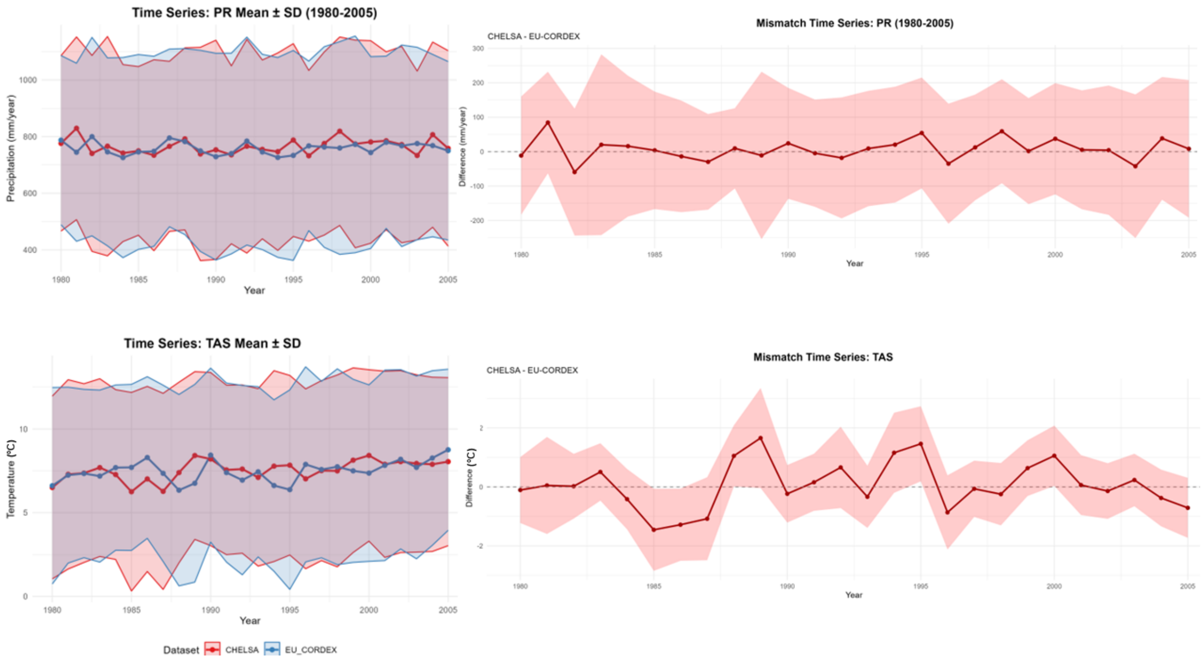


Figure 5. CHELSA and EURO-CORDEX temperature and precipitation discrepancies

For scenario forcing, the processed EURO-CORDEX archive provides a consistent basis for contrasting historical conditions with relative future changes under low, intermediate, and high-end pathways (RCP2.6/4.5/8.5). The scenario signal is illustrated using EURO-CORDEX derived relative changes for temperature and precipitation over 2081–2100 relative to the historical baseline (Figure 6), capturing both the mean response and spatial heterogeneity critical for forest impact attribution. Averaged over the pan-European land mask (i.e., the SafeNet European domain land grid cells), E European-scale warming increases strongly with forcing across mean and extreme temperature metrics. Under SSP1-RCP2.6, the European-mean changes are TAS +1.17 °C, TAS_max (daily maximum 2 m air temperature) +1.19 °C, and TAS_min (daily minimum 2 m air temperature) +1.18°C, with mapped grid-cell changes on the non-negative display scale spanning approximately 0-2.64 °C (TAS), 0-2.46 °C (TAS_max), and 0-2.95 °C (TAS_min). Under SSP2–RCP4.5, the European-mean changes increase to TAS +2.03 °C, TAS_max +2.06 °C, and TAS_min +2.04 °C, with mapped ranges of approximately 0-4.57 °C (TAS), 0-4.25 °C (TAS_max), and 0-5.11 °C (TAS_min). Under SSP5–RCP8.5, warming is substantially larger, with European-mean changes of TAS +3.83 °C (0.60–8.64 °C), TAS_max +3.90 °C (0.52-8.03 °C), and TAS_min +3.85 °C (0.74-9.65 °C). For precipitation, the European-mean response remains comparatively small across pathways, but the mapped fields show structured regional contrasts that are important for local forest exposure (Figure 6). The sign and magnitude of precipitation change over Mediterranean Europe are scenario-dependent: under RCP2.6 and especially RCP4.5 the signal is mixed, with parts of the Mediterranean showing weak increases or near-neutral changes, whereas under RCP8.5 the pattern shifts toward more pronounced drying across southern/Mediterranean regions alongside increased precipitation at higher latitudes, consistent with EURO-CORDEX assessments and IPCC AR6 regional syntheses for Europe(IPCC, 2023; Jacob et al., 2014; Vautard et al., 2021) (Figure 6).

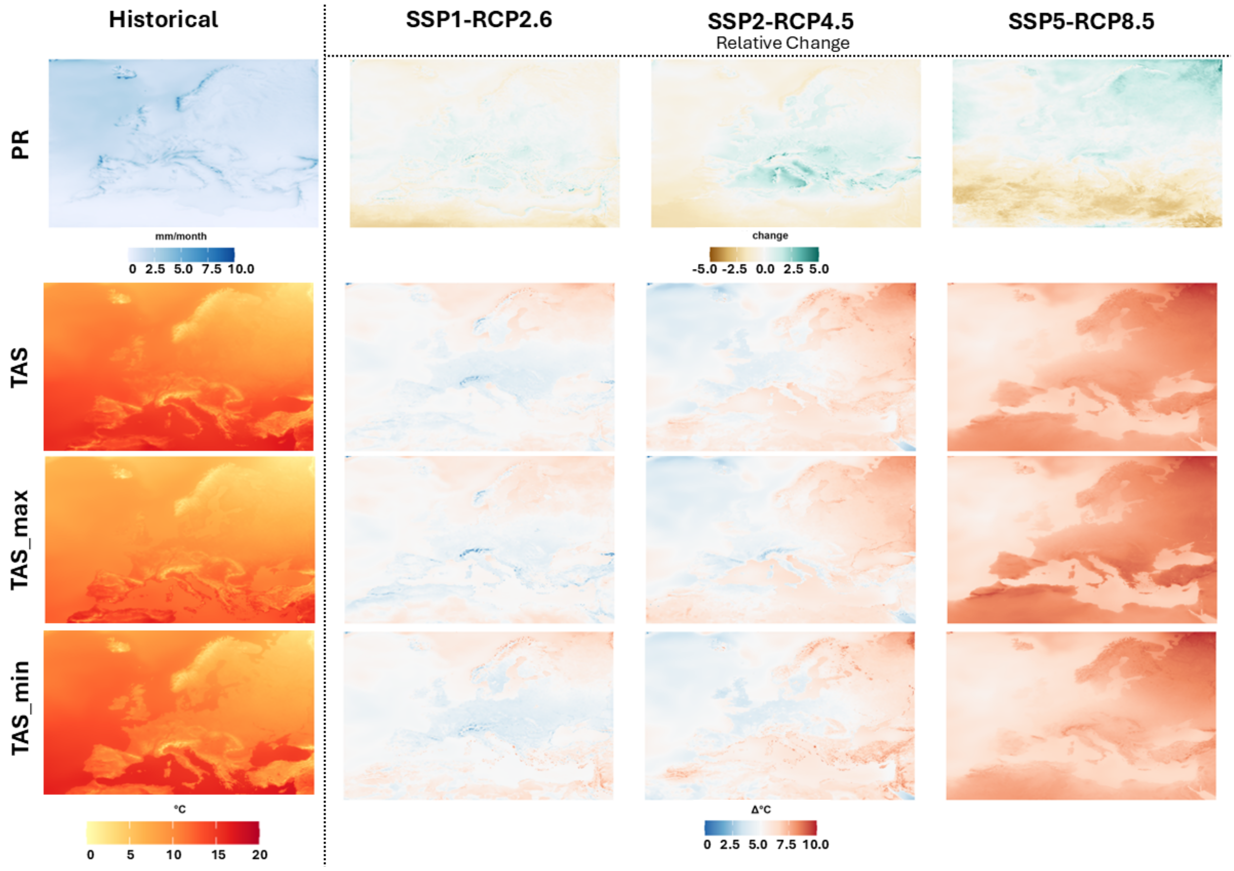


Figure 6. EURO-CORDEX precipitation (PR) and temperature (TAS_min, TAS_max, TAS) historical and relative future changes

Finally, atmospheric CO_2 trajectories highlight the expected divergence among pathways over the 21st century, providing a transparent record of the CO_2 forcing delivered alongside the meteorological boundary conditions and applied uniformly over the modelling domain as an external concentration time series derived from the CMIP6 SSP concentration pathways (Meinshausen et al., 2020). The CO_2 boundary condition is therefore presented as an explicit, scenario-consistent forcing that complements the meteorological drivers, ensuring that radiative forcing context and CO_2 fertilisation relevant signals evolve coherently in time. In the processed series, CO_2 reaches 426.6 ppm in 2025 and follows the CMIP6-recommended pathways to 2100, reaching approximately 446 ppm (SSP1-2.6), 603 ppm (SSP2-4.5), and 1135 ppm (SSP5-8.5) (Figure 7).

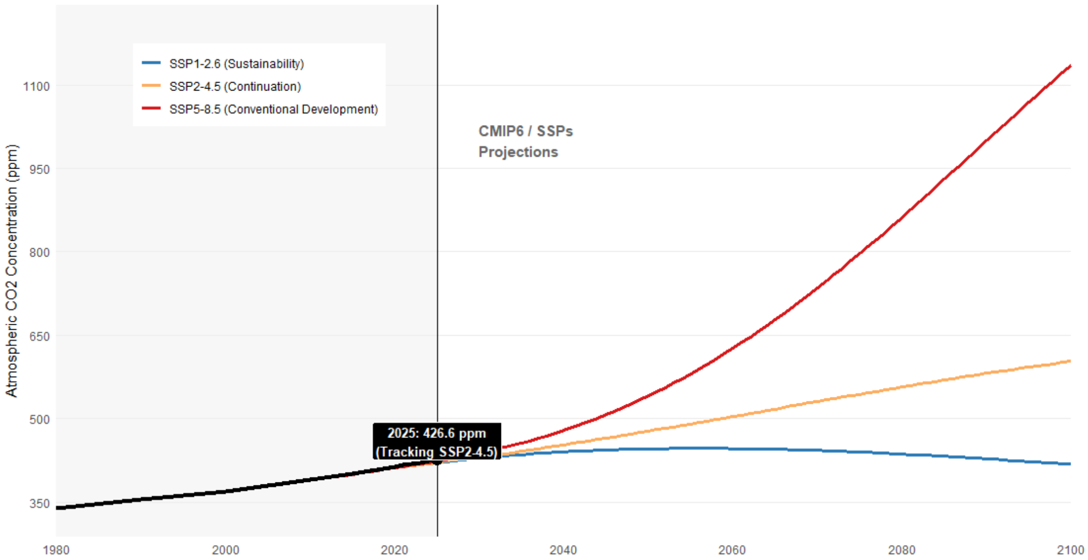


Figure 7. Historical and future atmospheric CO_2 concentrations (ppm)

4.2. Land use

Across the processed land-cover fractions, Europe's aggregate composition remains dominated by cropland, grassland, forest, and shrubland (Pflugmacher et al., 2019), but the direction and magnitude of change diverge strongly by scenario, consistent with the SSP narratives translated through LUH2 and the Europe-specific LUCAS-LUC downscaling framework (Hoffmann et al., 2023; Hurtt et al., 2020). Unless stated otherwise, land-use indicators are reported for the pan-European modelling domain ("Whole Europe"), with EU27+UK provided as a nested subregional subset for policy-relevant interpretation and benchmarking. In the historical segment (1950-2015), changes are modest at continental scale (e.g., forest: 21.92% → 22.27%, urban: 0.35% → 0.66%, with larger redistribution within non-forest natural classes such as shrubs: 14.61% → 11.84%). From 2020 to 2100, the land-cover signal separates clearly where under SSP-RCP2.6, forest fraction increases from 22.48% to 26.07% (+3.59 percentage points (pp)), largely compensated by declines in grass (-2.74 pp) and shrubs (-1.41 pp), while cropland remains broadly stable (~33.7-33.8%). Under SSP2-RCP4.5, forest rises more moderately (22.00% → 23.61%; +1.61 pp), whereas SSP5-RCP8.5 exhibits near-stationary forest cover (21.95% → 21.97%; +0.02 pp) alongside small compensating changes among natural classes and a continued increase in urban fraction (to 0.96% by 2100). These aggregate trajectories provide a concise verification that the processed time series preserves the expected reforestation vs. stabilisation scenario separation embedded in SSP-based land-use pathways (Figure 8).

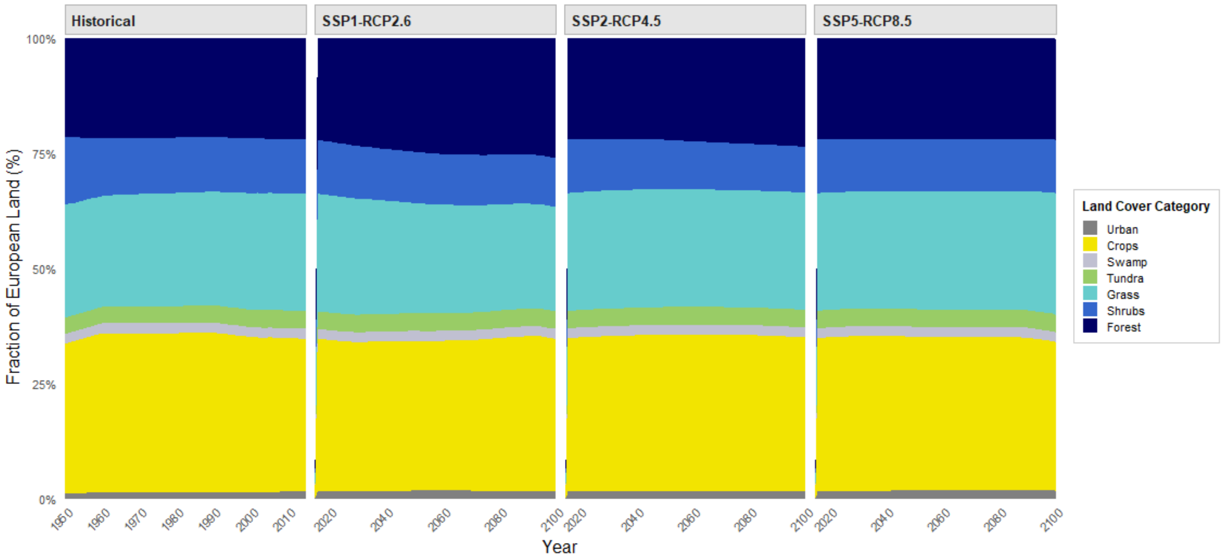


Figure 8. European land cover changes (1950-2100)

Spatially, the processed forest fraction change maps show that these continental scale signals arise from structured regional redistributions rather than uniform shifts. Under SSP-RCP2.6, the mean forest share increases by +2.24 pp (2050), +2.92 pp (2070), and +3.59 pp (2100) relative to 2020, with widespread afforestation signals across large parts of temperate Europe and more localised declines in some high-latitude and/or Mediterranean-margin cells. Under SSP2-RCP4.5, the corresponding mean changes remain smaller (+0.10 pp, +0.71 pp, +1.61 pp), and the map pattern is correspondingly patchier. Under SSP5-RCP8.5, forest change remains close to zero through mid- and late-century (≈ -0.03 pp by 2050/2070; +0.02 pp by 2100), with the map dominated by weakly negative to neutral signals. Interpreted as scenario input diagnostics, these fields provide clear, traceable spatial targets for downstream attribution of forest responses to land cover forcing differences, while remaining consistent with SSP expectations (Hoffmann et al., 2023; Hurtt et al., 2020; O'Neill et al., 2014) (Figure 9). Note that these forest-fraction change maps represent prescribed land-cover trajectories from the SSP land-use forcing (LUCAS-LUC) and therefore do not capture climate-driven forest dieback or biome shifts; such effects are assessed in downstream ecosystem/sector modelling when land cover interacts with EURO-CORDEX climate, CO_2 and soil constraints.

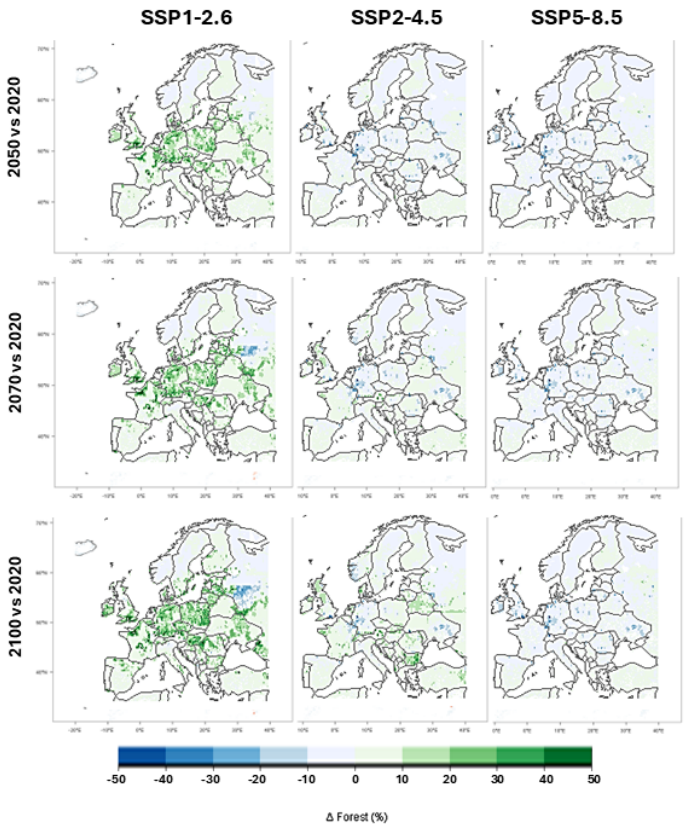


Figure 9. Forest fraction change (2020-2100) for SSP scenarios

When expressed as total forest area over time, the same scenario separation emerges in a way that is directly usable for cross-model benchmarking. For the whole European domain, the processed series indicates strong expansion under SSP-RCP2.6, rising from 454.5 Mha (2020) to 485.7 Mha (2100) (+31.2 Mha; +6.9%), with a mid-century maximum of 487.3 Mha (2060). Under SSP2-RCP4.5, forest area increases more modestly from 454.5 Mha to 462.1 Mha (+7.6 Mha; +1.7%). Under SSP5-RCP8.5, total forest area is essentially stable to slightly declining (454.5 Mha → 448.7 Mha; -5.8 Mha; -1.3%). For EU27 plus United Kingdom (EU27+UK), the pattern is similar but with smaller absolute magnitudes: SSP-RCP2.6 increases from 148.7 Mha (2020) to 173.8 Mha (2100) (+25.1 Mha; +16.9%), SSP2-RCP4.5 from 148.7 to 159.8 Mha (+11.1 Mha; +7.5%), while SSP5-RCP8.5 declines from 148.7 to 147.7 Mha (-1.0 Mha; -0.7%) (Figure 10).

Note that, the forest-area totals reported here are computed directly from the LUCAS-LUC gridded land-cover fraction labelled "forest" over the SafeNet European domain mask and therefore reflect the dataset's land-cover definition, not an inventory-based "forest land" definition as used in FAO/FRA and national statistics (FAO, 2022). As a result, absolute forest area (e.g., EU27+UK in 2020) may differ from FRA-reported values in either direction, depending on differences in classification rules (land cover vs land use), minimum canopy/area thresholds, treatment of temporarily unstocked areas, and domain/mask/resolution effects. In our domain-specific comparison, the gridded land-cover estimate is typically lower, but this is not a general rule. In this deliverable, we intentionally do not apply any statistical alignment or shifting to match external inventories; where required, model-specific integration steps (ORCHIDEE/G4M-X/GLOBIOM) will handle reconciliation/calibration to ensure consistency with benchmarking datasets while preserving the scenario-driven spatial and temporal signals.

Cumulative afforestation further clarifies the mechanism behind the forested area divergence by separating net area gains attributable to afforestation from the overall forested area trajectory. In the processed data, cumulative afforested area grows rapidly under SSP1-RCP2.6, reaching 30.5 Mha (2050) and 51.4 Mha (2100) for the whole European domain, and 25.8 Mha (2050) and 36.1 Mha (2100) for EU27+UK. As defined in Section 4.2, “Whole Europe” refers to the SafeNet European domain land mask, and “EU27+UK” is the nested administrative subset used for policy-relevant reporting. Under SSP2-RCP4.5, cumulative afforestation remains much smaller (2.7 → 15.7 Mha by 2050→2100 for whole Europe; 1.5 → 9.5 Mha for EU27+UK), and under SSP5-RCP8.5 it is minimal (~0.3 → 2.4 Mha for whole Europe; ~0.1 → 0.8 Mha for EU27+UK). These contrasts are consistent with the intended SSP bracket in which sustainability-oriented pathways support land-use transitions compatible with net forest expansion, whereas conventional development pathways generally do not require (or incentivise) large scale afforestation in the harmonised land use translations (Figure 10). Note that the end-of-century up-turn is a feature of the prescribed LUCAS-LUC land-use forcing. It reflects an acceleration of net conversion into the forest class in the final decade (2090–2100) as the SSP land-allocation trajectory converges to its 2100 endpoint, rather than climate-driven biome dynamics. Climate-driven shifts in forest suitability, productivity, and stress are assessed in downstream ORCHIDEE/G4M simulations.

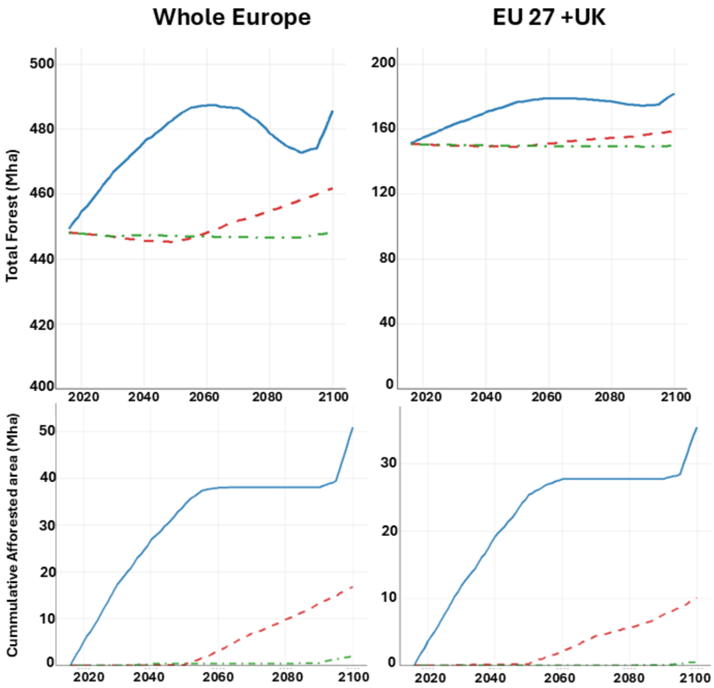


Figure 10. Total forest area and cumulative afforested area for Whole Europe and EU27+UK

Finally, the processed historical to future behaviour is directionally consistent with the broader literature that documents recent European forest expansion linked to land use change (e.g., agricultural abandonment and afforestation) (Fuchs et al., 2013; Potapov et al., 2015) and emphasises that future forested area outcomes depend strongly on socioeconomic pathways and policy stringency (Popp et al., 2017; Riahi et al., 2017). In this deliverable context, the key point is to demonstrate that the harmonised land-use inputs reproduce (i) plausible historical-scale continuity and (ii) a clean, scenario-consistent separation in both forest fraction and forest area/afforestation totals, providing a robust boundary condition basis for subsequent forest impact analyses within the SafeNet modelling chain.

4.3. Plant Functional Types

Forest plant functional type (PFT) trajectories provide a scenario-consistent description of how forest area is allocated among the main forest functional groups within the land-use forcing, complementing the total forested area diagnostics in Section 4.2. In 2020, aggregated forest-PFT area totals 454.5 Mha for the whole European domain and 148.7 Mha for EU27+UK (minor differences across SSP branches reflect early divergence after the 2015 scenario split; Section 4.2). Across scenarios, forest area remains dominated by evergreen conifers (~53-54%) and temperate deciduous broadleaf forests (~45%), with temperate broadleaf evergreen occupying a small Mediterranean-focused fraction (~1-2%), the expected structural property of European forest distributions given the underlying land-cover to PFT translation methodology (Brus et al., 2012; Poulter et al., 2015).

For the whole European domain, the low-forcing sustainability pathway (SSP1-RCP2.6) exhibits the clearest expansion across forest PFTs. Evergreen conifer area increases from 241.9 Mha (2016) to 256.3 Mha (2100) (+14.4 Mha; +5.9%), temperate deciduous broadleaf expands from 200.5 Mha to 221.8 Mha (+21.4 Mha; +10.7%), and temperate broadleaf evergreen grows from 6.6 Mha to 7.2 Mha (+0.6 Mha; +9.4%). Consistent with the forest-area diagnostics (Section 4.2), total forest-PFT area increases from 454.0 Mha (2020) to 485.2 Mha (2100) (+31.2 Mha; +6.9%). Interannual variation remains smooth relative to the scenario signal (2020-2100 mean ± SD: conifer 250.4 ± 4.2 Mha, deciduous 214.0 ± 6.4 Mha).

The intermediate pathway (SSP2-RCP4.5) preserves the same PFT ordering but with smaller net changes where evergreen conifer 241.5 → 245.2 Mha (+3.7 Mha; +1.5%) and temperate deciduous 199.7 → 209.2 Mha (+9.4 Mha; +4.7%), alongside broadleaf evergreen 6.6 → 7.2 Mha (+0.6 Mha; +8.4%), yielding a total forest-PFT change of +13.7 Mha (+3.1%). SSP5–RCP8.5 remains effectively flat (-0.1 Mha total; -0.0%), with small offsetting changes (evergreen conifer -0.5 Mha, deciduous +0.5 Mha, broadleaf evergreen -0.04 Mha).

For EU27+UK, the hierarchy holds with sharper compositional implications due to the smaller, intensively managed domain. Under SSP1-RCP2.6, evergreen conifer rises from 96.3 Mha (2016) to 107.7 Mha (2100) (+11.4 Mha; +11.8%) while temperate deciduous increases from 48.3 Mha to 67.1 Mha (+18.8 Mha; +38.9%), shifting the deciduous share from ~32% (2016) to ~37% (2100). Total forest-PFT area gains 30.8 Mha (+20.4%). SSP2–

RCP4.5 shows smaller growth (+8.2 Mha; +5.5%), while SSP5-RCP8.5 exhibits slight decline (-1.1 Mha; -0.7%) with broadly stable PFT proportions.

These PFT trajectories represent scenario land-cover allocations (prescribed forest-type evolution within boundary conditions), not climate-driven biome shifts from vegetation dynamics. This distinction enables clean attribution where the land-use/PFT forcing signal interacts with climate/CO_2 forcings in downstream models (e.g., ORCHIDEE) to produce realised productivity, carbon, and disturbance outcomes (Figure 11). Accordingly, potential biome/functional shifts will be assessed using ORCHIDEE realised vegetation outputs (e.g., changes in dominant tree PFT and forest productivity/stress indicators) and reported as diagnostic layers alongside, rather than as replacements for the prescribed land-cover forcing.

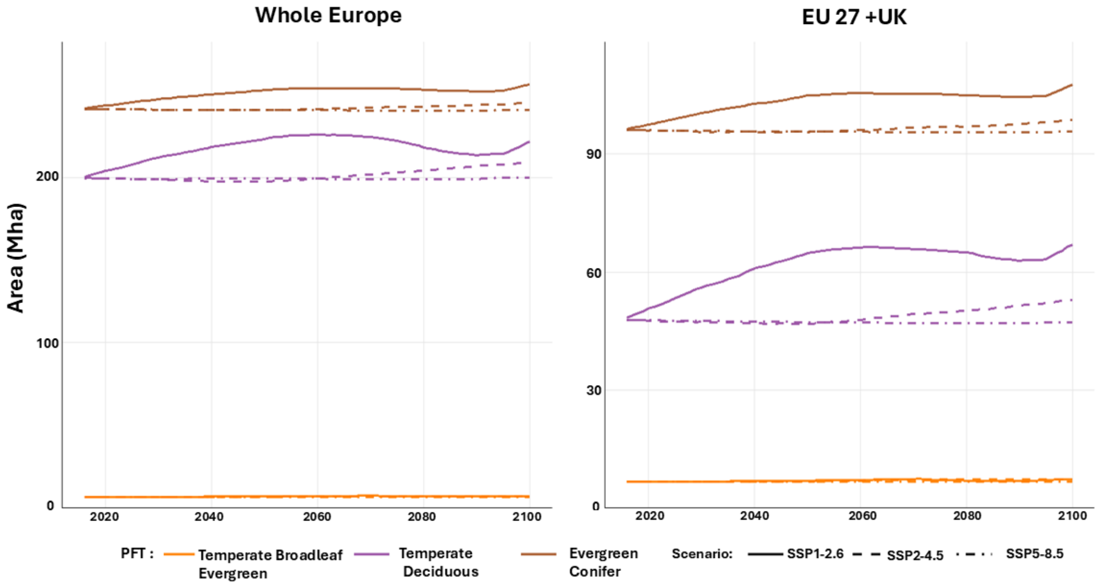


Figure 11. PFT area changes (2020-2100) for SSP scenarios

4.4. Soil data

The delivered soil boundary-condition layers provide a consistent, Europe-wide characterisation of edaphic controls relevant to forest water balance and carbon cycling, using two complementary gridded products, HWSD2 and ISRIC. Across both products, the processed maps reproduce expected continental-scale gradients in soil texture and hydrological capacity, while highlighting differences in spatial detail attributable to their mapping approaches (Figure 12). Note that Figure 12 uses panel-specific colour scales, so it supports qualitative pattern comparison rather than direct cross-product magnitude comparison. Furthermore, ORCHIDEE evolves soil biogeochemical pools (e.g., soil carbon, and nutrients where enabled), but the gridded physical soil-property layers used here (texture, depth, AWC) are treated as fixed boundary conditions and are not dynamically updated within the forcing package.

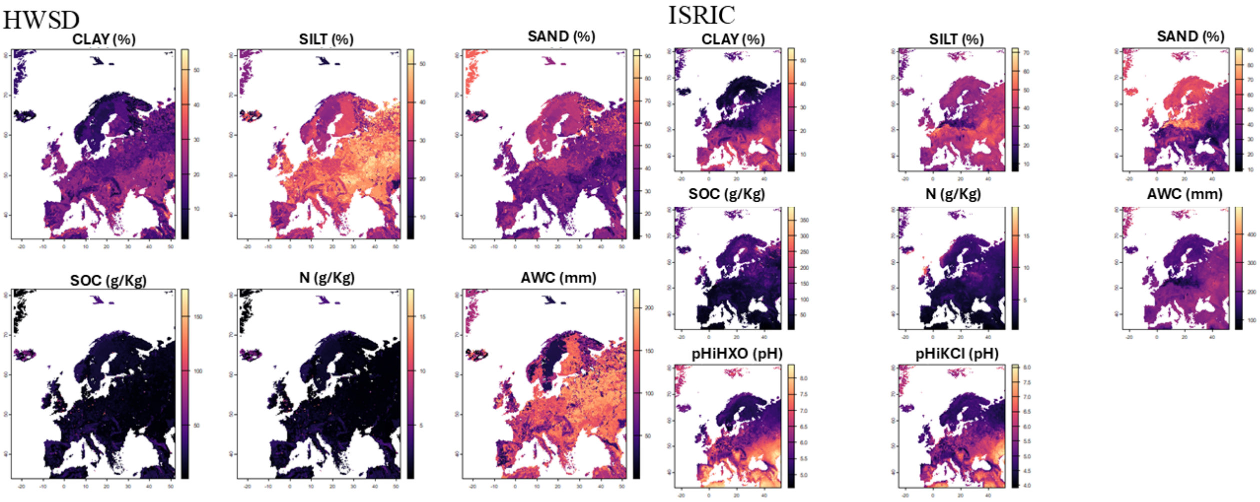


Figure 12. HWSD2 and ISRIC soil data variables

Texture fractions (clay, silt, sand) show the strongest cross-product coherence, with both products exhibiting plausible regional structure for European forest zones. ISRIC expresses finer heterogeneity in mountainous and ecotonal areas, while HWSD2 shows smoother, categorical patterns characteristic of its polygon-based harmonisation. Both products provide soil organic carbon (SOC) and plant-available water capacity (AWC) with coherent large-scale patterns but greater local divergence, reflecting known challenges in mapping carbon and water-retention properties.

Evaluation against ICP Forests observations confirms strong texture agreement where topsoil correlations are clay (ISRIC r=0.57; HWSD2 r=0.72), silt (r=0.86; r=0.80), sand (r=0.83; r=0.83); subsoil remains robust (clay r=0.78/0.71; silt r=0.78/0.78; sand r=0.83/0.83). These values align with literature showing particle-size fractions are more stable and predictably mapped than biogeochemical attributes (Hengl et al., 2014). SOC correlations are lower, as expected (topsoil r=0.21-0.25; subsoil r=0.26-0.44), reflecting SOC's small-scale heterogeneity and management sensitivity. Critically for drought diagnostics, whole-profile AWC shows strong agreement (ISRIC r=0.77; HWSD2 r=0.66), confirming suitability for water-limitation attribution (Figure 13). The apparent regression-to-the-mean pattern (low values overestimated, high values underestimated) is expected when comparing plot-scale ICP observations to gridded soil products (support mismatch and spatial smoothing) (Nakhavali et al., 2025) while post-hoc calibration approaches can reduce this effect, they are outside the scope of this boundary-condition deliverable.

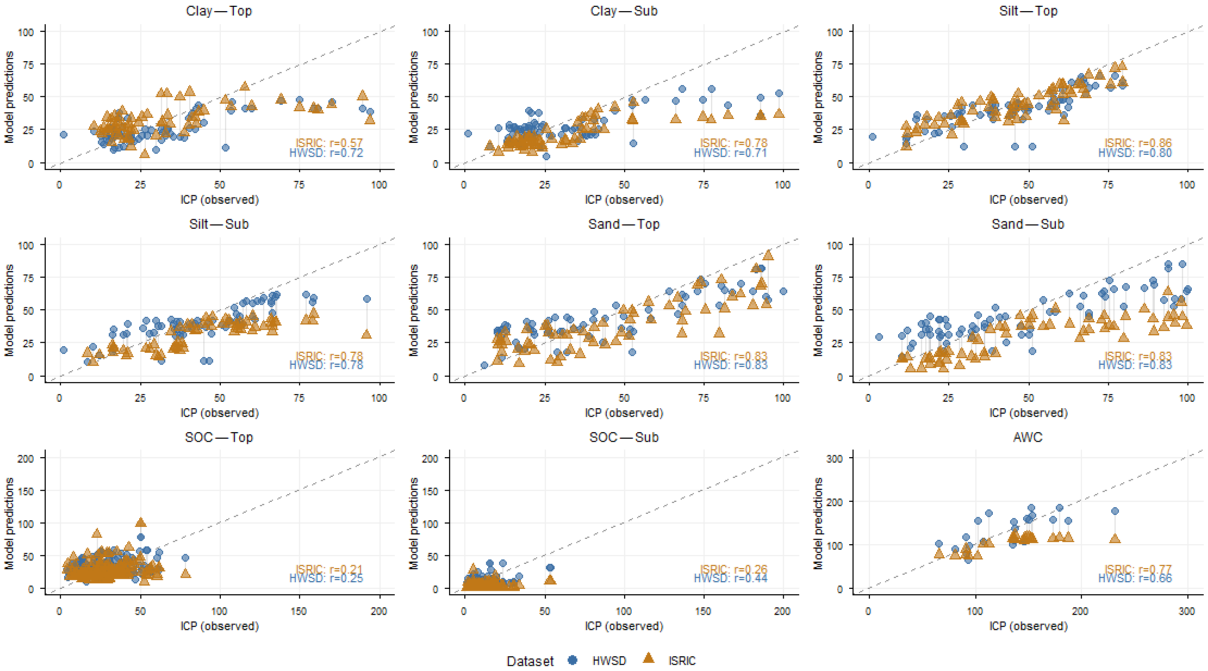


Figure 13. HWSD2 and ISRIC soil data variables evaluation against ICP observations

These results yield two operational conclusions for SafeNet: (i) texture and AWC provide robust, observation-consistent constraints across products, and (ii) SOC requires cautious local-scale interpretation, motivating the dual-product delivery for uncertainty-aware analyses.

5. Scenario data integration and modelling

SafeNet delivers a single, scenario-consistent boundary-condition package that integrates climate, land use / PFTs, soils, and atmospheric CO_2, structured for reproducible ingestion across the ORCHIDEE and G4M-X modelling suite. All inputs share a common European land mask and harmonised geospatial conventions (grid definition, indexing, and units), with CF-compliant NetCDF as the primary interchange format and clear provenance from source archives to model-ready products. Importantly, this integration is implemented as a sequential, one-way boundary-condition approach: the socioeconomic (land use/land cover) and biophysical (climate/soils/CO_2) trajectories are prescribed as external drivers to the ecosystem models to ensure tractability and enable clean attribution of scenario differences. Consequently, feedback loops are not represented explicitly within the boundary-condition package, e.g., climate-driven changes in forest growth, mortality, disturbance, or species composition/biome shifts do not directly feed back into subsequent land-use allocation or management decisions within the forcing itself. This framing should therefore be interpreted as ecosystem and sector-model responses conditional on the prescribed trajectories, while providing a robust foundation for future work toward more dynamically integrated human–Earth system feedback.

To ensure compatibility with the ORCHIDEE configuration used in SafeNet, three practical choices are applied:

- Single-source meteorological forcing for ORCHIDEE (EURO-CORDEX only). ORCHIDEE is forced with a continuous EURO-CORDEX archive spanning spin-up and transient simulation (historical segment followed by the relevant RCP extension; exact transition depends on availability per GCM–RCM chain). CHELSA is retained for high-resolution baseline diagnostics and evaluation but is not used as ORCHIDEE forcing.
- Regrouping to the ORCHIDEE PFT set. The 16-class LUCAS-LUC/LANDMATE PFT scheme differs from the reduced PFT set activated in ORCHIDEE. An explicit deterministic crosswalk regroups the 16 classes into ORCHIDEE-compatible PFT fractions while preserving fractional closure (non-applicable tropical classes are zero in Europe; irrigated/rainfed crops are merged where not distinguished). Regrouping is performed by (i) merging source classes into the nearest ORCHIDEE groups, (ii) converting categorical “dominant PFT” fields to fractional cover at the ORCHIDEE grid where required, and (iii) ensuring fractions sum to 1 over land cells (non-vegetated classes such as urban/bare remain explicitly tracked but are excluded from the forest-PFT fraction normalisation used for ORCHIDEE). Scripts and mappings are archived in the SafeNet repository.
- Single-column soil parameters for ORCHIDEE. Because the ORCHIDEE version used in SafeNet does not require vertically discretised soil-property forcing, depth-resolved ISRIC/HWSD2 layers are aggregated into ORCHIDEE-ready effective-column parameters (depth-weighted summaries, including whole-profile AWC). Depth-explicit layers are retained for evaluation and for workflows that require vertical structure.

Technical integration harmonises: (i) time-resolved EURO-CORDEX climate stacks (historical + RCP scenario extensions) as continuous meteorological drivers for ORCHIDEE; (ii) annual land use/land cover and PFT fractional layers tracing SSP narratives through 2100; (iii) soil parameters delivered as effective-column layers for ORCHIDEE (including whole-profile AWC), with depth-explicit (topsoil/subsoil) layers retained for evaluation/diagnostics; and (iv) CMIP6 SSP CO2 concentration pathways as uniform external forcing. This package underpins ORCHIDEE simulations combining EURO-CORDEX meteorology, land cover/PFTs, dual soil products, and SSP-consistent CO_2. ICP Forests serves exclusively for validation (Section 4.4), while HWSD2 and ISRIC support modelling and sensitivity testing. The same inputs enable WP4.1 G4M integration, where harmonised land-use/forest fractions provide scenario-consistent boundary conditions.

6. Stakeholder validation

Stakeholder validation was undertaken through an EU-level online co-design workshop on 11 December 2025, organised under WP1 (Stakeholder engagement strategy) to test the interpretability and plausibility of the scenario framing and to identify priority risks and management considerations relevant to SafeNet’s forest-sector analyses. Invitations were issued to 40 European-scale stakeholders spanning policy, industry, research, and civil society/NGOs, based on the EU-level stakeholder mapping conducted in WP1. The invite list covered EC policy contacts (SafeNet project/policy officers and additional contacts identified within DG ENV and DG CLIMA), large industrial actors, umbrella organisations representing forest owners/managers and regulatory actors (e.g., Forest Europe and related networks), certification bodies, and NGOs, alongside the SafeNet Advisory Board and a sister project. In total, 36 stakeholders registered and 13 stakeholders attended. Attendance was weighted toward NGOs, research and certification bodies, and umbrella organisations; EU-level policy officers did not attend, despite targeted outreach. Including project partners (speakers and facilitators), the session comprised 22 participants. Participants also provided their current country of residence via an interactive exercise, illustrating a broad European geographic spread (Figure 14).

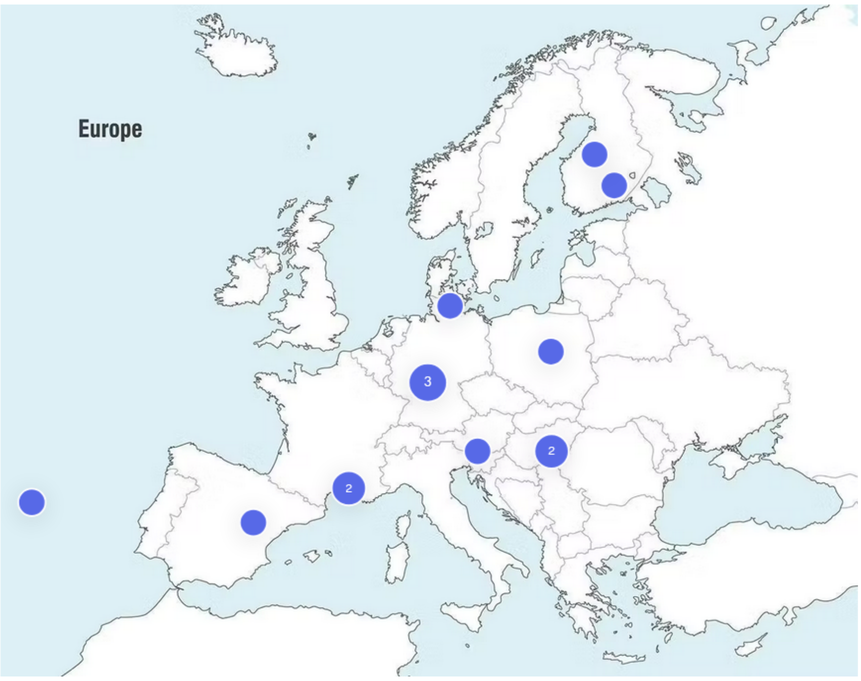


Figure 14. Geographic distribution of stakeholder workshop participants

The workshop followed an interactive format structured around two core topics: (i) discussion of the three selected scenarios and their perceived feasibility, ambition level, and key socio-economic and natural risks for the forestry sector; and (ii) a structured elicitation exercise on forest management options and the extent to which these may shift toward more “extensive/conservation-oriented” versus more “intensive/production-oriented” strategies under different futures. Each topic began with short plenary inputs, followed by facilitated break-out discussions supported by online tools (Mentimeter and Miro) and guided by a unified facilitator guide developed in collaboration with WP1 and WP3. Notes were captured in real time via the shared Miro board by both participants and facilitators, followed by plenary reporting-back and Q&A, during which additional notes were taken by the main facilitator. No video recordings were made, in line with agreed privacy rules. Following the workshop, facilitators produced consolidated written summaries from the break-out notes and plenary reporting.

Across discussions, participants broadly recognised the scenario bracket as a useful framing device but stressed that outcomes should be interpreted as conditional on implementation capacity. Comments highlighted practical constraints that can limit real-world delivery even under “ambitious” pathways (e.g., governance and funding limitations, policy continuity, and pressures such as grazing/browsing), as well as sector-relevant climate-risk concerns (e.g., more frequent hot–dry extremes, drought stress, dieback and elevated mortality, especially in parts of central and southern Europe). Participants also flagged broader socio-economic risks for the forestry sector (e.g., institutional constraints and enforcement challenges) that are typically under-represented in large-scale modelling exercises. These inputs were used to tighten the narrative framing in the deliverable, to make explicit that the boundary-condition package represents prescribed trajectories rather than guaranteed real-world pathways, and to prioritise regional diagnostics and transparent documentation of workflow limitations so that downstream ORCHIDEE and G4M-X results can be interpreted against the stakeholder-identified risk and feasibility lenses. Operational design reflects this guidance: (i) scenario-consistent land-use/PFTs in model-ready formats; (ii) spatial detail preservation for attribution (regional climate/soils); (iii) dual soil products for uncertainty quantification; and (iv) transparent documentation (DOIs, provenance, QC metrics) ensuring reproducibility (Figure 15).

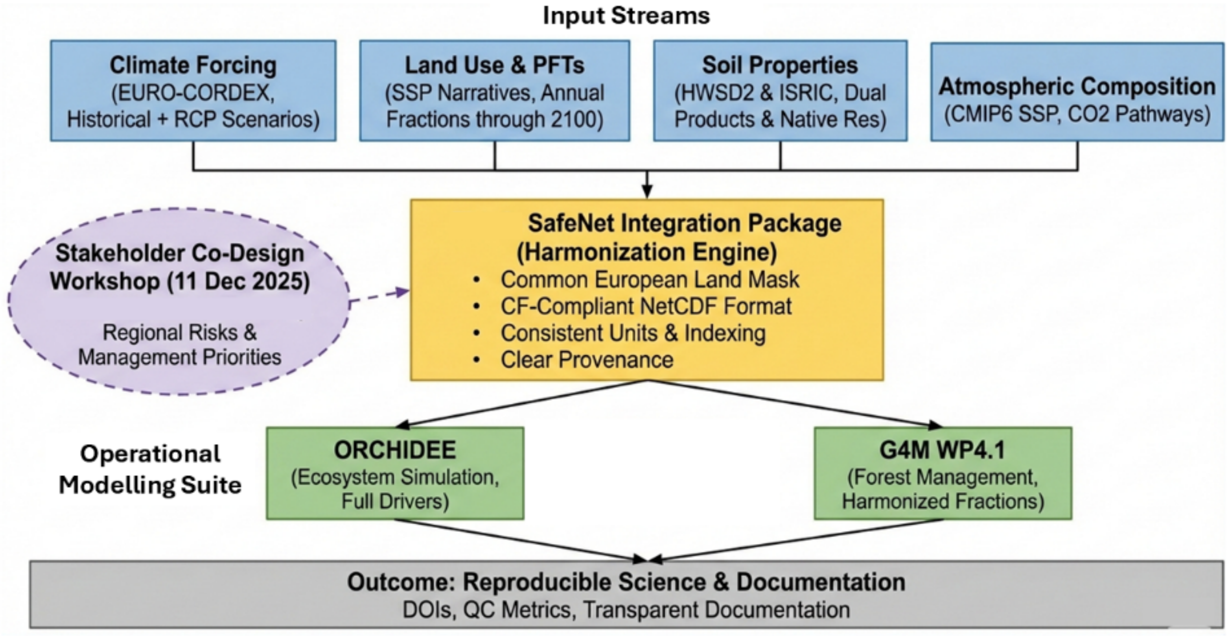


Figure 15. SafeNet scenario Data Integration and Modelling Workflow

Data availability

All SafeNet boundary-condition processing scripts (climate, land use/PFT, soils, CO_2) are provided in the project GitHub repository and are archived for long-term reproducibility on Zenodo as: Mahdi (Andre) Nakhavali & Di Fulvio (2026), SAFENET – Adopted land use scenarios with predicted forest expansion maps (release), Zenodo, doi:10.5281/zenodo.18175075.

Because the underlying input datasets are third-party products with their own licensing and ownership constraints, SafeNet does not redistribute the raw source data. Instead, we distribute the full processing pipeline (scripts + configuration + metadata/QC routines) that retrieves the authoritative source products from their original repositories and reproduces the harmonised, model-ready forcing layers described in this deliverable (subject to user access/registration requirements at those repositories).

Climate forcing data were obtained from the EURO-CORDEX/CORDEX ensemble (available via the ESGF nodes at https://euro-cordex.net/), complemented by the CHELSA climatologies (https://chelsa-climate.org/?utm_source=chatgpt.comhttps://www.chelsa-climate.org) for high-resolution baseline diagnostics. The land-use and land-cover boundary conditions were derived from the LUCAS-LUC historical dataset for Europe (1950–2015; DOI: 10.26050/WDCC/LUC_hist_EU_v1.1) and its future scenario extensions to 2100 (DOI: 10.26050/WDCC/LUC_future_EU_v1.1), together with LANDMATE PFT fractions (DOI: 10.26050/WDCC/LM_PFT_LandCov_EUR2015_v1.0). Upstream global land-use harmonisation followed the LUH2 CMIP6 dataset (https://luh.umd.edu). Atmospheric CO_2 trajectories were taken from CMIP6 input4MIPs greenhouse-gas concentration forcings (https://esgf-node.llnl.gov/search/input4mips/). Soil boundary data originated from ISRIC (https://soilgrids.org/) and the Harmonized World Soil Database v2.0 (HWSD2) (https://www.fao.org/soils-portal/soil-survey/soil-maps-and-databases/harmonized-world-soil-database-v20/en/).

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SafeNet

Safeguarding Biodiversity
and Carbon-rich Forest
Networks in Europe

Project Coordination

Jukka Forsman | jukka.forsman@luke.fi

Mikko Peltoniemi | mikko.peltoniemi@luke.fi

Jacqueline Moustakas-Verho | jacqueline.moustakas-verho@luke.fi

Project Communications

Mathilde Vidal | mathilde@erinn.eu

More Information

Website | safenet-project.eu

Bluesky | @safenet-eu.bsky.social

LinkedIn | @SafeNet Project

Funded by
the European Union

Funded by the European Union under the Horizon Europe Programme, Grant Agreement No. 101181981 (SafeNet). Views and opinions expressed are, however, those of the author(s) only and do not necessarily reflect those of the European Union or European Research Executive Agency (REA). Neither the European Union nor the granting authority can be held responsible for them.