Final report on methodology of land cover datasets for global and regional climate models, including publication of the data

D2.3

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About OptFor-EU

OptFor-EU wants to co-develop a Decision Support System (DSS) with forest managers and other forest stakeholders, that provides them with suitable climate adaptation and mitigation options for science-based optimising forest ecosystem services (FES) (including decarbonisation) and enhancing forest resilience and its capacities to mitigate climate change across Europe.

The project 'OPTimising FORest management decisions for a low-carbon, climate resilient future in Europe (OptFor-EU)' will build a Decision Support System (DSS) to provide forest managers and other relevant stakeholders with tailored options for optimising decarbonisation and other Forest Ecosystem Services (FES) across Europe.

Based on exploitation of existing data sources, use of novel Essential Forest Mitigation Indicators and relationships between climate drivers, forest responses and ecosystem services, OptFor-EU has five specific objectives:

- Provide an improved characterisation of the Forest-Climate Nexus and FES;
- Utilise end-user focused process modelling;
- Empower forest end-users to make informed decisions to enhance forest resilience and decarbonisation;
- Provide a novel DSS service; and
- Bridging different EU strategic priorities, robust science, and stakeholders in the forest and forest-based sectors.

Based on a supply-demand approach, the methodology combines an iterative process of data consolidation, modelling, and co-development of solutions alongside forest managers and other practice stakeholders in all European Forest Types. The DSS will be designed and tested at 8 case study areas, to provide a ready-to-use service, near to operational (TRL7) at European level, while a user adoption and up-take plan will maximise the societal and business impact.

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List of abbreviations

Acronym / Abbreviation	Meaning / Full text
AFM	Alternative Forest Management
BAU	Business-as-usual
CORDEX	Coordinated Downscaling Experiment
CRU	Climatic Research Unit
CSA	Case Study Area
EEA	European Environment Agency
EFT	European Forest Types
ESA CCI	European Space Agency Climate Change Initiative
FMP	Forest Management Practices
FPS	Flagship Pilot Study
GT-SUR	Ground Truth dataset of the LUCAS land use and land cover SURvey
LAI	Leaf Area Index
LANDMATE PFT	LAND surface modifications and its feedbacks on local and regional cliMATE Plant Functional Type
LUCAS	Land Use and Climate Across Scales
LUCAS LUC	Land Use and Climate Across Scales Land Use Change
LULCC	Land Use and Land Cover Change
RCM	Regional Climate Model
PFT	Plant Functional Types
WCRP	World Climate Research Program
WDCC	World Data Center for Climate

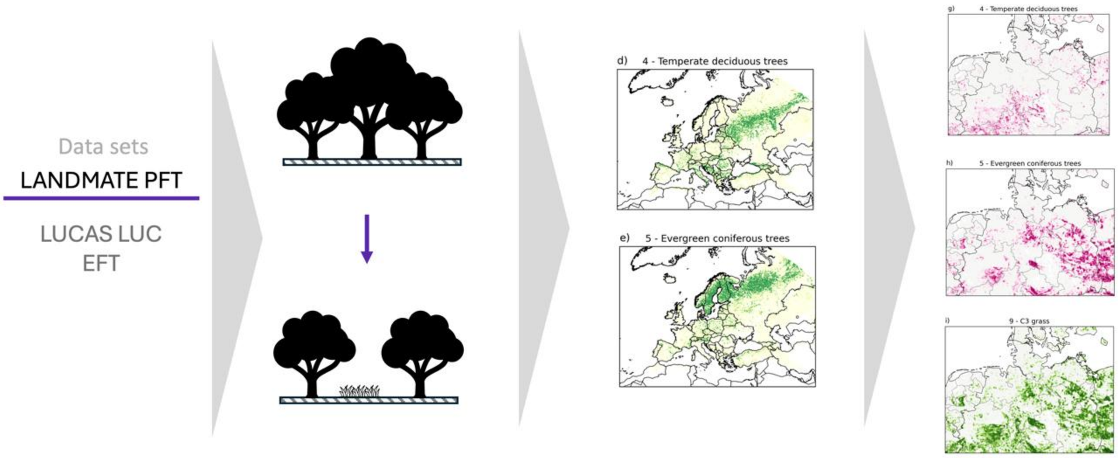
EXECUTIVE SUMMARY

This deliverable addresses the need for a land cover dataset with implemented forest management practices (FMPs) for regional climate models (RCMs). Within OptFor-EU, forest-climate interactions are studied with different model approaches, which have different requirements on their land cover datasets. After the context for this deliverable in Section 1, the available datasets within this project are described in Section 2.

- LANDMATE PFT dataset: A high-resolution (~ 2 km) land cover dataset suitable for RCM studies on convection-permitting scales in Europe.
- LUCAS LUC dataset: A high-resolution (~ 10 km) dataset showing historical and projected land use and cover changes, including future scenarios such as SSP126, which represents strong afforestation in Europe.
- EFT dataset: A detailed and consistent dataset (D1.1) representing the tree distribution across Europe at 100 m horizontal resolution.

In Section 3, we describe the implementation of the FMP thinning into the LANDMATE PFT dataset for two selected Case Study Areas (CSAs,) CSA4 (Eastern Lowlands of Lower Saxony, Germany) and CSA6 (Arges and Teleorman county, Romania). We align our assumptions with the forest model experiments in D2.2 *Report on new Forest Management Practices (FMP) in forest models and implications for land cover change parametrisation in climate models* (Neumann et al. 2024b), and adapt them to the feasibility of regional climate model (RCM) studies. In the end, a land cover dataset with implemented FMP is created that shows a reduced tree fraction and an increased grass fraction in model grid cells. The dataset is published at 0.0275° horizontal resolution for the two selected CSAs on a rotated grid at an openly accessible Zenodo repository. For addressing a different grid or additional CSAs, the source code for creating the dataset is published as well (Pop et al. 2024). Section 4 gives an outlook on the implementation of this dataset into RCMs, which will affect land surface properties and lead to effects and feedback in the atmosphere through altered land-atmosphere exchange processes. Section 5 provides an overview of the data and code availability used for this deliverable.

Graphical Abstract



1. Context

Within OptFor-EU, the interaction between forest and climate is studied with different modelling approaches. These approaches have different requirements, which were compiled as part of a project-wide survey (Table 1). The aim of this deliverable is to develop a new dataset for regional climate models (RCMs), which includes forest management practices (FMPs), building the basis for modelling the effects and feedbacks of FMP on local and regional climate conditions. This dataset has to match the requirement of both RCMs used within this project, REMO2020-iMOVE and RegCM5+CLM4.5. The simulations will be conducted for selected CSAs on high resolution (~ 3 km), which implies the need of a high-resolution land cover dataset. The choice of a suitable land cover dataset is crucial in regional climate modelling. Land cover datasets define the spatial distribution of land surface characteristics, which determine land-atmosphere exchange processes (Hoffmann et al. 2023).

In accordance with D2.1 *Report on the FMP and their relevance in different CSA* (Neumann et al. 2024a) and D2.2 *Report on new Forest Management Practices (FMP) in forest models and implications for land cover change parametrisation in climate models* (Neumann et al. 2024b*)*, and as a result of stakeholder information collected within the framework of this project, it was decided to implement the forest management practice of thinning forest stands. Thinning plays an important role in business-as-usual (BAU) forest management (D2.1, Neumann et al. 2024a), modifying land surface properties, which affect the exchange of energy and substances between land and atmosphere. Therefore, we expect various effects and feedbacks on local and regional climatic conditions.

After providing an overview and comparison of existing land cover datasets applied within OptFor-EU (Section 2), this deliverable describes the implementation of the selected FMP thinning in the selected land cover dataset at high spatial resolution making it suitable for regional climate modelling on 3 km resolution (Section 3).

Table 1: Landcover dataset requirements for all models within WP2.

Partner	Model	EFT/PFT datasets used until now	EFT map or different EFT/PFT dataset required?	Spatial resolution	Spatial extent	Geogr. projection	Temp. resolution	Temp. extent	Format
CNR	Forest model 3D-CMCC-FM	Forest data	EFT map	Min. ~ 1 km	entire Europe	none, WGS84 (preferred)	At the beginning of simulation	none	.txt; .csv
BOKU	Forest model PICUS	Forest data	EFT map	1 hectare	entire Europe	none, WGS84 (preferred)	none	none	.tif
GERICS/ Hereon	RCM REMO 2020-iMOVE	GLC2000, LUCAS LUC PFT (tested)	PFT maps, Continental scale: built on existing datasets	Continental scale: ~ 10 km	Continental scale: entire Europe	Rotated coordinate system	yearly	Continental scale: 1950 – 2100	.nc

			(LUCAS LUC)						
	RCM REMO 2020-nh-iMOVE		CSA: high-resolution data (eg. LANDMATE PFT) with included FMP	CSA: ~ 0.0275° (~3 km)	CSA: Lower-Saxony, Arges and Teleorman county			CSA: best no time constraint	
NMA	RCM RegCM5+ CLM4.5	LUCAS LUC (tested)	PFT maps, Continental scale: built on existing datasets	Continental scale: ~ 10 km	Continental scale: entire Europe	Lambert Conformal	yearly	Continental scale: 1950 – 2100	.nc, .grib
	RCM RegCM5+ CLM4.5		CSA: high-resolution data (eg. LANDMATE PFT) with	CSA: ~ 0.0275° (~3 km)	CSA: Arges an Teleorman county			CSA: best no time constraint	

			included FMP						
MOHC	Land surface model (JULES)	ESA CCI LC (converted to PFTs)	EFT maps and PFT maps	EFT map	CSAs	WGS84	single' representa tive' period (baseline) or yearly time series	flexible	.nc

2. Land cover data sets for Europe and CSAs

2.1. LANDMATE PFT dataset

The LAND surface modifications and its feedbacks on local and regional cliMATE (LANDMATE) – plant functional type (PFT) dataset is a gridded, high-resolution dataset created for regional climate modelling studies by Reinhart et al. (2022b). The LANDMATE PFT dataset provides PFT maps for Europe for the period 1992-2015 in 0.1° (~10 km) resolution and a PFT map for Europe for the year 2015 in 0.018° (~2 km) (Fig. 1). The dataset was published by Reinhart et al. (2022a) and is freely available at the World Data Center for Climate (WDCC) at the German Climate Computing Center (DKRZ):

https://doi.org/10.26050/WDCC/LM_PFT_EUR_v1.1

The LANDMATE PFT dataset represents land use and land cover with 16 PFTs (Annex 1, Fig. 1), of which six PFTs are related to tree distributions (Fig. 2): Tropical Broadleaf Evergreen Tree, Tropical Broadleaf Deciduous Tree, Temperate Broadleaf Evergreen Tree, Temperate Broadleaf Deciduous Tree, Coniferous Evergreen Tree, and Coniferous Deciduous Tree. PFTs became a common concept in Earth System Modelling (Poulter et al. 2015) as they group land use and land cover according to similar phenological and physiological characteristics. The biophysical and biogeochemical characteristics of the PFTs, which are often represented as a mosaic of the land tile of the model grid cell, affect exchange processes between land and atmosphere.
The LANDMATE PFT dataset is based on the ESA CCI land cover dataset but extends it by the consideration of climate information: 2 m mean temperature and precipitation data derived from the observational datasets E-OBS (Cornes et al. 2018) and CRU (Harris et al. 2020). This climate data is used to define the Holdrige life zones (Holdrige, 1967), a commonly used method for ecosystem classification (Wilhelm et al. 2014, Zeng et al., 2002). The LANDMATE PFT dataset was generated by combining the satellite-based land cover data from ESA CCI with the Holdridge life zones derived from the climate data, using regridding methods and cross-walking procedures. The quality of the LANDMATE PFT dataset was evaluated against ground truth data from GT-SUR. In addition, the map of 2015 was also compared to the ESA Poulter map 2015 (Reinhart et al. 2021).
The evaluation and comparison showed good quality of LANDMATE PFTs particularly for the tree PFTs, which makes it suitable for its use within OptFor-EU (Reinhart et al. 2022b). Further, the LANDMATE PFT dataset is the basis for the LUCAS LUC dataset, which is also used by both RCMs in WP2 in OptFor-EU.

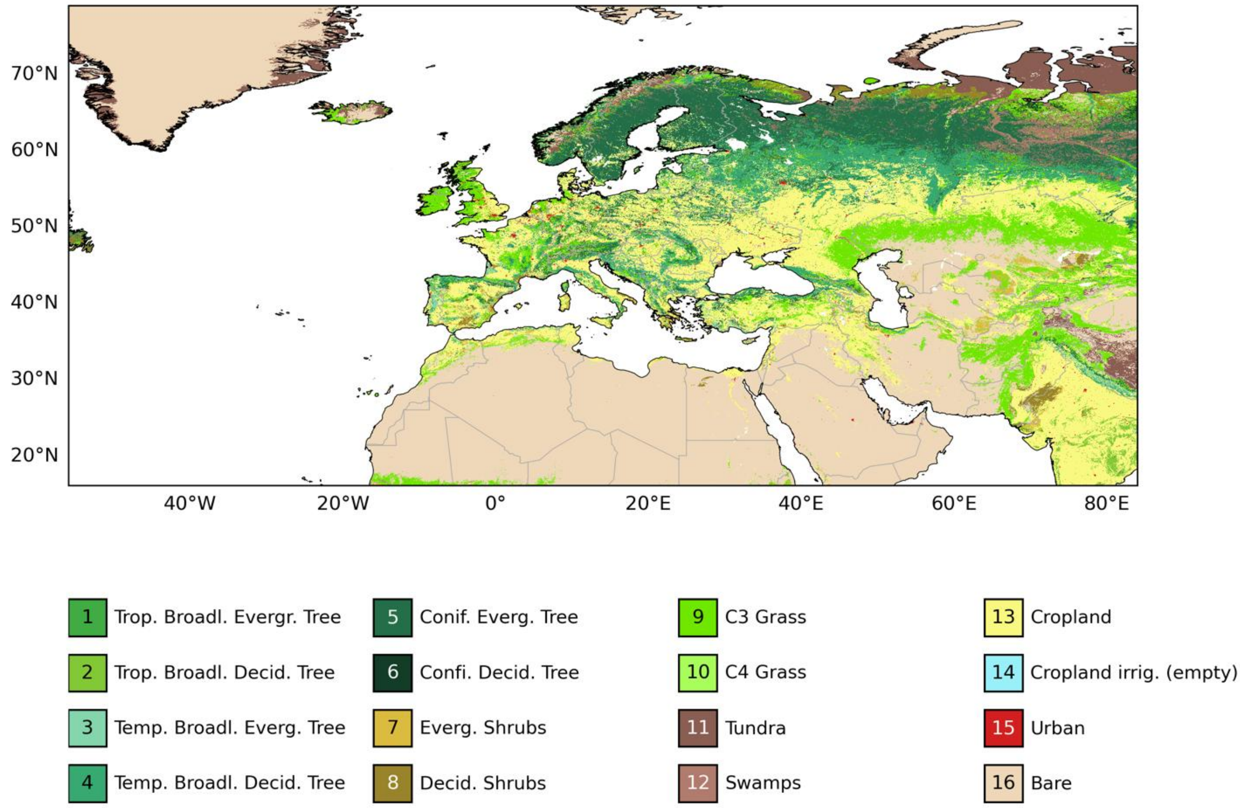


Figure 1: Spatial distribution of dominant PFT classes in the LANDMATE PFT map 2015 at 0.018° (~2 km) horizontal resolution.

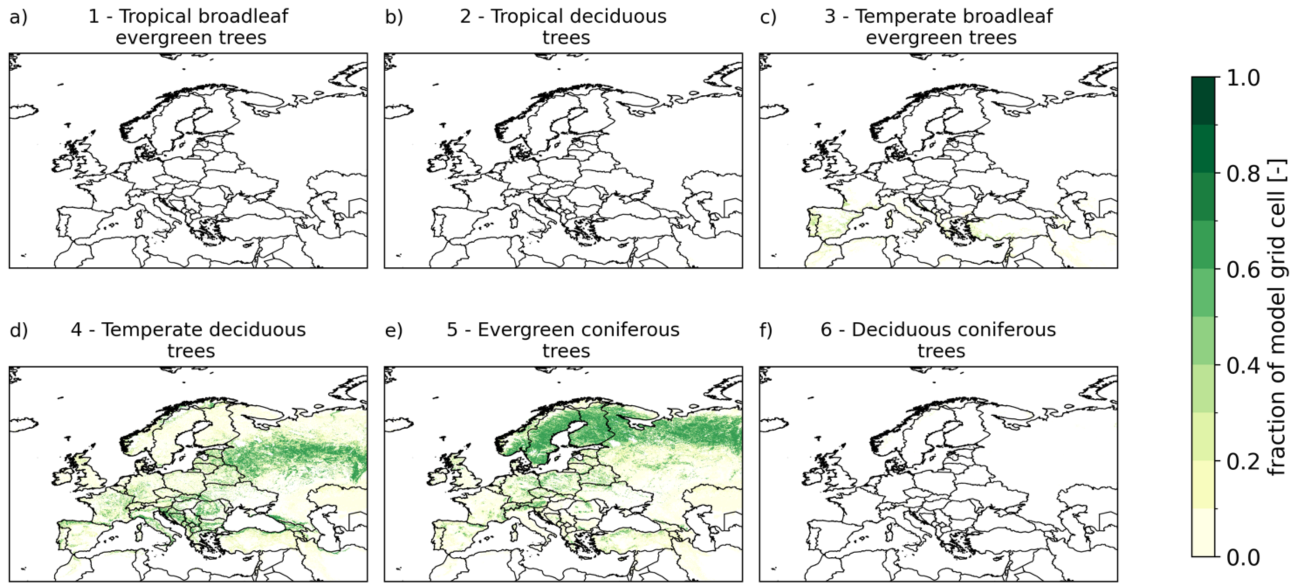


Figure 2: Spatial distribution of tree PFTs in the LANDMATE PFT map of 2015 at 0.018° (~2 km) horizontal resolution.

2.2. LUCAS LUC dataset

Based on the LANDMATE PFT map of 2015, the land use land cover change dataset LUCAS LUC was developed by Hoffmann et al. (2023). This dataset retains the same PFT definitions but extends it by including data for the PFT "cropland irrigated". In addition, LUCAS LUC extends the LANDMATE PFT dataset by a long-term temporal dimension, accounting for annual land use and land cover changes (LULCC) for the historical period 1950-2015, as well as for different land use change scenarios projected until 2100. These annual LULCC were generated based on information on land use transitions from the Land-Use Harmonization 2 (LUH2) dataset (Hurtt et al., 2020), which was developed as a global dataset for historical and future land use scenarios within the World Climate Research Program (WCRP) Coupled Model Intercomparison Project (CMIP). Using the land cover of 2015 from the LANDMATE PFT dataset at 0.1° horizontal resolution, land use transitions were translated to annual changes of PFT fractions, which are calculated backwards in time to 1950 (historical, Hoffmann et al., 2022b) as well as forwards in time to 2100 for various SSP scenarios (future, Hoffmann et al., 2022a) employing a newly developed land use translator by Hoffmann et al. (2023). In LUCAS LUC, tree cover is given special attention. The development of European tree PFTs from 1950 – 2010 is based on the dataset from McGrath et al. (2015).

The procedure generated annual LULC maps on 0.1° horizontal resolution tailored to the requirements of the regional climate modelling community. For the European continent, the LUCAS LUC dataset was compared to multiple LULCC datasets. More details of the development and the uncertainties of LUCAS LUC are given in Hoffmann et al. (2023). The datasets were published by Hoffmann et al. (2022a, b) and are open access, available at the WDCC at DKRZ:

LUCAS LUC historical land use and land cover change dataset for Europe (Version 1.1) at WDCC at DKRZ: https://doi.org/10.26050/WDCC/LUC_hist_EU_v1.1

LUCAS LUC future land use and land cover change dataset for Europe (Version 1.1) at WDCC at DKRZ: https://doi.org/10.26050/WDCC/LUC_future_EU_v1.1

By representing transient LULCC at comparatively high resolution, LUCAS LUC addresses the need to consider transient LULCC in regional climate modelling studies. LUCAS LUC became an established dataset in the regional climate modelling community by its use in the WCRP Coordinated Downscaling Experiment (CORDEX) Flagship Pilot Study (FPS) Land Use and Climate Across Scales (LUCAS, Rechid et al. 2017).

Within OptFor-EU, we employ the LUCAS LUC dataset for Europe-wide simulations, which cover all CSAs, for the historical period as well as for future scenarios. As LUCAS LUC includes changes in forest cover (Fig. 3 - Fig. 5), it allows for the investigation of the effects of afforestation and deforestation on regional climate. For the future scenario, we selected the SSP126, which not only considers the strongest afforestation assumptions (Hurtt et al. 2020, van Vuuren et al. 2017), but we also expect a distinct signal from LULCC to atmospheric processes, which is not overlaid by strong greenhouse gas forcings as in scenarios with higher greenhouse gas concentrations.

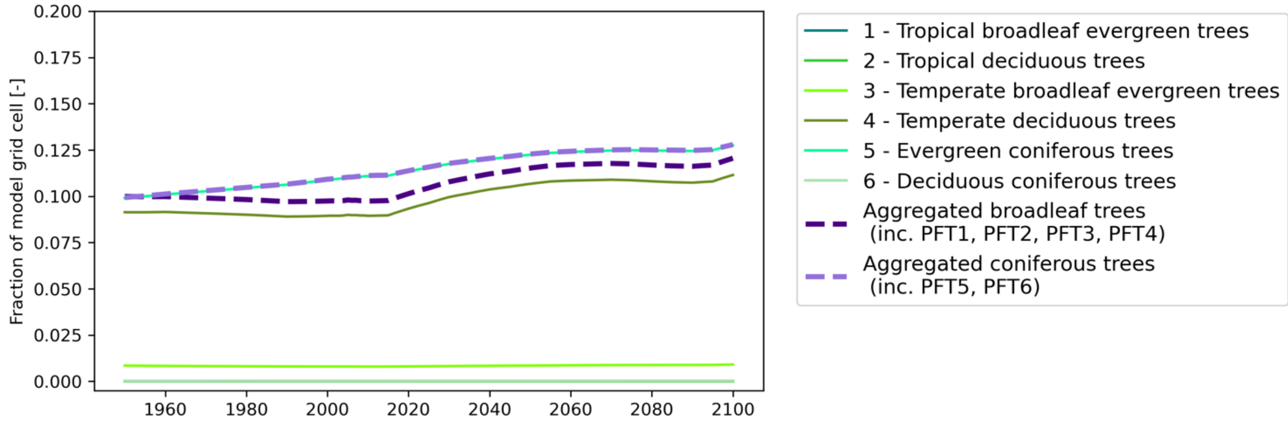


Figure 3: Development of tree PFTs and aggregated tree types in LUCAS LUC in grid cells of 0.1° horizontal resolution averaged over the European continent for the historical period (1950 – 2015) and the future scenario SSP126 (2015 – 2100). PFT1, PFT2, PFT6 are overlaying each other due to their negligible extent in Europe.

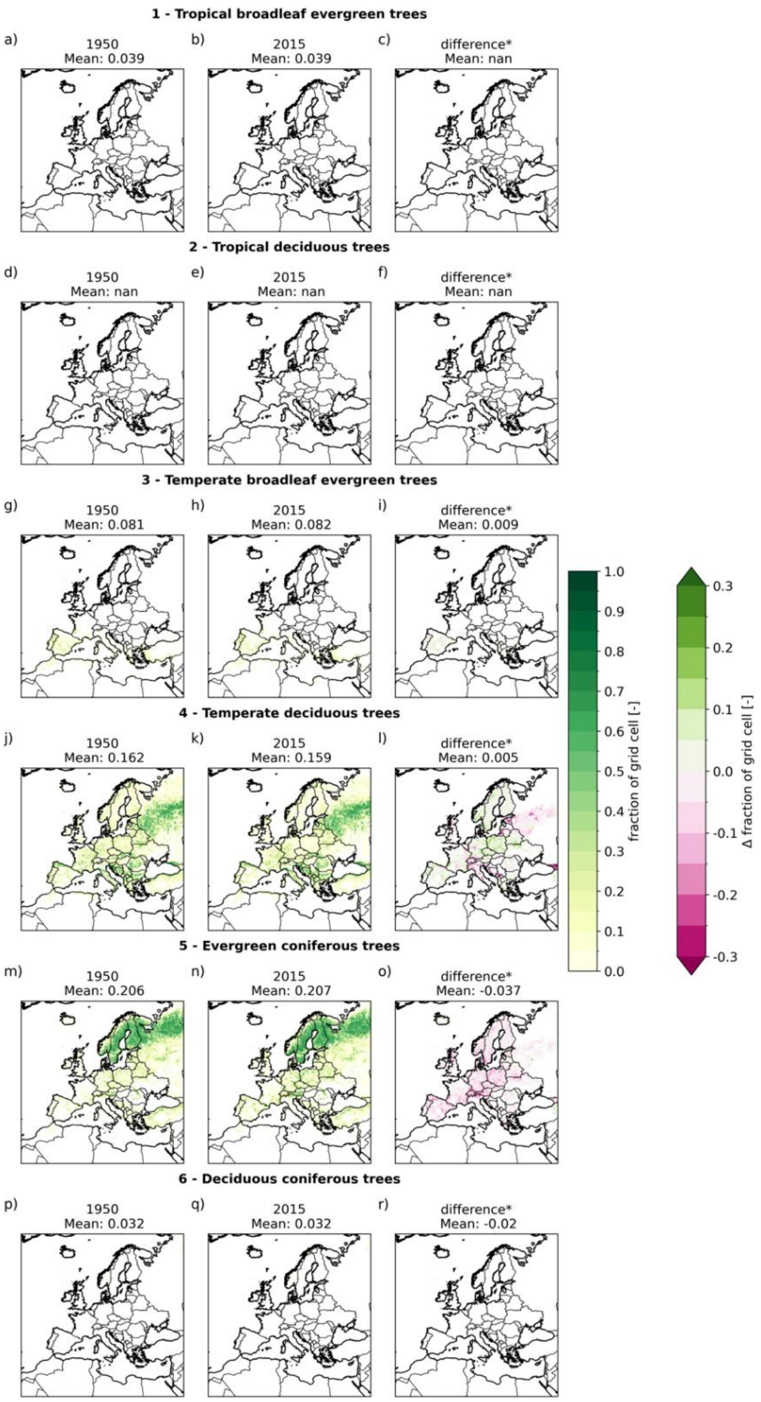


Figure 4: Spatial distribution of tree PFTs in LUCAS LUC at 0.1° horizontal resolution. Comparison of the spatial distribution in 1950 (first column) and 2015 (second column) and its difference (third column). *difference = distribution of 1950 - distribution of 2015.

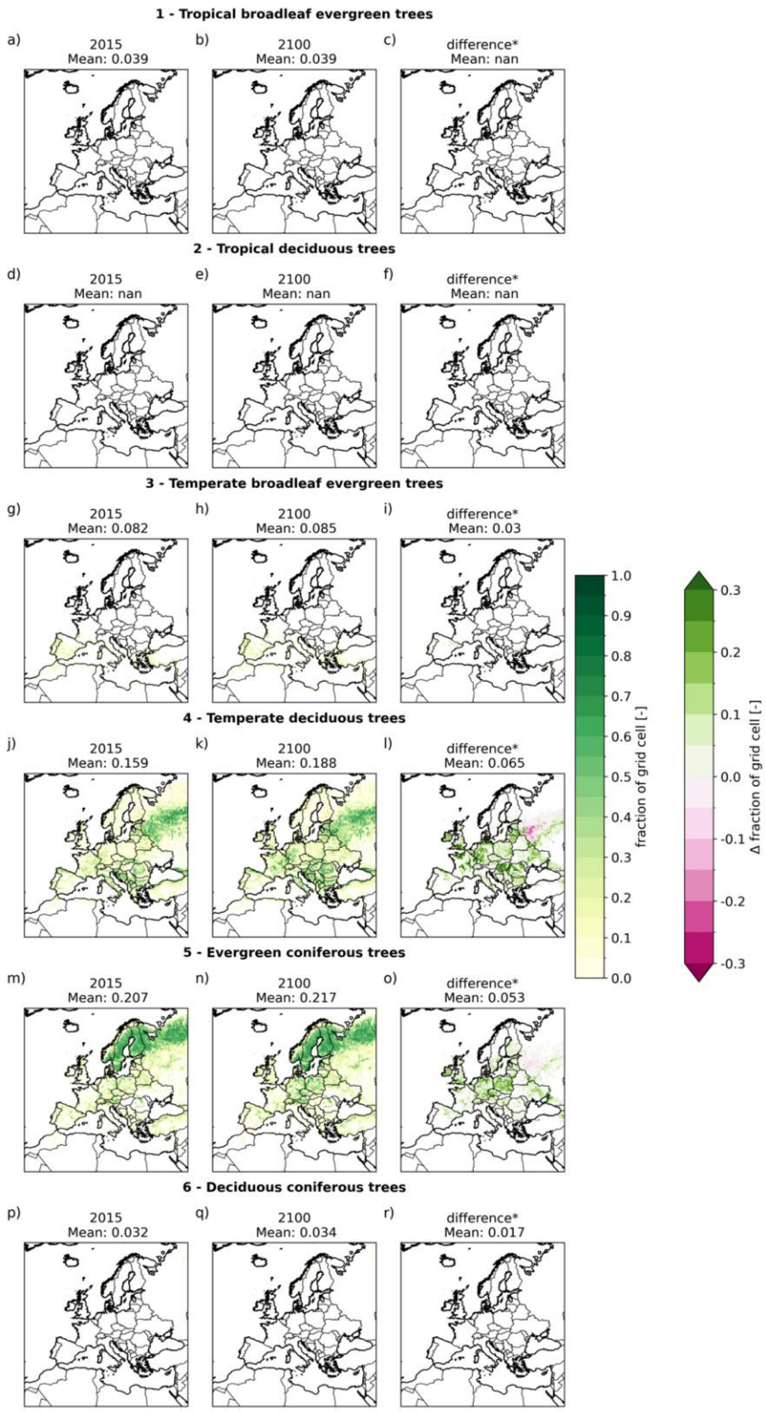


Figure 5: Spatial distribution of tree PFTs in LUCAS LUC at 0.1° horizontal resolution. Comparison of the spatial distribution in 2015 (first column) and 2100 (second column) and its difference (third column). *difference = distribution of 2100 - distribution of 2015.

2.3. EFT dataset

The EFT dataset created for D1.1 *Gridded dataset of European Forest Types* (Gianetti & Zorzi, 2023) is a gridded, high-resolution dataset, describing the distribution of 14 forest tree species in Europe at 100 m horizontal resolution (Fig. 6). It considers information on biogeographic regions, bioclimate, natural vegetation, water, soil wetness, and the orography. In order to create this dataset, the procedure from Gianetti et al. (2018), was extended to include additional datasets on river catchments and forest types from the EEA. This dataset is a static dataset, involving maps from the year 2017. It focuses on providing a detailed, consistent representation of forest types. However, it does not incorporate temporal changes for the past period nor for future scenarios. Further information on its development can be found in D1.1 *Gridded dataset of European Forest Types* (Gianetti & Zorzi, 2023).

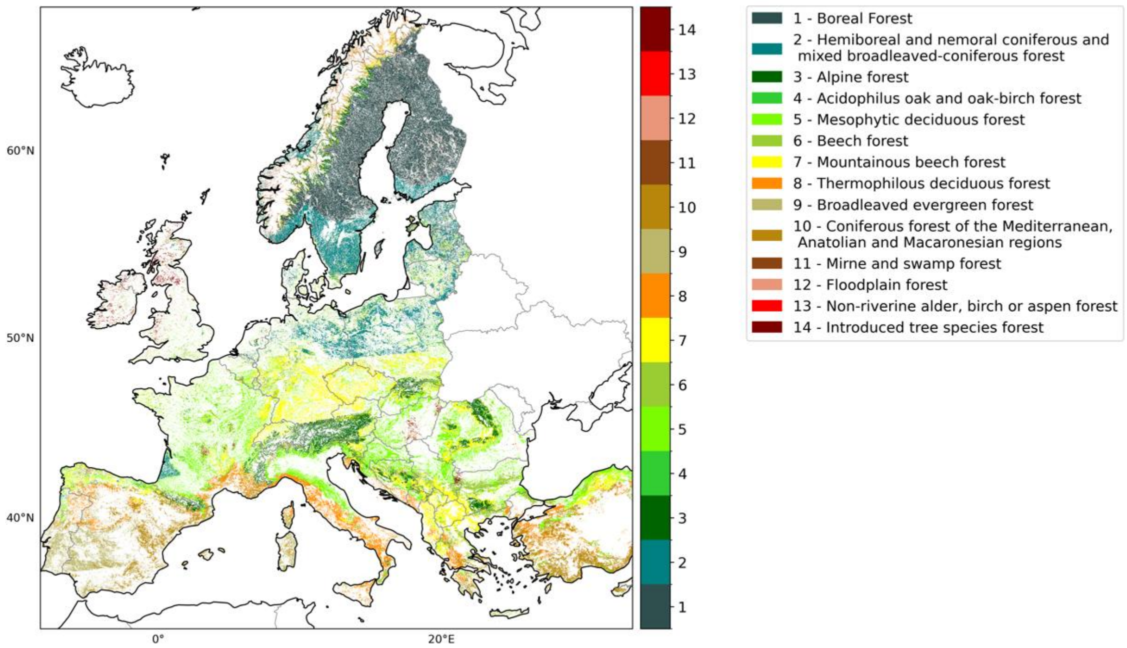


Figure 6: Spatial distribution of EFTs at 100 m horizontal resolution.

2.4. Comparison of LANDMATE PFT and EFT datasets

All three datasets, LANDMATE PFT dataset, LUCAS LUC, and the EFT dataset show different levels of detail in representing the spatial distribution of forests and trees. In the following, we compare the LANDMATE PFT map 2015 on 0.018° and the EFT dataset to estimate the differences in the spatial distribution of forest and tree classes within each dataset. For comparing purposes, we also include the ESA CCI PFT dataset from Harper et al. (2023). In the comparison procedure, we first aggregate and interpolate the EFT dataset and the ESA CCI PFT dataset to 0.018°, which is the coarsest resolution of all three datasets and the original resolution of the LANDMATE PFT dataset. Secondly, we classify broadleaved and coniferous trees in each dataset according to Table 2 and analyse the aggregated data in two selected CSAs, CSA 4 (Eastern Lowlands in Lower Saxony, Germany, Fig. 7) and CSA 6 (Arges and Teleorman counties, Romania, Fig. 8).

Table 2: Classification and aggregation of the different tree and forest classes in the three datasets EFT dataset, LANDMATE PFT dataset and ESA CCI dataset.

	LANDMATE dataset	ESA CCI	EFT dataset
Original resolution	0.018° (~ 1 km)	300 m	100 m
Class aggregation	broadleaved 1 - Tropical broadleaved evergreen trees 2 - Tropical deciduous trees 3 - Temperate broadleaved evergreen trees 4 - Temperate deciduous trees	broadleaved Broadleaved deciduous trees (TREES-BD) Broadleaved evergreen trees (TREES-BE)	broadleaved 4 - Acidophilus oak and oak-birch forest 5 - Mesophytic deciduous forest 6 - Beech forest 7 - Mountainous beech forest 8 - Thermophilous deciduous forest 9 - Broadleaved evergreen forest

			11 - Mire and swamp forest 12 - Floodplain forest 13 - Non-riverine alder, birch or aspen forest
	coniferous 5 - Evergreen coniferous trees 6 - Deciduous coniferous trees	coniferous Needleleaved evergreen shrubs (TREES-ND) Needleleaved evergreen trees (TREES-NE)	coniferous 1 - Boreal Forest 2 - Hemiboreal and nemoral coniferous and mixed broadleaved-coniferous forest 3 - Alpine forest 10 - Coniferous forest of the Mediterranean, Anatolian and Macaronesian regions
	mixed -	mixed -	mixed 14 - Introduced tree species forest

Figure 7 shows the spatial distribution of broadleaved (a-c) and coniferous trees (d-f) in CSA4 (Eastern Lowlands of Lower Saxony). For CSA4, forests and trees are concentrated on the eastern part of Lower Saxony. Broadleaved trees are mainly found in south-east (Fig. 7a-c), whereas coniferous trees are mainly found in north-east of the analysis region, namely the Eastern Lowlands of Lower Saxony (Fig. 7d-f).

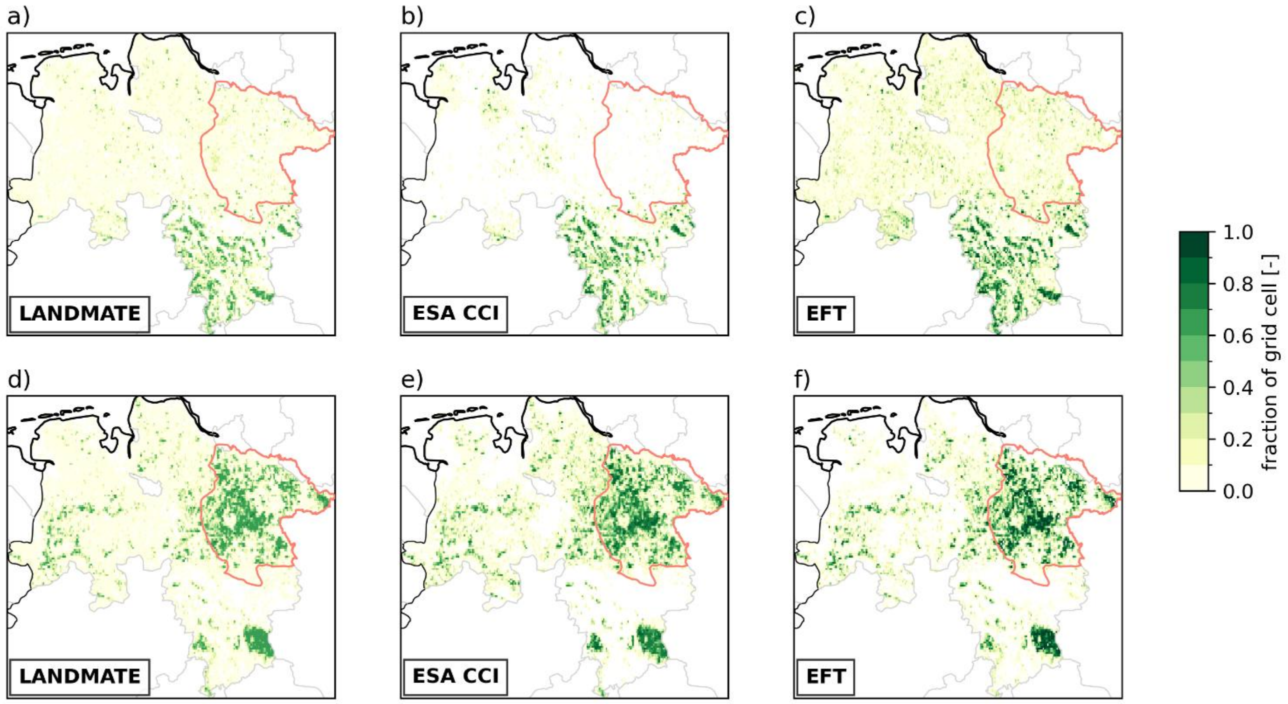


Figure 7: Spatial distribution of aggregated broadleaved (a - c) and coniferous (d - f) trees from the PFTs and EFTs datasets. Data is shown as fraction of grid cells with 0.018° horizontal resolution for CSA4 (Eastern lowlands of Lower Saxony, red outline).

The forests of Lower Saxony cover about 25% of the state's land area, totalling around 1.2 million hectares (NMELV, 2024). These forests are spread across three main regions: the Eastern Lowlands around 430,000 hectares, the Lower Saxony Uplands, and the Western Lowlands with each less than 400,000 hectares. In Lower Saxony, approximately 30% of the forest area consists of broadleaf forests, 21% is coniferous forests, and mixed forests make up about 49% of the total forested area. The most common coniferous species are Scots pine (*Pinus sylvestris*, 29%) and Norway spruce (*Picea abies*, 12%). Most common broadleaved species are European beech (*Fagus sylvatica*, 14%) and oak (*Quercus* spp., 13%). Conifer-dominated forests are common in the sandy, less fertile soils of the Eastern Lowlands. In contrast, the Lower Saxony Uplands, including the Harz Mountains and Solling, have more diverse forests with a higher presence of broadleaved species. Recent trends show a shift towards mixed forest structures.

Recent studies using remote sensing and machine learning have enhanced our understanding of tree species distribution across Germany. Welle et al. (2022) used Sentinel-2 time series data to map dominant tree species, highlighting the effectiveness of these methods for regional forest assessments. Similarly, Blickensdörfer et al. (2024) combined Sentinel-1 and Sentinel-2 data with National Forest Inventory (NFI) datasets to map 11 tree species classes, considering mixed-species stands and environmental gradients. A comparison with the mapping of dominant tree species by Welle et al. (2022) aligns well with the distribution patterns presented in Figure 7 for Lower Saxony.

In CSA6 (Fig. 8) broadleaved trees are the dominant class (Fig. 8a-c). Coniferous trees (Fig. 8d - f) are located mainly in the north of the CSA, in the Carpathian Mountains. The Vața area in the Argeș Region of Romania is home to a diverse range of forest tree species, reflecting the region's varied ecological conditions. Coniferous species such as Norway spruce are prevalent in the higher altitudes of the Carpathian Mountains, thriving in cooler, moist conditions (García-Duro et al., 2021; Bonannella et al., 2022). Silver fir (*Abies alba*) is also common in these areas, often found alongside Norway spruce (García-Duro et al., 2021). Broadleaved species are well-represented, with European beech dominating the lower and mid-altitude forests (San-Miguel-Ayanz et al., 2016). Sessile oak (*Quercus petraea*) and pedunculate oak (*Quercus robur*) are prevalent in the lower altitudes and valleys, benefiting from the warmer and drier conditions (García-Duro et al., 2021; Bonannella et al., 2022).

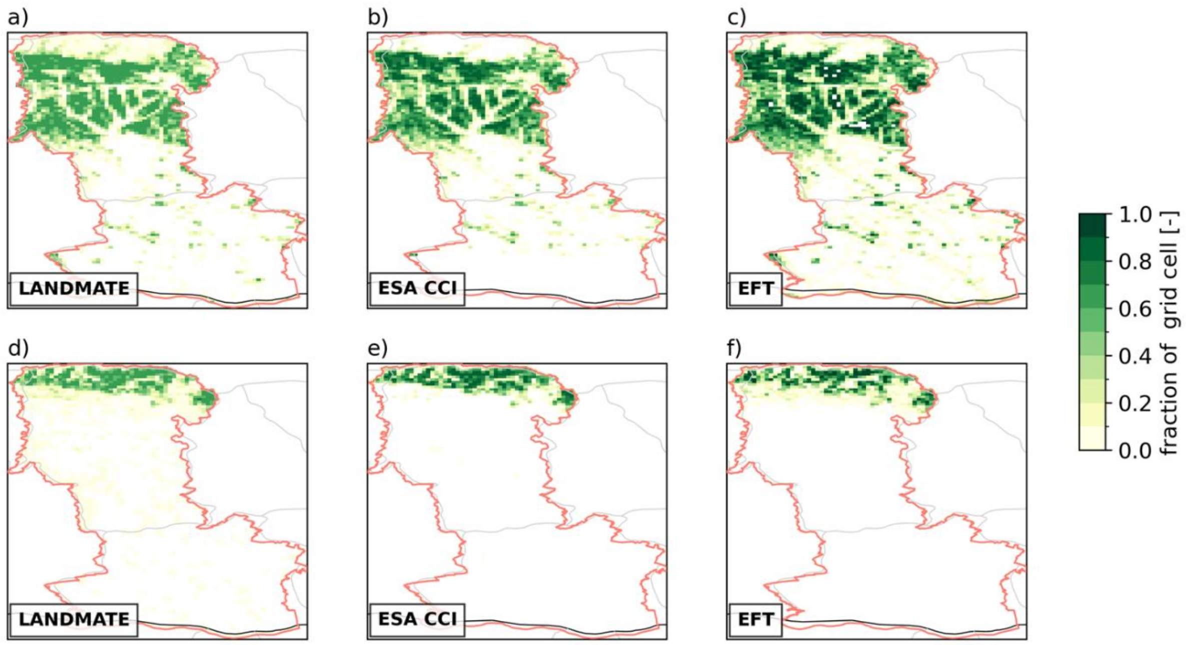


Figure 8: Same as Figure 7. Spatial distribution of aggregated broadleaved (a - c) and coniferous (d - f) trees from the PFTs and EFTs datasets. Data is shown as fraction of grid cells with 0.018° horizontal resolution for CSA 6 (Arges and Teleorman county, red outline)

In general, all three datasets show the same patterns of the distribution of the tree classes. However, the LANDMATE PFT dataset shows in general the lowest tree fraction, whereas the EFT dataset shows the highest tree fractions for broadleaved and coniferous trees (Fig. 9). Furthermore, the LANDMATE PFT dataset and the EFT dataset show low fractions all over Lower Saxony, whereas the ESA CCI dataset doesn't show any tree distribution. The differences in the datasets appear mainly due to different classification and definitions of land cover.

In general, the datasets show good agreement. We selected the high-resolution LANDMATE PFT map for 2015 at 0.018° horizontal resolution as the basis for implementing the FMP thinning. With the high-resolution, the PFT concept and the consideration of climatic zones, it is a suitable dataset for regional climate modelling studies.

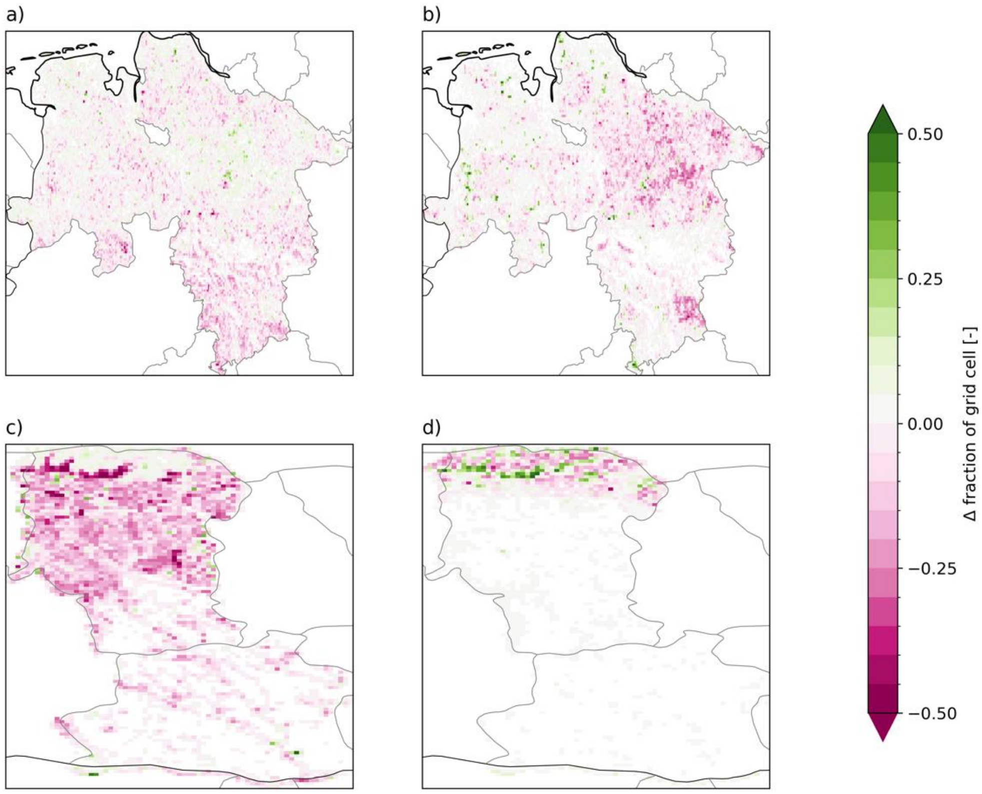


Figure 9: Difference between the spatial distribution of broadleaved (a and c) and coniferous trees (b and d) in the LANDMATE PFT and the EFT dataset shown as fraction of grid cells with 0.018° horizontal resolution for CSA4 (Eastern lowlands of Lower Saxony) (a and b) and CSA6 (Arges and Teleorman county) (c and d).

3. Including FMP in landcover dataset

3.1. European high-resolution landcover dataset

As the first step in implementing FMPs in the LANDMATE PFT dataset that can be used by RCMs, we interpolate the LANDMATE PFT map 2015 to the model grid. We plan to do high-resolution simulations on convection-permitting scale at 0.0275° horizontal resolution. On convection-permitting scales convective processes are resolved, whereas on coarser scales (> 4 km) they must be parameterized and are one major source of uncertainties in regional climate model simulations (Kendon et al. 2021). We interpolate the LANDMATE PFT dataset from its original 0.018° horizontal resolution to 0.0275° using the conservative interpolation method. Conservative interpolation preserves the sum of the quantities of the dataset and does not add new values. It is a suitable method for interpolating discontinuous variables such as landcover fractions or precipitation. Further, our regional climate models use a rotated coordinate system. Rotated coordinate systems have the advantage of equally sized grid cells, which simplifies equations. Together with the interpolation of the LANDMATE PFT dataset to 0.0275° horizontal resolution, we rotate the coordinate system.

The result for the six tree PFTs is shown in Figure 10. The distribution of all PFTs can be found in Annex 1, Figure 2. The spatial distribution of the tree fractions shows that Europe's tree distribution is mainly defined by temperate deciduous trees (Fig. 10d) and evergreen coniferous trees (Fig. 10e). Evergreen coniferous trees are widely spread in Northern Europe. Temperate broadleaved trees and evergreen trees are present with very low fractions in Southern Europe (Fig. 10c). Deciduous coniferous trees are found exclusively in Siberia, while tropical tree PFTs don't play a role in Europe.

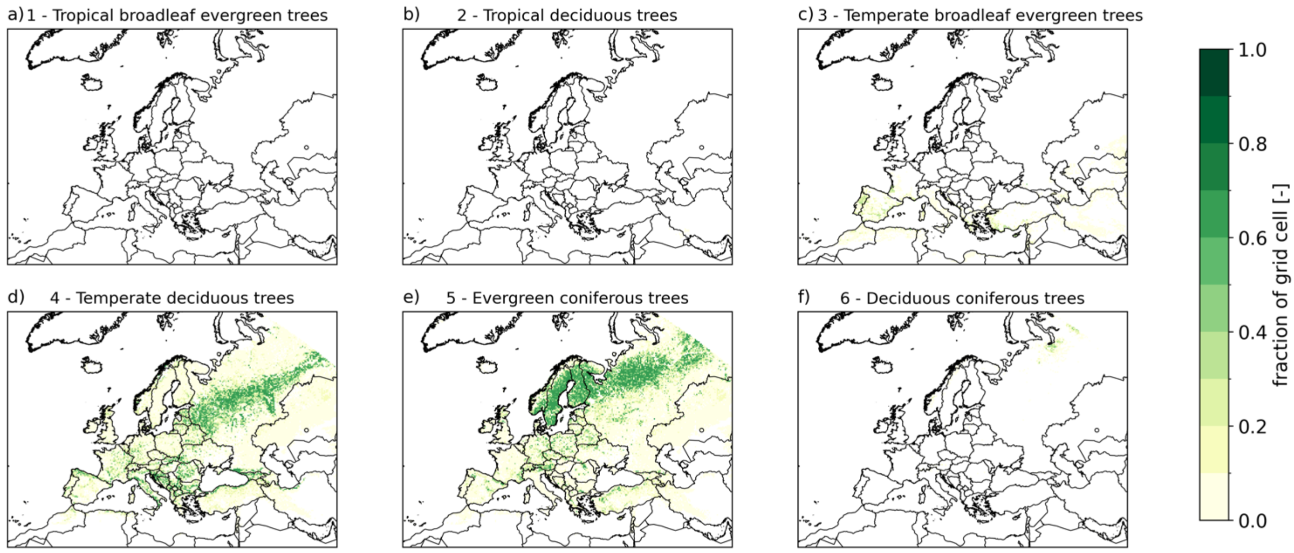


Figure 10: Spatial distribution of tree PFTS in LANDMATE PFT 2015 dataset interpolated to 0.0275° for the entire European continent.

3.2. Representing FMP in regional climate modelling

In accordance with D2.2 *Report on new Forest Management Practices (FMP) in forest models and implications for land cover change parametrisation in climate models* (Neumann et al. 2024b) and the forest model simulations, we selected thinning as FMP to implement in our regional climate model simulations. Thinning of forest stands is a critical silvicultural practice involving the selective removal of trees to reduce competition for resources among the remaining trees, thereby enhancing their growth and vitality (Forest Research, 2011). By decreasing tree density, thinning improves access to light, water, and nutrients, which can result in increased growth rates and improved tree health (Forest Research, 2011). Additionally, it can help mitigating wildfire risks by reducing fuel loads, thereby influencing fire behaviour and protecting forest ecosystems (Moreau et al., 2022). Thinning can help shaping desired stand structures and compositions, which are often key objectives in sustainable forest management (Forest Research, 2011). Furthermore, thinning plays a crucial role in supporting forest resilience to climate change by fostering the development of robust and diverse tree species that are better equipped to withstand environmental stresses (Ganatsas et al., 2024). However, thinning can also have drawbacks. For instance, it may increase the risk of windthrow, where trees are uprooted by strong winds, as previously sheltered trees become more exposed (del Rio et al. 2017). It can also disrupt soil and water systems, potentially leading to soil erosion or compaction, and changes in water quality (Moreau et al., 2022). Moreover, thinning operations can affect sensitive habitats and species, requiring careful consideration of biodiversity impacts.

Thinning also influences the local microclimate by altering forest structure. It increases light penetration and air movement within the forest, raising soil and air temperatures while reducing humidity (Menge et al., 2023). Thinning can increase the surface albedo of forest stands, with effects being more pronounced in broadleaved stands compared to coniferous ones (Otto et al., 2014). Additionally, thinning may enhance carbon sequestration by promoting the growth of remaining trees, which absorb more carbon dioxide (Ganatsas et al., 2024), although this effect is not always consistent (Mund et al., 2002). Accordingly, thinning requires careful, adaptive management to balance its ecological benefits with socio-economic and environmental risks.

Thinning results in a less dense forest. In a land cover dataset with PFT fractions, thinning can be represented by decreasing the tree PFT fractions and increasing the grass PFT fraction (D2.2, Neumann et al. 2024b). By changing the tree-grass proportion in a model grid cell, the land surface properties are directly affected. In an RCM, land surface properties such as albedo and LAI are averaged for the land tile of a grid cell with respect to their fraction and seen as aggregated value by the atmosphere. Surface roughness, another land surface property, is aggregated using the blending height concept (Claussen et al., 1991). These direct modifications of the land surface characteristics affect atmospheric conditions by land-atmosphere interactions, changing for example evapotranspiration, near-surface temperature and the humidity profile, which are important climate regulation variables (D1.2, Linser et al., in prep.). More details on the effects and feedbacks of thinning can be found in D2.2 *Report on new Forest Management Practices (FMP) in forest models and implications for land cover change parametrisation in climate models* (Neumann et al. 2024b*)*.

In order to represent thinning in a land cover dataset suitable for RCMs, thinning characteristics need to be adapted to the land surface representation in RCMs. The driving characteristics are the thinning intensity and its frequency. D2.1 *Report on the FMP and their relevance in different CSA* (Neumann et al. 2024a) and D2.2 *Report on new Forest Management Practices (FMP) in forest models and implications for land cover change parametrisation in climate models* (Neumann et al. 2024b*)* show that the intensity varies with the tree type, tree age and the region. However, in our RCMs REMO2020-iMOVE and RegCM5+CLM4.5, trees are represented as PFTs. Therefore, for aligning the RCM experiments with the forest model experiments, the EFTs must be translated to PFTs from the LANDMATE dataset, with multiple EFTs falling in one PFT class (Tab. 3). The LANDMATE dataset shows that the European tree distribution is mainly defined by temperate deciduous trees (Fig. 10d) and evergreen coniferous trees (Fig. 10e). Furthermore, there is no tree age representation in our RCMs, which allows only one mean intensity for each PFT. In regional climate modelling, it is possible to implement thinning with business-as-usual (BAU) thinning intensities as well as to follow extreme thinning scenarios as new alternative forest management (AFM) with higher thinning intensities, which are expected to show distinct thinning effects and feedbacks. One way of addressing the thinning frequency is to prescribe an already thinned forest in the land cover dataset to the RCMs enabling the comparison to not thinned forest using the regular dataset.

Table 3: Allocation of EFTs to LANDMATE PFTs.

LANDMATE PFT	EFT
1 - Tropical broadleaved evergreen trees	-
2 - Tropical deciduous trees	-
3 - Temperate broadleaved evergreen trees	9 - Broadleaved evergreen forest
4 - Temperate deciduous trees	4 - Acidophilus oak and oak-birch forest 5 - Mesophytic deciduous forest 6 - Beech forest 7 - Mountainous beech forest 8 - Thermophilous deciduous forest 11 - Mire and swamp forest 12 - Floodplain forest 13 - Non-riverine alder, birch or aspen forest 14 - Introduced tree species forest
5 - Evergreen coniferous trees	1 - Boreal Forest 2 - Hemiboreal and nemoral coniferous and mixed broadleaved-coniferous forest 3 - Alpine forest 10 - Coniferous forest of the Mediterranean, Anatolian and Macaronesian regions

6 - Deciduous coniferous trees	-

3.3. FMP in selected CSAs

We selected the thinning procedures from BAU in D2.2 Report on new Forest Management Practices (FMP) in forest models and implications for land cover change parametrisation in climate models (Neumann et al. 2024b) (FM1 – FM3) and averaged the thinning intensities from FM1 – FM3, assuming uniformly distributed age classes, as RCMs typically cannot account for tree age. The averaging resulted in a thinning intensity of 14.8%. Consequently, we applied a thinning intensity of 15% to the tree PFTs in the LANDMATE PFT dataset. For a better comparison of the effects and feedback caused by thinning, we apply the same thinning intensity to all tree PFTs in the LANDMATE PFT dataset across different regions. The tree PFT fraction of each grid cell is decreased, while the C3 grass fraction is increased by the same factor, as C4 grass plays a rather negligible role in the LANDMATE PFT dataset for Europe (Fig. 11, Fig. 12). The results are shown in Figures 11 and 12. These changes in proportions will be prescribed to the RCMs in order to investigate their influence on land-atmosphere exchange processes and quantify the effects on atmospheric variables.

In addition to the dataset for the two CSAs, which uses a rotated coordinate system, we address the issue of varying coordinate systems across different RCMs (Tab.1) by developing and publishing the source code for the dataset creation (Pop et al. 2024). The code can be adapted to any target coordinate system and extended for additional CSAs.

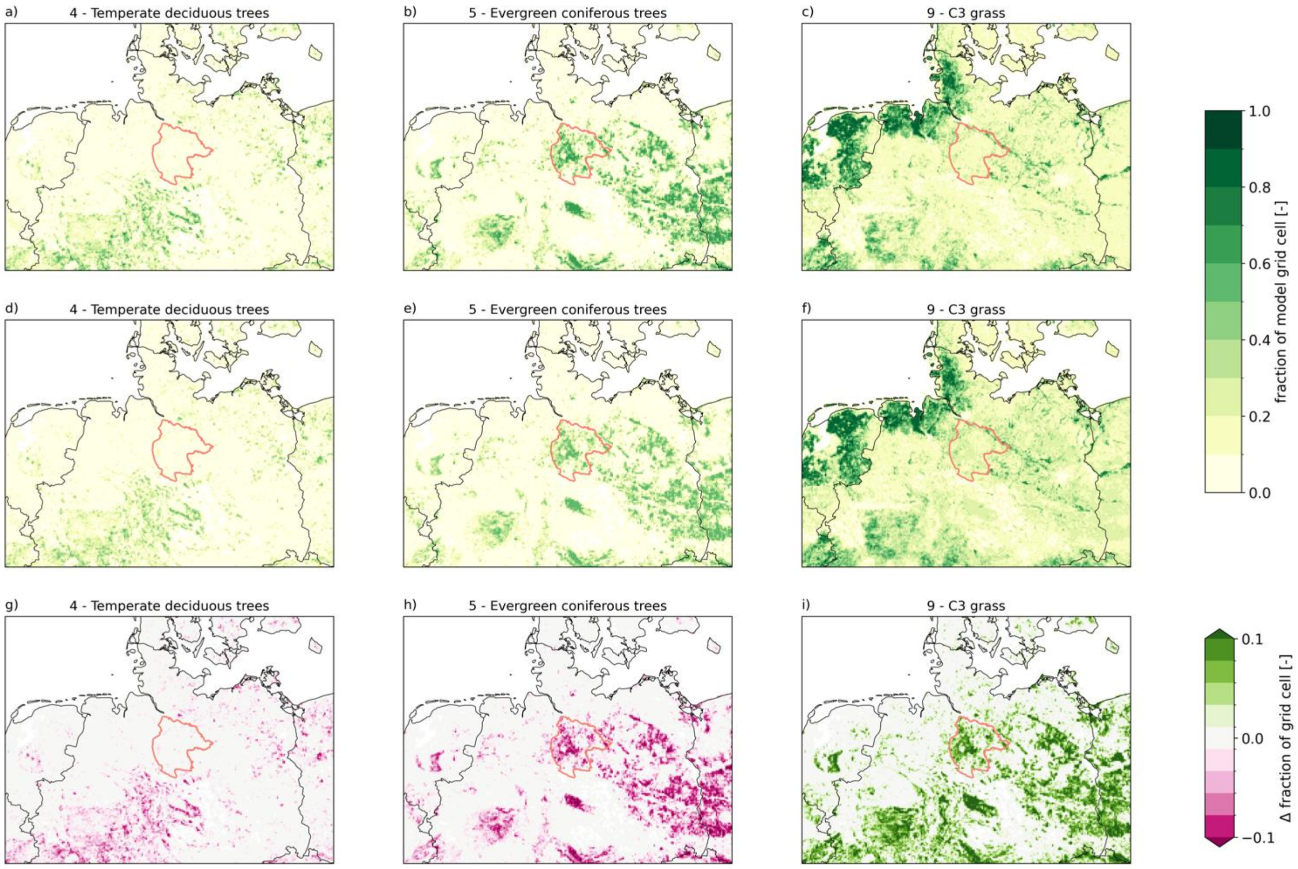


Figure 11: Spatial distribution of affected PFTs by thinning (15%) in the LANDMATE dataset for the model domain covering CSA4 (Eastern Lowlands of Lower Saxony). Panels a-c) show the original data, d-f) display the data after applying the thinning procedure (new dataset), and g-i) illustrate the differences between the original dataset and the thinning procedures. Data is interpolated to 0.0275° and rotated to the target model grid.

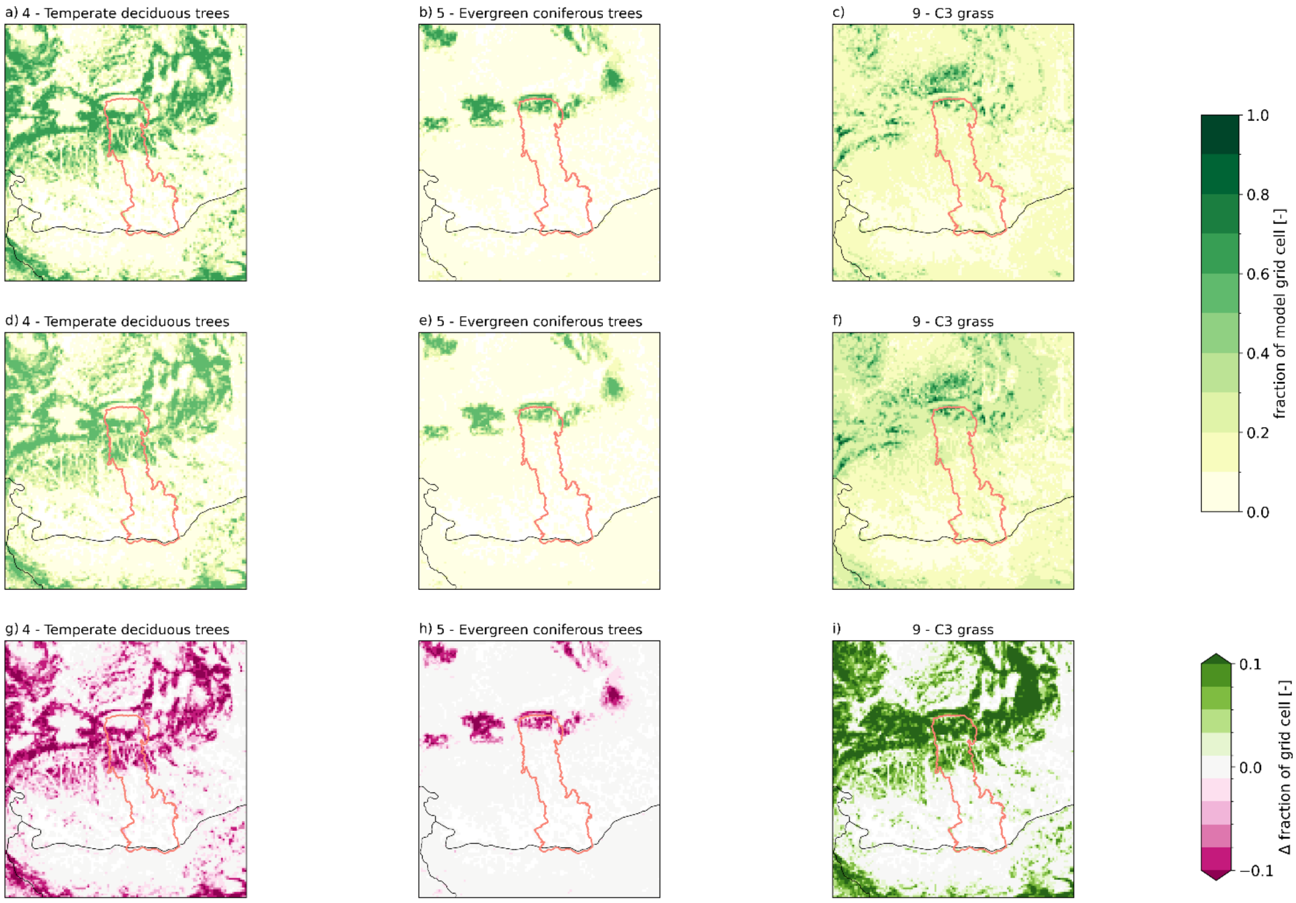


Figure 12: Spatial distribution of affected PFTs by thinning (15%) in the LANDMATE dataset for the model domain covering CSA6 (Arges and Teleorman county). Panels a-c) show the original data, d-f) display the data after applying the thinning procedure (new dataset), and g-i) illustrate the differences between the original dataset and the thinning procedures. Data is interpolated to 0.0275° and rotated to the target model grid.

4. Summary and outlook

The different model approaches within OptFor-EU are associated with different requirements on the representation of land cover (Tab. 1). The two RCMs, REMO2020-iMOVE and RegCM5+CLM4.5, conduct coordinated simulations. The first set of RCM simulations is conducted for the European continent covering all CSAs and using the new dataset LUCAS LUC developed by Hoffmann et al. 2023. These experiments include transient LULCC at 0.11° horizontal resolution. After evaluation experiments, which assess the uncertainty of our models using reanalysis forcing, we conduct experiments for the historical period (1950 – 2014) and for the SSP126 scenario (2015 - 2100) implying strong afforestation.

In order to represent the FMP thinning, we will conduct a second set of RCM simulations for selected CSAs on convection-permitting scale at 0.0275° (~3 km) horizontal resolution. For this set of simulations, a high-resolution dataset with an implemented thinning procedure had to be developed. In this deliverable we describe the development of a new land cover dataset that includes thinning for both selected CSAs: CSA4 (Eastern Lowlands in Lower Saxony) and CSA6 (Arges and Teleorman county). We use the LANDMATE dataset at 0.018° horizontal resolution as basis and, as first step, interpolated it to our target resolution of 0.0275°. As second step, we implemented thinning with a changed tree-grass-proportion in the grid cells. We take advantage of the different model approaches in OptFor-EU and link our assumptions to the experiments conducted by the forest models in D2.2 *Report on new Forest Management Practices (FMP) in forest models and implications for land cover change parametrisation in climate models* (Neumann et al. 2024b*)* under the BAU procedures. The dataset is publicly available for the two selected CSAs. For addressing different coordinate systems or additional CSAs, the source code for the dataset creation is published with the data (Pop et al. 2024).

The new data will be implemented in both RCMs and simulations for both CSAs will be performed with and without the FMP thinning. The effects of changes in forest-grass proportions on land surface characteristics and land-atmosphere exchange processes will be examined, along with further impacts and feedback on the atmosphere and climatic patterns. Here, we will focus mainly on regional climate regulating variables selected in D1.2 *Report on a novel set of Essential Forest Mitigation Indicators (EFMIs), including indicator factsheets with open-access code* (Linser et al., in prep.):

- Temperature
- Precipitation
- Soil moisture
- Evapotranspiration

- Water vapour content
- Runoff

5. Code and data availability

The LANDMATE PFT dataset can be freely downloaded from the WDCC at the German Computing Center DKRZ under https://doi.org/10.26050/WDCC/LM_PFT_EUR_v1.1

The LUCAS LUC dataset can be downloaded from WDCC under https://doi.org/10.26050/WDCC/LUC_future_EU_v1.1 for future time period, and under https://doi.org/10.26050/WDCC/LUC_hist_EU_v1.1 for the historical period.

The EFT dataset is available as D1.1 within the OptFor-EU project.

The dataset with the implement FMP as well as the code for its generation is published on Zenodo under https://doi.org/10.5281/zenodo.14450424.

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ANNEX 1 LANDMATE PFT map 2015

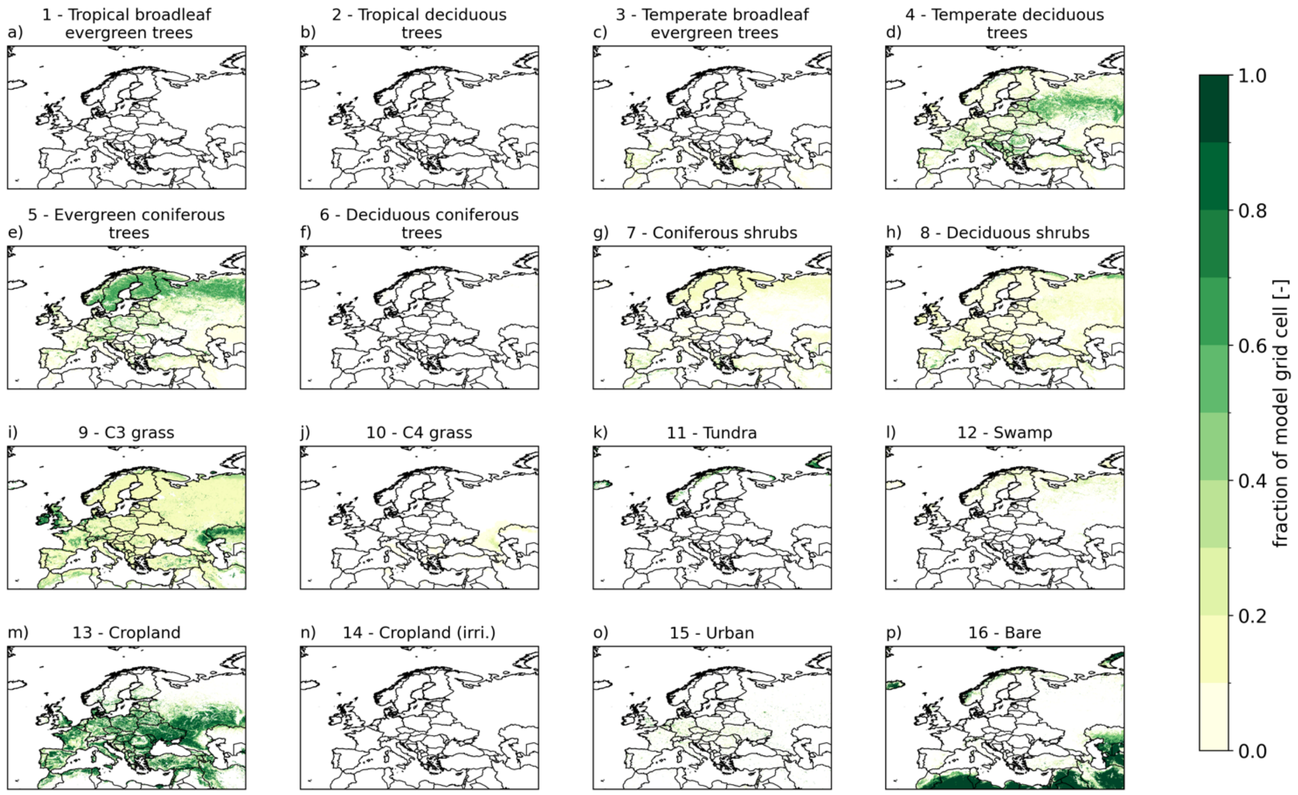

Figure 1: Spatial distribution of all PFTs in the LANDMATE PFT map of 2015 distribution at 0.018° horizontal resolution.

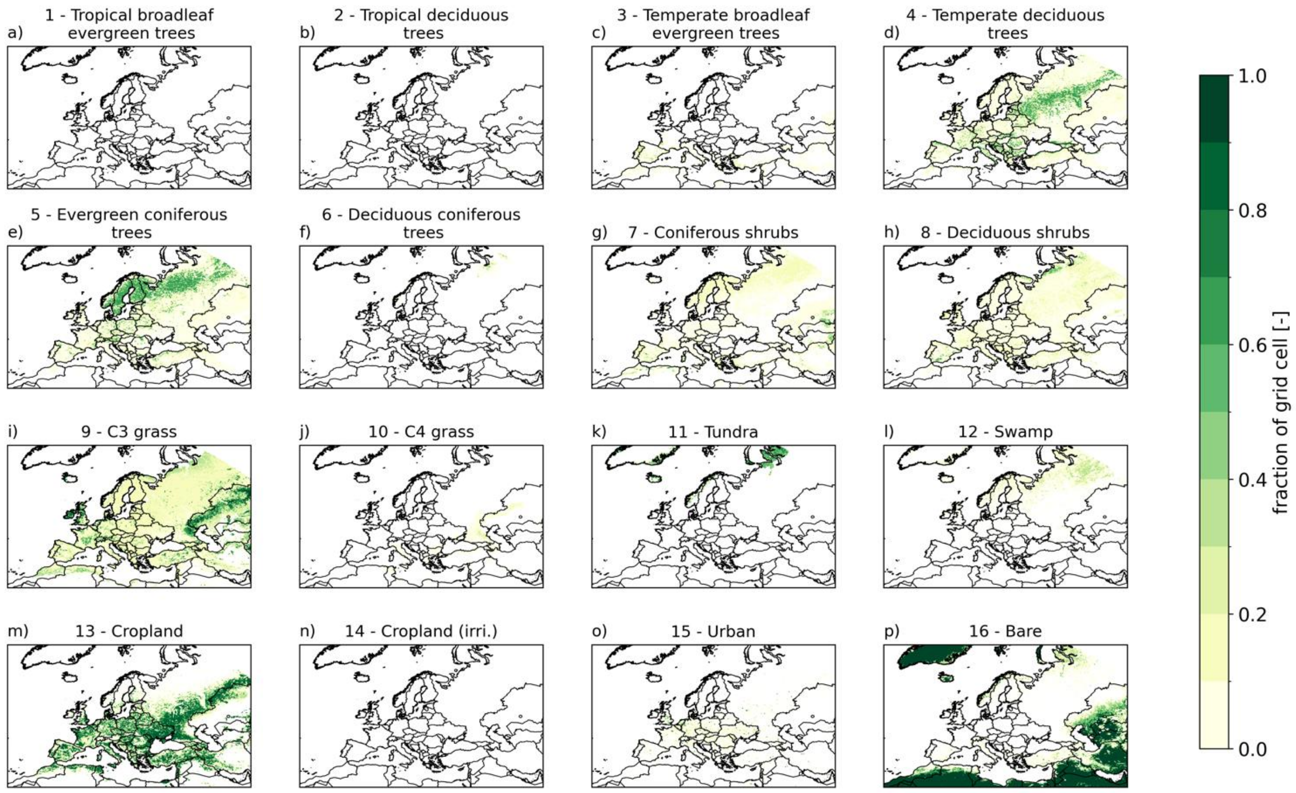

Figure 2: Spatial distribution of all PFTs in the LANDMATE PFT map of 2015 distribution conservative interpolated to 0.0275° horizontal resolution.

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