FIREURISK - DEVELOPING A HOLISTIC, RISK-WISE STRATEGY FOR EUROPEAN WILDFIRE MANAGEMENT

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D3.2 – Continental land-use change scenarios and stylised fuel management scenarios for the 21st century

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Executive Summary

Purpose of the report

This Deliverable is a companion document to the datafiles found at the following link DataverseNL entitled, “Continental Land Use Change scenarios and stylized fuel management scenarios” of the FirEUrisk project. As part of Work Package 3, “Adaptation to future fire regimes,” D3.2 sought to develop future land use scenarios for 2015 and the decades from 2020 to 2050. The 1960-2050 land use dataset is an integral data input for Dynamic Global Vegetation Models (DGVM) by incorporating variables critical to fuel distribution across European landscapes, such as afforestation, forest fragmentation, and land abandonment, which will in turn improve the ability of the DGVMs to forecast future fire regimes [1], [2]. Therefore, this deliverable also includes a harmonization effort that links the land use change scenarios to historic reconstructions for the 1960-2015 period. This report details the methods used to generate the scenario data and the current status of the stylized fuel management scenarios being developed in parallel with D2.4 (“Map of land management strategy options at European scale”) in WP2.

Main findings

Given the DGVM need for consistency with historic land use data, we linked the scenarios to representations of historical land use back to the year 1960. Historic baseline data was provided via the HILDA+ dataset [3], which combines several open data streams to estimate land use change (LUC). Although other datasets exist which seek to reconstruct land use in the 20th century, such as the Historical Database of the Global Environment (HYDE) [4], they are generally not specific to Europe and are based on assumptions about management practices and/or relationships between land cover types for the period. The future land use scenarios were simulated using CLUMondo, a spatially explicit and dynamic land system change model [5]. We adopted Shared Socioeconomic Pathways (SSP) 1 (“Sustainability”) and SSP3 (“Regional rivalry”) to explore the effects on land use of divergent developmental paths for Europe. While the time series developed is based on a 1-km resolution, we made a conversion in aggregating the data to a 9-km resolution and an aggregated land cover class legend to match that used natively in the DGVMs.

Early results for D2.4 on land management strategies (LMS) to reduce fire risk are presented to identify the pathway towards implementing these in the scenarios. Based on a systematic literature review and expert input, we focus on three LMS: removal of vegetation (e.g., silviculture, pruning), herbivory (e.g., grazing), and prescribed burn (e.g., traditional burning practices). The results will be used to develop stylized scenarios which will be superimposed on the CLUMondo scenarios and will explore possible consequences of different levels of LMS uptake on land use in a second tier of WP3.

Conclusions and next steps

To understand potential policy trade-offs in the EU, such as the Green Deal, and practices, such as traditional prescribed fire use, on Land use change and fuel distribution across European landscapes, and to adapt and prepare accordingly, models are needed which can test how such policies and practices may affect fuel composition and distribution. Operationalizing a successful strategy to abate the negative effects of wildfire and manage the tradeoffs of fuel management in the context of Europe's heterogeneous landscapes, socioeconomics, and land-uses calls for a holistic understanding of the risks in current and future climatic, political, and socioeconomic conditions [6]–[8]. This deliverable presents more accurate land use scenarios for the 21st century which focus on landscape characteristics that are relevant to fire risk management in the EU.

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List of Acronyms

HILDA+	HIstoric Land Dynamics Assessment +
LUC	Land Use Change
DGVM	Dynamic Global Vegetation Models
SSP	Shared Socioeconomic Pathway
RCP	Representative Concentration Pathway
CLUMondo	Conversion of Land Use at Mondial scale
LMS	Land Management Strategy
FAO	Food and Agriculture Organization
CMIP6	Coupled Model Intercomparison Project
CHELSA	Climatologies at high resolution for the earth's land surface areas
CORINE	Coordination of Information on the Environment; here, the land cover inventory managed by the European Environmental Agency
HYDE	History database of the Global Environment
LUH'2	Land Use Harmonization^2
LULC	Land Use or Land Cover
EU	European Union

1 Introduction

In ancient and present day cultures, fire can be used anthropogenically for many purposes, such as food procurement, e.g., driving or attracting game, vegetation management, e.g., to encourage regrowth of fodder for animals [9], or to create more mosaic type landscapes, encouraging advantageous biodiversity [9], [10]. Wildfire can also play an important role in ecosystems, creating diversity in landscape patterns and species compositions [11], [12]. However, a complex combination of climate [13], [14] and land use change (LUC) creates new patterns, or regimes, of fire across European landscapes [1], [11], [15], [16]. Fires are becoming more intense, more frequent, or present in areas which have not typically been associated with fire [17]. Operationalizing a successful strategy to abate the negative effects of wildfire and manage the tradeoffs of fuel management in the context of Europe's heterogeneous landscapes, socioeconomics, and land-uses calls for a holistic understanding of the risks in current and future climatic, political, and socioeconomic conditions [6]–[8].

For example, the Biodiversity Policy for 2030, part of the EU Green Deal, ambitiously seeks to plant 3 billion trees in the EU [18]. Offering promising results for biodiversity, conservation, and carbon sequestration, the policy may also create trade-offs. For example, large scale tree planting could create competition with other land use demands. Reforestation in sparsely forested areas could also change the forest canopy structure which could change fire risk and intensity [19]. Introduction of maladapted or especially flammable species of vegetation is also a risk [20], e.g., the large-scale plantation of eucalyptus in Portugal [16]. Alternatively, increasing urbanization could increase the wildland urban interface, a known contributor to fire in Europe where most wildfire is initiated by humans [21]. Population trends towards urbanization may also lead to great rates of land abandonment, a major driver of fire risk as tree and shrub cover increased on unmanaged agricultural lands [22]–[24]. In the context of managing fire risk, consideration should be given to the effects of land use changes on fuel composition and distribution across landscapes [25]. The trade-offs between fire risk, biodiversity, climate change mitigation need to be weighed carefully to produce favorable outcomes.

To understand potential policy trade-offs in the EU, such as the Green Deal, and practices, such as traditional prescribed fire use, on land-use change and fuel distribution across European landscapes, and to adapt and prepare accordingly, models are needed which can test how such changes may affect fuel composition and distribution. Current models have been found to inaccurately estimate fire patterns in human dominated landscapes [1]. More accurate land use scenarios for the 21st century which focus on landscape characteristics that are relevant to fire risk management in the EU—including forest connectivity and land abandonment—are needed [26].

Activity 3.1.2 of the FirEUrisk project developed LUC scenarios for policy implementation and fuel management. These scenarios span the decades from 2015 to 2050, and are linked to historic land use reconstructions for the decades from 1960 to 2010 and land system modeling. Historic baseline data was provided from the HILDA+ dataset [3], which combines several open data streams (remote sensing, reconstructions and statistics) to estimate LUC. The future land use scenarios were simulated using CLUMondo, a spatially explicit and dynamic land system change model [5]. These time series of historic reconstruction and future scenarios are data inputs to Dynamic Global Vegetation Models (DGVM). While the time series is based on a 1-km resolution, we made a conversion in aggregating the data to a 9-km resolution and an aggregated land cover class legend to match that used natively in the DGVMs. The 1960-2050 land use dataset is an integral data input for Dynamic Global Vegetation Models (DGVM) by incorporating variables critical to fuel distribution across European landscapes, such as afforestation, forest fragmentation, and land abandonment, which will in turn improve the ability of the DGVMs to forecast future fire regimes [1], [2].

2 Data and models

To examine how climate, policy, economic trends, and vegetation change may intersect with fire risk in Europe, it was necessary to couple several models and datasets. Key datasets included the historical land use/cover maps from HILDA+ and future land use/cover scenario from CLUMondo. CLUMondo uses several underlying datasets as input, including world region level global trade modelling outcomes for the Shared Socioeconomic Paths (SSPs) scenarios at global scale. Key models included CLUMondo and the Dynamic Global Vegetation Model (DGVM) to estimate potential shifts in vegetation and fuel. The following sections give an overview of each of these datasets and models, followed by a more detailed description of the parameters, settings, and assumptions used to run them.

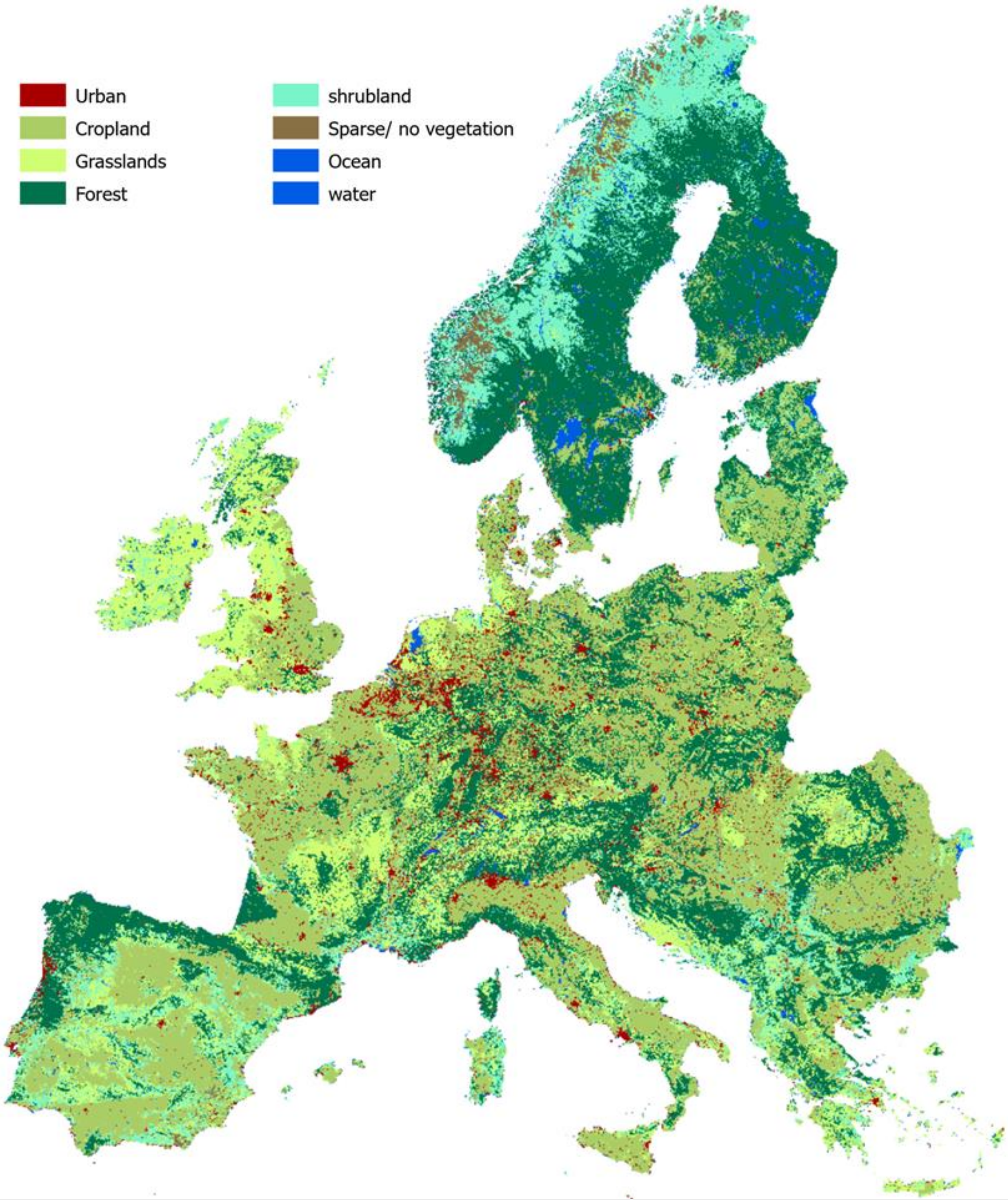
2.1 HILDA+

The Historic Land Dynamics Assessment+ (HILDA+) dataset [3] is an updated version of HILDA, developed by Fuchs et al. in 2013 [27], [28]. Spatially explicit at a 1-km resolution and specific to Europe, HILDA was a novel product which synthesized several data sources, including historical records, such as military maps and available land cover datasets from CORINE, the University of Maryland land cover classification, Eurostat, and FAO amongst others to create reconstructed land use maps of Europe [27], [28]. As land use data is not available for most of the 20th century, this historical reconstruction was needed in order to avoid legacy effects and to determine vegetation age for the DGVM models.

The HILDA+ dataset improves upon the original HILDA dataset in several ways. It is available at a global scale, which allows coverage of several FirEUrisk project areas not previous included in the HILDA dataset. It also combines several high resolution sources for remote sensing data and national land use inventories with subnational statistics, providing a more empirically based spatial product of land use. It is available for the years 1900-2019, with significant quality and accuracy improvements after 1960 (data before this period was backcasted, using the year 2000 as a base year). HILDA+ results were cross-validated by Winkler et al. with aerial photography in 73 locations across Europe taken between 1950-1970. HILDA+ was produced at a 1-km resolution with 7 land use classes (see Fig. 4 for list of classes).

Although other datasets exist which seek to reconstruct land use in the 20th century, such as the Historical Database of the Global Environment (HYDE) [4], they are generally not specific to Europe and are based on assumptions about management practices and/or relationships between land cover types for the period. HYDE, for example, is based on per capita land-use estimates and population maps, using FAO inventories for calibration of the per capita land-use areas. The historical part of the Land Use Harmonization[2] (LUH2) [29] is based on HYDE, which gives the data similar limitations.

Figure 1: Original HILDA+ data at 1-km resolution for the year 1960



2.2 CLUMondo: A spatially explicit land use model

2.2.1 Conceptual overview of the model

We opted to use CLUMondo for this deliverable. CLUMondo is the latest generation in the CLUE model framework used to simulate future land system scenarios based on predefined demands for goods and services (e.g. crops or livestock) while also considering local spatial characteristics and climate change [5]. The model is similar to other spatial allocation models (where socioeconomic, soil, terrain, and climate characteristics define the spatial pattern of LUC), making it a suitable choice to demonstrate land use responses to climate change. However, CLUMondo also offers several advantages in terms of land use modelling. Typically, detailed, spatially explicit land use or land cover (LULC) models simulate changes from one distinct LULC to another based on dominant LULC in the units of simulation. CLUMondo, however, takes a land systems approach, allowing for a more nuanced interpretation of land uses and, consequently, their service provision. This includes simulation of changes in cropland, grazing, and settlement intensity as well as incorporation of mosaic land systems. Mosaics, representing multiple land uses within a pixel, are reflected by estimated percentages of land cover (e.g., 30-70% forest, 20-40% grassland, and 10% bare soil/rocks in a 1-km^2 cell). In this way, a single land system can offer multiple goods and/or services. For example, a mosaic of cropland, grassland, and settlements can provide harvest, fodder, and shelter services, respectively.

- Area restrictions
- Conversion restrictions
- Competitive advantage
- Local suitability
- Neighborhood influence
- Conversion resistance

Figure 2: Example CLUMondo parameters used to empirically interpret global socioeconomic pathways

To achieve these simulations, CLUMondo allocates future changes to land systems based on their allocation suitability. CLUMondo uses a series of input attribute values specific to certain land systems. These attributes reflect the land system's individual suitability in local contexts, ability to provision specific goods, potential for a change in land use, susceptibility to neighbourhood effects, and restrictions to conversion. In combination with anticipated regional demands for goods and services produced by exogenous models (e.g., GLOBIOM), CLUMondo optimizes potential solutions and allocates the results in a spatially explicit manner [30], [31]. As it systematically runs each year's input of demands and suitability for a region, CLUMondo allocates a corresponding land system to each pixel, subject to the input conversion rules supplied to the model. Once a solution is found which appropriately allocates the matched demands and land systems, the model moves to the next year to begin the process again.

Building from a base representation of current land systems at the beginning of the simulations, CLUMondo allows a user to empirically explore the effects on land use of projected future societal demands and outcomes of current policy decisions. Policies focusing on sustainability efforts, for example, can be quantified in CLUMondo via conversion resistance to natural forest, thereby making natural forest conservation more likely. Similarly, the potential effects of technological innovations and climate change can be reflected through the yearly input demands fed to the model. The specific inputs and parameters used in the model are derived from scenarios which reflect possible environmental and economic trajectories, such as the SSPs, further elaborated in the next section.

2.2.2 Land systems map & associated provision of goods and services by land systems

For the simulations developed in this deliverable, we ran CLUMondo with a land systems map adapted from the land system map developed by Dou et al. in 2021 [32] representing land systems in 2015. This map was simplified in an effort to decrease the computational burden by grouping small-extent land classes with similar characteristics and set pixels in the water class as non-changed areas. This produced 21 land classes, and includes mosaics and land use intensities.

Figure 3: Land systems map (2015) used as a base map used in CLUMondo. Settlement intensity refers to imperviousness; forest intensity refers to wood production levels, cropland intensity to inorganic fertilizer input and field size; grassland intensity to livestock amounts, mowing frequency, and inorgani

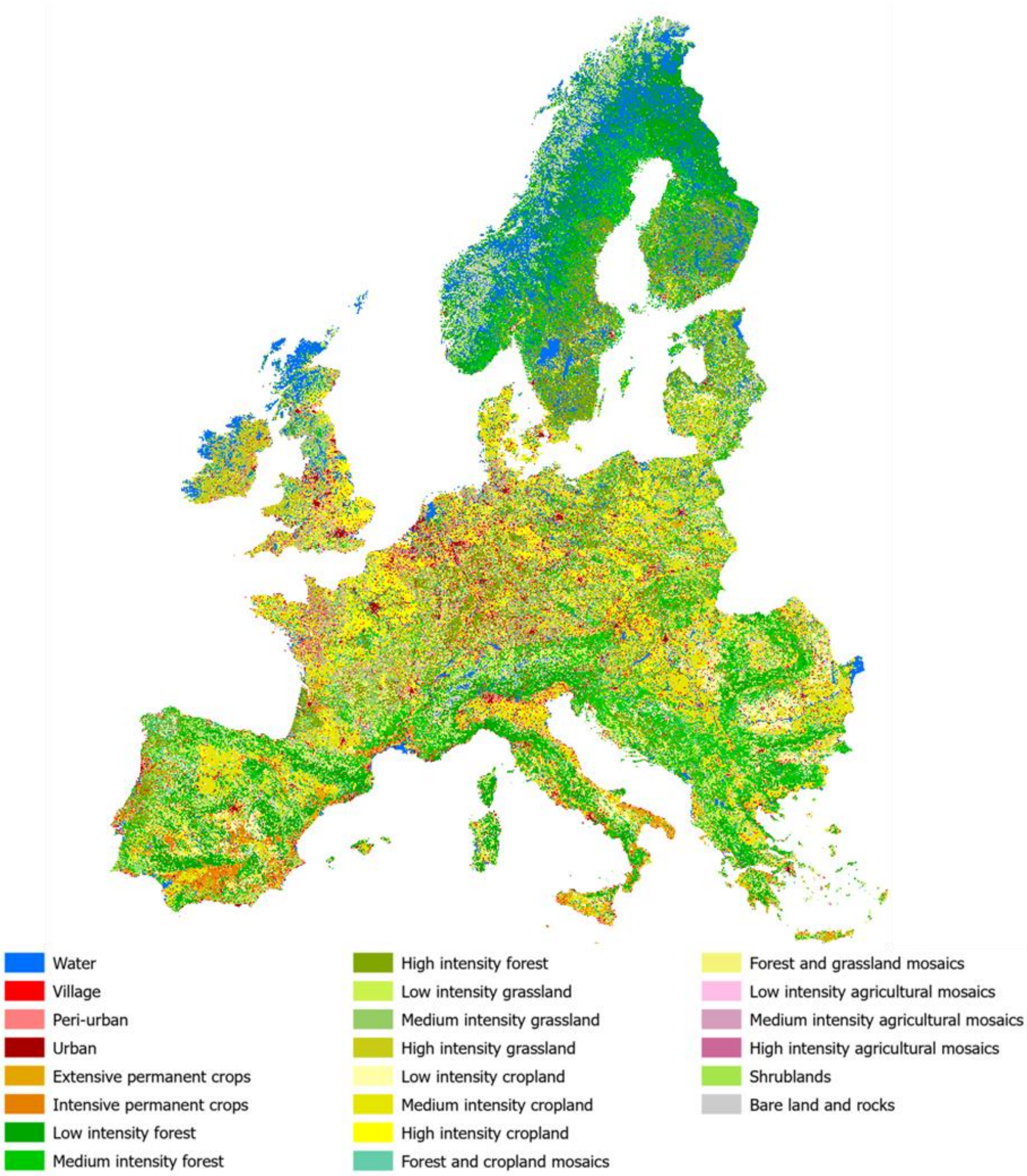
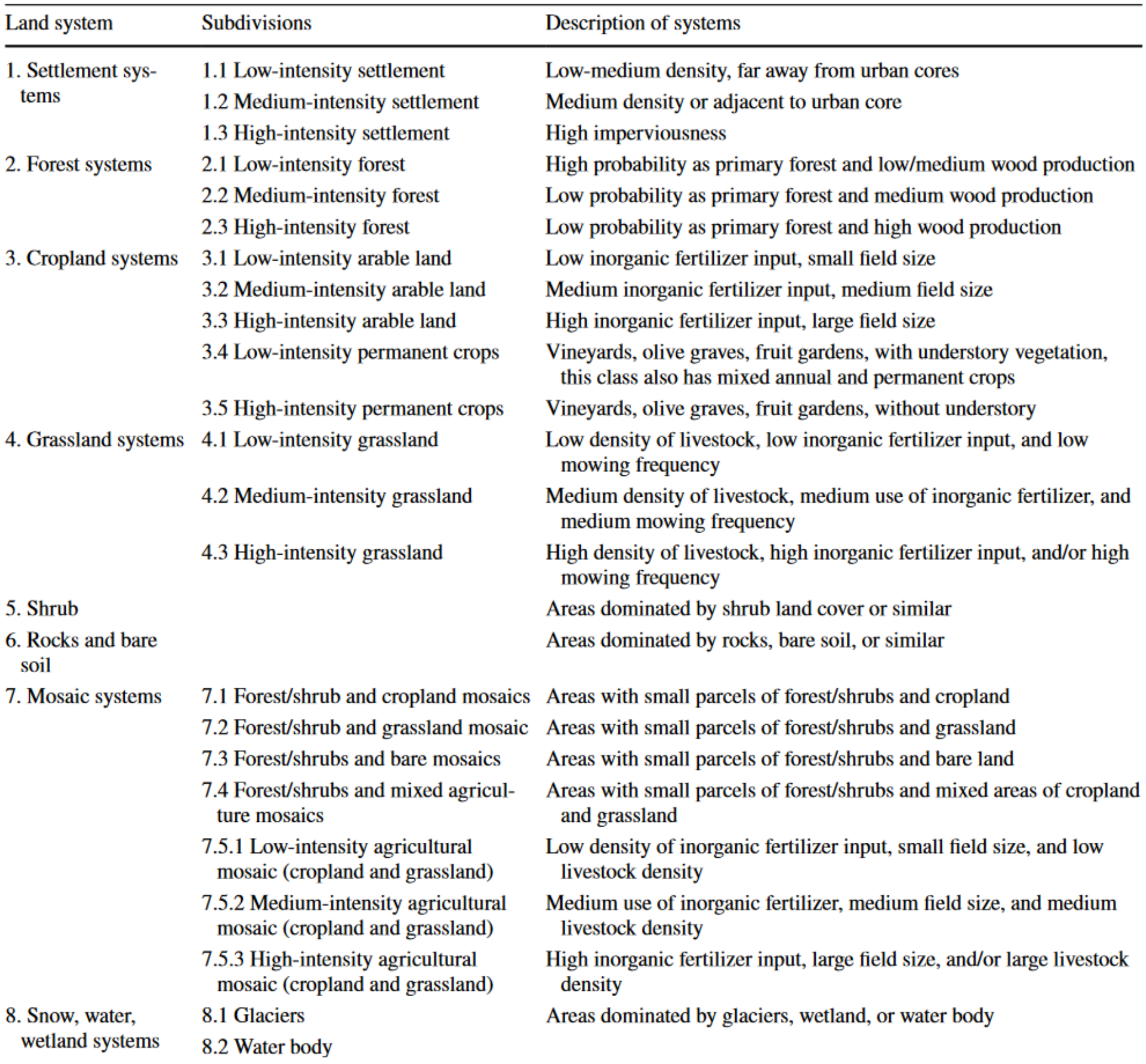


Table 1: Land system descriptions from Dou et al. 2021, including details on intensity definitions and mosaics



Land system	Subdivisions	Description of systems
1. Settlement systems	1.1 Low-intensity settlement	Low-medium density, far away from urban cores
	1.2 Medium-intensity settlement	Medium density or adjacent to urban core
	1.3 High-intensity settlement	High imperviousness
2. Forest systems	2.1 Low-intensity forest	High probability as primary forest and low/medium wood production
	2.2 Medium-intensity forest	Low probability as primary forest and medium wood production
	2.3 High-intensity forest	Low probability as primary forest and high wood production
3. Cropland systems	3.1 Low-intensity arable land	Low inorganic fertilizer input, small field size
	3.2 Medium-intensity arable land	Medium inorganic fertilizer input, medium field size
	3.3 High-intensity arable land	High inorganic fertilizer input, large field size
	3.4 Low-intensity permanent crops	Vineyards, olive graves, fruit gardens, with understory vegetation, this class also has mixed annual and permanent crops
	3.5 High-intensity permanent crops	Vineyards, olive graves, fruit gardens, without understory
4. Grassland systems	4.1 Low-intensity grassland	Low density of livestock, low inorganic fertilizer input, and low mowing frequency
	4.2 Medium-intensity grassland	Medium density of livestock, medium use of inorganic fertilizer, and medium mowing frequency
	4.3 High-intensity grassland	High density of livestock, high inorganic fertilizer input, and/or high mowing frequency
5. Shrub		Areas dominated by shrub land cover or similar
6. Rocks and bare soil		Areas dominated by rocks, bare soil, or similar
7. Mosaic systems	7.1 Forest/shrub and cropland mosaics	Areas with small parcels of forest/shrubs and cropland
	7.2 Forest/shrub and grassland mosaic	Areas with small parcels of forest/shrubs and grassland
	7.3 Forest/shrubs and bare mosaics	Areas with small parcels of forest/shrubs and bare land
	7.4 Forest/shrubs and mixed agriculture mosaics	Areas with small parcels of forest/shrubs and mixed areas of cropland and grassland
	7.5.1 Low-intensity agricultural mosaic (cropland and grassland)	Low density of inorganic fertilizer input, small field size, and low livestock density
	7.5.2 Medium-intensity agricultural mosaic (cropland and grassland)	Medium use of inorganic fertilizer, medium field size, and medium livestock density
	7.5.3 High-intensity agricultural mosaic (cropland and grassland)	High inorganic fertilizer input, large field size, and/or large livestock density
8. Snow, water, wetland systems	8.1 Glaciers	Areas dominated by glaciers, wetland, or water body
	8.2 Water body	

2.2.3 Elaboration of Shared Socioeconomic Pathways 1 & 3 for FirEUrisk D3.2

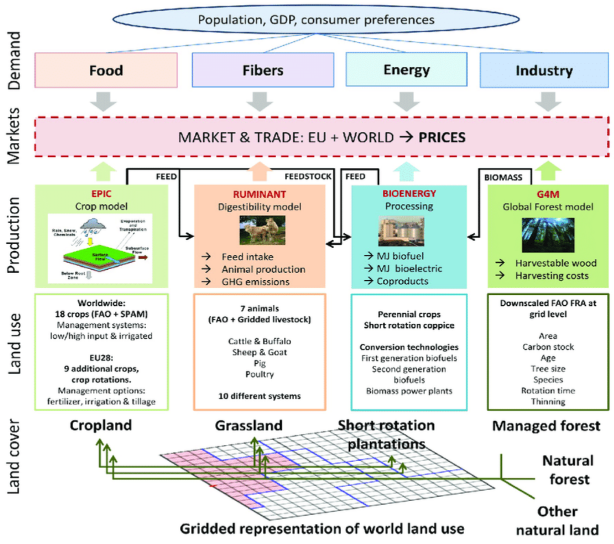
Figure 4: Shared Socioeconomic Pathways adopted for this deliverable, 1 & 3, in bold, green to red color indicating decreasing sustainability, respectively

The SSPs were developed in 2016 by a team of international scientists and modellers and published. As summarized in Fig. 3, the SSPs synthesize a wide-range of research and current trends to elaborate five envisioned scenarios, each representing potential global trajectories of economics, environment, and ecosystem service provision in light of global climate change. SSP1, “Sustainability,” and SSP3, “Regional Rivalry,” were used for this deliverable as agreed to by WP3 partners.

For each SSP, we adopted the sector specific storylines (see Table 2) and translated them into the following components of CLUMondo: projected societal demands for land use-related goods and services, productivity of individual land systems, and rules for land use transition preference. For both, we developed the scenarios and projected the demand to the year 2050 based on the productivity change produced by GLOBIOM [33] (Fig. 4), a bottom-up, partial equilibrium, integrated assessment model developed by the International Institute for Applied Systems Analysis which integrates global trade and global demand-supply. The demand values from GLOBIOM for each of the SSPs are reported in Table 2.

SSP1, “Sustainability,” explores the effects of relevant policies aimed at a more sustainable future, such as the Green Deal [34]–[36] on different forest management scenarios and corresponding land demands. The associated climate projection, Representative Concentration Pathway (RCP) 2.6, which assumes a high effort to reduce emissions and increase renewable energy and emissions capture, was used to account for changing climatic conditions. A summary of the SSP1 narrative by sector can be found in Table 3.

Figure 5: Representation of GLOBIOM from IIASA



In contrast to SSP1, SSP3 anticipates an overall decrease in population, especially in the south and east regions of Europe. Livestock and crops also decrease, especially in the south. Agricultural production becomes more polarized overall, as farms become larger and adopt conventional practices. Demand for permanent crops increases significantly for all of Europe, especially the south, while demand for forest products decreases with this scenarios assumption of decreases in adoption of biofuel energy sources. We adopted RCP7.0 as the associated climate projection for SSP3, which indicates mixed renewable and fossil fuel energy generation, limited public transportation options, and an overall low effort to curb emissions.

Table 2: Elaboration of demand for goods and services provided to CLUMondo for generation of future land use scenarios

	SSP1-Sustainable				***SSP3-Regional Rivalry***			
Change by 2050	east	north	south	west	east	west	south	north
Population	-8%	32%	6%	14%	-14%	4%	-13%	-7%
Annual crops	10%	12%	-25%	5%	-1%	-13%	-31%	-2%
Permanent crops	23%	9%	30%	27%	50%	41%	56%	53%
Livestock	9%	30%	-15%	-9%	-9%	-13%	-19%	-6%
Forest products	25%	15%	17%	23%	16%	10%	5%	9%

Table 3: Sectorial summaries used in CLUMondo for SSP1

Urbanization	Assuming that environmental awareness & value increases amongst European populations, legislation is anticipated to encourage and protect natural landscapes and sustainable farming. Following the preference for village and peri-urban lifestyles, we place strict rules on the urbanization process in CLUMondo, allowing village and peri-urban land systems which can accommodate marginal agricultural activity.
Agricultural changes	Agricultural production is assumed to diversify and innovate which a focus on sustainability. This was simulated in CLUMondo through the promotion of crop and livestock production on several land systems, including mosaics, which include cropland. We disallowed marginalization in the short-term for current high-intensity cropland & grassland to low-intensity systems. However, re-wilding of high-intensity agricultural land, resulting in, for example, low-intensity grassland and shrubs is possible which may lead to an increased fire risk. Increasingly diversified and multi-functional mosaic landscapes are anticipated in the transition from industrial farming and grazing systems currently seen in Europe.
Production efficiency	Agricultural productivity is assumed to be affected by climate change, technology development, and modified ecosystem service provision. Europe's farms in southern regions are anticipated to see crop yields decrease by 14%, in contrast to other regions of Europe in which yields are anticipated to increase. We assumed that productivity change only occurs in medium to high-intensity agricultural land uses. Technological innovation is not anticipated to effect low-intensity agricultural areas, leaving the productivity of these areas unaffected.
Regional differences	Regional differences are seen in demand and agricultural production in Europe. Annual crop production increases in the west and north regions at 6% and 12%, respectively, and decreases by 25% in the south. The south and west also see a decrease in demand for livestock products, as demand in the north and east increases. In contrast to the anticipated overall small increase in population for the whole EU and a 32% increase predicted for Europe's northern region, the population of the eastern region is expected to decrease by 8%.
Climate change impacts	RCP-2.6 was selected based on its alignment with SSP1. We used five bioclimatic variables and 12 social-environmental variables in our model to predict the suitability of the adopted land systems. We used five different models to develop climate projections for the bioclimatic variables. These were averaged and statistically downscaled from the Coupled Model Intercomparison Project (CMIP6) to 30 arcsec, ~1-km resolution, sourced via the CHELSA dataset [37]. Updated on an annual basis within the model, climate change effects were implemented through spatial preference for different land systems.

2.2.4 CLUMondo Parameterization for FirEUrisk

The methods used to run the CLUMondo simulation were similar to those previously adopted in studies by Malek et al. amongst others (see [5], [30], [38]–[40]). These studies have more detail on the parameterization and function of CLUMondo, which we summarize here under the categories of suitability, land system service, and conversion order and resistance. We ran the simulation as four separate regional models, reflecting the heterogenous characteristics and associated demands amongst Europe's regions. Annexes of the values used for each of the following parameters will be made available following publication in the coming months.

Suitability

The spatial suitability of the 21 land systems in CLUMondo were based on 18 literature-derived characteristics such as climate, soil, and socioeconomic conditions. Logistic regressions were used to empirically calculate the suitability of individual land systems using these characteristics as explanatory variables. Factors with significant correlations are then retained and used to calculate probability in CLUMondo.

Land system service

Each of the 21 land systems used in CLUMondo can produce a list of goods and services, which includes crop production, livestock, shelter, and wood products. To develop the valuation of goods and services, an average value of each service for each land system type is extracted. The underlying data for the calculation included population density maps, livestock units, wood production values, statistical records, and application of nitrogen, as available.

Conversion order and conversion resistance

The conversion order and conversion resistance parameters in CLUMondo direct the model's prioritization process for changing land uses. Conversion order quantifies the amount of demand a land system can produce while conversion resistance indicates the difficulty of conversion from one land use to another. By fitting numeric values to each of these parameters, the model is able to optimize a solution to meet the demand input in the context of policy, land use trends, or societal shifts in values and spatial priorities.

2.3 Integration of historic and scenario datasets

Given the DGVM need for combined historical and future scenario data on land use that minimizes legacy effects, the HILDA+ dataset and CLUMondo results needed to be integrated. Our objective was to develop a dataset of decadal interview from 1960 to 2050 at a 9-km resolution which adhered to the legend agreed upon by project partners. We began this process by first agreeing upon a common legend with partners as seen in Figure 5.

We created a raster mask using the CLUMondo 2015 land systems map as a standard. The CLUMondo maps were thus all prepared using the Lamberts Equal Area projection at a 1-km resolution with a set extent. To ensure alignment between the scenarios and historic raster, the HILDA+ data was then reprojected using this raster mask as a snap raster using the "project" function in the terra package (v.1.3-22) available for R software [41] . We opted to use "nearest neighbor" as the sampling method as this is the preferred method for discrete data, such as the land classes values which each cell in the HILDA+ datasets is composed. Specific details on the original and final spatial settings for all rasters are available in the metadata file included with the datasets.

We then translated the HILDA+ and CLUMondo land classes to the DGVM classes at 1-km resolution using the following methods in R, also using the terra package. For HILDA+, we followed the aggregation scheme in Figure 6 to reclassify the classes in each year of the parent dataset and create a new, separate raster for each individual DGVM class (with pixel-specific percentage covers). Given CLUMondo's land system's approach, in which several land systems types are composed of more than one land cover or use (e.g., 30-70% forest cover), it was necessary to prepare an aggregation scheme that would allow retention of the mosaic values and a smooth transition between HILDA+ and the future CLUMondo scenarios. To resolve this issue, we used the cross tabulate tool in ArcGIS pro to create a table comparing HILDA+ 2015 and CLUMondo 2015. We first reclassified the CLUMondo non-mosaic classes to their DGVM equivalent (see Figure 6). The final cross tabulated table examines the relationship between classes in one raster with that of another. More details can be found in Figure 7, which fully lays out the process. For the year 2015, we retained the HILDA+ results, translated to the DGVM classes as percent cover rasters for each class (8 rasters total). For 2020, we first compared CLUMondo 2020 and 2015 to determine the cells in which a transition occurred ("transition cells"). In the final timeseries raster product, the cross tabulate table values were used in each of the transition cells. Stable cells received the HILDA+ 2015 value in the equivalent cell.

With all rasters at the same resolution, projection, and extent, each were then aggregated at 9-km resolution to fit the native resolution of the DGVM models. This also was carried out in R via the "aggregate" function in the terra package, using a factor of nine (i.e., the aggregation of 1-km to 9-km pixels) and the "mean" function as the method with which to perform the aggregation.

Finally, it was a priority for the project to include peatland data for Europe given its relevance in climate change, degradation, and fire regime processes. With the permission of the authors, we included separate datafiles for the "The Peatland Map of Europe," developed by Tanneberger et al. in 2017 [42] as a static map for the years 2015 to 2050. Please note that there is no reconstruction of peatland area made. Peatland is an extra attribute that can be combined with the land cover, so, by such combination we can have pixels that are peatland but have a different land cover compositions (peatland with 80% grassland and 20% forest).

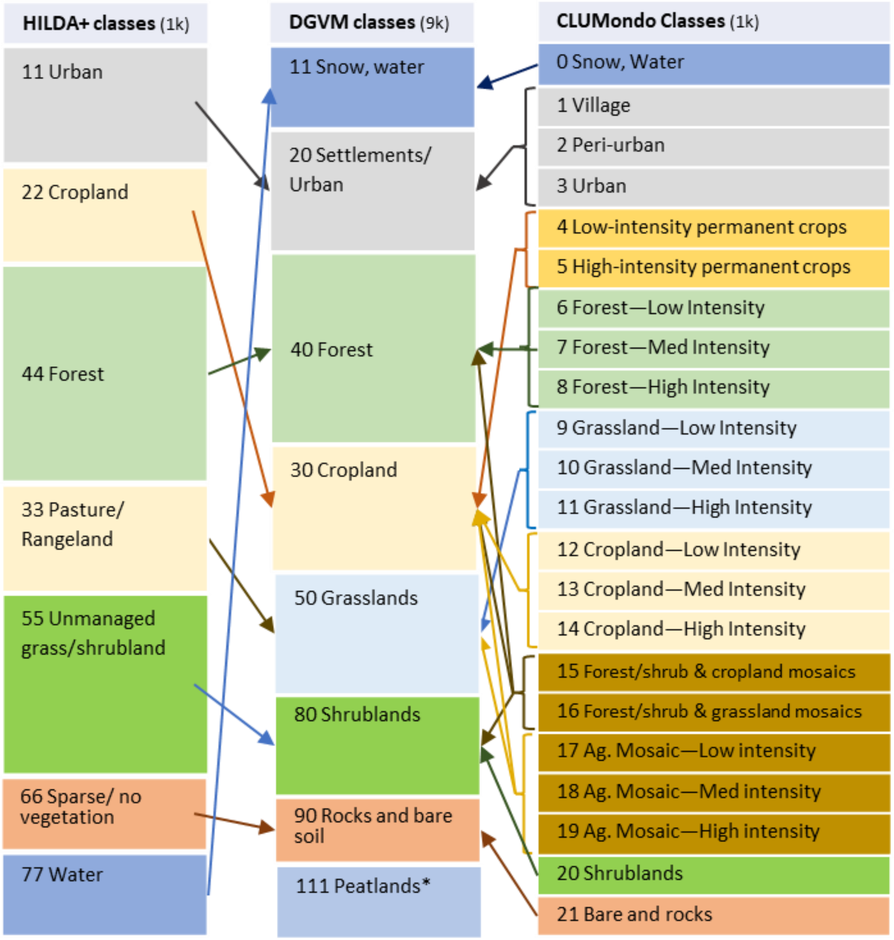


Figure 6: Scheme for the aggregation of CLUMondo and HILDA+ to the adopted DGVM legend

Figure 7: Step by step example of processing method for HILDA+/CLUMondo harmonization

Step 1:
Calculate the cross tabulate table (in ArcPRO)

Illustration

ZoneRas

1	1	0	0
	1	2	2
4	0	0	2
4	0	1	1

ClassRas

10	11	11	10
13	13	11	12
	10	10	12
13	12	11	10

▨ Value = NoData

Tabarea1.dbf

=

VALUE	VALUE_10	VALUE_11	VALUE_12	VALUE_13
0	3	1	1	0
1	2	2	0	1
2	0	1	2	0
4	0	0	0	1

`TabulateArea(ZoneRas, "VALUE", ClassRas, "VALUE", Tabarea1.dbf, 1)`

There are three "0" cells which have 10s, one with an 11, one with a 12

FEATURE ZONE DATA:
2015 HILDA (1km, DGVM classes)

Crop	Forest
Grass	Forest
Crop	Crop
Grass	Forest

FEATURE CLASS DATA: 2015 CLUMondo (1km, DGVM classes for all but mosaics

Mosaic 1	Mosaic 1
Grass	Mosaic 2
Mosaic 1	Mosaic 1
Mosaic 2	Crop

CROSS TAB TABLE FROM ARCPRO

VALUE	VALUE_ Mosaic1	VALUE_ Mosaic2	VALUE_ Crop	VALUE_ Forest	VALUE_ Grass
Crop	3	0	0	0	0
Forest	1	1	1	0	0
Grass	0	1	0	0	1

Transition rules (percent cover based on cross tabulation)

VALUE	Mosaic1	Mosaic2	Crop	Forest	Grass
Crop	.75	0	0	0	0
Forest	.25	.5	1	0	0
Grass	0	.5	0	0	1

Step 2: 2015 (TS=Time Series)

HILDA 2015 in DGVM classes
(NAME: HILDA_2015_DGVM_ALL)

Grass	Grass
Forest	Forest
Water	Crop
Grass	Crop

Only HILDA+, All classes are 100% cover

2015 TS **Grass** raster (in DGVM classes)

100%	100%
0	0
0	0
100%	0

2015 TS **forest** raster (in DGVM classes)

0	0
100%	100%
0	0
0	0

8 TIMESERIES (TS) RASTERS TOTAL

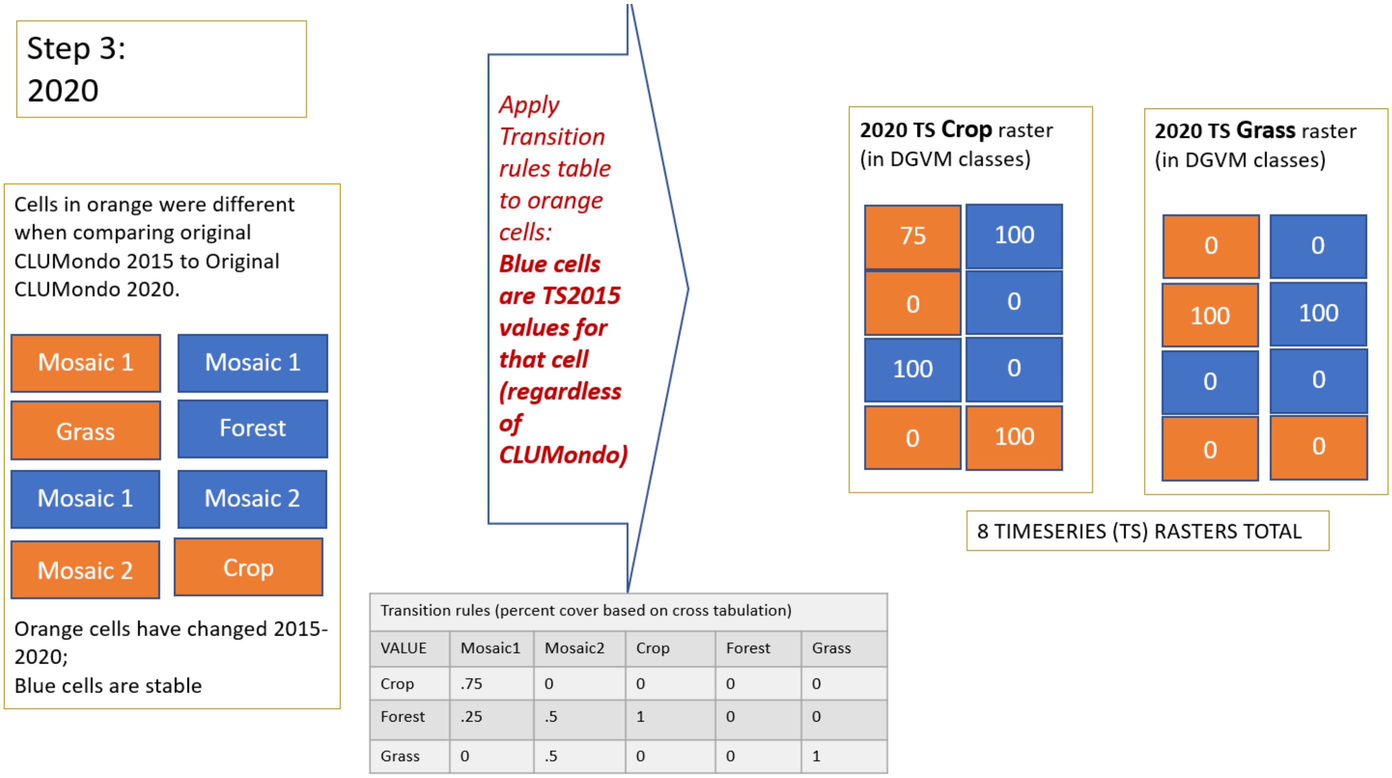
2015 TS **Crop** raster (in DGVM classes)

0	0
0	0
0	100%
0	100%

2015 TS **Water** raster (in DGVM classes)

0	0
0	0
100%	0
0	0

Figure 7: Step by step example of processing method for HILDA+/CLUMondo harmonization (continued)



Cells in orange were different when comparing original CLUMondo 2015 to Original CLUMondo 2020.

Orange cells have changed 2015-2020;
Blue cells are stable

Apply Transition rules table to orange cells: ***Blue cells are TS2015 values for that cell (regardless of CLUMondo)***

Transition rules (percent cover based on cross tabulation)

VALUE	Mosaic1	Mosaic2	Crop	Forest	Grass
Crop	.75	0	0	0	0
Forest	.25	.5	1	0	0
Grass	0	.5	0	0	1

2.3.1 Stylized Fuel Management Scenarios

In WP2, Task 2.2, we analyzed different land use practices that can mitigate fire hazard. In general, these practices aim to change the overall structure of vegetation across the landscape to increase heterogeneity and decrease fire proneness. Certain land covers, such as shrublands and forests, are more fire-prone, especially in configurations which place fuels in close proximity (e.g., densely arranged, unpruned pine forests) [25]. We refer to these as land management practices (LMS). We have chosen to focus on three LMS: removal of vegetation (e.g., silviculture techniques), herbivory (e.g., grazing), and prescribed burn (e.g. traditional burning practices). Based on a systematic literature review and expert input, we are developing guidelines on the use of these LMS in Europe for deliverable 2.3 which is due in project month 40; and maps of LMS options for deliverable 2.4, due in project month 40.

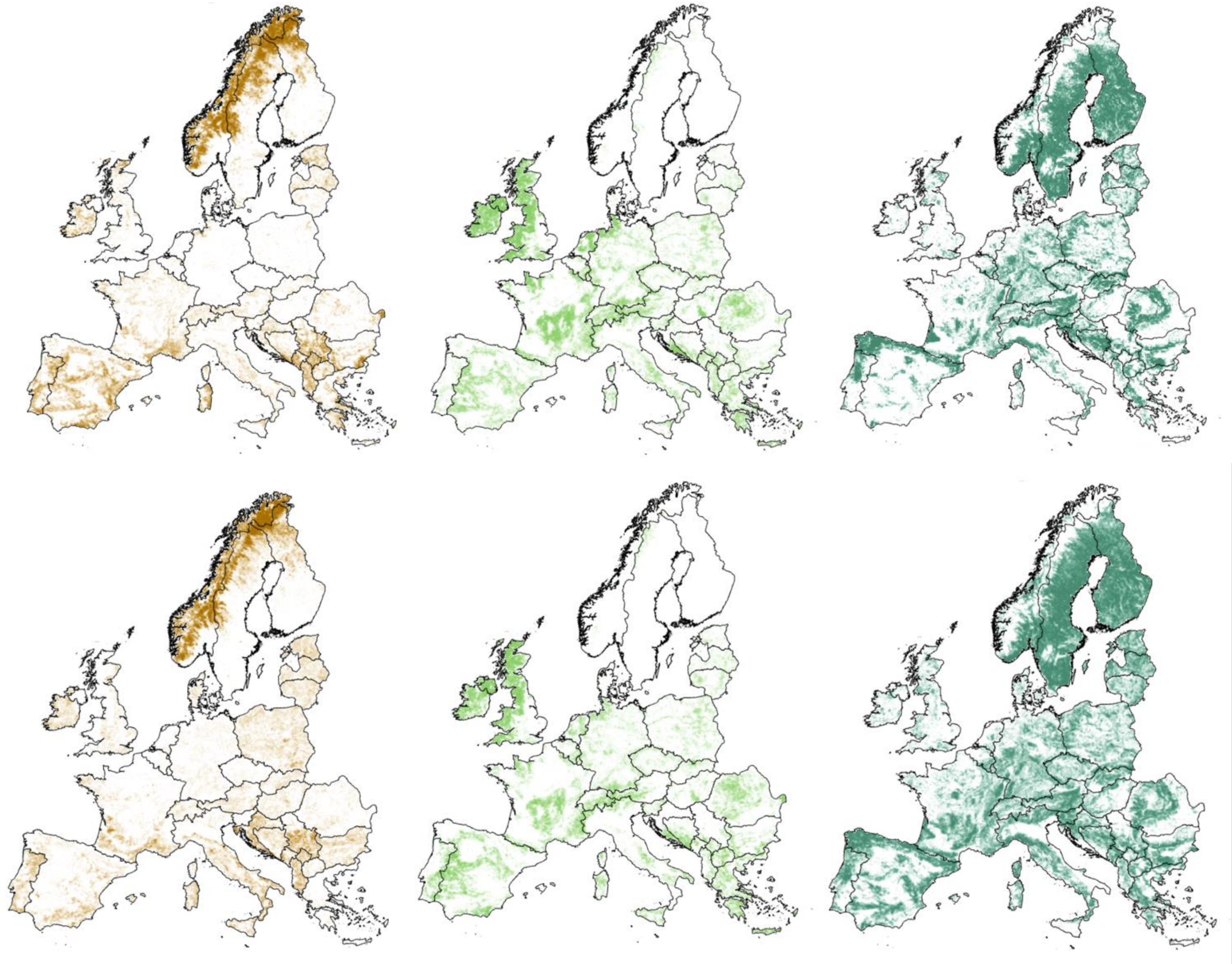
As the results of these deliverables become available, we will use them to develop stylized scenarios which will be superimposed on the CLUMondo scenarios previously described. The scenarios will explore possible consequences of different levels of LMS uptake on land use. For example, low uptake of the strategies may see spatial patterns of increased shrub and tree growth in areas previously dominated by herbaceous cover, such as abandoned agricultural lands. These scenarios will be used in a second tier of WP3 to support the development of stylized fuel management scenarios.

3 Results

3.1 Historic land use change

This deliverable produced a set of raster maps representing the land use/cover composition of each of the DGVM's classes for the years between 1960 and 2050 for Europe. In the sections below, we provide a summary of how the trends manifest differently for SSP1, "Sustainability," and SSP3, "Regional Rivalry" (also known as "Relentless"). As can be seen in Figure 8, HILDA+ reports that forest cover in Europe has increased between 1960 and 2015. All 88 raster's (8 land cover types for 11 years, spanning 1960-2050) produced are available for download with metadata included on DataverseNL.

Figure 8: HILDA+ 1960 (top three maps) and 2015 data (bottom three maps) for shrublands, grasslands, and forest at 9-km resolution, aggregated to the DGVM classes. Areas in color represent land cover estimated by the HILDA+.

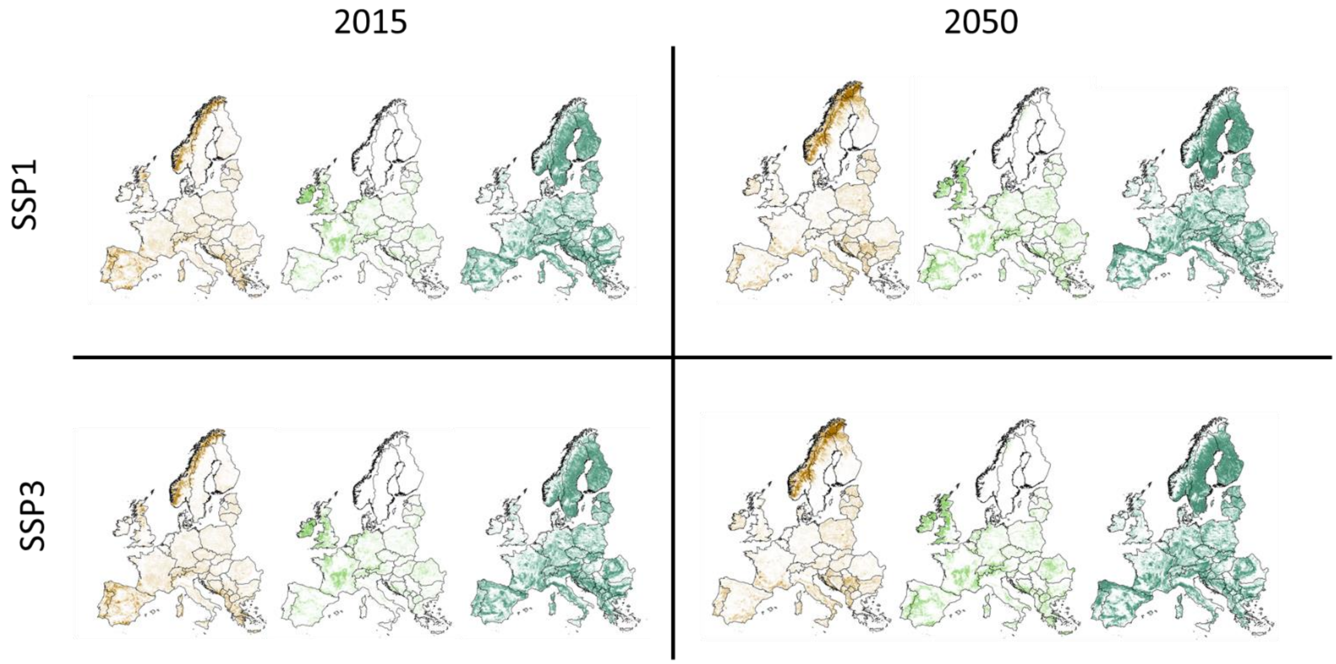


3.2 LU Changes for SSP1 & 3 Projections

The CLUMondo results for **SSP1** anticipates a nearly 8% increase in the **population**, with preferences for villages and peri-urban landscapes increasing populations in those areas. The results indicate more forest areas overall in Europe, but moving towards higher **forest** intensity over time (meaning fewer natural, low intensity forests). This additional forest cover comes mostly from current grassland areas. **Grasslands** suffer significant decreases, especially medium and high intensity grasslands which see reductions around 75% of the current cover. **Agricultural** production diversifies overall, with shifts in intensity as the low and medium classes decrease by more than half and agricultural mosaics move towards higher intensities. The shift from agricultural land to more grassland and shrubland could lead to an increased fire risk, similar to the fire risk trends associated with land abandonment currently being seen in Europe. **Cropland** areas decrease overall, but agricultural mosaics that include cropland and grassland increase in intensity.

For **SSP3,** the **population** decreases by nearly 10% as countries compete for resources. This exacerbates the rural exodus, especially in southern Europe. **Forest** production still sees an increase in Europe overall, but less than that seen in SSP1. **Grasslands** see a slight drop in intensity in the eastern and western regions of Europe, but increase in the south. **Crop productivity** dips, especially in southern Europe which sees a nearly 18% decrease. **Agricultural** production sees a polarization in which mid-size farms change to either small farms or large conventional farms.

Figure 9: Comparison of changes in land cover in SSP 1 & 3 between 2015 and 2050. Brown represents shrubland cover, light green represents grassland cover, and dark green represents forest cover.



3.3 Stylized fuel management scenarios

Presently, we have early results for potential LMS adoption areas for herbivory and vegetation removal. Figure 9 is an example of the mapped fuel removal results for Spain and Portugal. This map was developed by combining a fire hazard index developed by FirEUrisk consortium partners (in preparation, Ochoa et al. 2022—Fig. 8) and an index of adoption likelihood developed via literature review and expert input. The index of adoption likelihood for fuel removal combines three data points: accessibility (travel time to cities) reflecting the importance of access for the equipment and workforce needed for fuel removal [43]; wealth (poverty index), reflecting this LMS relatively (compared to the other LMS) high costs [44]; and land systems, such as forest intensity classes, to indicate areas in which removed fuel could be used for bioeconomies [32].

Figure 10: Stylized map of potential for fuel removal (mechanical, silviculture, etc.) developed in Task 2.2 for Deliverable 2.2 (due in project month 40). Suitability reflects factors representing the likelihood of adoption. Fire hazard is a composite of fire weather, fire history, and other indicators associated with fire proneness.

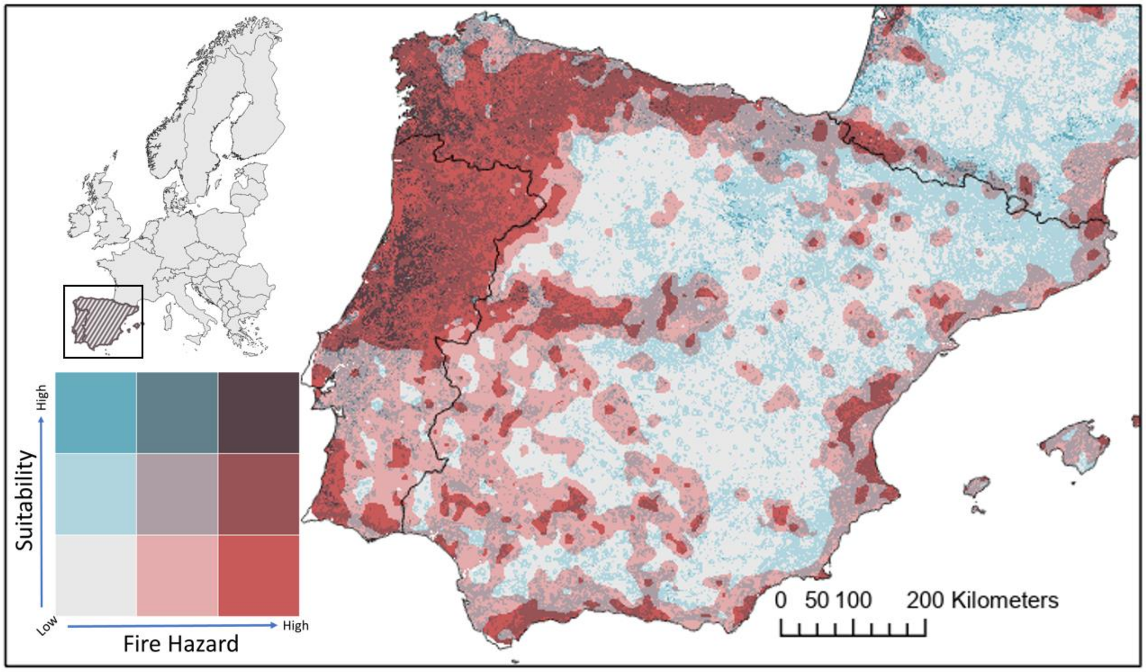
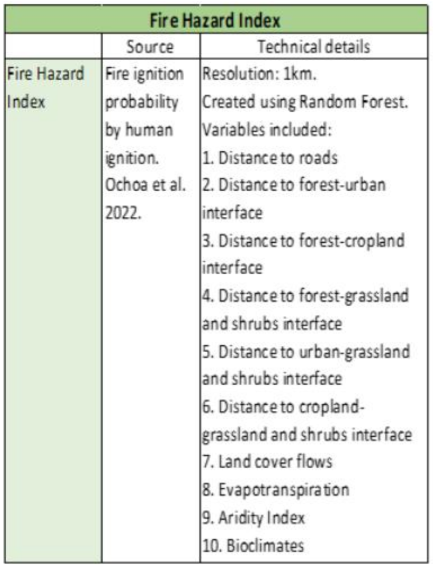
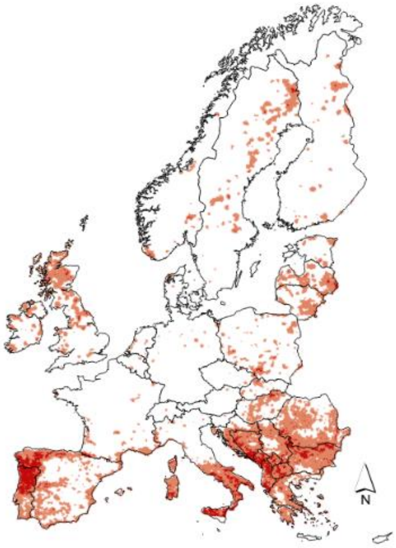


Figure 11: Fire Hazard map, unpublished. Ochoa et al. 2022 (in preparation)



Fire Hazard Index		
	Source	Technical details
Fire Hazard Index	Fire ignition probability by human ignition. Ochoa et al. 2022.	Resolution: 1km. Created using Random Forest. Variables included: 1. Distance to roads 2. Distance to forest-urban interface 3. Distance to forest-cropland interface 4. Distance to forest-grassland and shrubs interface 5. Distance to urban-grassland and shrubs interface 6. Distance to cropland-grassland and shrubs interface 7. Land cover flows 8. Evapotranspiration 9. Aridity Index 10. Bioclimates



4 Overview of results

For this deliverable, we provided land use scenarios for 2015 and the decades from 2020 to 2050 linked to representations of historical land use reaching back to 1960. The future land use scenarios are prepared following two potential socioeconomic pathways, SSP1, “Sustainability,” and SSP3, “Regional Rivalry.” In summary, this deliverable achieves the following:

- **Long-term land use for Europe**: The resulting dataset is the first long term Europe-specific land use scenarios set which is aligned with historic reconstruction.
- **Coupled modelling**: The dataset is translated to fit in a model chain that includes global economic models, spatial land use models, and fire risk assessment by the DGVMs.
- **Harmonization**: Harmonization of scenario data of this nature with historic data is notoriously difficult. Typically based on several different data sets and diverging definitions of land cover classes, harmonization is inherently imperfect. For other research methods, harmonization tools such as Hurtt or LUH2 are used. Here, we developed a tailored method which is appropriate to the data and its anticipated use.
- **Data with depth**: The data made available for this deliverable is a land cover product. However, the underlying data used contains high spatial detail and land management effects.
- **Stylized fuel management scenarios**: Land management is a critical component of managing fire hazard. This deliverable provides a base from which to build stylized fuel management scenarios in parallel with the ongoing work in WP2 Task 2.2 (due in project month 40). In this fashion, the findings will be synthesized into a series of stylized fuel scenarios representing low and high adoption of the proffered land management strategies, which can be matched with land use scenarios developed in the current deliverable.

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6 Annex A: Sector policy summaries used in CLUMondo

SECTOR	EU GREEN DEAL	*CBD-POST 2020 GLOBAL BIODIVERSITY FRAMEWORK*	CLUMONDO IMPLEMENTATION
1 STRICT PROTECTION-AREA TARGET	Protect 30% of land in Europe by 2030;	*Action Target 2: By 2030, protect and conserve … at least 30 per cent of the planet with the focus on areas particularly important for biodiversity*	**Conversion restriction:** certain land system conversions are restricted within the protected area; protected areas are expanded every five years.
2 RESTORATION-AREA TARGET BY 2050	Restoring degraded ecosystems	*Increased extent of natural ecosystems by at least 15%*	**Demand**: Three demands were added as additional demands to the SSP1 societal demands: areas of low-intensity forests, areas of low-intensity grassland, and total areas of low-intensity grassland and forests. **Conversion restriction**: change to forest and grassland classes more likely happen at certain spatial locations than other locations
3 AGRICULTURE	Reduction of the use of fertilisers by at least 20% by 2030	*By 2030, reduce pollution from all sources, including reducing excess nutrients by 40%*	**Demand**: total nitrogen application as additional demand; **Land use service**: nitrogen usage in land use matrix decreases annually
4 FORESTRY	Plant 3 billion new trees by 2030; we assumed 2 billion more trees will be planted by 2050	*Increase in secondary natural forest cover*	**Demand**: number of trees in all land use classes is set as an additional demand; **Conversion rules**: change to forest land class more likely to happen at certain spatial locations than at others
5 URBANIZATION		*By 2030, increase benefits from biodiversity and green/blue spaces for human health and wellbeing, including the proportion of people with access to such spaces by at least [100%], especially for urban dwellers.*	**Conversion rules**: different urban land use classes are given higher weights than others; land use service (population) provided by different urban land use classes change annually

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7 Annex B: GLOBIOM Demands

EU-Total	**Reference**	**Baseline (2015)**	**Sustainable SSP1 -2050**		**Relentless SSP3 -2050**	
				change %		change %
Population (million)	SUSFANS	536	577	7.6	485	-9.6
Annual crop production (1000 t)	SUSFANS	1050318	1083930	3.2	981554	-6.5
Permanent crop production (1000 t)	FAO	73228	94424	28.9	113099	54.4
Livestock production (1000 lsu)	SUSFANS	104194	99261	-4.7	94292	-9.5
Wood production (1000 m^3)	SUSFANS	486497	586777	20.6	539500	10.9
Crop net trade (export minus import)(1000t dm)		-26707.5	-70606	164.4	-31805.8	19.1
lsp net trade (1000tdm)		1360	638.0	-53.1	1045.7	-23.1
GDP (bn USD)		11230.9	24703	120.0	17280	53.9
Climate change paring	CMIP6 and Chelsa		RCP2.6 (SSP126)		RCP7.0 (SSP370)	
Change in crop productivity			13%-24% yield increase in the medium and high intensity cropland in the north, west, east, and 14% decrease in the South.		About 4% less increase (ranging from 8%-20%) in corresponding land systems and region compared to SSP1, and 18% decrease in the South.	
Change in livestock productivity			About 15% increase in medium and high-intensity grazing land systems increase in South and West; slight decrease in North and East regions.		Slight decrease in high-intensity grassland system in West and East Europe increase in South	

Protected area	Natura2000		Land system can only become less intensively used within Natura2000 boundaries.	
Urbanization	Natura2000		Any type of urbanization can only happen outside of Natura2000. Villages and peri-urban landscapes can be used for marginal agricultural activities, as preferred lifestyle. Only low-intensity, non-natural land systems can be converted to villages and peri-urban first, and gradually change to urban areas.	Any type of urbanization can only happen outside of Natura2000. No restriction on the land systems that can be converted to urban areas. Due to the population decline, population in village landscapes decreased over time in Southern Europe.
Agricultural development			Agricultural production transits to more diversified and various land systems and production models	Agricultural production is polarized as small farms and large conventional farms