D6.1

Conceptualizing the LAMASUS Toolbox

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Authors	Davide Tita, Evelina Sandström, Esther Boere, Peter Verburg

Abstract

This report conceptualizes the LAMASUS Toolbox. This Toolbox aims to bridge the gap between economic land use models operating at country and NUTS2 regional levels and those functioning at higher spatial or farm-specific resolutions. The key objectives of the report are to align thematic definitions of land use classes across different models, ensuring consistency in assumptions about available land for various uses, and integrating sectoral analysis to generate cohesive land use patterns.

The LAMASUS Toolbox is an innovative initiative led by Vrije University Amsterdam in collaboration with key international partners such as IIASA, EC, WUR, BOKU, and PBL. The Toolbox addresses the critical need for integration between macroeconomic land use models operating at broader spatial scales, such as country and NUTS2 regional levels, and more detailed models functioning at higher spatial or farm-specific resolutions. Its primary aim is to enhance the coherence and reliability of land use projections and policy assessments across different scales by bridging existing gaps in model alignment and data consistency.

The Toolbox achieves this by standardizing thematic definitions of land use classes across disparate modeling frameworks and ensuring uniformity in the assumptions regarding the availability and utilization of land across various uses. This standardization is pivotal for integrating sectoral analyses, thus enabling the generation of cohesive and realistic land use patterns that are essential for rigorous impact assessments focused on biodiversity and climate change.

Furthermore, the LAMASUS Toolbox aims to facilitate the translation of complex economic and environmental data into actionable insights, thereby enabling policymakers to make more informed decisions regarding land use planning and management. This report delineates the conceptual underpinnings of the toolbox, documents the methodology developed for translating and scaling model outputs, and discusses the implications of this tool in the broader context of the LAMASUS project. By providing a flexible yet robust framework for model integration, the LAMASUS Toolbox enhances the accuracy and applicability of land use projections and contributes significantly to the sustainability of land management practices, aligning with global environmental goals and policy directives. This abstract introduces the motivations behind the Toolbox and underscores its potential to revolutionize land use modeling and policy analysis at multiple governance levels.

Keywords

Model linkages, LULUCF, NUTS2

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Task leader	Esther Boere	28/02/2025
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Coordinator	Petr Havlík (IIASA)	28/02/2025
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Nature of the deliverable	*Python Markdown and report with pilot prototype and plan designs*	*R and dataset*

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Abbreviations

AFOLU	Agriculture, Forestry and Other Land Use
AGEMOD	Agricultural Member States Modelling
CAPRI	Common Agricultural Policy Regional Impact
MAgPIE	Model of Agricultural Production and its Impact on the Environment
CGE	Computable General Equilibrium
CAP	Common Agricutural Policy
CLUMondo	Conversion of Land Use Modelling Framework
EU	European Union
FAMOS	FArm Optimisation Model Space
FARMDYN	Dynamic mixed farm model
GAEC	Good Agricultural and Environmental Conditions
GHG	Greenhouse Gas
GLOBIOM	Global Biosphere Management Model
IMAGE	Integrated Model to Assess the Global Environment
IPCC	Intergovernmental Panel on Climate Change
LPJmL	Lund-Potsdam-Jena managed Land
MAGNET	Modular Applied General Equilibrium Tool
MITERRA	Miterra-Europe
NUTS2	Nomenclature of Territorial Units for Statistics (2)
OA	Organic Agriculture
PASMA	Positive Agricultural Sector Model of Austria
PE	Partial Equilibrium
SSP	Shared Socioeconomic Pathways
SUPREMA	Support for Policy Relevant Modelling of Agriculture
RCP	Representative Concentration Pathway
ROW	Rest Of the World

1. Introduction

Agricultural and land-use modelling has played a crucial role in analyzing climate and biodiversity impacts by simulating land management practices, assessing greenhouse gas emissions, and evaluating habitat changes under various policy and environmental scenarios, providing insights into sustainable strategies for balancing food production, conservation, and climate goals. For more robust estimates, this is often done with multiple models in a so-called model intercomparison. For example, Van Meijl et al. (2018) presented a set of alternative scenarios using five global climate and agro-economic models. These models, which included integrated assessment (IAM) (i.e., IMAGE), partial equilibrium (PE) (i.e., CAPRI, GLOBIOM, MAgPIE), and computable general equilibrium (CGE) models (i.e., MAGNET), ensured a comprehensive representation of both biophysical and economic features. Stehfest et al. (2019) expanded on this work by investigating the key drivers of global land-use projections under different socio-economic pathways, using the same set of models, earlier mentioned and performing sensitivity analysis to assess model differences. Their study highlighted cropland and pasture as significant land-use drivers for the future.

However, despite these contributions, significant gaps remain, particularly in addressing the discrepancies in trade-offs and synergies between models and resolving differences in outcomes, highlighting the need for further research to refine and harmonize modeling approaches in this field. Recognizing these gaps, Leclère et al. (2020) emphasized the need for a shift toward integrated assessments, in terms of combination of models, to better evaluate sustainable development goals and align with global policy targets, including the EU Green Deal and the Common Agricultural Policy (CAP). Gocht et al. (2021), through the SUPREMA project, highlighted the strengths and limitations of approaches like PE and CGE models. They emphasized the importance of integrating global and regional models to improve the consistency of agricultural and land-use assessments. However, recurring discrepancies between models, driven by differences in resolution and assumptions, remain a significant challenge. These issues cannot be resolved through intercomparison alone, highlighting the need for harmonized and integrated modelling approaches.

Building upon this foundation, the LAMASUS project, especially through Deliverable 6.1, aims to overcome these challenges by aligning assumptions and establishing stronger connections between global models and spatially explicit, high-resolution frameworks (Verburg & Overmars, 2009). LAMASUS seeks to move beyond the limitations of top-down methodologies prevalent in current literature, offering a bottom-up perspective that provides deeper insights into European land-use dynamics and their interactions with macroeconomic models. The innovative framework, designed and described in this deliverable, ensures that the results are both relevant and actionable, contributing significantly to bridging the gap between global and regional modelling efforts (Gocht et al., 2021). A core goal of the LAMASUS project is to develop a toolbox of forward-looking models that assess the feasibility and land-use implications of achieving the EU Green Deal policy objectives. While the models are not entirely new, they will be significantly enhanced within the project to better capture land use management across varying spatial scales and purposes.

Work Package (WP) 6 is central to advancing high-resolution spatial land system modeling for policy assessment. The overarching aim of WP6 is to develop a new generation of high-resolution spatial land system modelling for policy assessment. This includes three main objectives:

i. to develop a flexible framework for coupling large-scale economic models with high-resolution spatial and behavioural models (Task 6.1);
ii. to configure spatial land-use models to address interconnected policy questions, including climate, agricultural, and land-use policies (Task 6.2);
iii. to design behavioural models that provide insights into land-use decision-making processes and validate high-resolution modeling in regional case studies (Task 6.3).

The first milestone of WP6 focused on drafting the conceptual framework for the LAMASUS Toolbox—a robust system designed to translate model outcomes across different spatial scales. This includes economic models at the country or NUTS2 level (e.g., GLOBIOM, CAPRI, IMAGE, MAGNET) and high-resolution land-use models (CLUMondo), as well as farm-level models (PASMA, FARMDYN). Further details are provided in the Annexes 5.1. In this deliverable, we build on the initial draft by harmonizing differences in land-use class definitions, ensuring compatibility across models, and offering consistent assumptions about land availability for various uses.

Secondly, a core objective of the LAMASUS project is to develop the high-resolution CLUMondo model, which will produce a new European map at a 1 km² resolution. This second objective enables the assessment of mid-century land-use changes and provides the basis for analyzing the policy targets outlined in the project, such as the CAP, the Green Deal, and the Nature Restoration Law in subsequent work packages and tasks.

While WP6 focuses on the theoretical and methodological development of the Toolbox, its practical implementation will occur in WP8. In WP8, the Toolbox will be applied to evaluate real-world policy scenarios and assess their impacts on land use, biodiversity, and climate goals. By linking the conceptual advancements of WP6 with the applied modeling and scenario evaluations of WP8, the project ensures a seamless transition from theoretical development to practical application.

This deliverable provides a foundational framework for coupling methods and presents examples of potential linkages between models, serving as a critical step towards the development of the LAMASUS Toolbox. A central focus of the report is the mapping and harmonization of assumptions regarding land-use classes across all models, with supplementary materials, such as datasets, included as part of the Toolbox.

The deliverable is structured into four sections, each addressing specific objectives. Section two provides an overview of the assumptions underpinning each model, offering essential background for understanding their interactions. The third section dives into specific model linkages, detailing the methods, rationale, and preliminary outcomes of these connections. Finally, the fourth section summarizes the findings, highlighting the implications of the proposed coupling methods and how they contribute to bridging gaps in scale, resolution, and sectoral analyses. The linkages are available on GitHub.

2. Models in the LAMASUS Toolbox

In this section, we outline the key assumptions underlying the European-wide models used in the LAMASUS project, along with a detailed explanation of the harmonization process. Additionally, we describe the unique characteristics of each model, focusing particularly on their differences for land cover, land use, and land management. A dataset linked to this deliverable is available (Annexes 5.3 and Excel sheet), offering an overview and mapping across the models. For more detailed information, Annex I includes an in-depth explanation of the models and links to their respective websites. Harmonization is a crucial step in aligning the assumptions across different models to ensure compatibility and effective coupling. The process will standardize definitions, assumptions, and frameworks to address discrepancies and ensure consistency in the outputs across models.

The LAMASUS project employs a diverse set of models to analyze land-use dynamics and their broader implications, including GLOBIOM, IMAGE, MAGNET, CAPRI, and CLUMondo (referenced below and abbreviations in the glossary). Each model offers unique capabilities and insights tailored to different aspects of land use, agriculture, and policy analysis.

- GLOBIOM (IBF-IIASA, 2023) is a global recursive dynamic PE model of the forest and agricultural sectors. Regarding land use and climate, one of its strengths is its detailed greenhouse gas (GHG) emissions accounting from Agriculture, Forestry, and Other Land Use (AFOLU), following IPCC accounting guidelines. Further, GLOBIOM evaluates the complexities of the food and energy nexus, operating at both NUTS2 and global scales to explore resource demands and subsequent land use changes.
- IMAGE is an IAM framework that simulates the interactions between human activities and the environment to explore long-term global environmental change and policy options in the areas of climate, land, and sustainable development (Doelman et al., 2018; Stehfest et al., 2014; Elzen et al., 2008). Its strengths lie in the interactions between nature and human behaviour, particularly at the global level. It provides a dynamic understanding of how climate, energy, and land systems co-evolve, offering valuable insights into the interplay between environmental and societal changes.
- MAGNET is a recursive dynamic, multi-region, multi-sector CGE model (Woltjer et al., 2014) that assesses the impacts of agricultural policies, climate change, trade, and land-use changes. By incorporating endogenous price and demand mechanisms, MAGNET explores how land and labor supplies adjust to various economic and policy drivers.
- CAPRI is a detailed PE model of the agricultural sector (Britz et al., 2003). One of its strengths is the detailed representation of the Common Agricultural Policy (CAP) reforms and other agricultural sector policies. Its focus on European agriculture makes it indispensable for analyzing the effects of EU policy changes.
- CLUMondo (Verburg et al., 2011; 2013) is a high-resolution dynamic model that integrates both biophysical drivers and socio-economic factors to simulate land-use allocation at a 1 km resolution. Its dual approach, combining bottom-up biophysical processes and top-down socio-economic factors, allows for a comprehensive assessment of land-use changes (Verburg & Overmars, 2009). When coupled with macroeconomic models, CLUMondo provides a detailed representation of both land-use change trajectories and broader societal transitions.

The main differences between the models used in the LAMASUS project lie in their representation of market trade and goods, as well as their land use and land management coverage, baseline maps and spatial and temporal resolutions. Macro-economic models, such as MAGNET, GLOBIOM, and CAPRI, feature an endogenous representation of market trade and the prices of goods, meaning that supply, demand, and prices are determined within the model itself based on the interactions of economic agents. In contrast, IMAGE and high-resolution models, like CLUMondo, typically use exogenous representations of markets, where market prices and trade patterns are determined externally, often based on assumptions or external data inputs, rather than being generated internally by the model.

Another key difference lies in the base year data used to depict land-use changes. GLOBIOM uses a baseline from the year 2000, suitable for global agricultural and forestry analyses. IMAGE employs a 1970 baseline, reflecting its focus on long-term human-environment interactions. MAGNET uses a 2017 map for current economic and policy assessments, while CAPRI relies on 2004 as the historical baseline to align with conditions following the European agricultural activity up to current days. CLUMondo employs more recent base year data from 2020, starting from a current representation of land use but being unable to provide a validation period of land use change. Temporal resolution further distinguishes these models.

A full representation of land cover is provided in the Annex Section 5.1 and accompanying dataset. We highlight the key differences in land use and cover between the models and describe the results of harmonizing the land classes (Table 1). Macro-level models generally use unique land cover classes that do not depict the intensity of production. However, they can often differentiate the share of total production under a certain management system within the land cover class. CLUMondo bases its classes on mosaics of different land covers and the intensity of certain activities (e.g., from low-intensity to high-intensity arable cropland).

Lastly, macro-economic models, including MAGNET, GLOBIOM, and CAPRI, operate on a 10-year time step, reflecting their focus on long-term trends and policy impacts. In contrast, high-resolution models like CLUMondo and IAMs like IMAGE use yearly time steps, providing a more granular view of short-term changes. These distinctions underscore the diverse capabilities of each model, which together provide complementary perspectives for understanding and analysing land-use systems.

Table 1. Macro-economic models and high-resolution model comparison of assumptions

	GLOBIOM	**CAPRI**	**IMAGE**	**MAGNET**	**CLUMondo**
Model base-year	2000 and solved recursively dynamic	2004	1970	2017	2020
Model time step (years)	10	10	Yearly	5 for mid-term (up to 2050) 10 for long-term (up to 2100)	Yearly

	GLOBIOM	CAPRI	IMAGE	MAGNET	CLUMondo
Model resolution	NUTS2	NUTS2	World regions	Global - Country/AEZ or NUTS2 (EU)	1 km^2
Model type	Partial Equilibrium	Partial Equilibrium	Simulation model coupled to General Equilibrium	General Equilibrium	Spatial simulation model
Underlying Land Cover Map	GLC2000 and Corine Land Cover	Corine Land Cover	IMAGE potential vegetation map with HYDE land use	Same as IMAGE	Sandstrom et al., 2023
Trade Representation	Takayama-Judge spatial equilibrium, homogenous goods	Armington spatial equilibrium of quality differentiation, heterogenous goods	Represented through MAGNET	Armington spatial equilibrium	No trade representation
Demand-side Representation	Explicit price elasticities, exogenous income elasticities	Explicit price and cross-price elasticities	Explicit price and income elasticities in MAGNET	Explicit price and income elasticities	Exogenous representation through other macro-economic models
Supply-side Representation	Spatially explicit Leontief production systems Leontief covering alternative production systems	NUTS2 level non-linear programming models in the EU. Linear system of supply functions in the ROW	Potential yield from LPJmL dynamic global vegetation model combined with MAGNET productivity projections	Assess production of agricultural products based on combinations of primary and intermediate production factors	Spatially explicit weights at the regional level for land conversion
Land Representation	Explicit link to agricultural and forestry activities	Explicit link to agricultural activities in the EU, land supply and demand functions in the ROW, allocated to products	Available land for types of activities, per 5 arc-mind grid-cell, depending on biophysical suitability and availability	Dynamic land supply function[i] accounting for the availability and suitability of land for agricultural use, based on	Land use intensity determines the area needed to meet demand based on macroeconomic models

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[i] Van Meijl et al., 2006

	GLOBIOM	CAPRI	IMAGE	MAGNET	CLUMondo
				information from IMAGE.	and biophysical drivers[ii]
Land covers per model	Cropland, grassland, short rotation plantations, managed forests, unmanaged forests, and other natural vegetation land, other agricultural land, wetlands	Arable cropland, perennial cropland, wetlands, permanent grassland, forest, artificial surfaces, other sparsely vegetated land	Urban areas, peatlands, natural vegetation, cropland, grassland, permanent cropland, other land uses	Unmanaged forest, managed forest, cropland, grassland	Urban areas, forest, arable cropland, grassland, permanent cropland, mixed forest with grassland, cropland mosaics
Allowed conversion	Conversion allowed for expected profitability (i.e. forest to agriculture and not the opposite)	The regulation of land supply is modelled as a consistent resource constraint in the land-use allocation model and agricultural land	Conversion given by the spatial suitability with some restrictions	Conversion given by the efficiency of the production system	Conversion is allowed for some land uses but restricted in natural areas, with expert input applied during conversion (e.g., agricultural abandonment to secondary forest) based on spatial suitability from biophysical drivers.
Cost associated with land conversion	Non-linear conversion cost - increasing with the area of land converted at the regional level - that is taken into account in the producer optimization behaviour.	Like GLOBIOM	Represented through MAGNET	No direct cost, but potential price rise due to the optimisation of production, land supply and elasticities/prices	Conversion matrix for land types that allow likelihood conversion based on the probability

In addition to the global modelling framework, regional case studies will play a critical role in verifying and refining the rules and parameterization of high-resolution spatial models. These

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[ii] Van Vliet & Verburg, 2018

studies are designed to ensure that spatial land-use models accurately capture farm- and agro-forestry-level decisions and account for local variations (Schönhart et al., 2011). By harmonizing the assumptions between high-resolution spatial models and farm-level implementations, these case studies will bridge the gap between global-scale insights and local-scale realities. A key focus of this approach is transitioning from land-use allocation driven solely by biophysical factors to strategies that integrate cost-effectiveness, agronomic practices, and the opportunity costs of switching practices at the country level. Models such as FAMOS/PASMA (Schmid, 2004) and FARMDYN will be utilized to explore these dynamics (Kuhn er al., 2019, Kuhn et al., 2020. Kuhn et al., 2022). The task will involve comparing the assumptions, input data requirements, and results across the different models to identify areas of alignment and divergence. Sensitivity analyses, conducted by BOKU, will further assess the trade-offs and synergies among the models, providing deeper insights into their performance and applicability WP6.1 and WP7.1. The outcomes of this work will feed into subsequent tasks, including an evaluation of policy scenarios (WP8) and climate change projections, ensuring that the integrated framework is robust and policy relevant.

2.1. CLUMondo recent development

The base map of CLUMondo serves as the starting point for the model at large. The purpose of updating the map was twofold: 1) to update the land use management data to achieve the most spatially detailed and current representation of the European land systems as possible, 2) to narrow down the number of land systems to simplify the modelling as the previous version of the land system map by Dou et al. (2021) increased the computing processing time. The old map was also created with a specific focus on biodiversity while in this case we wanted to create a base map that could be used for multiple study purposes.

Table 2 shows the new land systems included in the base map for CLUMondo with the base year 2020. The Table shows how the legend is further simplified while modelling by combining certain land system classes and lists which land systems are not simulated at all. It also shows what the land system legend will look like after modelling with post-processing.

To classify land cover, new high-resolution spatial data was used. For grassland and urban land, high-resolution data from Copernicus was used, for arable cropland the EU crop map from d'Andrimont et al. (2021) was used in combination with Corine data, forest was based on data from Senf and Seidel (2021) and for permanent snow data from GLIMS was used.

Furthermore, wetlands were added as a dynamic land system from previously having been static. The forest management classes were also changed from pure intensity classes to more usage-based management classes, based on the map from Oostdijk et al. (2023), this is to better represent the diversity of uses a forest can have.

Table 2. Land use management legend, simplifications made for modelling and planned post-processing of legend for CLUMondo (table adjusted from Sandström et al. 2023)

LEGEND OF LAND SYSTEMS CLASSES	**SIMPLIFICATIONS MADE FOR MODELING**	**POST-PROCESSING**
Low-intensity arable cropland	Low-intensity arable cropland	Low-intensity arable cropland

Medium-intensity arable cropland	Medium-intensity arable cropland	Medium-intensity arable cropland
High-intensity arable cropland	High-intensity arable cropland	High-intensity arable cropland
Permanent crops	Permanent crops	Permanent crops
Low-intensity settlements	Low-intensity settlements	Low-intensity settlements
Medium intensity settlements	Medium intensity settlements	Medium intensity settlements
High-intensity settlements	High-intensity settlements	High-intensity settlements
Wetlands	Wetlands	Wetlands
Water & Glaciers* Bare rock & Shrubs	CONSTANT (do not include in simulation, depict as no data and later fill it up with the different land uses)	Water & Glaciers Bare rock & Shrubs
Low-intensity grasslands	Low-intensity grasslands	Low-intensity grasslands
Medium-intensity grasslands	Medium-intensity grasslands	Medium-intensity grasslands
High-intensity grasslands	High-intensity grasslands	High-intensity grasslands
Forest, shrub and cropland mosaics	Forest, shrub and cropland mosaics	Forest, shrub and cropland mosaics
Forest, shrub and grassland mosaic	Forest, shrub and grassland mosaic	Forest, shrub and grassland mosaic
Primary forests	Primary and close to nature forestry	Primary forests
Close-to-nature forestry		Close-to-nature forestry
Combined-objective forestry	Combined-objective forestry	Combined-objective forestry
Intensive forestry	Intensive & very intensive forestry	Intensive forestry
Very intensive forestry		Very intensive forestry

Another focal point was the development of current forest management maps. To achieve this, the conceptual mapping units and the division of land use were refined to include all human processes and activities. These functions can change over time due to various factors, such as socioeconomic developments. To address potential issues, distinct land systems were classified to better understand the patterns behind different types of land use. This classification ultimately aims to optimize land use for both human needs and nature conservation.

2.2. FOREST MANAGEMENT BASELINE MAP

As for the baseline map classification a decision tree was employed, illustrated in Figure 1, to generate a map for forest management for Europe at 1 km^2 resolution. Three classes of forest management are distinguished (Table 2). These classes distinguish forest management by their intent and intensity

Table 3. Forest management classes definition

FOREST MANAGEMENT CLASS	DEFINITION
Close-to-nature forestry + primary forest	Barely disturbed forests with a nature function. No to barely any management in place.
Combined objective forestry	Mixed objective forests without a single dominant objective in the management strategy. Functions may include protection, recreation, wood production or other functions.
Intensive forestry + very intensive forestry	Forests managed dominantly for wood production. Rotation length is based on maximum profit. Large patches of forests are cut down for wood production either in one period or over a longer period. The trees are cut down in a short time period (i.e. shorter or equal to maximum profit), cut in large patches (i.e. big clear-cuts) and/or consist of fast-growing species only.

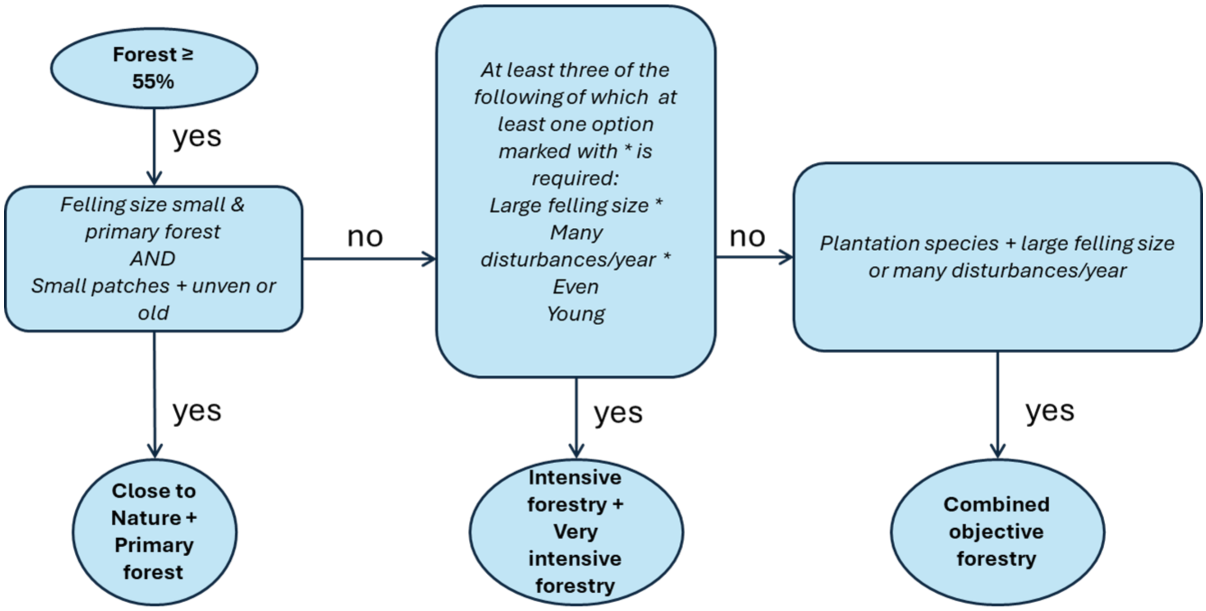

Figure 1. Decision Tree for forestry management map

The resulting forest management map was fine-tuned through a validation and calibration process using secondary data sources. First, a soft validation was conducted by comparing our forest management map with the harvesting intensity map by Verkerk et al. (2015), which was developed using different methods and input data. We found that most of the areas classified as intensive forest management and plantation forests in our map aligned with regions of higher harvesting intensity in Verkerk et al.'s map, except in Scandinavia, the Mediterranean, and the Balkans.

To further validate these findings, we compared the extent of intensive forest management and plantation forests in our map with roundwood production data. A significant discrepancy between the country-level average and the roundwood production per km², as derived from our map, indicated potential over- or underestimation of intensive forest management or plantation coverage. Again, we observed an overestimation of wood production in the Mediterranean, the Balkans, and Scandinavia.

Lastly, we calibrated our map using data from FOREST EUROPE (2020) and conducted small-scale case studies utilizing Google Maps (Street View) and national forest management maps. Adjustments were made by modifying thresholds in the decision tree to better align with reported production data from FOREST EUROPE. The specific calibration details are provided in the Figure 1.

2.3. INTEGRATING THE RESPONSE FUNCTION FROM MACRO-ECONOMIC MODELS TO HIGH-RESOLUTION MODELS

2.3.1. EPIC response functions with high resolution models

In the following sections we describe harmonizing the macro-economic models' land-use classes and the corresponding response function with the high-resolution model.

At this stage, the current outputs include the EPIC alignment for both Cropland and Grassland, under which externalities from these agricultural activities were calculated. In order to achieve this, it was necessary to align the LUM classes and the associated intensities that distinguish the crop model from the high-resolution model.

To accomplish this, we mapped the LUM classes in EPIC to their counterparts in CLUMondo (Table 4), considering land-use intensities across both models. By emphasizing the most distinctive class in CLUMondo, we could represent land allocation and capture the temporal dynamics of specific land use classes at a finer scale, thereby revealing the nuanced spatial variability of these externalities.

Table 4. Land use intensities mapping between EPIC and CLUMondo

CROPLAND CLASSES AND SCENARIOS			
Class EPIC	**Name**	**CLUMondo LUM Classes**	**LUM number in CLUMondo**
M1.rf	**Very, low intensity rainfed**	**Low-intensity arable cropland**	6
M2.rf	**Low intensity, rainfed**	**Low-intensity arable cropland**	
M3.rf	**Medium-high intensity, rainfed**	**Medium-intensity arable cropland**	7
M4.rf	**High intensity, rainfed**	**High-intensity arable cropland**	8
M5.rf	**Very high intensity, irrigated**		
M5.Ir	**Very high intensity, irrigated**		
Reference Scenario (REF)	**Mix (rf/Ir)**	**Medium-intensity arable cropland**	7
GRASSLAND CLASSES AND SCENARIOS			
15	**Very high-density managed pasture system**	**High intensity grasslands**	11
16	**High density managed pasture system**	**High intensity grasslands**	11

17	**Moderate density managed pasture system**	**Medium intensity grasslands**	10
18	**Low density managed pasture system**	**Low-intensity grasslands**	9
19	**Very high density managed grassland**	**High intensity grassland**	11
20	**High density managed grassland**	**High intensity grassland**	11
21	**Moderate density managed grassland**	**Medium intensity grasslands**	10
22	**Low density managed grassland**	**Low-intensity grasslands**	9
23	**Rough grazing**	**Low-intensity grasslands**	9
24	**Silvo-pastoral agroforestry**	**Low-intensity grasslands**	9
25	**Managed semi-natural and natural grassland**	**Medium intensity grasslands**	10
26	**Unmanaged semi-natural and natural grassland**	**Low-intensity grasslands**	10

To represent the carbon stock dynamics, we followed the procedure described by Frank et al., (2024). By multiplying the area under cropland management with an emission factor we will be able to calculate the emissions given from arable crop production (see Equation 1).

$$SOC\ emissions\ CL\ management\ =\ Area\ CL\ r\ CL\ *\ Emission\ factor\ CL \qquad \text{(I)}$$

To estimate the emission factor for cropland (CL) and represent soil organic carbon (SOC) dynamics and SOC emissions accurately, the approach presented in Frank et al. (2024) was also used. SOC response functions for each of the crop rotation and tillage system represented in GLOBIOM were estimated at the grid level using a biophysical process-based crop model EPIC. To include the estimated SOC response functions for CLUMondo, this can be done by aggregating the different crops as a basket of products. The baseline of outcomes was then created by matching the intensity of EPIC and CLUMondo.

The same approach, harmonizing the LUMs of EPIC to the one of CLUMondo, was adopted for grassland. Noteworthy is that grassland areas do not represent total existing grasslands but productive grasslands for animal feeding only. The grassland area in GLOBIOM thus depends on animal feed demand, grassland productivity estimated by EPIC for each SimUID and total grassland area according to CORINE. SOC emissions from grassland management (GL) will be calculated by multiplying grassland area (grassland remaining grassland, GL r GL) with a country-specific emission factor GL (see Equation 2).

$$SOC\ emissions\ GL\ management\ =\ Area\ GL\ r\ GL\ *\ Emission\ factor\ GL \qquad \text{(II)}$$

The emission factor used for grassland is based on reported UNFCCC data by dividing reported emissions from grassland remaining grassland by existing grassland area (Frank et al., 2024). The emission factor for other land converted to grassland (excluding emissions from deforestation to avoid double counting as reported by G4M) were also calculated.

The initial results of this integration, as shown in Figure 2 indicate an overall increase in SOC in the topsoil across all management classes. However, this trend is more pronounced in low-intensity systems. While medium- and high-intensity classes also contribute to SOC accumulation, they are accompanied by more widespread losses at the NUTS2 level across the European Union.

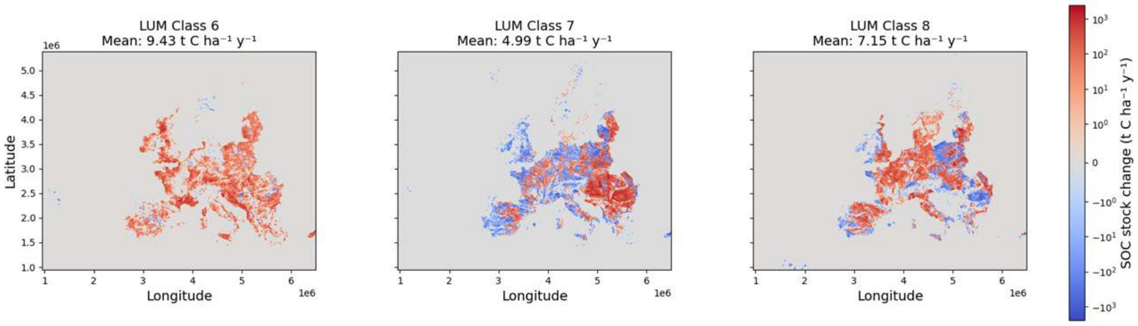

Figure 2. SOC changes between 2040-2020 in CLUMondo high resolution model for arable land from low intensity to high intensity. In blue we are observing the loss of SOC and in red the increase of SOC in EU NUTS2 level.

Conversely, grasslands exhibit an opposite trend, potentially due to the current protection scenario of NATURA2000 areas in CLUMondo, which emphasizes the protection of lower- and medium-intensity grasslands. Although this approach may influence SOC. As reflected in production per livestock demand this approach does not necessarily translate into a positive impact on SOC pools. Moreover, the distribution of intensive grassland classes in the CLUMondo simulations is not uniform across EU territories.

At last, both grassland and cropland were separately compared over the timeframe of 2040-2020 by using the 20-year mean annual rate change in the EPIC outputs.

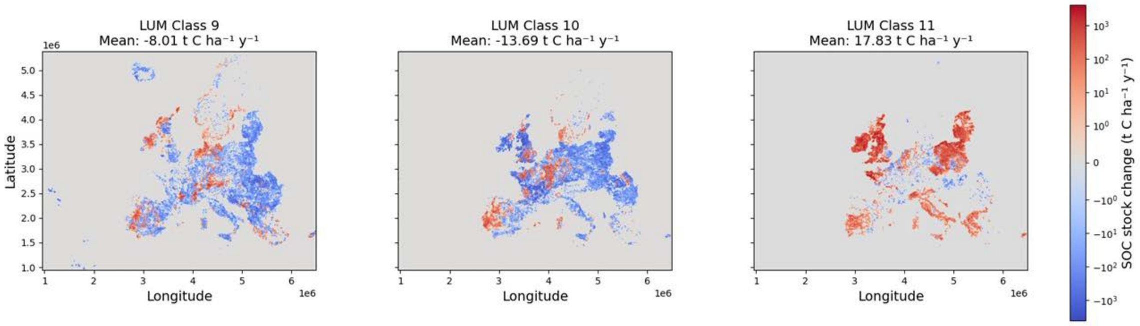

Figure 3. SOC changes between 2040-2020 in CLUMondo high resolution model for grassland from low intensity to high intensity. In blue we are observing the loss of SOC and in red the increase of SOC in EU NUTS2 level

Additionally, yield, nitrogen oxide (NO_3) losses, and residue management were integrated into the analysis to account for disparities in land allocation between the EPIC model—which primarily emphasizes agricultural activities, and CLUMondo, which allocates land among a broader array of classes (Annex 5.2). By aggregating the Land Use Modules (LUMs) and considering all arable crops as a composite basket of products within CLUMondo, mean yields for arable cropland were derived as 2.92 t ha^{-1} for low intensity, 4.49 t ha^{-1} for medium intensity, and 6.79 t ha^{-1} for high intensity arable cropland. Similarly, the nitrogen losses associated with fertilization in arable cropland exhibited a corresponding trend, with values of 16.99 kg ha^{-1}, 60.55 kg ha^{-1}, and 152.82 kg ha^{-1} for low, medium, and high intensity, respectively. In terms of residue management, high-intensity arable cropland—characterized by enhanced conservation practices (WP 5) demonstrated the highest residue accumulation at 2911.94 kg ha^{-1}. Conversely, within grassland systems, the mean yields for LUM9, LUM10, and LUM11 were 1.14 t ha^{-1}, 2.46 t ha^{-1}, and 4.35 t ha^{-1}, respectively, while residue management exhibited an inverse trend compared to arable cropland, with the lower intensity LUM showing a higher residue accumulation of 4717.23 kg ha^{-1}.

2.3.2. Biodiversity response functions g4M within CLUMondo

To integrate all the response functions derived from the model g4M, we created a baseline map where every species has its correspondent of the LUM intensity in CLUMondo (Figure 4). Afterwards, will be created the net change of biomass production for the land use intensity (e.g., close-to-nature and nature forest, intensive forestry, and combined objective forestry).

Then the change between the baseline map and future projections will be calculated based on different LUM. This can allow the high-resolution model to account the biodiversity change that are going to be explored by assessing the expansion of landscape features in WP8.

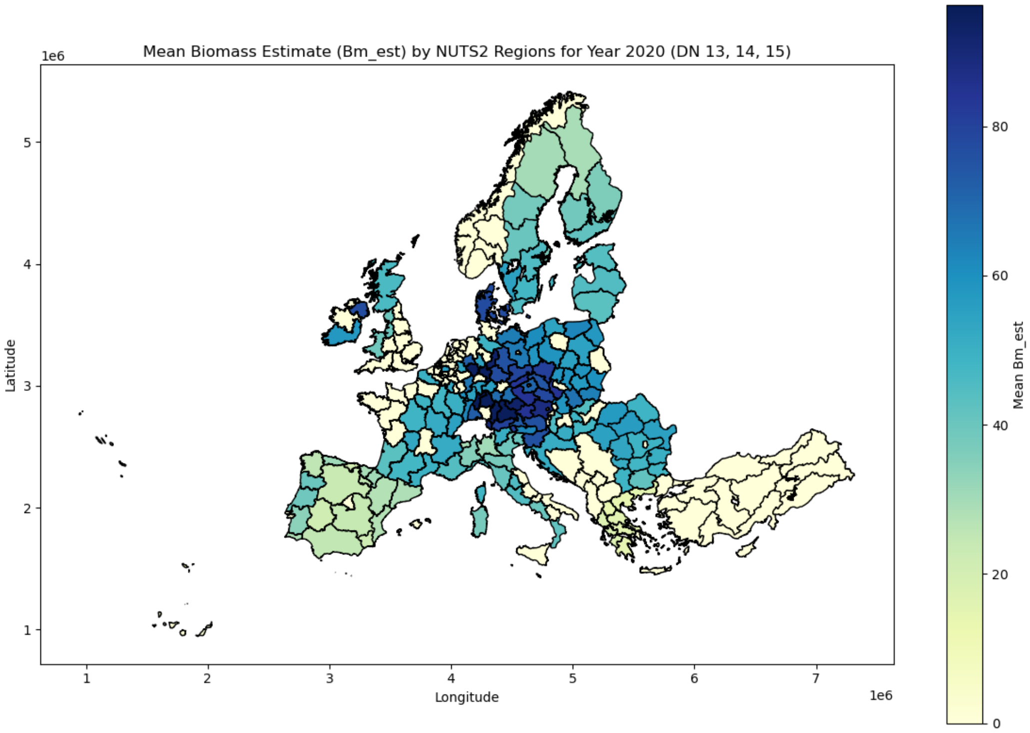

Figure 4. Baseline map biomass per year 2020 with the CLUMondo LUM classes at NUTS2 level with an extended rotation time (Tau coefficient in G4M)

In this scenario, which considers only the protection of NATURA2000 areas without additional policy interventions, we analyse the changes in living biomass within the CLUMondo SSP370 run. Specifically, Figure 5 illustrates the variation in living biomass for land use classes 13, 14, and 15 (see Table 3 for class definitions). By aligning the CLUMondo simulations with the response functions from the g4M model, we observed a mean change across all LUM intensities.

The most significant increase in living biomass is driven by the combined objective forestry class, with an average gain of 18.32 t C ha^{-1}, followed by intensive and very intensive forestry, which shows a mean increase of 17.04 t C ha^{-1}. Additionally, although to a lesser extent, some areas of close-to-nature and primary forests also experienced an increase in biomass.

As expected, these trends were anticipated, given that the policy scenario remains unchanged while ensuring the protection of NATURA2000 areas. Moving forward, in the next steps of WP8, we will refine the scenario by incorporating the expansion of landscape features and integrating outputs from other dynamic process-based models such as G4M and GLOBIOM. This will allow us to further fine-tune projections based on different LUM intensities, improving our understanding of both the current state and future trajectories of biomass accumulation and the wood production sector dynamics.

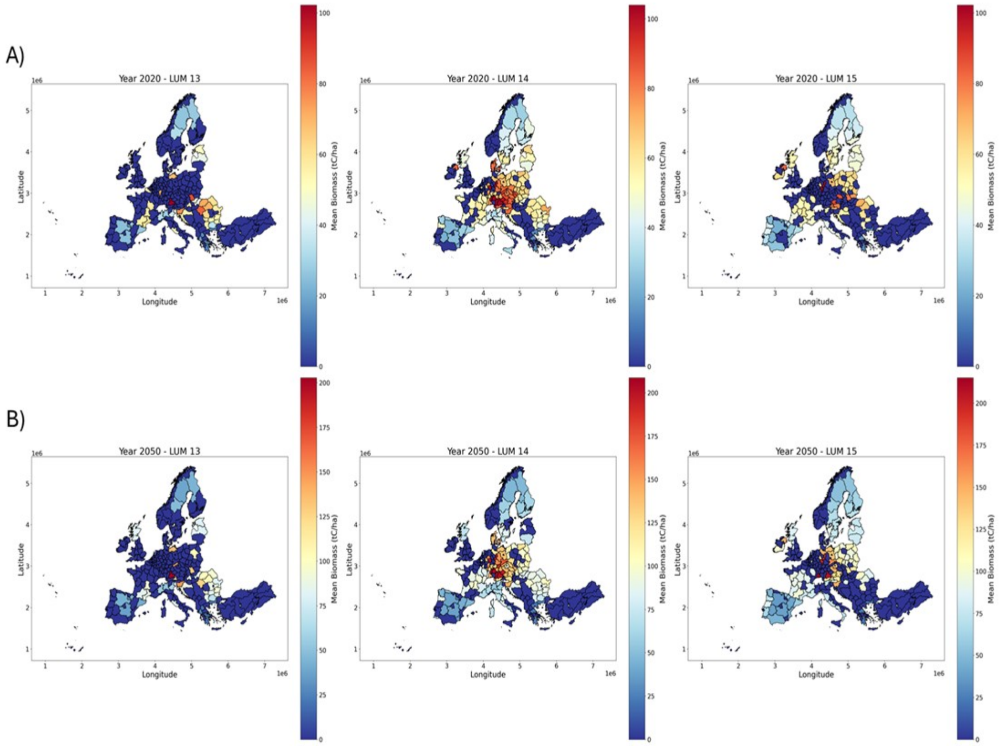

Figure 5. Existent forest living biomass for the time stamp 2020 (A) and the time stamp 2050 (B), for the LUM 13,14,15.

2.3.3. ORCHIDEE response function in high-resolution models

In WP 5, the land surface model ORCHIDEE was used to simulate the general climate impact of transitions between croplands, grassland and forest (e.g., soil albedo, heat budgets). Specifically, the model was used to represents carbon cycling, heat and water budgets of different types of forests, grasslands, and croplands in a consistent way but with a limited representation of management intensities. To simulate the future climate projections, they followed the high mitigation scenario SSP126 and the low mitigation scenario SSP370, based on IPSL-GCM.

To compare the simulations done with CLUMondo. We need to match the projection based on the biomass and wood harvest as well the distribution of species within the intensities of forest classes and for the moment see the distribution within the model of the different variables to be assessed. To see the difference within the climate projections, we will compare the IPSL-GCM with the CHELSA database ensemble of GCM to reduce the uncertainties in the representation of future projections, by using a high-resolution model and describing the rainfall pattern more accurately (Fierke et al., 2024).

Regarding the SOC, stocks can be simulated through the transition from a land use to another following the same methodology that was used in ORCHIDEE where LUM1 and LUM2 denote the land use before and after conversion, like in the WP5.

$$\Delta SOC = SOCLUM2 - SOCLUM1$$

This integration in high-resolution model will improve the representation of SOC stock changes in EU soils. Especially, by considering the shift between land uses from arable, forest and grassland.

3. Linkages and scenarios between macro-economic models and high-resolution models

3.1. Baseline linkages

Having explored the models and their key similarities and differences, it is now essential to consider the various approaches for linking them. Economic modeling linkages can be established using different methods. Britz (2008) identifies three primary approaches: model chains without calibration, one-way calibration, and sequential calibration.

Model chains without calibration involve transferring data from one model to another without any feedback between the interlinked models. For example, linkages such as AGLINK-AGMEMOD, and to some extent MAGNET-IMAGE, fall into this category. In these cases, macro or market simulation results from one model are used as exogenous inputs for another (Gocht et al., 2021). One-way calibration, on the other hand, involves adjusting one model to align its outputs with those of another. This method is exemplified in the MITERRA-AGMEMOD linkage, where the parameters of MITERRA are adapted to match the economic outcomes generated by AGMEMOD. Typically, this involves a top-down calibration process, where more disaggregated outputs or response parameters are harmonized with higher-level model results (Gocht et al., 2021).

Sequential calibration is characterized by iterative feedback between interconnected models (iterative linkages in section 3.2.3), with each model generating and utilizing its own outputs in a cyclical process. For example, the CAPRI partial equilibrium model and IFM-CAP linkage employ this method. In this case, the market module calculates equilibrium prices and quantities by solving supply and demand interactions, while the supply module determines output quantities based on these prices. Prices and quantities are exchanged iteratively between the modules until market equilibrium is achieved, even in complex, multidimensional product settings (Gocht et al., 2021).

For the development of this Toolbox, the choice of linkages plays a crucial role in integrating demand-side representations for agricultural production, wood, livestock, and population growth from macroeconomic models. As a starting point, one-way linkages—such as using GLOBIOM-CAPRI outputs as inputs for CLUMondo, are employed to establish the baseline for the approach (Figure 6). These initial linkages allow for the exploration of scenario-specific impacts, with notable differences observed in certain areas highlighted by the circled regions. These changes particularly highlight the transition from medium and high-intensity forestry to high-intensity cropland (228519, 162848 km²) how varying socioeconomic pathways influence land-use dynamics. Adding quantitative data on these changes would further enrich the analysis and provide deeper insights into these transitions.

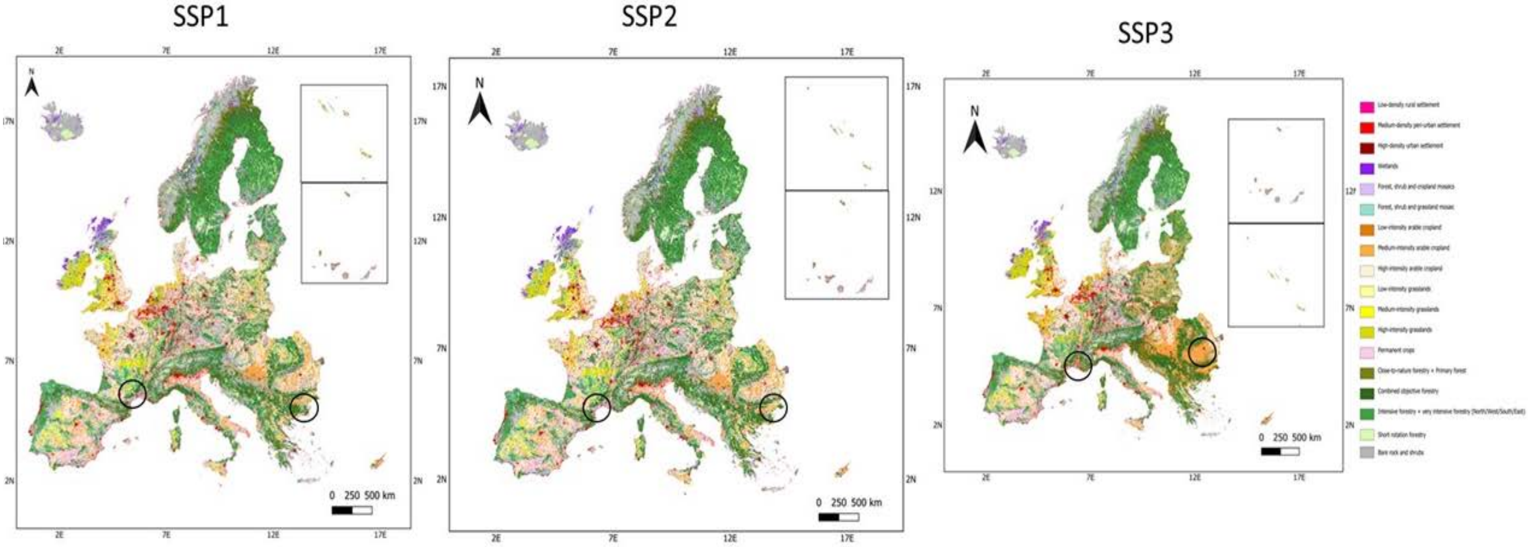

Figure 6. Land-use projections for Europe under SSP1, SSP2, and SSP3 scenarios, illustrating the results of a one-way calibration linkage where outputs from GLOBIOM-CAPRI serve as inputs for the CLUmondo model to represent land use changes by 2050.

The primary goal of the LAMASUS project, however, is to implement sequential linkages with iterative feedback between macroeconomic models and high-resolution models. The Toolbox offers a methodology for fine-tuning the parameterization of specific macroeconomic outcomes, ensuring improved alignment and consistency across linked models (Figure 7).

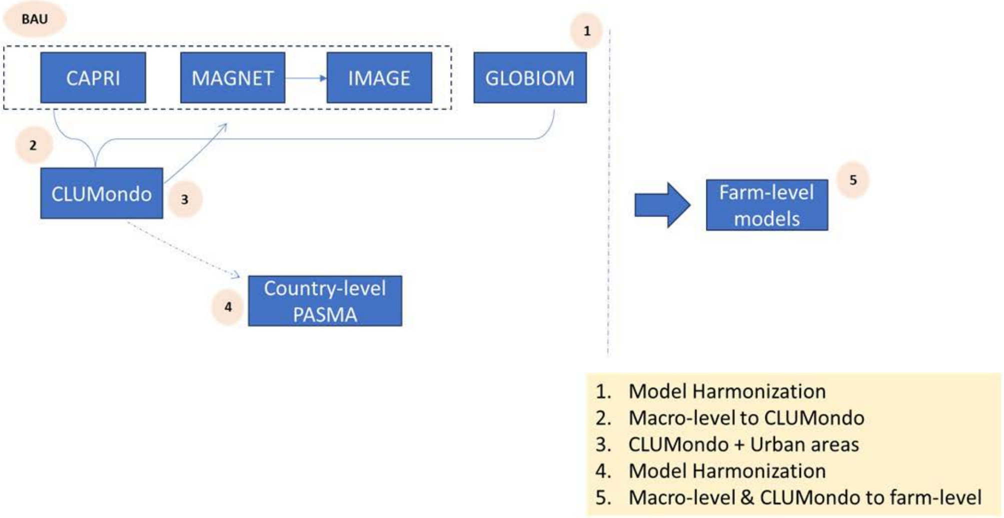

Figure 7. Overview of model linkages established in the LAMASUS project and potential interlinkages from high-resolution and farm-level models aimed to shape the exploratory and comprehensive scenarios in WP8

3.1.1. Macro-level to CLUMondo

Representing socio-economic changes and trade commodities in the AFOLU sector within the CLUMondo model requires linking macro-economic variables to CLUMondo. To do so, we followed the linkages proposed by Dou et al. (2023). Since this application focuses on Europe, land-use demands are shaped by global demographic and economic trends. We based these demands on outcomes from GLOBIOM (Havlík et al., 2011; Lauri et al., 2019). All SSP scenario projections anticipate the European population increase of 0.1%, in line with the UN world population prospects. Furthermore, demand for most goods and services are expected to rise marginally, except for livestock products especially dairly products, which are expected to decrease (EC, 2024).

Comprehensive details on the land use interpretation and parameterization of the reference scenario are provided in the Annex Section 5.1 (Table 7) and the accompanying dataset, which offer a complete mapping for each model, delineating the variables that were incorporated and those that were not included currently. In the following paragraph, we describe the methodological framework adopted for the agricultural sector.

In terms of agriculture, CLUMondo differentiates between land use classes for annual and perennial crops. Therefore, production at the regional level is taken from GLOBIOM for annual crops (e.g., wheat, rice, maize, barley) and permanent crops (e.g., olives, grapes, fruits) using CAPRI data. This differentiation is based on Table 6 (Annex), which provides the mapping of the main elements or variables, which are integrated as production by sector into CLUMondo. This distinction accounts for spatial suitability, dietary roles, and biodiversity impacts. We also incorporated land-use conversion rules and spatial model settings derived from the SSP storylines. Natura2000 areas and peatlands were preserved in the baseline maps of CLUMondo, preventing their conversion to arable land. Furthermore, in the next steps of the project a linkage between IMAGE and CLUMondo will be established, in which the variables that are going to be used are cereal production (e.g., rice, wheat, other cereal grains CGR) and also permanent crop production derived by total area for Europe per single item divided by country shares per crop, according to FAOSTAT data. This will be followed by interpolation to calculate the production of each crop across Europe (t ha^{-1}).

Accordingly, the forest sector was modeled by integrating wood production outputs from GLOBIOM, derived by aggregating final product categories. These include sawnwood (reported in 1000 m^3 of sawnwood), pulpwood (expressed as 1000 m^3 of pulplogs), industrial plantation biomass (combining both sawlogs and pulplogs in 1000 m^3), other industrial roundwood biomass (in 1000 m^3), and fuelwood biomass (quantified as 1000 m^3 of wood fuel).

3.1.2. High resolution to macro-level (URBAN LINK)

We shift our focus from a global perspective to high-resolution modeling and its integration at the macro level. The CLUMondo model operates with a fine spatial resolution of 1 km per pixel, enabling the precise detection of land-use changes. As detailed in Section 2, CLUMondo distinguishes itself from other models through this enhanced resolution. Leveraging this capability, the primary output provided to the macro level is the net expansion of urban areas. CLUMondo's comprehensive land classification (see Annexes 5.3), allows it to project changes over classes that are not represented in the macro-level models, such as urban land. To enrich macro-level models, urban land projections under different SSPs are calculated using CLUMondo at the 1km resolution and transferred to the macro-level models at the NUTS2 level. The benefit of this is that this will influence also the available land for conversion in land covers that are represented in the macro-level models and therefore lead to a better representation of changes in for example agricultural and forest land.

To achieve this adaptation, an overlay was created between the 1 km resolution results from CLUMondo and the NUTS2 layer used by macroeconomic models. This approach enabled the assessment of land-use changes under different scenarios, as documented in the annex of the dataset on urban changes. Codes for Urban changes and the response functions within CLUMondo are available on GitHub.

Urbanization trends across Europe from 2020 to 2050 are found in the preliminary baseline runs (Figure 8). The analysis highlights significant growth in medium-density peri-urban areas, particularly in Eastern Europe. Low-density rural areas are expected to remain relatively stable, decreasing slightly from 21% to 20%. In contrast, medium-density peri-urban areas are projected to increase substantially from 36% to 42%. Meanwhile, high-density urban areas are forecasted to decline from 43% to 38%, indicating a shift toward more distributed urbanization patterns. Under the SSP2 scenario, urban expansion is projected to exceed 4.2 million hectares, primarily driven by peri-urban growth (highlighted in yellow and green close to cities on the map). When comparing the two time periods, from 2020 to 2030 and from 2030 to 2040, the projections indicate the development of 1.4 million hectares of new urban areas by 2030 (Figure 15, Annex), increasing to 2.6 million hectares by 2040 (Figure 16).

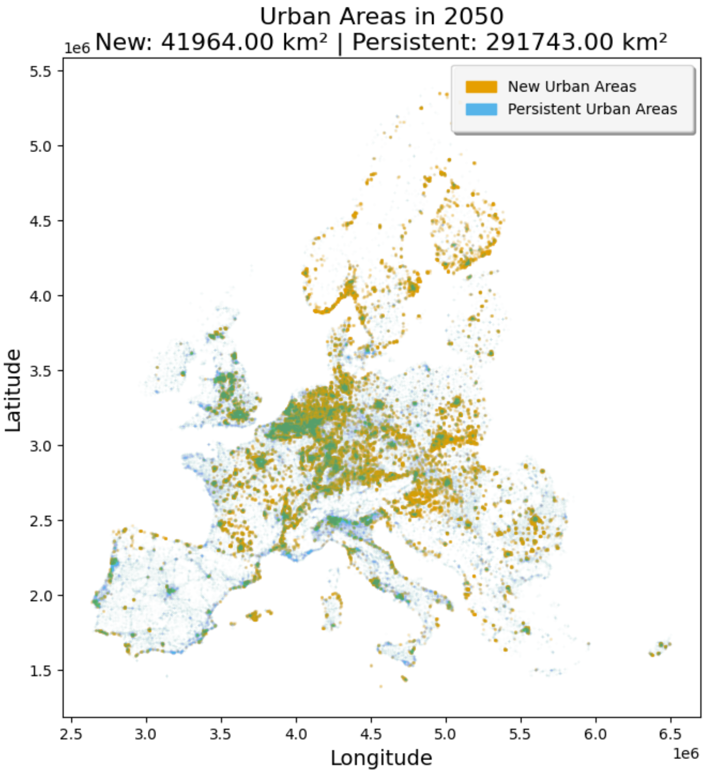

Figure 8. Urban expansion from 2020 to 2050 across a modelled geographical area, showing both persistent and newly developed urban areas (respect 2020). Persistent urban areas (depicted in light blue) are locations that remained urban across the years, while new urban areas in (orange).

This analysis underscores the importance of integrating high-resolution spatial data with macroeconomic analyses to capture regional variation and land-use dynamics. The main objective in the bottom-up approach that CLUMondo can offer is to refine the parameters of agricultural and forestry production given by the macro-economic levels, by gaining insights from a finer resolution.

3.2. SCENARIO SPECIFIC LINKAGES

Once the Toolbox is fully developed and the linkages between the models are operational, the next step is to integrate it into the policy framework by applying it to scenario analyses. Ambitious policies like the European Green Deal, the Common Agricultural Policy (CAP), and the Nature Restoration Law require transformative changes in land use, biodiversity, and ecosystem restoration. Achieving these objectives demands a robust analytical approach. The iterative linkages between macroeconomic and high-resolution models enable a dynamic exchange of critical data and insights. This interplay allows for a comprehensive understanding of how localized land-use changes are influenced by broader economic, environmental, and societal systems. As seen in the section above, high-resolution models provide granular assessments of local suitability, while macroeconomic models evaluate the wider economic and societal impacts on European farmers and citizens, ensuring a holistic evaluation of policy implications. This section delves into the scenarios enabled by these linkages, focusing on key themes such as the restoration and enhancement of landscape elements, the expansion of organic agriculture, and the achievement of afforestation targets.

3.2.1. CLUMondo to macro level

CLUMondo’s capabilities offer a powerful tool for assessing the integration of landscape elements and peatland restoration into sustainable land-use planning. By analysing land-use changes at a fine spatial scale (e.g., 1 km resolution), CLUMondo enables precise identification of the spatial distribution of landscape elements and the effects of their expansion on biodiversity and ecosystem services.

For example, it can evaluate how measures like maintaining 4% of agricultural land as landscape elements under the Good Agricultural and Environmental Conditions (GAEC) standards or achieving the EU Green Deal’s ambitious target of 10% by 2030, influence biodiversity hotspots and opportunities for ecosystem restoration. These targets underscore the EU's commitment to transformative change, as highlighted Czúcz et al., (2022) and (Visconti et al., 2024), marking a significant step toward fostering resilient ecosystems and sustainable land management.

The Nature Restoration Law complements these efforts by mandating the restoration of organic soils in agricultural areas, particularly drained peatlands, which are vital carbon sinks and biodiversity reservoirs. Member States are required to implement phased measures targeting the restoration of: (a) at least 30% of these areas by 2030, with a minimum of 25% rewetted; (b) 40% by 2040, with one-third rewetted; and (c) 50% by 2050, maintaining the same one-third threshold. This ensures alignment between local actions and EU targets, such as rewetting at least 25% of organic soils by 2030 and increasing to one-third by 2040. These actions yield substantial carbon sequestration benefits, enhance water regulation, and foster ecosystem resilience, further supporting EU climate adaptation and biodiversity goals.

However, while CLUMondo excels in its spatial precision and localized insights, it faces challenges in capturing broader economic impacts. Its focus on local land-use dynamics means it lacks the capacity to evaluate systemic economic responses, such as shifts in production, consumption, trade flows, and market prices. Addressing these larger-scale implications requires integration with macroeconomic models like GLOBIOM, CAPRI, MAGNET, or IMAGE. These models analyse how land-use changes influence agricultural markets, global trade, and socioeconomic outcomes. To bridge the gap between localized analysis and broader economic implications, iterative linkages between CLUMondo and macroeconomic models are essential. CLUMondo outputs—such as changes in land-use patterns, the spatial distribution of restored peatlands, or areas meeting enhanced landscape element targets—can serve as key inputs for macroeconomic models. These outputs provide detailed information that can be aggregated and used to assess the economic consequences of policy measures at regional, national, or EU-wide scales. These macroeconomic models can, in turn, feedback information into CLUMondo, such as shifts in market demand, trade dynamics, or economic incentives. This iterative process strengthens the linkage between spatial and economic modeling, ensuring that policies like the Green Deal and Nature Restoration Law are evaluated for both their spatial feasibility and economic impacts.

3.2.2. Macro level to CLUMondo

Macroeconomic models play a pivotal role in informing high-resolution models like CLUMondo by capturing the dynamic pressures on land under varying scenarios. For example, policy targets such as expanding organic farming may result in lower agricultural yields, subsequently driving up prices and reducing production. Similarly, measures like the introduction of landscape elements under GAEC standards can intensify agricultural production and contribute to yield reductions. These changes must be accurately integrated into CLUMondo to reflect the cascading effects on land-use dynamics and ensure robust scenario evaluations. By refining the parameterization of land supply curves and incorporating higher-resolution economic data, macroeconomic models enhance the precision of land-use and land-supply projections. This iterative exchange of data between scales requires continuous alignment and refinement of outputs. Through the integration of localized insights from CLUMondo, macroeconomic models provide feedback to adjust and fine-tune scenarios spatially. This process incorporates outputs from WP6 (Task 6.2), WP7 (Task 7.1), and WP8 (Task 8.2), allowing an exploration of policy impacts, including those of the European Green Deal and CAP's GAEC standards, at a detailed spatial level.

3.2.3. Iterative linkages

The iterative feedback loop between macroeconomic and high-resolution models ensures that scenario evaluations remain consistent, allowing for ongoing adjustments and enhancements. By fostering a two-way linkage (iterative linkage), this approach aligns spatially detailed insights from CLUMondo with systemic economic evaluations from macroeconomic models, improving the capacity to address complex policy challenges.

Iterative linkages are being established to facilitate seamless data exchange and integration across models and work packages. Organic agriculture (OA) serves as a pivotal example for these linkages, enabling the comparison of estimates from WP4 and CLUMondo under WP7. By incorporating socio-economic and biophysical drivers as key determinants of OA location suitability, CLUMondo provides spatially explicit insights that are further refined through integration with macroeconomic models like CAPRI, GLOBIOM, MAGNET, and IMAGE. Data exchange between work packages ensures effective coupling, allowing for scenario exploration at the European NUTS2 level and supporting tailored case studies, such as those focused on landscape elements in France under the LAMASUS project. Iterative feedback loops between CLUMondo and macroeconomic models enhance both spatial precision and the ability to assess economic and systemic impacts of policy measures (Figure 9).

The first feedback loop highlights the interaction between CLUMondo and the macroeconomic models. CLUMondo provides fine-grained, spatially explicit data on urban changes, such as shifts in land-use classes, the expansion of urban areas as have been. This information is then used by macroeconomic models to assess broader economic implications, such as production, trade, and market adjustments. In return, macroeconomic models provide feedback on economic drivers, including market demand and policy incentives, which can influence the next iteration of land-use simulations in CLUMondo. This cyclical process ensures that both scales of analysis, spatial and economic, are mutually informed as have been discussed in the section 3.1.2.

The second feedback loop focuses on the occurrence of organic agriculture (OA) in Europe, emphasizing the integration of CAPRI with CLUMondo. In WP 6.2, we will explore the results derived from WP 4, by using an approach that goes from ex-post to ex-ante, in line with the iterative linkages. In this context, CLUMondo's outputs, driven by socio-economic and biophysical factors such as soil suitability, climate conditions, and landscape structure, provide spatially explicit insights into the potential distribution and expansion of organic agriculture (Figure 9). CAPRI, on the other hand, incorporates these spatial patterns to evaluate the broader economic and market impacts, including production, consumption, and trade dynamics associated with organic farming adoption. This iterative exchange ensures that the spatial distribution of OA, as influenced by biophysical factors in CLUMondo, is effectively coupled with CAPRI's economic and policy scenarios. In return, CAPRI's insights on market trends, consumer demand, and policy incentives (e.g., subsidies or certifications for organic production) can inform further refinements in CLUMondo's simulations. This interaction is particularly critical for assessing how the expansion of organic agriculture aligns with policy goals outlined in the Green Deal and CAP. Further analysis will be conducted by establishing additional linkages with GLOBIOM and CLUMondo to assess policy drivers and regional land use change. These data will inform the analysis in WP 7.2.

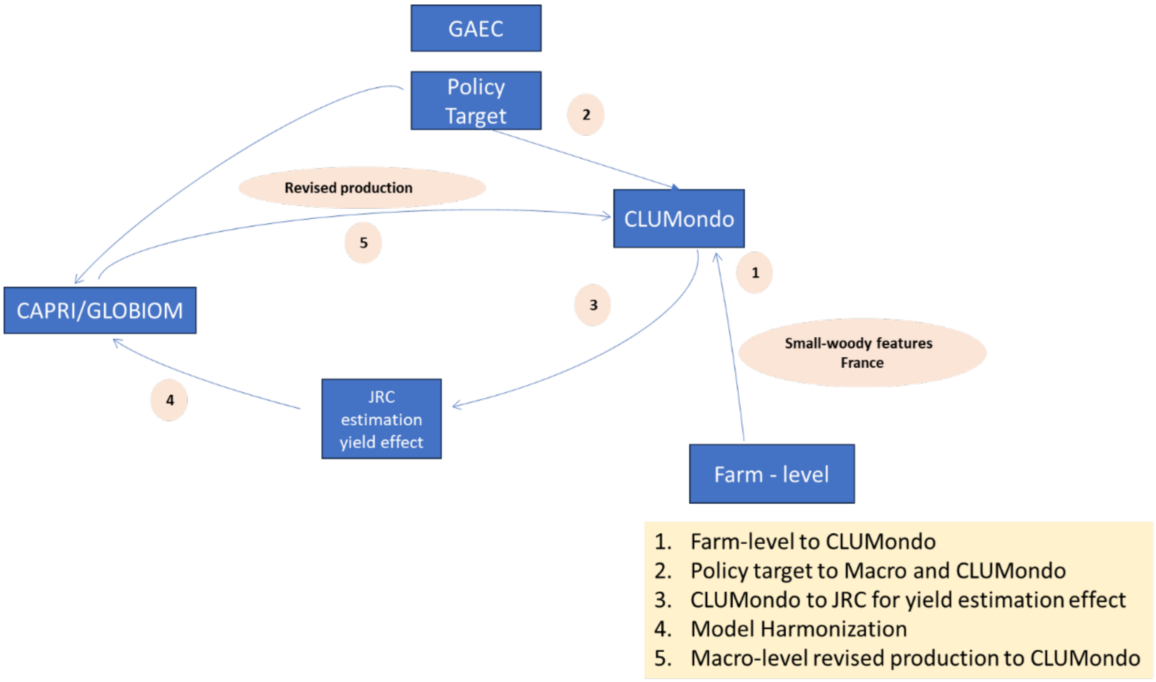

Figure 9. Example of Integrated modelling framework showing the cyclic feedback between the CAPRI/GLOBIOM models and the CLUMondo model. This diagram illustrates the continuous exchange of data and outcomes between these models, emphasizing their iterative nature.

The final feedback loop, as illustrated, focuses on the expansion and restoration of landscape features under the European Green Deal and Good Agricultural and Environmental Conditions (GAEC). Using CLUMondo's spatial modelling capabilities, the process identifies suitable areas for expanding landscape elements like hedgerows, trees, and other small woody features. This spatially explicit data is critical for informing CAPRI's economic assessments, evaluating the impacts of afforestation and landscape restoration measures, including potential trade-offs with agricultural productivity. As demonstrated in the WP4 assessment, landscape elements at the country level are delineated by small, fragmented land parcels (Figure 9). This iterative approach ensures that policy evaluations consider both spatial feasibility and economic sustainability. By following the methodology outlined by Schulp et al. (2019), to assess landscape dynamics and variations in land use intensity across different classes. Through a scenario analysis on different targets of GAEC measures being met by 2050 in CLUMondo, it's possible to delineate supply curves on their occurrence that can be integrated into marginal cost functions in GLOBIOM and or CAPRI in order to inform expansion of landscape features and impacts on production at a more regional level. This approach will improve the parameterization of land allocation assessments, particularly in relation to agricultural production, carbon storage.

The novelty of this approach lies in scaling insights from high-resolution models to more coarse macroeconomic models (Verburg & Overmars, 2009). This offers improved parameterization of inputs for assessing biodiversity outcomes, addressing the challenges of balancing agricultural production with landscape conservation (le Clech et al., 2024; Heidenreich et al., 2024, Kasiske et al., 2024). This approach directly contributes to the ongoing debate between land-sharing and land-sparing strategies, providing actionable insights into potential trade-offs and synergies (Burian et al., 2024).

Lastly, the organic agriculture (OA) scenario serves as a prime example of the importance of these iterative linkages, connecting biophysical and economic modelling to form a comprehensive basis for broader assessments. This approach enables detailed evaluations of policies related to sustainable agriculture, biodiversity, and ecosystem services, linking local insights with regional and EU-wide objectives. Notably, the analysis of organic agriculture certificates revealed that hotspots are often located in mountainous areas or densely populated regions like Madrid and Paris. Maintaining robust linkages between models focused on biophysical drivers and macro-economic models which is crucial for supporting the EU's policy targets, ensuring that interventions are both practically feasible and economically viable.

4. CONCLUSION AND NEXT STEPS

The iterative linkages established between high-resolution and macroeconomic models represent a significant advancement in integrating spatial and economic analyses. Progress has been made, exemplified by the downscaling of GLOBIOM to CLUMondo. However, there are still notable gaps and opportunities for enhancement. For instance, the absence of integrated linkages with IMAGE highlights an area ripe for further development. Additionally, while datasets like urban net expansion provide a solid foundation, they require regular updates to accurately reflect the dynamic scenarios essential for establishing robust linkages.

A key challenge in this integration is the time delays associated with data sharing and the parameter adjustments necessary to incorporate feedback loops. These delays impede the iterative process and refinement of scenarios, underscoring the need for improved workflows and enhanced coordination between modelling teams. Streamlining these processes is critical for the effective use of these linkages.

As part of the LAMASUS project, modelling teams will focus on deepening these connections. Specific initiatives include continuing the downscaling efforts from macro-level models to CLUMondo for baseline integration and country-level downscaling, such as for France, under T6.1 and T7.1. Scenario-specific linkages will be enhanced, where CLUMondo will contribute organic farming location maps and regression analyses to macro-level models. Priority will also be given to iterative linkages that entail adjustments to land supply functions based on iterative feedback between models (Table 5).

Moreover, in WP7 we will further explore linkages between high-resolution models and their integration with farm-level assessments utilizing the PASMA and FARMDYN models developed at BOKU. These efforts will bridge local, regional, and national scales to ensure that policies align with on-the-ground realities and broader sustainability goals.

In conclusion, the linkages established in this deliverable will be carried forward into an explorative and comprehensive scenario assessment of actual EU policies, including the CAP, Green Deal, and Nature Restoration Law. The modelling teams will examine various EU-relevant policies through a quantitative example provided by the URBAN net expansion dataset. This dataset will be continually updated throughout the project, allowing for fine-tuning through both bottom-up and top-down approaches as discussed in the previous sections.

Table 5. Task overview of the linkages and harmonization of the models outcomes.

Baseline / Linkage	**Link**	**Description**	**LAMASUS WP / Task**
Baselines	Macro-level to CLUMondo	Downscaling of baselines	T6.1/T7.1
		Country-level downscaling of France	T6.1/T7.1
	CLUMondo to macro-level	Shift land supply of macro-models based on land use change (e.g. urban)	T6.2/T7.3
Scenario-specific linkages	CLUMondo to macro-level	Organic farming: Location map to macro-level models	T6.4
		Organic farming: Regressions on the likelihood for convergence to inform specification of cost curves	T6.1 + 6.4
	Macro-level to CLUMondo	Scenario linkages based on T8.2 discussions.	WP8
	Iterative linkages	Adjust land supply functions based on iterative linkages	T6.2/T7.3

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5. Annexes

5.1. Model description

Below is a short overview of the models that will be used in the LAMASUS project WP6 and 7.

CAPRI

CAPRI is a partial equilibrium (PE) model that models the agricultural sector. It is made up of a market module and a supply module. It accounts for 47 agricultural products in 77 countries and 40 trade blocks. The spatial scale can go as low as NUTS2 level for EU27, Norway, Turkey and the western Balkans. This can be further divided by ten different farm types for each NUTS2 region. Since CAPRI is an agricultural sector model its strength is in the details of the agricultural sector it can provide.
Website: https://www.capri-model.org/

GLOBIOM /G4M

GLOBIOM/G4M consists of two iteratively linked models, GLOBIOM and G4M. The Global Biosphere Management Model (GLOBIOM) is a global recursive dynamic partial equilibrium model of the forest and agricultural sectors. The model is based on a bottom-up approach where the supply side of the model is built-up from the bottom (land cover, land use, management systems) to the top (production/markets). The agricultural and forest productivity is modelled on a spatially explicit level through links to biophysical models (crop models, forest growth models etc.) for different production systems. The model computes a market equilibrium for agricultural and forest products by allocating land use among production activities to maximize the sum of producer and consumer surplus, subject to resource, technological, demand, and policy constraints. Demand and international trade are represented at the level of 58 world regions. The model is calibrated to the year 2000.
G4M estimates the impact of forestry activities (afforestation, deforestation, residue harvest and forest management) on biomass and carbon stocks. By comparing the net present value of managed forest (difference of wood price and harvesting costs, income by storing carbon in forests) with income by alternative land use on the same place, a decision on afforestation or deforestation is made. The model incorporates empirical forest growth functions for major tree species groups. G4M is spatially explicit and runs on a 0.5° x 0.5° resolution. Since the model does not represent either forest markets or other economic sectors, it has to rely on information from other sources – (i.e. GLOBIOM or other databases) – for wood prices, land rents, urban sprawl etc. Similarly, information about natural disturbances comes as input to the model. As outputs, G4M produces estimates of forest area change, carbon sequestration and emissions in forests, impacts of carbon incentives (e.g. avoided deforestation) and supply of biomass for bio-energy and timber.

Management intensity:

In the current EU version of GLOBIOM, European cropland management is represented by three different tillage systems (conventional, reduced, and minimum tillage) and respective assumptions on crop residue management. In the rest of the world outside Europe, GLOBIOM cropland management systems are represented as: subsistence farming, low-input (rainfed), high-input (rainfed) and irrigated. The livestock sector is represented (for EU and ROW) by extensive and intensive production systems. The main forest management options considered

by G4M are variation of thinning, harvest intensity and forest residue collection. The harvest intensity is modelled through defining whether forest is used for intensive wood production (managed) or not (unmanaged), and for the intensively used forest the harvest is determined by the choice of rotation length. The rotation length can be individually chosen but the model can estimate optimal rotation lengths to maximize increment, stocking biomass or harvestable biomass.
Website: https://iiasa.github.io/GLOBIOM/

IMAGE

IMAGE 3.2 is an integrated assessment modelling framework that simulates the interactions between human activities and the environment (Stehfest et al., 2014) to explore long-term global environmental change and policy options in the areas of climate, land, and sustainable development (for detailed model description see SI section 1.3). IMAGE consists of various sub-models describing land use, agricultural economy, the energy system, natural vegetation, hydrology, and the climate system. Socioeconomic processes are modelled at the level of 26 regions. Most environmental processes are modelled on the grid-level at 30 or 5 arc-minutes resolution.
Agriculture, forestry, and land-use dynamics are modelled on the IMAGE-LandManagement model's grid-level (Doelman et al., 2018). Demand for crop and livestock products, trends in agricultural intensification, and trade dynamics are provided by the economic general equilibrium model MAGNET (Woltjer et al., 2014). Gridded land-use dynamics are implemented in the dynamic global vegetation model LPJmL to model effects on the carbon and hydrological cycle (Müller et al., 2016; Schaphoff et al., 2018) and to the global nutrient model (GNM) to model the nitrogen and phosphorus cycles (Beusen et al., 2015). LPJmL provides data on potential crop and grass yields, land-use change emissions, and irrigation water use while considering the impact of climate change. Adaptation to climate change in the food system is included by informing MAGNET about the regional impact of climate change leading to changes in agricultural production and trade flows. The simulation model TIMER represents the energy system with high technological detail for 12 primary energy carriers, including bioenergy. Land use for the production of bioenergy as determined by TIMER is implemented on the grid-level in IMAGE-LandManagement. GHG emissions from energy, industry, and land use are inputs to the simple climate model MAGICC, which emulates complex climate models to calculate global mean temperature change (Meinshausen et al., 2011). The climate policy model FAIR-SimCAP uses MAC curves to determine cost-optimal emission pathways to achieve specific climate targets (den Elzen et al., 2008).

Management intensity:

"Management intensity crops, expressing actual yield level compared to potential yield. While potential yield is calculated for each grid cell, this parameter is expressed at the regional level. This parameter is based on data and exogenous assumptions - current practice and technological change in agriculture - and is endogenously adapted in the agro-economic model." - https://models.pbl.nl/image/index.php/Agricultural_economy
Website: https://models.pbl.nl/image/index.php/Welcome_to_IMAGE_3.2_Documentation

MAGNET

MAGNET (Modular Applied GeNeral Equilibrium Tool) is a recursive dynamic, multi-region, multi-sector computable general equilibrium (CGE) simulation model (Woltjer and Kuiper, 2014). The principal data source is the Global Trade Analysis Project (GTAP) database (Aguiar et al., 2019), with detailed transactions accounts covering intermediate input purchases between 65 different activities and public, private and investment final demands. All demands are differentiated by domestic and foreign origin, whilst the GTAP data also includes gross bilateral trade flows between all countries/regions. The data provides different sets of prices due to the presence of tax and subsidy data, as well as international transport margins data. In its current incarnation, the GTAP version 10 database has a coverage of 141 countries/regions and eight production factors. With a series of in-house activity and commodity splits (mainly bio-based), the MAGNET version of this data has coverage of up to 124 activities and 138 commodities.

Upon this database is calibrated the MAGNET model. Originally based on the LEITAP model, a key advancement of MAGNET is its modular design. For example, in the sphere of the bioeconomy, the model incorporates state-of-the-art modules for (inter alia) the Common Agricultural Policy (including rural development), agricultural land supply, production quotas, tariff rate quotas, biofuels directives and irrigation water in agriculture. Moreover, the model is flexible enough to include different production technologies by activity (“nesting”) and parametric assumptions governing the ease of transfer of factors between different activities as well as options for allocating investments. As a market model, MAGNET provides typical market indicators (prices, outputs, demands, exports, imports), whilst through the support of satellite databases MAGNET is able to provide physical indicators (e.g., land areas, water usage, nutritive intake, employment, greenhouse gases, air pollution etc.) and more recently, circularity indicators (Philippidis et al., 2021), MAGNET can be paired with the IMAGE model, where frequently parameters on productivity, climate change impacts and protected areas area exchanged.

MAGNET has been extensively used to assess the impacts of agricultural (Boulanger and Philippidis, 2015), trade, land (Schmitz et al., 2014) and bioenergy policies (Philippidis et al., 2017; van Meijl et al., 2018) on the economy at global scale; providing insights regarding land use, agricultural prices, nutrition, household food security, international trade, bioeconomy, climate change, etc. The model is developed by the MAGNET consortium, led by Wageningen Economic Research (WecR) and also includes the Joint Research Centre (JRC) of the European Commission and the Thünen-Institute (TI).

Website: https://www.magnet-model.eu/

CLUMondo

CLUMondo is a high-resolution spatial allocation model that simulates future land system changes based on factors like land use demand, location characteristics (e.g., precipitation), conversion rules, and spatial policies (e.g., protected areas). It can handle various land system types, including mosaic landscapes such as peri-urban areas, and considers both food production and a wider range of ecosystem services. The model uses a dynamic, forward-looking approach to allocate land systems by evaluating their suitability, conversion rules, and competitive advantage in fulfilling land-based demands. Suitability is calculated based on environmental and socio-economic factors, and the allocation process iterates over each region's pixels until demand is met. Policies like forest protection or conversion restrictions can be integrated into the model to reflect sustainable scenarios. Over time, CLUMondo can adapt to changes in demand for land services due to factors like shifts in diets, population growth, or technological advances. The model has been applied in various studies, including those by Malek et al. (2018), Schulze et al. (2021), and Wolff et al. (2018). More details can be found at CLUMondo's website.

https://www.environmentalgeography.nl/site/data-models/models/clumondo-model/

CLUE model

The different versions of the CLUE model (CLUE, CLUE-s, Dyna-CLUE and CLUE-Scanner) are among the most frequently used land use models globally. Applications range from small regions to entire continents. The CLUE model is a flexible, generic land use modeling framework which allows scale and context specific specification for regional applications (Verburg et al.,2024; Veldkamp & Fresco, 1996). In the next section we could see how it was used as a way to connect different land use models, given the versatility of the application of this model itself.
https://www.environmentalgeography.nl/site/data-models/data/clue-model/

FARMDYN

FARMDYN is a dynamic mixed integer bio-economic farm scale model that provides a flexible, modular template to simulate different farming systems (dairy, mother cows, beef fattening, pig fattening, piglet production, arable farming, biogas plants) at single farm scale. The model features multiple dynamics including comparative-static, short run, or fully dynamic, with simulations that can span several decades. It utilizes integer variables to capture indivisibilities in investments such as machinery and buildings, as well as labour use. Farm management decisions like feeding, manure management, and labour are depicted with a sub-annual temporal resolution, some even bi-weekly. Farm labour, machinery, and stable use are modelled in rich detail. It also includes highly detailed farm branch activities, such as intensities for arable and grass crops, and differentiated feeding schemes for all animal types accounting for lactation or feeding phase. The machinery park is available in different mechanization levels. The model incorporates environmental accounting modules that track the flow from different nitrogen compounds, CO2eq, phosphorus compounds, and features a wide range of Agri- and agri-environmental policies including the CAP, German implementation of the Nitrate Directive, and various agri-environmental schemes. It includes multiple biodiversity indicators and is parameterized for multiple countries besides Germany, including Switzerland, Norway, and the Netherlands. Additionally, it offers both deterministic and stochastic programming versions; the latter treats all variables as state-dependent, allows for scenario tree reduction, and covers different risk measures such as value at risk and MOTAD. The model has been applied in various studies, including those by Heinrichs et al. (2021), Kuhn et al. (2020), and Kuhn et al., (2019). More details can be found at FARMDYN's website.

https://farmdyn.github.io/documentation/

FAMOS

This contribution presents the farm optimization system FAMOS, in which typical agricultural and forestry operations in Austria are derived according to regional and structural criteria and modeled using the method of Mathematical Programming. A heterogeneous pool of operational data is systematically processed, with clearly defined interfaces allowing flexible application of the integrated data and model system. This provides a foundation that facilitates regular data renewal and model development and can be used for accompanying policy analyses. FAMOS is applied to quantify the effects of the reform of the Common Agricultural Policy at the farm level. Initial results indicate that the effects at the farm level vary significantly, resulting in both losers and winners.

https://www.econstor.eu/bitstream/10419/236549/1/dp09-2004.pdf

PASMA

A spatially explicit bio-economic integrated assessment quantifies impacts at 1km grid resolution in order to take into account the heterogeneity of Austrian agricultural landscapes. The model was applied to assess impacts of the Common Agricultural Policy (CAP) post-2013 on regional producer surplus resulting were slightly positive and payments shift from intensive to extensive production regions (Kirchner et al., 2013). The economic impact of climate change it is led by changes in precipitation patterns. Policy change leads to intensification of land use in favourable cropland and grassland regions and extensification in marginal regions. Regional climate change amplifies land use intensification with increases in crop yields, e.g. in Alpine regions, and land use extensification with declining crop yields, e.g. in eastern cropland regions. Environmental indicators deteriorate at national level in all scenarios. The highly spatially diverging impacts can offer an assessment for more localised and targeted measures.

https://epub.boku.ac.at/download/pdf/1930890.pdf

5.2. FULL REPRESENTATION OF LAND COVER

Cropland

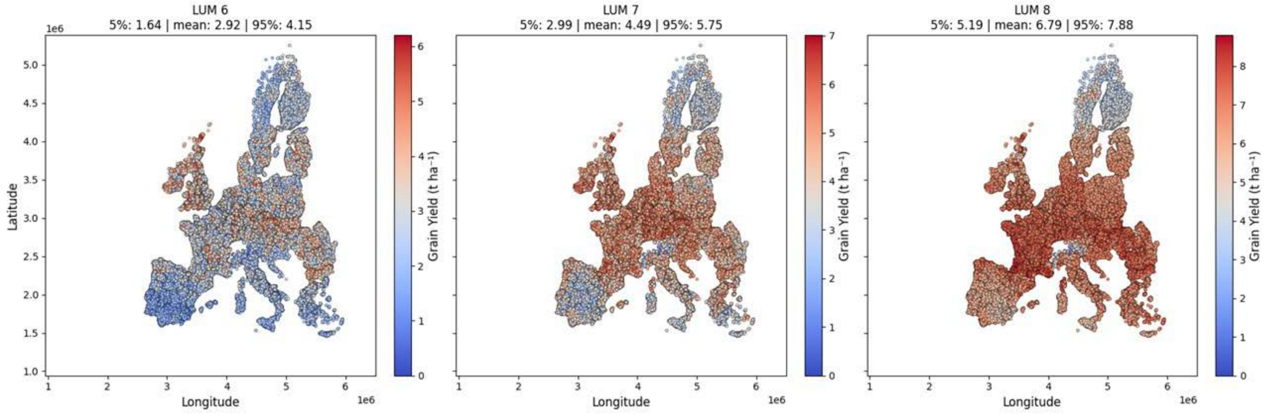

Figure 10. Arable crop yield (t ha-1) within CLUMondo land use intensities. From LUM 6 (low intensity cropland) to LUM 8 (high intensity cropland)

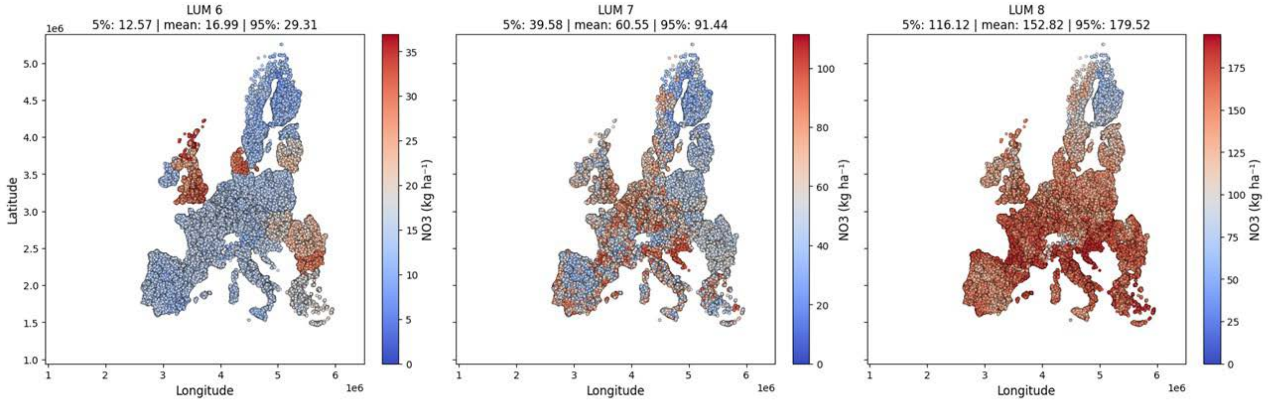

Figure 11.Nitrogen losses from Nitrogen fertilization in arable cropland (kg ha-1). From LUM 6 (low intensity cropland) to LUM 8 (high intensity cropland)

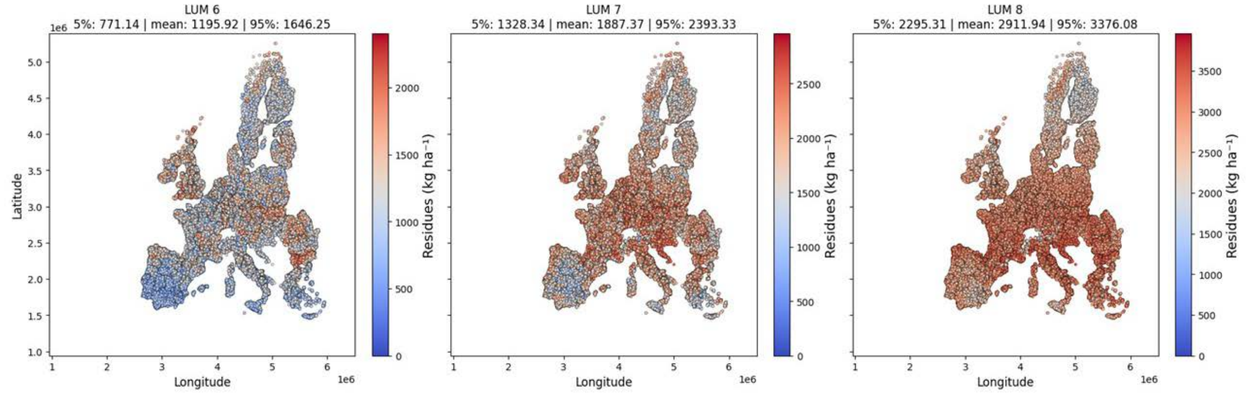

Figure 12.Residues in arable cropland (kg ha-1). From LUM 6 (low intensity cropland) to LUM 8 (high intensity cropland)

Grassland

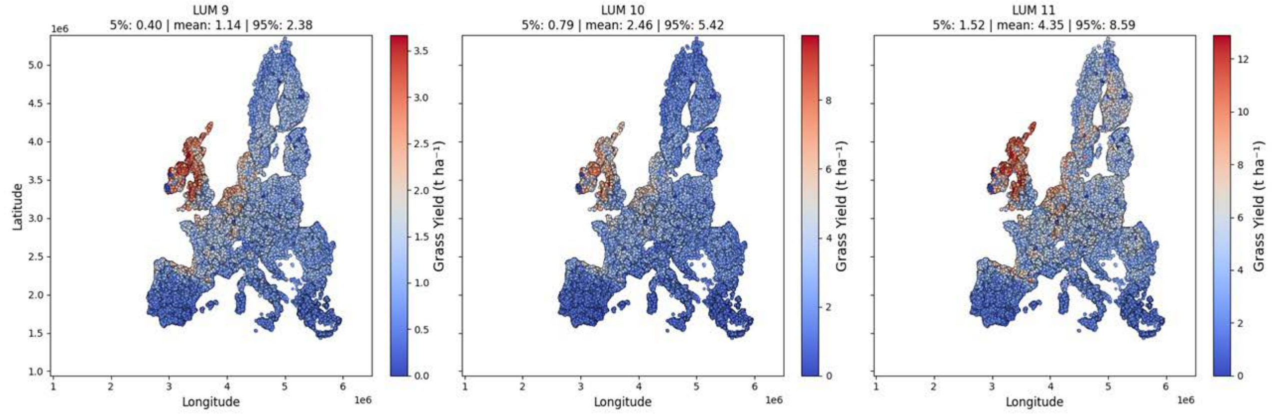

Figure 13. Grass yield (t ha-1) within CLUMondo land use intensities. From LUM 9 (low intensity cropland) to LUM 11 (high intensity cropland)

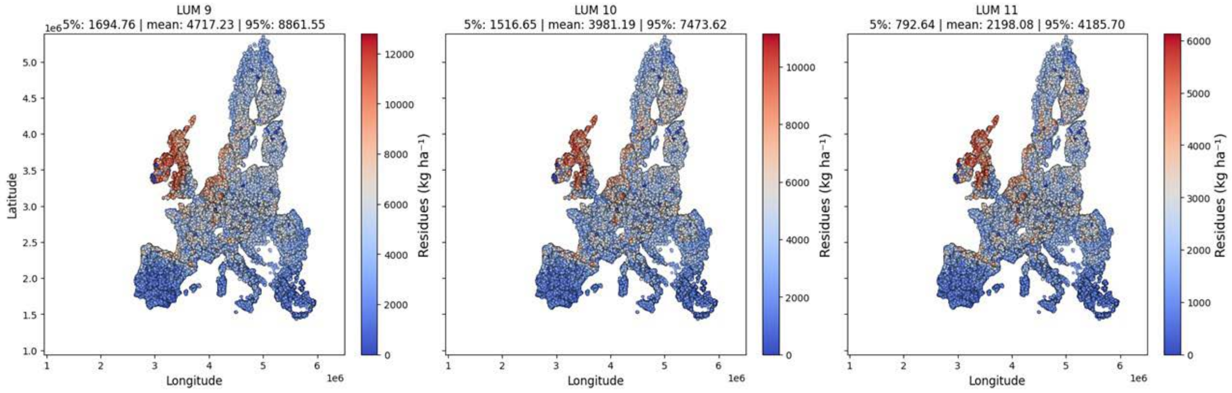

Figure 14. Residues in Grassland (kg ha-1). From LUM 9 (low intensity grassland) to LUM 11 (high intensity grassland)

5.3. LAND USE INTERPRETATION AND PARAMETERIZATION OF THE REFERENCE SCENARIO

Table 6. Mapping of items or variables that are going to be used in CLUMondo Scenario. The arrow (→) indicates the inputs from the demand side within the CLUMondo environment, and the slash (/) denotes which outputs from the SSP2 models will be not included in the linkages.

GLOBIOM ITEMS/VARIABLES	UNITS	LINKAGE	CLUMONDO INPUT	UNIT
POPT	Million	→	Population growth	Million
CRP PROD (WHT+CGR+OSD+PFB+SGC)	1000 t	→	Arable crops production	1000 t
LSP PROD	1000 t	→	Livestock production	1000 t
FOR LAND	1000 ha	→	Wood production	1000 ha
CAPRI items/variables	**Units**	**Linkage**	**CLUMondo Input**	**Unit**
POPT	Million	→	Population growth	Million
Cereals, Oilseeds, other arable crops and vegetables	Not Used	/	Arable crop production	/

Grapes, citrus, olives, apples, “other fruits”, new energy crops (CRP|PRM)	1000 t	→	Permanent crop production	1000 t
Fodder and all cattle activities	Not Used	/	Livestock production	/
n/a		/	Wood production	/
Image items/variables	**Units**	**Linkage**	**CLUMondo Input**	**Unit**
POPT	Million	→	Population growth	Million
RICE and WHEAT and CGR	1000 t	→	Arable crop production	1000 t
Single items from VFN and OSD	1000 t	→	Permanent crop production	1000 t
LSP	Not Used	/	Livestock production	/
For LAND	Not Used	/	Wood production	/

Table 7. Land use representation in the models

CAPRI classes	IMAGE classes	MAGNET	GLOBIOM classes	CLUMondo_classes
Arable Cropland	Arable cropland	Arable Cropland	Cropland	Low-intensity arable cropland
				Medium-intensity arable cropland
				High-intensity arable cropland
Permanent Cropland	Permanent Cropland	Permanent cropland	Permanent Cropland	Permanent Cropland
Arable Cropland	Arable cropland	Arable Cropland	Cropland	Forest/shrub and cropland mosaic

Grassland	Grassland	Grassland	Grassland	Low-intensity grasslands
				Medium-intensity grasslands
				High-intensity grasslands
Artificial surfaces	Urban areas	Urban areas are not represented	Other category	High-density urban settlement
				Medium-density peri-urban settlement
				Low-density rural settlement
				High-density urban settlement
Unmanaged Forest	Unmanaged Forest	Natural Forests	Unmanaged Forest	Primary Forests and Nature Forestry
Managed Forest	Natural vegetation	Managed Forests	Managed Forest	Multifunctional forestry
			Plantation Forests	Combined objective forestry and Plantation Forestry
Wetlands and Marshes	Peatlands	Wetlands	Wetlands (aggregated in another category)	Wetlands
Other sparsely vegetated land	Other land uses	-		Forest/shrub and grassland mosaic

			Other Agricultural Land	Forest/shrub and cropland mosaic

Maps of urban areas per time step 2020-2030 and 2020-2040

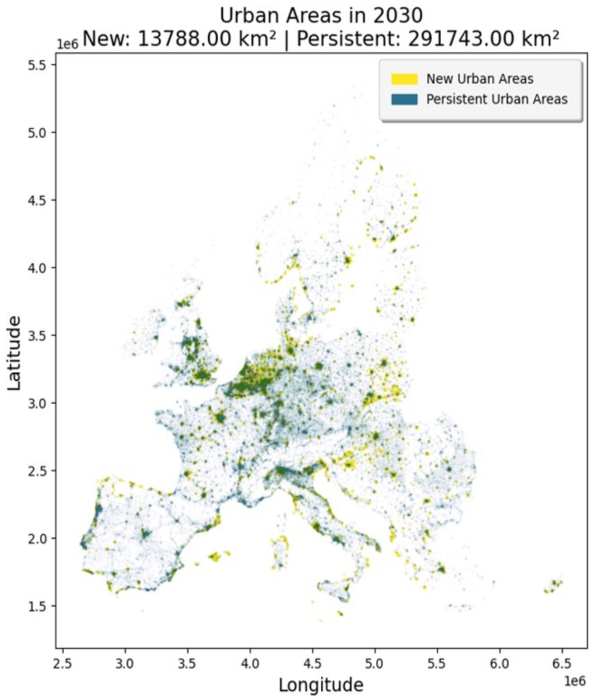

Figure 15.Urban expansion from 2020 to 2030 across a modelled geographical area, showing both persistent and newly developed urban areas (respect 2020). Persistent urban areas (depicted in light blue) are locations that remained urban across the years, while new urban areas in yellow.

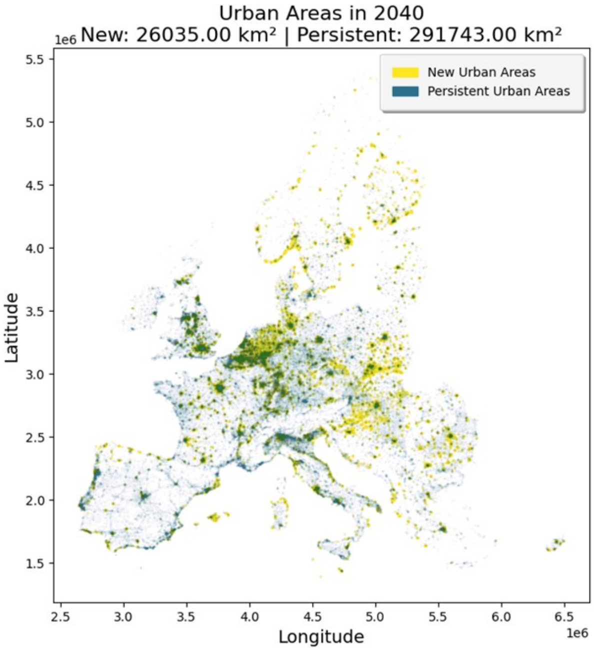

Figure 16.Urban expansion from 2020 to 2040 across a modelled geographical area, showing both persistent and newly developed urban areas (respect 2020). Persistent urban areas (depicted in light blue) are locations that remained urban across the years, while new urban areas in yellow.