Analysis of the competition between land, energy and food using the TERRA module of WILIAM System Dynamics IAM

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Published in Renewable and Sustainable Energy Reviews, Volume 216, July 2025, 115651
https://www.sciencedirect.com/science/article/pii/S1364032125003247?via%3Dihub
DOI: https://doi.org/10.1016/j.rser.2025.115651

Highlights

- A novel platform for the analysis of land, food and energy interactions is presented.
- It identifies the biophysical limits of energy and agro-ecological transitions.
- A wide range of land, forest, food and energy management policies are provided.
- It works with 9 world regions, 12 land uses, 14 food items, 14 GHG and 11 crops.

ABSTRACT

Integrated Assessment Models (IAMs) are computational tools used to explore energy futures and sustainable transitions. This paper presents the WILIAM-TERRA model, a novel platform for the analyzing the interactions between land, food, energy and the environment. WILIAM-TERRA is integrated in the Within Limits Integrated Assessment Model (WILIAM), a new open-source model that has been designed to address several limitations of existing IAMs.

WILIAM-TERRA explores the energy transitions, both from the point of view of the sinks (climate change) and from the point of view of the resources (biofuels, forests and solar electricity). Additionally, is focuses on the ecological transition of the food system including dietary changes, sustainable agriculture and regional food exchanges. These features provide a broader scope than the traditional emissions-based approach of most IAMs, enabling a more systemic analysis.

Some results of the interaction of diet policies with forest and cropland expansion, of the effect of wood extraction in forests integrity and of the carbon capture in grasslands have been presented. These results represent only a small sample of what can be analysed with WILIAM-TERRA and should be further explored in the future.

KEYWORDS

IAM models; WILIAM-TERRA; WILIAM; Land-Use Changes; Diets; Biofuels; Forests; Climate Change Impacts.

1. INTRODUCTION

Human activities are widely recognized as key drivers pushing biophysical processes of the Earth toward, and in some cases beyond, their planetary boundaries[1]. The complexity of these human activities and their interactions with nature demands holistic perspectives to address the challenges of sustainability and guide human societies towards safe and sustainable futures. Integrated Assessment Models (IAMs) are computer programs that use mathematical models incorporating representations from various disciplines such as economics, environmental sciences and technology to capture interactions between human and biophysical systems. A variety of IAMs exists due to the different approaches used to describe these interactions, with a predominant focus on climate change [2–6].

Despite significant advancements in the field many IAMs share a core set of assumptions whose validity is being disputed in the scientific community [7–11]. The Within Limits Integrated Assessment Model (WILIAM) is a new open-source model that has been designed to address limitations of existing IAMs, such as: an often too simplistic representation of the economic processes [12–14], the absence of key dimensions as social [15,16], material [17,18] and finance dimensions [7,19], the assumption of very high (renewable and non-renewable) energy potentials [20–23], the neglect of metabolic implications of future energy investments (ie, Energy Return on Investment, EROI) [24,25], address challenges of 100% renewables systems (notably variability renewable energies) [26,27], capture main interactions between different dimensions [7,18].

Lack of transparency has also been highlighted as an issue in the field of IAMs and most of them are not open source models [8,28,29]. At the core of development motivation is also the possibility to simulate different sustainability strategies (Green Growth, Postgrowth, etc.) which has motivated the inclusion of conventional and heterogenous policies [30–33].

Most IAMs contain economic models based on conventional general or partial equilibrium achieved through the widespread use of prices as mechanism of optimization (for example, 28 out of the 32 models described in IPCC report [34] are based on well-functioning markets in equilibrium). This approach is based on optimization techniques of different types and assumes that, at every time, perfect or almost perfect matching between supply and demand is achieved,

therefore, the information about the delays and dynamic limitations of the systems is lost. Optimization is also a factor that limits their capacity to compute feedbacks [35].
WILIAM represents the economy based on the principles of Ecological Macroeconomics, assumes limits to the extraction of renewable and non-renewable resources, is grounded in a feedback-rich system dynamics simulation (rather than optimization) and does not assume equilibrium or factor substitutability.

Although the first IAMs were focused on the relations between energy, economy and climate change, models that address land use, agriculture, water and forests are increasingly being included. A detailed description of the most relevant is found the Annex on 'Scenarios and Modelling Methods' of the IPCC report [34].

In some cases, specific models with a bottom-up philosophy have been developed, such as the bioenergy-land-use module (GLUE) [36], which solves the system of land-use and biomass flow balance under a set of conditions including food and wood demand; the Model of Agricultural Production and its Impact on the Environment (MAgPIE) [37], a global land use allocation model connected to the grid-based dynamic vegetation model LPJmL [38]; or the Global Biosphere Management Model (GLOBIOM) [39], used to analyse the competition for land use between agriculture, forestry, and bioenergy. These bottom-up models are often used with well stablished IAM platforms, such as IMAGE [40] with MAgPIE [37] and LPJmL [38], and MESSAGE [41] with GLOBIOM [39].

In other cases, IAMs contain their own environmental modules. GCAM (Global Change Assessment Model), for example, is an open source IAM that addresses the linkages between energy, water, land, climate, and the economy based on price-driven optimization and includes crop production in a context of market equilibrium [42].

GLOBIOM, MAgPIE-LPJmL and GLUE are highly disaggregated, consider multiple crops, livestock and land uses and use grid-based spatial analysis. All of this enables them to provide very detailed estimates of land use changes, crop production and vegetation growth, but they are based on a sequential structure and have limited interactions with economic, technological and social variables. Another limitation of most IAMs that contain land and environmental modules is that they focus on climate change and are dedicated to understanding *how land use, food production, energy and water resources may contribute to climate change, and how* *climate change may affect those resources*. This approach disregards other key challenges, such as biodiversity loss, soil erosion, forest deterioration or food sufficiency.

A small number of IAMs are based on dynamic simulation instead of optimization and have fewer limitations when addressing feedback and strong interactions but tend to have much lower level of detail or scope than previous ones. FeliX [43,44] is a stylized model that treats economy, energy, carbon cycle, biodiversity, water, population and land use at an aggregated world level and with no differentiation between crops categories or food items. FeliX dynamics are often based on exogenous policy options and its low aggregation prevents it from capturing many of the trade-offs between land and energy. ANEMI [45] is an integrated assessment model that emphasizes the role of water resources. It is based on system dynamics simulation and is intended for analysing long-term global feedbacks that drive global change. The latest versions of ANEMI include some basic features related to climate change effects on land yield and potentially arable land for food production but its focus is the assessment of water resources. C-ROADS [46] is a well stablished and open-source system dynamics model oriented towards modelling the carbon cycle which has evolved to EN-ROADS model [47], endogenizing some of the drivers of emissions. The carbon cycle model of C-ROADS has been used with permission from its authors as the basis of WILIAM Climate module.

This paper describes a newly designed module of WILIAM model: WILIAM-TERRA, a System Dynamics, non-spatial and integrated model that combines historical trends, human and natural interactions. Some results of its ability to address the interactions between energy, land and food production are also presented. The novelty of WILIAM-TERRA compared to the land modules of existing IAM's lies in its feedback-rich approach and its broader objectives.

According to Gambhir et al. [8] in almost all cases IAMs are designed to meet specified climate or emissions constraints at the lowest "cost", but WILIAM-TERRA is not focused on optimising a specific emissions pathway. The main objective of WILIAM-TERRA is understanding the complex interactions between land use, energy, biophysical constraints and human demands. The System Dynamics approach provides the platform for this type of systemic analysis, which is difficult to achieve with other types of models.

The objectives of WILIAM-TERRA are:

- Explore the relationships between the energy transition and the biological resources in terms of sinks (climate change, biodiversity impacts) and resources (food, energy, forest products).
- Set the limits of land resources to the rest of the modules of the WILIAM model.
- Analyse the trade-offs and opportunities of the ecological transition of the food system, including dietary changes and agricultural management. It also includes the food exchanges between regions

These objectives set a wider scope than the traditional emissions-based approach of most IAMs and enable a more systemic analysis, although a full coverage of greenhouse gases emissions from all sources is also included.

WILIAM-TERRA is not a spatial grid-based model, as this methodology is not compatible with System Dynamics software. The high spatial disaggregation of grid-based well stablished IAMs such as GLOBIOM, LPJmL or MAgPIE is not achieved in WILIAM-TERRA. Nevertheless, it includes the disaggregation of 9 regions, 14 food categories, 12 land uses and 13 land products (11 of them crops). This offers a good balance between the granularity of grid-based models with limited feedback and the simplicity of stylized, feedback-rich dynamic models. The transparent and open-source philosophy of the WILIAM model is also a feature that increases its attractiveness.

WILIAM is a modular model that allows most of its modules to be used separately. TERRA can be linked to the WILIAM model or independently, receiving exogenous inputs. The model is now calibrated, operational and able to provide useful results. However, as a new model, it is subject to continuous improvement in its data sources and interconnections.

In [48] some preliminary results using WILIAM-TERRA have been explored: the competition for land due to solar energy. The results show that the land required for solar would be 1–1.4 % of total land (an area equivalent to 55–75 % of current urban land) under realistic scenarios of solar energy growth. This would require integrated land-use and energy planning policies to mitigate impacts.

The organization of the paper is as follows: Section 2 provides a brief description of the WILIAM model and a detailed description of the WILIAM-TERRA module. Section 3 presents some results that show the capacities of this model. Finally, Section 4 presents the conclusions.

2. MATERIALS AND METHODS

2.1 WILIAM model

The Within Limits Integrated Assessment Model (WILIAM) has been developed under the LOCOMOTION H2020 project (a detailed description is available in project deliverables [49,50] and in the model's wiki [51]). WILIAM a model descendent from MEDEAS [52,53] and WoLiM [54]. Both WILIAM and MEDEAS models, focus on the detailed representation of the economic processes following a Dynamic Econometric Input-Output approach and consistently linking the economic and biophysical spheres according to the principles of Ecological Macroeconomics.

WILIAM is based on System Dynamics simulation programmed in VENSIM DSS software with an open-source version, it incorporates a multiregional framework with 9 global regions (some modules reaching higher disaggregation for the EU27 member states) and is structured into eight modules: Demography, Society, Economy, Finance, Energy, Materials, Land (TERRA) and Climate (see Figure 1).

The latest public version of the model can be downloaded from LOCOMOTION github [55] and a short summary explaining how to utilize or adapt this open-source model is provided in Annex H.

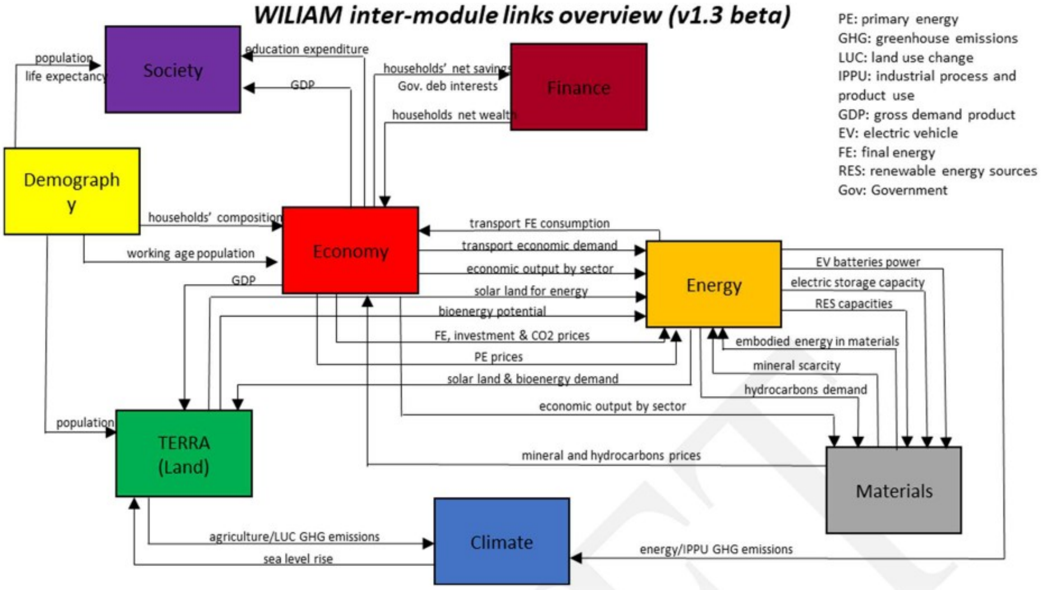


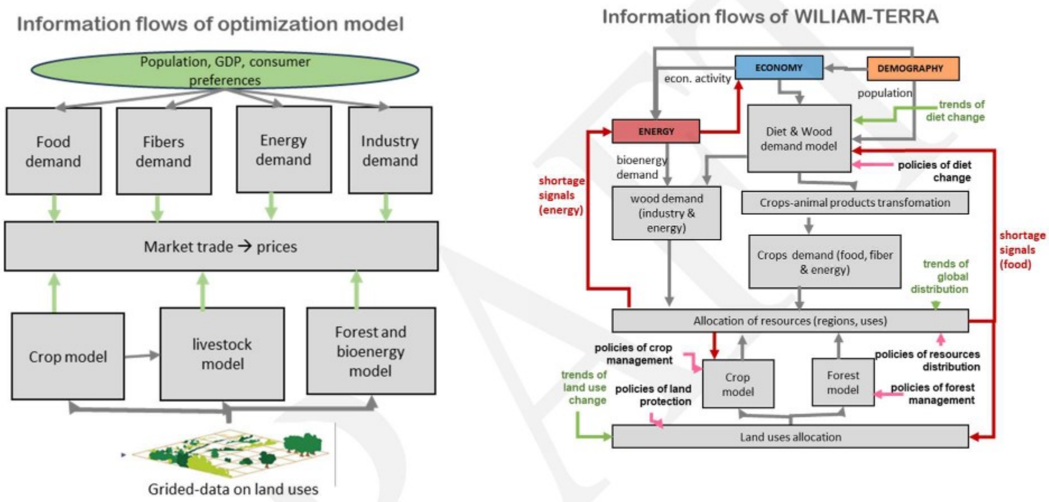
Figure 1. Schematic structure overview of the WILIAM model, representing the main linkages between the modules: society, demography, economy, finance, land, energy, materials and climate.

2.2 Features and information flows of WILIAM-TERRA

This section explains the differences between the feedback-rich structure of WILIAM-TERRA and that of optimisation-based (or recursive) IAMs. WILIAM-TERRA does not rely on economic indicators such as prices, elasticities or profitability to drive changes such as land uses or crop production. The authors believe that estimating these variables is rarely realistic in large and complex regions on a world scale. Nor does it use, in TERRA module, well-detailed policies such as carbon taxes or subsidies. Policies in WILIAM-TERRA are all decisions that can be made by humans in the broadest sense, and they are implemented through the biophysical changes that these decisions cause. The specific policies that governments can take to achieve these goals are beyond the scope of this model.

The diagram of Figure 2 represents the information flow of optimization models (e. g., GLOBIOM-MESSAGE, one of the most representative IAMs, has a similar structure) [56–58], as well as that of WILIAM-TERRA. Optimization models (see Figure 2-a) start with information of population, GDP and consumer preferences, which are either provided by other coupled models or set by exogenous scenarios. These inputs are used to calculate the demand for food, energy and industrial products. This demand is then adjusted to supply through optimization mechanisms based on prices.

Crop, meat and biomass production models are fed with highly detailed gridded land uses data, which include land potentials. Since the optimization mechanism aligns demand to production (by adapting land use and crop production), there are no disparities between demand and supply (unless the optimization fails). Once the optimization is completed, the model provides information on land-related emissions and-land use pathways.



(a) (b)

Figure 2. Comparison of the information flows in an optimization-based model (a) and in the WILIAM-TERRA model (b).

In WILIAM (see Figure 2-b), the Economy module provides economic activity and the Demography module provides population. Based on this, the Energy module calculates the demands related to land-uses which are sent to WILIAM-TERRA. The demand of bio-energy, population and economic activity are used to estimate the demand for crops and forestry products. The Crops and Yields and Forests submodules calculate the supply of forestry products and crops, based on a model of land uses.

The difference arises when demand and supply are compared, since WILIAM-TERRA does not include a price mechanism to adjusts supply and demand and find an equilibrium. Instead, it generates shortage signals when supply is unable to meet demand. These shortage signals

prompt the allocation of land to crop production, drive the redistribution of crops and whether the food supply is sufficient.
Shortage signals of wood and biofuels are sent to the Energy module, reducing the capacity to produce bioenergy. More information on these feedback loops can be found in Appendix G.

All these information flows create a dynamic behaviour that adjusts supply and demand, but not as immediately as optimization models do. Instead, it follows dynamic pathways that are influenced by past trends. Trends in land use changes, diets and the allocation of products across regions and uses are exogenous and based on historical data. A wide range of policy options, selected by the user, is added. Connections to other modules such as Energy and Economy occur at each time step (one quarter of a year by default).

These features make WILIAM more capable of analysing the complex interactions between energy, land and climate than the relatively "clumsy" highly detailed spatial models described in section 1. This dynamic behaviour mimics more closely the reality than optimization approaches, allowing for a better tracking of trends and the pace of the transitions.

WILIAM-TERRA does not aim to predict future land uses or emissions, since prediction is impossible in complex human systems. Instead, it seeks to extrapolate past trends and observe the effects of a wide range of policies on the system. This approach may help identify the key points and reveal the counterintuitive behaviours that emerge in complex systems.

2.3 General structure of WILIAM-TERRA

WILIAM-TERRA is interconnected with five WILIAM modules: Energy, Economy, Demography, Society and Climate (see Figure 3). It receives information on GDP per capita from the Economy module, population from the Demography module, temperature and climate change impacts on yields from the Climate module as well as the demand of liquid biofuels, solid biomass and land for renewable energy (mainly solar PV) from the Energy module. In return, it provides various outputs to these modules, including: the availability of crops and forestry products for energy and food as well as a stress signal related to land for solar energy.
WILIAM-TERRA operates with 9 regions [59], 14 food items categories, 13 land product categories (11 of which are crops) and 12 land use categories. More details about these categories can be found in Appendix A and its main features are summarized in Table 1.

WILIAM-TERRA incorporates a wide range of policies which are shown in Table 1 and are compared to the mitigation and removal measures presented in Table 7 of the Annex on 'Scenarios and Modelling Methods' of IPCC report [34]. A more detailed description is presented in Appendix C.

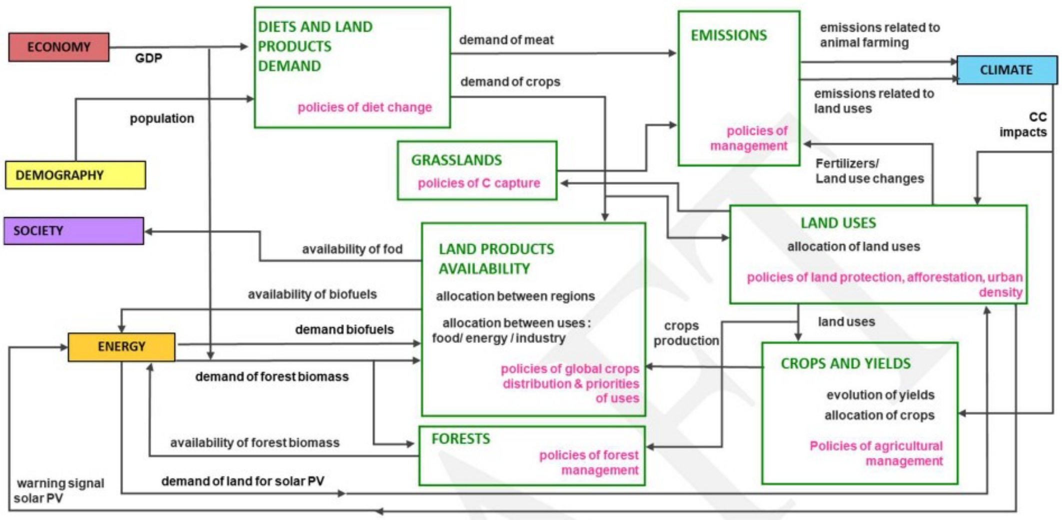


Figure 3. WILIAM-TERRA module and its connection with the rest of WILIAM model modules. White-green boxes are submodules of WILIAM-TERRA, boxes in other colour belong to other modules of WILIAM. Variables in pink are exogenous policies chosen by the user.

Table 1: Main features and policies of WILIAM-TERRA and their relation to IPCC mitigation measures.

Features of WILIAM-TERRA	**Description**
Land uses allocation	Represents the competition for land between cropland, afforestation, urban land and land for solar electricity, alongside all other and trends.
Crops production	Distributes cropland across 11 types of crops driven by the demand for food, energy (biofuels) and other uses.
Yields	Estimates the future evolution of crop yields based on past evolution, climate change impacts and soil erosion. Agricultural management policies are also incorporated.
Diets	Estimates the demand of 14 food items driven by the GDP of each region and influenced by dietary change policies.
Global markets	Represents the distribution of crops and forestry products among regions through a stylized pool market.
Forests	Estimates forest biomass stock as a result of net afforestation, timber extraction and forest growth. It allows setting sustainable limits for forest extraction.
Soil	Estimates soil carbon capture in pastures as a result of changes in management.

Policies in WILIAM-TERRA	Description	IPCC mitigation measure
Primary forest protection, Managed forest protection	Protects primary and managed forest areas from deforestation driven by the demands of other uses	Reduced deforestation, forest protection, and avoided forest conversion
Forest plantation increase	Increases the area of forest plantations	Silviculture
Forest loss limit	Protects forests from biomass extraction if forest stock falls below a chosen threshold	Forest management – conservation for carbon sequestration, Forest management – increasing timber/biomass extraction
PROTRA_utilization allocation policy priorities (policies of the WILIAM Energy module) PROTRA_capacity expansion priorities,	Policies from the WILIAM Energy module that regulate the demand for energy from different sources, including biomass and biofuels	Switch from traditional biomass and modern fuels Bio-electricity, including biomass, First and second-generation biofuels
Forestry self sufficiency	Policy that reduces the trade of forestry products between regions and increases regional self-sufficiency	
Wood for energy	Policy that prioritizes the use of forestry products for energy over industrial demand	
Crops for energy	Policy that prioritizes the use of crops for energy (biofuels) over the demand for food	
Cropland protection	Policy that protects cropland area from being converted to other uses	
Natural land protection	Policy that protects non forest natural areas from being converted to other uses	
Urban land density	Changes toward more or less compact cities	Urban form
Diet change	Change towards a desired diet (with several options that may vary by region)	Dietary changes, Substitution of livestock-based products with plant-based products
Traditional to industrial agriculture	Change from low input, subsistence agriculture to industrialized agriculture highly dependent on industrial inputs	Increasing agricultural productivity
Change to regenerative agriculture	Transition to agroecological regenerative agriculture with advanced soil preservation techniques	Nitrogen pollution reductions, changing agricultural practices enhancing soil carbon
Effect of oil and gas on agriculture	Policy that simulates the effect of a shortage of agricultural inputs derived from petroleum and natural gas	
Priorities of land product distribution among regions	Policy that modifies the distribution of crops and forestry products among regions	
Solar land from others	Policy that selects the land-uses from which land for solar power plants is sourced	
Land protection from solar	Protects other land-uses from being converted for solar energy deployment	
Solar land management	Type of land management under solar panels: permanent clearing of vegetation, management as pastures, or restore vegetation	
Grasslands management	Change in grassland management with several options, ranging from very unsustainable practices to regenerative grazing management for extensive ruminants	Livestock and grazing management Soil carbon enhancement, enhancing carbon sequestration in biota and soils
Manure management	Change to several options of manure management, including solid storage, dry lot, and pit storage.	Manure management

A detailed overview of the data sources used in WILIAM-TERRA is available in Appendix B, Appendix G analyses the dynamic stability of the model, its validation and the calibration of some of its features. An overview of its submodules is provided in the following sections.

2.4 Land Uses submodule

The Land Uses submodule calculates the available land by region by allocating it among 12 uses categories. These categories are primarily based on FAO's land uses classification with additions from land cover FAO categories to ensure completeness (see Appendix A).

Figure 4 shows a diagram of the main variables calculated in this submodule. Land use changes are driven by the continuation of observed past trends and from the following factors:

- Urban expansion (driven by population growth)
- Solar energy (driven by the demand for solar electricity)
- Cropland loss due to sea level rise
- Reforestation and forest plantations (driven by policies)
- New cropland (driven by the global shortage of crops)

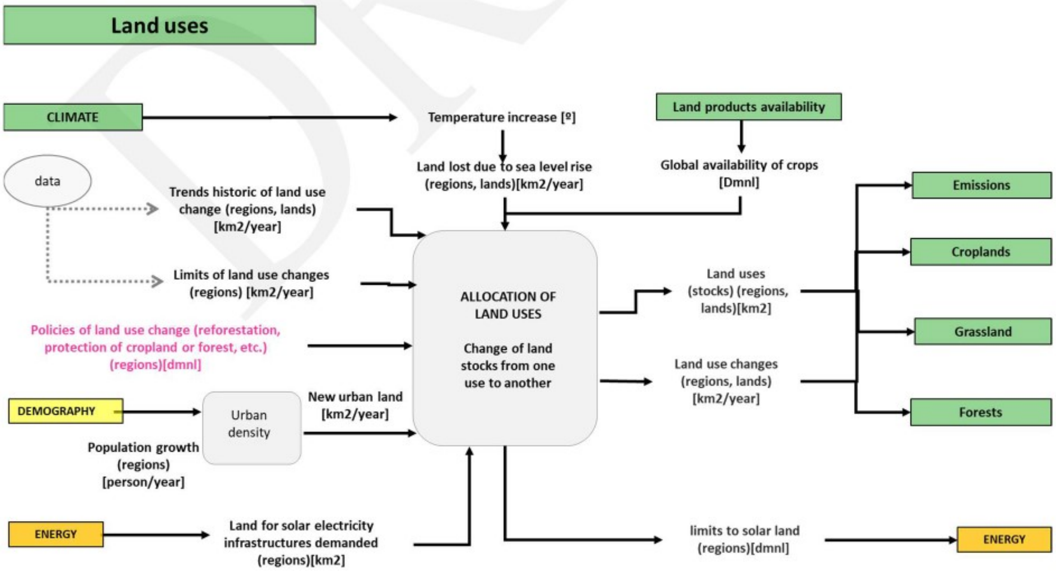


Figure 4. Land uses submodule: information flows. Green boxes represent WILIAM-TERRA submodules, while boxes in other colours belong to other WILIAM modules. Grey boxes represent endogenous calculations.

Variables in pink are exogenous policies chosen by the user. The subscripts of each variable are shown in parentheses, and the physical units are indicated in brackets.

The demand for land for cropland is governed by a feedback loop (described in the causal loop diagram of Figure 5) that ensures cropland adapts to the demand, within the limits imposed by land protection policies. A global signal of cropland availability is used to drive the growth of cropland in all the regions, as we assume that agriculture is globalized and crops shortage affects all regions similarly. The demand for land for solar energy follows a similar mechanism, as does the demand for plantations, although the latter feature is not yet activated.

In all the causal loop diagrams of the paper, the arrows represent information flows and have a "+" sign if an increase in the first variable increases the second variable (direct relation), and a "-" sign if an increase in the first variable decreases the second (inverse relation). A feedback loop occurs when there is a closed chain of arrows, and it is reinforcing if the number of "-" signs is even and stabilizing if it is odd.

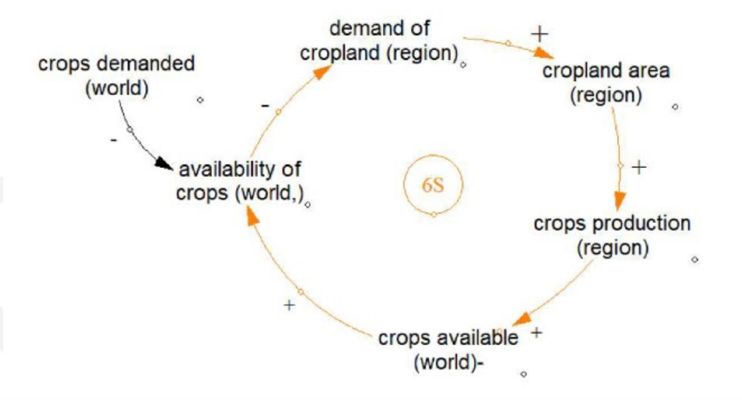


Figure 5. Feedback that ensures that the cropland adapts to the demand in the Land Uses and Crops and Yields submodule. The stabilizing loop that appears is called 6S. (see Annex I for a detailed explanation).

The Land Uses submodule is fundamentally based on the maintenance of trends of land evolution coupled with policies of demand and land protection. The allocation between the demands of different uses occurs within a dynamic of "all against all" competition in which priorities may be established. The Land uses submodule has been calibrated using land use data from FAOSTAT, supplemented with land cover data from FAO (see Appendix A). See Section 1 in Appendix E and G for a more detailed description.

2.5 Crops and Yields submodule

The Crops and Yields submodule manages the agricultural production. Once the Land Uses submodule has calculated the area of cropland, the Crops and Yields submodule calculates the percentage of land area dedicated to each crop creating the feedback described in Figure 6. It is driven by the relative shortage of each crop and reallocates land to those crops with the highest shortage, thereby, equilibrating demand and supply.

The submodule (see Figure 7 and Figure 8) allows the use of different priorities for each crop and maintains the numerical consistency (the sum of all shares must equal 1) using the dynamic shares mechanism [60].

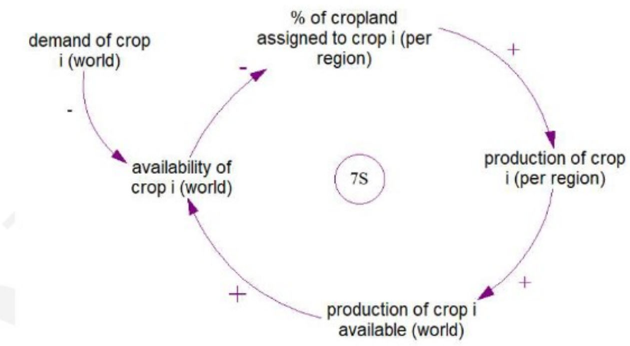


Figure 6. Causal loop diagram of the mechanism that allocates the cropland area among crops according to its relative shortage. The stabilizing loop that appears is called 7S.

The agricultural production is calculated by multiplying the area dedicated to each crop by the yields. Mixed or separated yields can be chosen for irrigated and rainfed crops, the selector SWITCH SEPARATE IRRIGATED RAINFED enables to choose between these options.

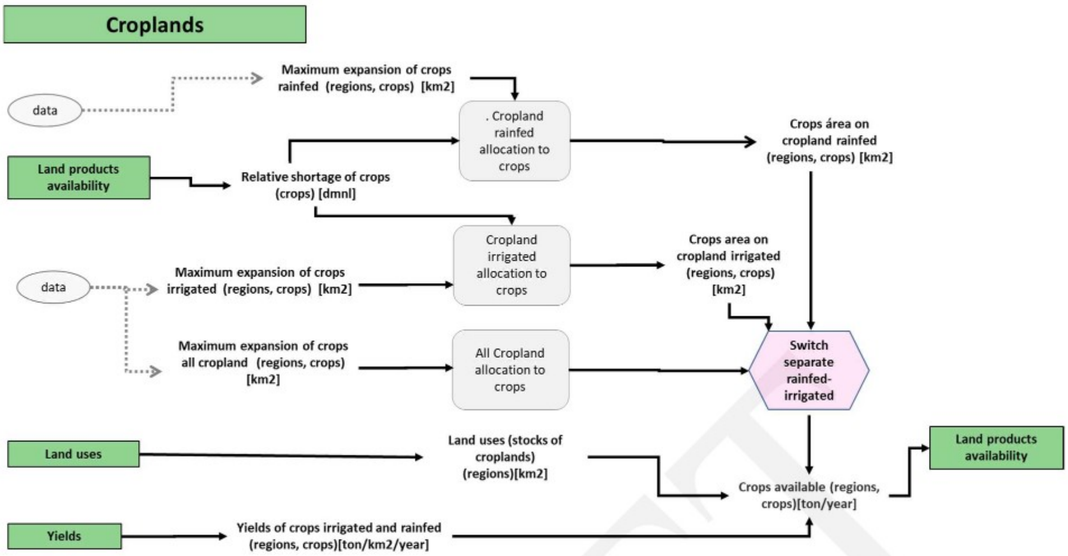


Figure 7. Crops and Yields submodule: flows of information. Green boxes are WILIAM-TERRA submodules, boxes in other colour belong to other modules of WILIAM. Grey boxes are endogenous calculations. Pink hexagon is a selector that enables the user to choose to separate (or not separate) rainfed and irrigated cropland. In parenthesis the subscripts of each variable are shown and in brackets the physical units.

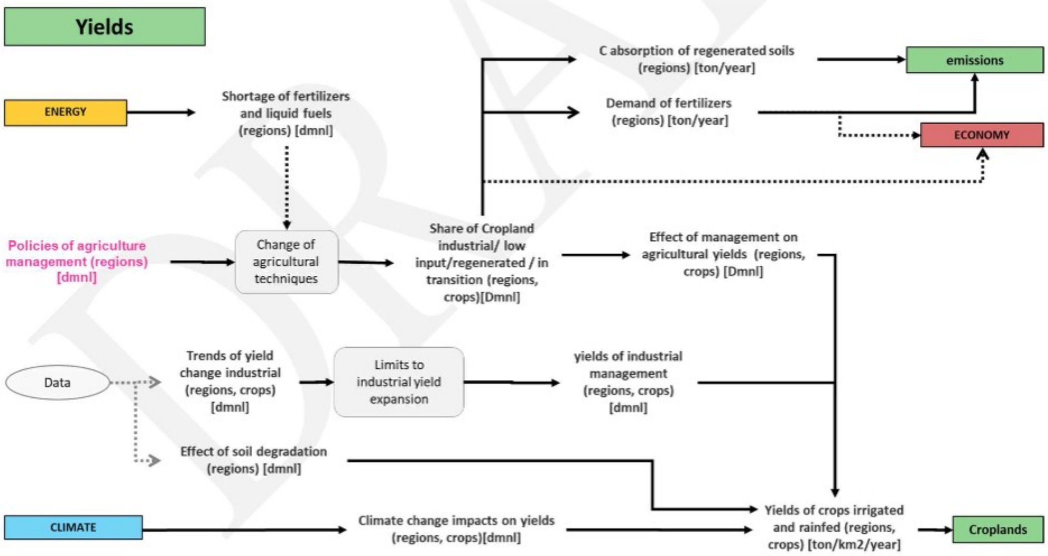


Figure 8. Crops and Yields submodule: flows of information. Green boxes are WILIAM-TERRA submodules, boxes in other colour belong to other modules of WILIAM. Grey boxes are endogenous calculations. Exogenous policies are in pink. Doted arrows are connections not fully implemented yet. In parenthesis the subscripts of each variable are shown and in brackets the physical units

WILIAM-TERRA considers various types of agricultural management. Developed regions are almost 100% based on high input industrial techniques, while developing nations still have significant shares of low inputs traditional agriculture. The shift from traditional to industrial farming increases the overall yield but also poses social conflicts, since it creates unemployment that sometimes cannot be compensated by other economic sectors [61]. The rising price of fertilizers due to scarcity of natural gas and oil might also force farmers to produce with low inputs as happened in Cuba and North Korea in the 1990's [62]. The transition to regenerative ecological management might also be driven by policies adopted by governments. All these possibilities have been included by considering five types of agricultural management:

- Industrial: high input agriculture.
- Traditional: low input agricultural techniques based on extensive use of manual labor.
- Low input: low input agriculture that would result from the eventual lack of fertilizers.
- Regenerative: agriculture that uses advanced ecological techniques.
- In transition: agriculture that has started the transition to regenerative practices but has not completed it.

The impact of climate change on crop yields is incorporated endogenously, drawing on the work published by Waldhoff et *al.* [63] and data on GHG concentrations from the WILIAM Climate module. Soil degradation on yields is also considered in a stylized way, according to FAO [64,65].

Two essential policies are applied in the Crops and Yields submodule: the change from tradition to industrialized agriculture and the transition to agroecological management. The eventual effect of oil and gas prices on agriculture, at present, is introduced as a policy since the endogenous relation with oil and gas prices has not been established yet. Data on the historical share of agriculture and relative yields of each crop and region under traditional and low input regime have been taken from the Map Spam database [66]. See Section 2, in Appendix E for a more detailed description.

2.6 Grasslands submodule

The grasslands submodule calculates the absorption of carbon in pastures soils. It incorporates the possibility of a gradual change to five types of pasture management: severely degraded, moderately degraded, improved grassland with medium and high input and regenerative grazing (agroecological management [67,68]). This enables test some options of nature-based carbon dioxide removal, which, according to IPCC [34] are only recently being implemented in IAMS. The flows of information are shown in 9 (see Section 3 in Appendix E for a more detailed description).

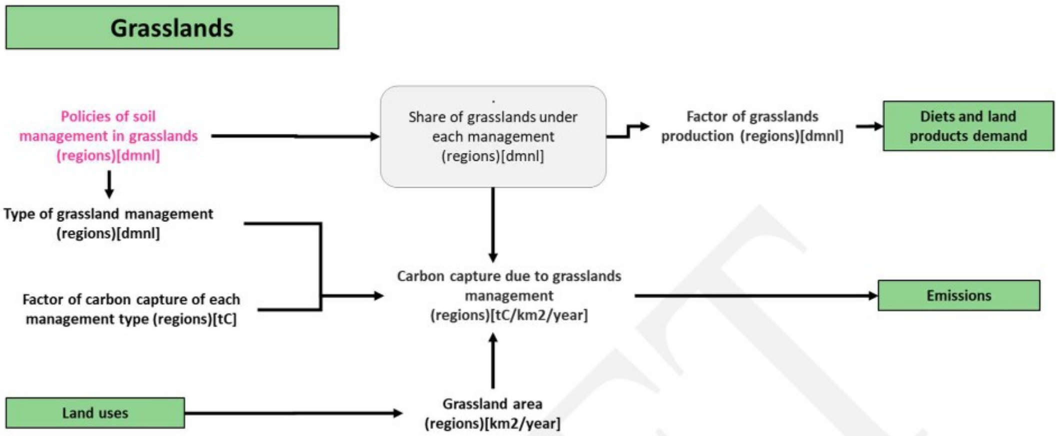


Figure 9. Grasslands submodule: flows of information. Green boxes are WILIAM-TERRA submodules. Grey boxes are endogenous calculations. Exogenous policies are in pink. In parenthesis the subscripts of each variable are shown and in brackets the physical units.

2.7 Forests submodule

The Forests submodule (see Figure 10) is based on a model of forest biomass balance that includes biomass growth, forest area changes, natural disturbances and extraction of forestry products for human use. It is an improved version of the model by Zhang et *al.* [69] adding the natural disturbance and the maximum biomass potentials calculated by Roebroek et *al.* [70]. This comprehensive approach considers the possibility of forest degradation due the extraction of biomass for energy and other uses, even though the forest area might not be reduced.

Forest submodule includes the distribution of the demand for forestry products among regions (differentiating energy and industrial uses) and a policy of self-sufficiency, that drives regions to depend less on imports to fulfil their wood demand. A policy of limits on forest extraction enables the halting of wood logging when the stock of biomass falls below a desired threshold. This policy restricts the biomass available for energy, consequently reducing the potential energy available to the Energy module.

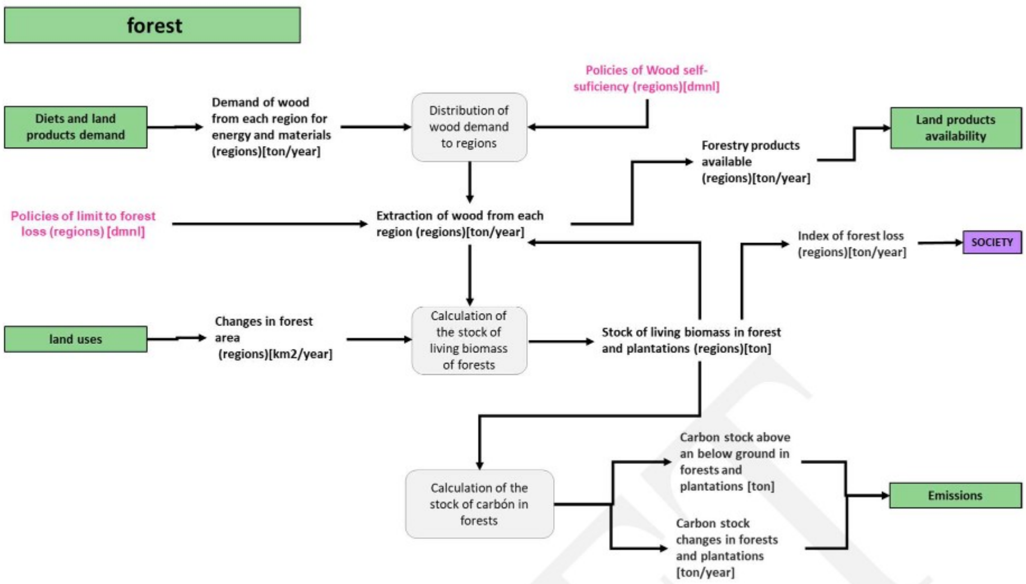


Figure 10. Forests submodule: information flows. Green boxes represent WILIAM-TERRA submodules. Grey boxes represent endogenous calculations. Variables in pink are exogenous policies chosen by the user. The subscripts of each variable are shown in parentheses, and the physical units are indicated in brackets.

The stock of forest biomass is used to calculate the carbon stock, both above and below ground, as well as the forests net CO_2 flows, using the values from Demand IPCC [71] and Machado et *al.* [72]. Refer to Section 4 in Appendix E for a more detailed description.

2.8 Diets and Land Products Demand submodule

The Diets and Land Products Demand submodule, as shown in Figure 11, computes the demand for a range of land products (crops and forestry products) required for food, energy, and industrial purposes.

The crops demanded for food are calculated based on diets driven by GDP, and are calculated for 9 regions and 14 food categories using the historical patterns of food consumption versus GDP per capita extrapolating or interpolating them. A policy of diet change is added to this GDP-driven diet. The options for the diet policy include a flexitarian diet, a 50% plant based diet, and a 100% plant-based diet (refer to Appendix D for more details).

The fish is subtracted to calculate the demand for food that comes directly from croplands (fish intake is considered to be unlimited at present version of the model). Finally, the crops demanded for food are determined by multiplying by an Agro-food transformation matrix, which relates food items to land products.

The crops required for biofuels and the wood required for energy are obtained from the Energy module and transformed from energy to land products using the data of the average products used for bioenergy in past years. The wood demanded for industry is proportional to the economic activity of the industries that are more intensive on the use of wood (Wood Manufacture and Construction). The average intensity of wood for industry is calculated using historical values of wood consumption divided by the economic output of those two sectors (source WIOD [73]).

The land products demand, calculated in this submodule, is confronted with the land products available, as estimated in Crops and Yields and Forest submodules, and distributed to regions and uses in the Land Products Availability submodule (see section 2.9 for a detailed explanation).

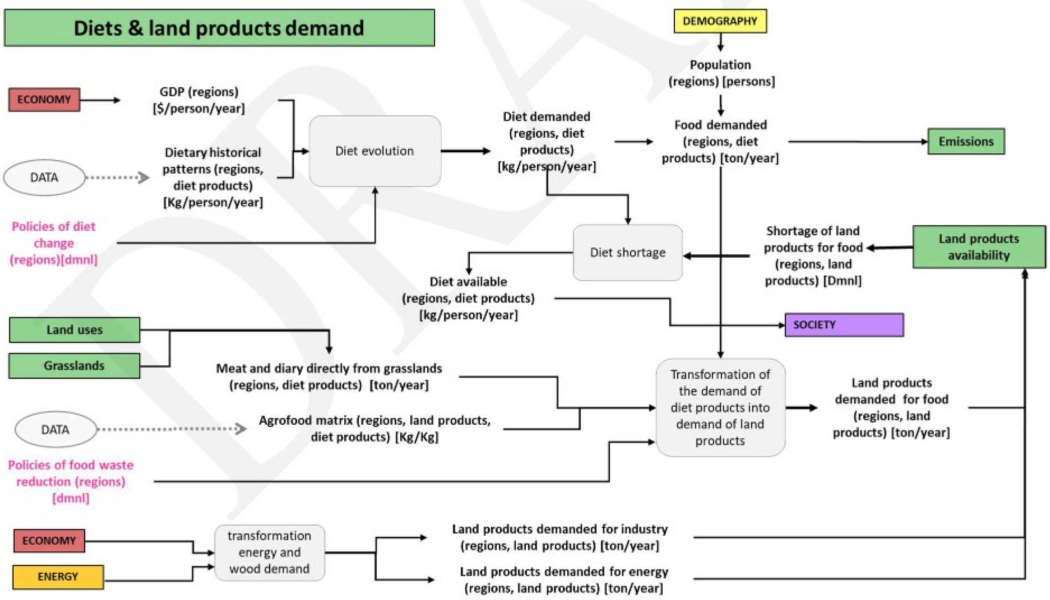


Figure 11. Diets and Land Products Demand submodule: information flows. Green boxes represent WILIAM-TERRA submodules. Grey boxes represent endogenous calculations. Variables in pink are exogenous policies chosen by the user. The subscripts of each variable are shown in parentheses, and the physical units are indicated in bracket.

If the demand for food exceeds production, a shortage signal appears. This signal is used to calculate the diet available, the one that would be considered realistic according to physical and policy limitations.

As illustrated in Figure 12, a reinforcing feedback loop could emerge if the diet available would become equal to the diet demanded, since the regions that receive less food would demand less food in the allocation between regions, would receive less and demand even less food until they demand cero. This is unrealistic behavior. Consequently, a deliberate discrepancy is maintained and the diet demanded might be different than the diet available, which is used to compute various nutritional indicators. These indicators are sent to the Society module of the WILIAM model, providing insights into the quality of nutrition of the population in each region.

The demand for forestry products is also confronted with the production in the Land Products Availability submodule. If the demand cannot be met, a signal is sent to Energy module to reduce the consumption of energy from forestry products. See Section 5, Diets and Land Products Demand Submodule, in Appendix E for a more detailed description.

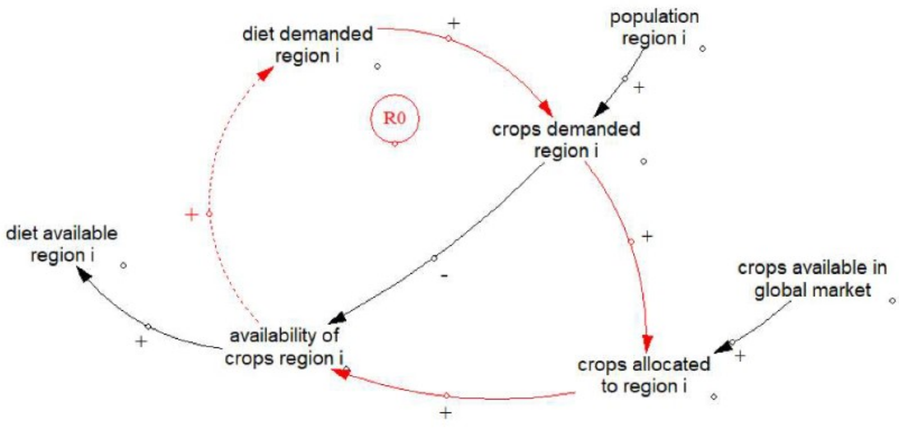


Figure 12. Cause loop diagram of the reinforcing loop that could appear in the Diet submodule. The red arrows form the loop called R0, the dashed arrow is not included in the model to avoid this feedback which leads to unrealistic behaviour.

2.9 Land Products Availability submodule

In the Land Products Availability submodule (see Figure 13), the supply and demand of land products are compared. The supply (land products available) is distributed first among regions and then among uses and, finally, compared with the demand to estimate their shortage/surplus. The distribution among regions considers the fact that, even when the production is not transported, most of it is subject to international prices, and the market is similar to a pool where all regions offer products and all regions demand. There is, nevertheless, a percentage of the production due to very small land holders that is not subject to these markets and is also considered.

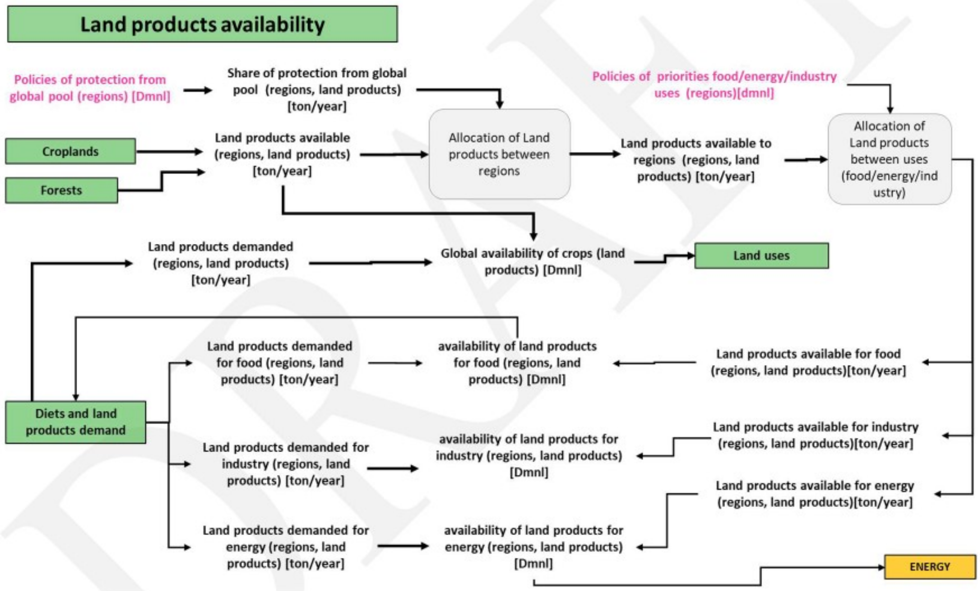


Figure 13. Land Products Availability submodule: flows of information. Green boxes are WILIAM-TERRA submodules. Grey boxes are endogenous calculations. Exogenous policies are in pink. In parenthesis the subscripts of each variable are shown and in brackets the physical units.

This pool distribution is modelled using the *allocate by priority* function in VENSIM and is based on the demand of each region calculated in the Diets and Land Products Demand submodule. Note that *this distribution is not a proper model of the international trade* but a simplified distribution centered on the relations between production and the final consumption of people.

The global availability of crops (which is a signal that compares global crops production and demand) is fed back to the Croplands and Yields submodule to regulate the amount of land dedicated to each crop and to the Land Uses submodule to regulate the land allocated to croplands. The availability of land products for food is sent to the Diets and Land Products Demand submodule to estimate the diet available and the land products available for energy go back to the Energy module to limit the amount of bioenergy consumed.

2.10 Emissions submodule

The Emissions submodule (Figure 14) dynamically calculates the following land-related GHG emissions:

- Agriculture, Forestry and Other Land Use (AFOLU) GHG emissions related to land use,
- Emissions related to land use changes and forestry activities (LULUCF),
- Agriculture emissions: fertilizers, rice cultivation and livestock (ruminants)

CO_2, CH_4, and N_2O emissions are endogenously calculated following the IPCC guidelines [74]. The equations vary by land use, and consider the specificities of regional climate, vegetation, and soil conditions in each of the regions.

LULUCF emissions are calculated based on the land use changes calculated in Land Uses submodule. In the case of those land use changes that imply carbon uptake (such as carbon stock increase, for example from grassland to forest), the time needed to reach the equilibrium in the new state, is considered.

The change in soil carbon due to different types of agricultural management is also calculated based on the information from the Crops and Yields submodule. See Section 7, Emissions Submodule, in Appendix E for a more detailed description of the equations involved in this submodule.

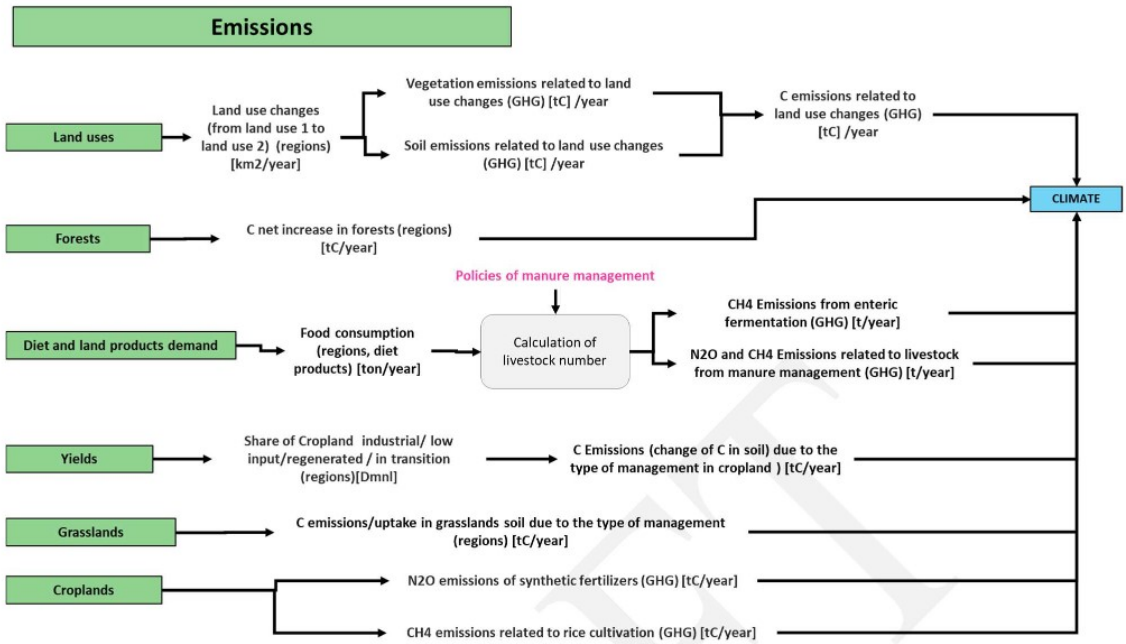


Figure 14. Emissions submodule: information flows. Green boxes represent WILIAM-TERRA submodules. Grey boxes represent endogenous calculations. Variables in pink are exogenous. The subscripts of each variable are shown in parenthesis and the physical units in brackets.

3. RESULTS OF WILIAM-TERRA

In this section some results of experiments are presented to show the possibilities of WILIAM-TERRA. They are intended to give a taste of the questions that can be explored with this model, but do not pretend to be definitive results. Solid results would require a literature review, a comparison with other models and a better estimation of some parameters. All that is beyond the scope of this article.

Table 2 shows a summary of the experiments carried out. *Base* is a run with no policies tested, *Experiment 1* shows the result of the policies of land protection and diet change, *Experiment 2* shows the policies related to forest management and *Experiment 3* shows some results of the policies of grassland management.

In all results shown in this section, WILIAM-TERRA is run independently from the rest of WILIAM. Population, GDP per capita and demand for biofuels are taken as exogenous inputs (see Appendix F). The evolution of crop yields is also shown in this appendix.

Table 2: summary of the experiments and policies tested

Experiment	Policies tested	Runs
Base		**Run 0:** yield trends, standard cropland limits, no policies
Experiment 1: effect of policies of land protection and diet changes under scenarios of moderate yields evolution, soil erosion, and climate change impacts on yields.	Primary forest protection, Managed forest protection Natural land protection Diet change	**Run 1-1:** no cropland expansion **Run 1-2:** no cropland expansion and diet change to 100% flexitarian in all regions.
Experiment 2: effect of wood demand on forest biomass stock under scenarios of demand growth and localization of the wood extraction	Forest loss limit, Forestry self sufficiency	**Run 2-1:** low demand for wood, no forest protection **Run 2.2:** low demand for wood, forest protected from deforestation **Run 2.3:** high demand for wood, forest protected from deforestation **Run 2.4:** high demand for wood, forest protected from deforestation and localization.
Experiment 3 Effect of management on pastures carbon capture	Grasslands management	**Run 3-1:** nominal management of pastures **Run 3-2:** degraded management (100% degradation starting in 2025 ending in 2050, 8 years installation time) **Run 3-3:** regenerative management (starting in 2025 ending in 2050, 50 years saturation time)

Experiment 1: Food availability under land protection and dietary changes

As sketched in Figure 15, there are several factors influencing food availability that are modelled in WILIAM-TERRA: land area, crop yields, climate change, agricultural management, diets, population and the demand for biofuels competing with food.

Experiment 1 tests some of these factors using some of the model's policies. Run 0 explores a baseline scenario with a reasonable increase in yields, subject to the effects of climate change and soil erosion (described in Appendix E, section 2) and approximate limits to cropland expansion (Appendix E, section 1). Run 1-1 activates a policy of forest and natural land protection that allows no expansion of cropland and Run 1-2 activates a policy of dietary change starting in 2025 and ending in 2050, so that in the last year the entire world population has a flexitarian diet (see Appendix D).

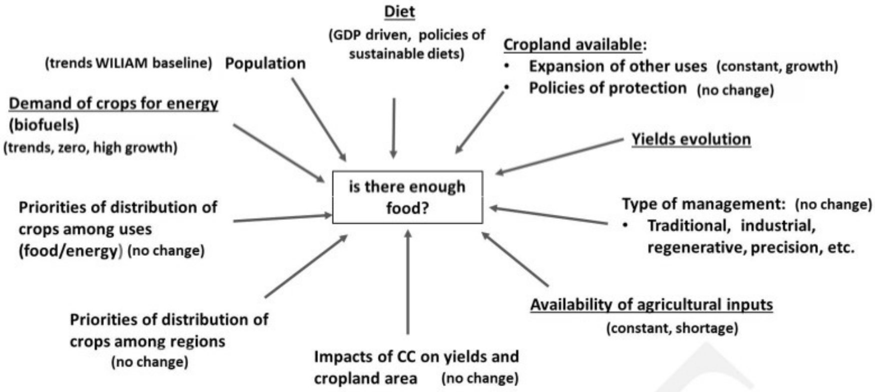


Figure 15. Several factors impacting food availability worldwide.

One of the indicators shown is the variable *Global availability of crops*, a comparison between the average available crops produced worldwide (*crops available for all regions* (lp_K)) and demanded crops (*crops demanded for all regions* (lp_K)) for all those land products lp_K that are crops.

$$Global\ availability\ of\ crops = \frac{\sum_{k=1}^{11} \frac{crops\ available\ for\ all\ regions\ (lp_k)}{crops\ demanded\ for\ all\ regions\ (lp_k)}}{Number\ of\ crops} \quad (1)$$

This variable is influenced by all the factors in Figure 15 and is equal to one in the historical period and when availability is the same as it is today, and less than one when there is more scarcity. It is therefore only an indicator of scarcity relative to today's situation, not an absolute indicator of malnutrition.

The results in Figure 16 (a) show that the global availability of crops for Runs 1-1 and 1-2 is slightly less than 1, because the expansion of cropland has been constrained (e.g. to protect biodiversity or mitigate climate change). This means that even with the dietary changes of Run 1-2, the increase in yields is not sufficient to meet the needs of the growing population. Figures 16(b) and (c) show that there is significantly less forest loss if cropland expansion is limited (the global forest area is about 54 million km2, so the saving is about 6%). Figure 16 (d) shows the total cropland production that, as expected, is smallest in Run 1-2. Figure 16(e) shows the reduction in methane emissions resulting from dietary change, but Figure 16(f) shows that this translates into a small change in the total radiative forcing caused by all greenhouse gases (GHG).

The reason for these relatively modest results of a global and relatively radical dietary change can be explained by the results shown in Figure 17. Although demand for ruminant meat is reduced in all regions except India (Figure 17(e)), demand for monogastric meat increases in India and LROW and in significant numbers (Figure 17(f)). The demand for oilseeds, cereals, fruits and vegetables, and legumes increases significantly as well in LROW and in some cases in India. This increase is greater when the dietary policy is applied to oilseeds, pulses, fruits and vegetables, because the current diets of LROW and India are below the standard of a healthy diet as defined by the flexitarian diet.

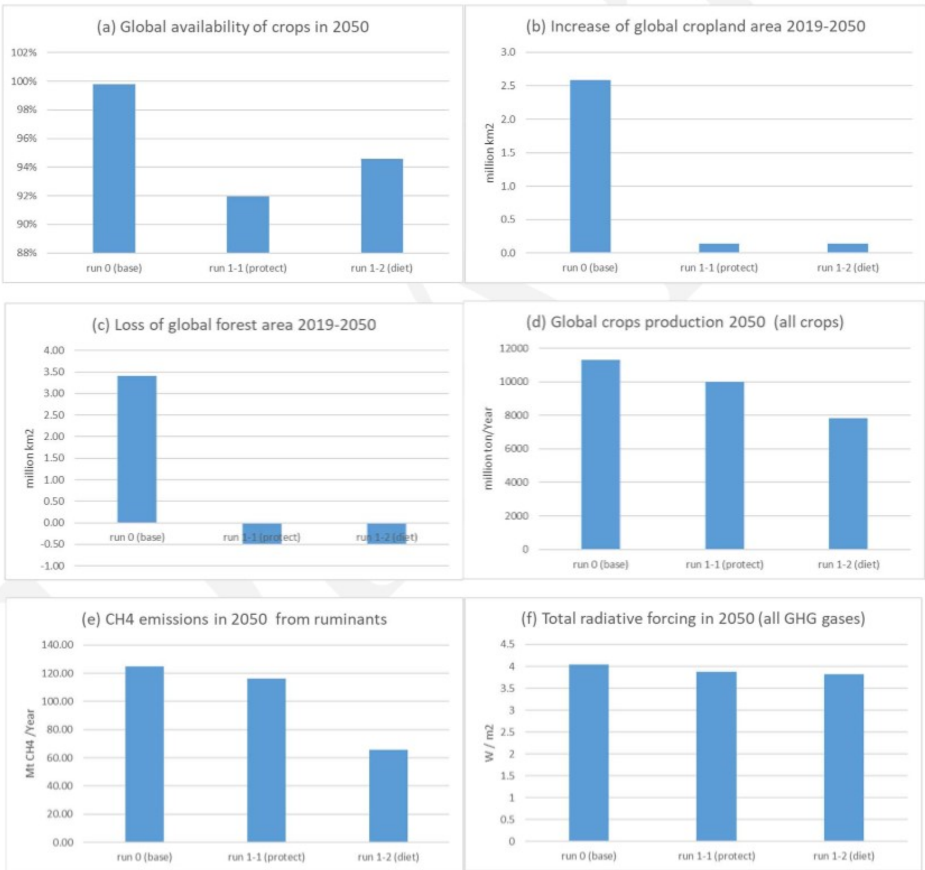


Figure 16: results of Experiment 1 for its three runs. (a) shows the signal of global availability of crops in year 2050, (b) the increment of cropland area and (c) the loss of forest area between 2019 and 2050. (d) shows the world crop production of all crops (added in kg) in year 2050, (e) the methane emissions derived from ruminant meat consumption and (f) the resulting radiative forcing caused by all GHG emission in 2050.

These results would be altered by more radical dietary changes, such as a 100% plant-based diet, but show the importance of regional analysis of food policies and their complex interactions with forests, yields and cropland, which can be analysed with WILIAM-TERRA.

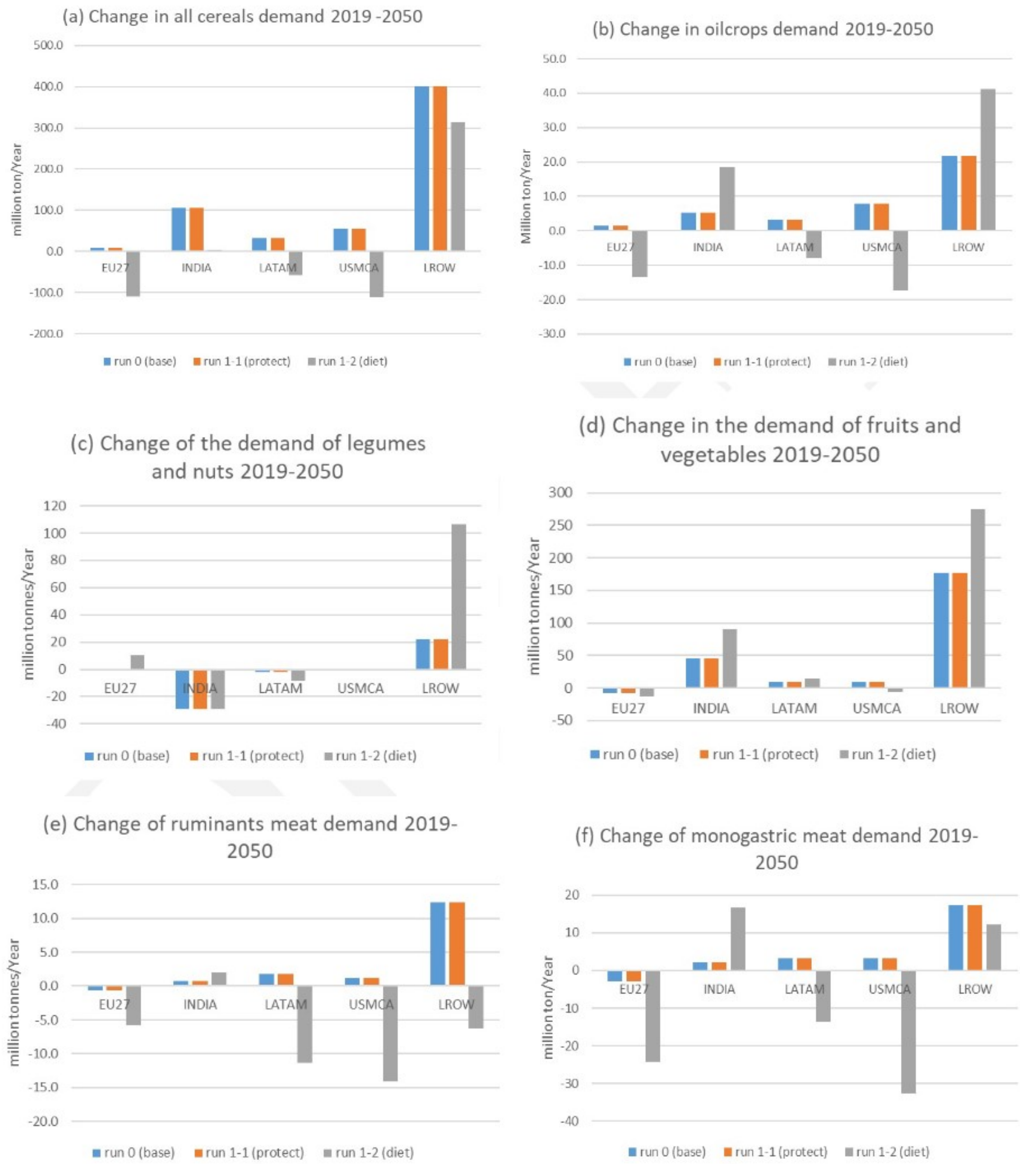


Figure 17: Results of Experiment 1. Figures (a), (b), (c) and (d) show the demand of several crops between 2025 and 2050 for some representative regions. Figures (e) and (f) show the demand of meat from ruminants and non-ruminants for the same regions.

Experiment 2: Deforestation and forest extraction

The runs of Experiment 2 show the effect of deforestation and forest harvesting. Figure 18 shows the above-ground forest biomass stock of China and LROW for four runs. Run 2-1 and Run 2-2 have a very low estimated demand for forest products for energy (stagnating from 2025 to 2050 and shown in Figure F4 in Appendix F), while the demand for other uses follows a normal trend (see Figure F7 in Appendix F). Run 2-3 and Run 2-4 have a high demand for energy (Figure F6 in Annex F) and the same demand for other uses as the previous runs. Run 2-4 shows the effect of the policy of forest self-sufficiency (localisation), which reduces trade between forest regions, so that each region meets its demand from its forests when the policy is fully implemented.

Figure 18(a) shows that the forest stock of LROW has been declining on a good path in recent decades, and if the demand for biomass for energy is restricted (Run 2-1) but, since deforestation continues, this path continues too. The results of run 2-2, without deforestation but with the same extraction as in run 2-1, show that a large part of the loss of LROW biomass stock is due to deforestation itself rather than to wood extraction. Nevertheless, as timber extraction increases in Run 2-3 and Run 2-4, the forest stock increases its annual loss. The loss is smaller in Run 2-4 when the localisation policy is activated, as LROW produces timber for the demands of other regions.

The same policy has a very different effect in China. The results of Run 2-1 and Run 2-2 are the same in China because this region has no deforestation (it is reforesting at a good rate). Forest extraction increases in all runs in Figure 18 (d) and reaches a very significant increase in Run2-4, showing the strong dependence of China on wood from other regions. In Run 2-3 and Run2-4, China's biomass stock decreases significantly at the end of the simulation, especially in Run 2-4, showing that a higher demand is not sustainable for China's forests.

These results should be taken with caution, as the authors are currently not very confident about the calibration of the WILIAM-TERRA forest submodule. Although the forest model has been fully calibrated with FAO data on biomass stocks and extraction [75], the process showed strange results for some regions (specially India and LATAM). The FAO data of forest stock shows very significant differences with other data of the literature. Pan et al. [76] for example, shows 60% more global biomass stock than FAO. That is the reason why a multi-model framework is currently being developed for the forest sub-module. The use of a set of models calibrated with different data will compensate the disparity of data.

However, the results shown in this section already demonstrate the high level of insight that WILIAM-TERRA can provide through the application of its policies.

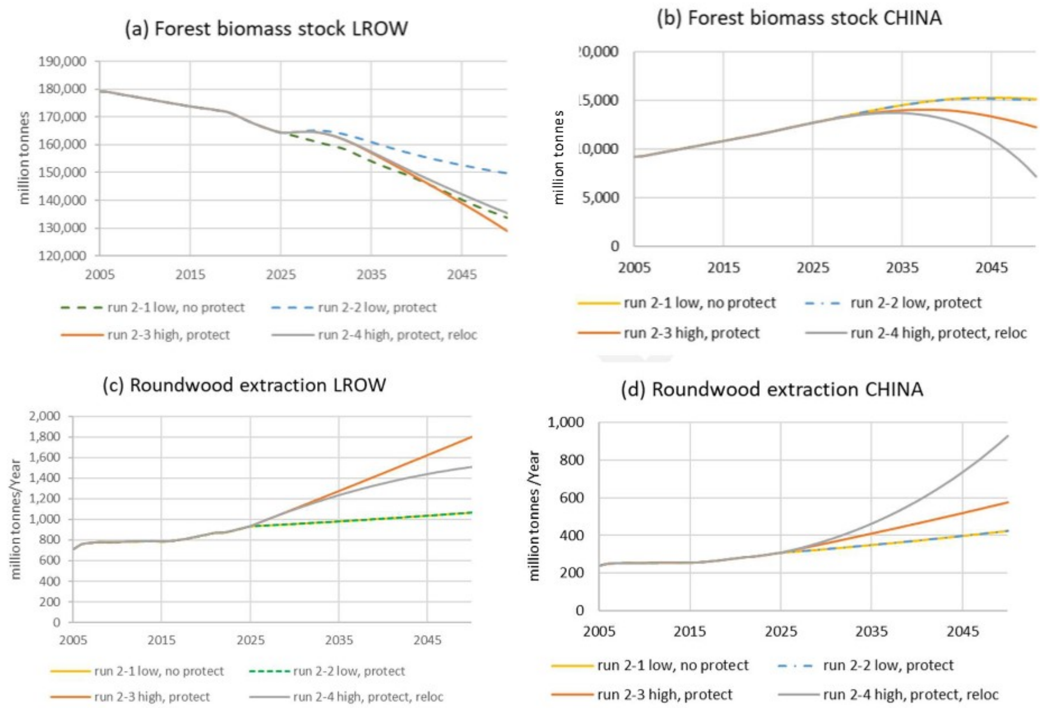


Figure 18: results of Experiment 2. In (a) and (b) the above ground forest biomass stock is shown for LROW and China in the four runs of Experiment 2. In (c) and (d) the roundwood extraction is shown for the same regions.

Experiment 3: grassland management

The results of experiment 3 compare three management options for grassland area (called permanent meadows and pastures in the FAO classification). In Run 3-1 the land has the nominal management used today, in Run 3-2 grasslands in all regions evolve to a highly degraded stage starting in 2025 and ending with complete degradation of all land in 2050. In Run 3-3, all grasslands evolve towards an agro-ecological regenerative management that maximises carbon sequestration in soils and doubles their carbon content when the policy is achieved 50 years later.

Figure 19 shows the emissions/capture of carbon in soils derived from this policy, which are zero in Run 3-1 because these are only the emissions derived from the policy. As the total carbon equivalent emissions in 2050 are about 56 Gt/year, these data of capture or release from grassland soils represent a significant proportion of global emissions. The cumulative carbon emissions over the whole period are shown in Figure 19 (b).

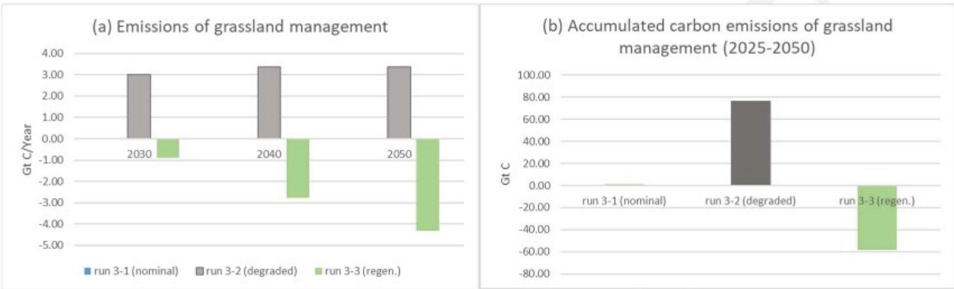


Figure 19: results of Experiment 3. The emissions derived from the change of management in grasslands in 2050 is in figure (a). The accumulated emissions (absorptions) are in figure (b).

As mentioned above, these results should be treated as preliminary tests and they explore only a small number of the possibilities that can be analyzed with the WILIAM-TERRA tool. Future research will focus on refining the data and developing realistic sets of scenarios that would allow solid conclusions to be drawn on each of the aspects related to the policies of the model.

Future research on WILIAM-TERRA will be focused on the following aspects:

- Refinement of all the model's parameters using in some cases data with a higher level of regional disaggregation (such as climatic regions for forests and crops).

- Detailed analysis of the interactions already existing with the WILIAM Energy module and establishment of interactions with the WILIAM Economy module.

- Introduction of indicators of biodiversity liked to land uses, forests and agricultural management.

- Detailed analysis of research questions similar to the ones presented in this article: the challenges of the energy transition, the global food demand, the ecological transition of the agriculture, etc.

4 CONCLUSIONS

This paper describes the WILIAM-TERRA model, a novel platform for the systemic analysis of land, food, energy and climate issues, and presents some results from its use. WILIAM-TERRA is part of the Within Limits Integrated Assessment Model (WILIAM), a new open-source model designed to address several limitations of existing IAMs by using a biophysical approach, limits to resource extraction and a feedback-rich System Dynamics simulation.

WILIAM-TERRA addresses land use, crop production, forests, diets and LULUCF emissions and allows a wide range of policies to be tested. Policies on afforestation, land protection, dietary changes, farming techniques, soil carbon in pastures, manure management, forest management, impacts of solar PV installations and distribution across regions are included.

All these features provide a broad platform for analyzing the sustainability of land use, focusing both on sinks (impacts on climate change, biodiversity, etc.) and sources (energy from biofuels, forests, solar PV). WILIAM-TERRA is also a tool for analyzing the ecological transition of the food system, including dietary changes, agricultural management and exchanges between regions. All these features allow for a more systemic approach than the traditional emissions-based approach of most IAMs.

Some preliminary results from the use of WILIAM-TERRA have been presented. The global availability of food is studied under scenarios of more and less cropland expansion and dietary changes. The sustainability of wood extraction is analyzed under some scenarios of energy demand and deforestation. The carbon sequestration capacity of grassland soils is analysed for two extreme management scenarios.

These results explore only a small part of the possibilities that can be analysed with WILIAM-TERRA. Further research will explore the wide range of panoramas that its feedback-rich structure and wide range of policies allows.

CONFLICTS OF INTEREST

There are no conflicts to declare.

ACKNOWLEDGEMENTS

This work has also been partially developed under the LOCOMOTION project, (grant agreement no. 821105), RethinkAction project (grant agreement No 101037104), NEVERMORE project (grant agreement No 101056858) and IAM COMPACT project (gran Agreement no. 101056306) all of under the EU Commision research and innovation programme. The authors gratefully acknowledge Stavroula Papagianni from CRES for providing some the data used in the model, Iván Ramos, from CARTIF for providing data of crop yields based on MapSpam database, Tommaso Brazzini from GEEDS for the study of the food obtained from grasslands, Leorely Ramos for her work on diet patterns, Marina Campano for her work on land uses, Juan Campos from GEEDS for his work on the forest model, Iñigo Capellán-Pérez from GEEDS for the work on photovoltaic integration with land uses, David Álvarez-Antelo from GEEDS for the technical support and Kaspar Roebroeck from the European Commission Joint Research Centre in Ispra for sharing with us the data used for the calibration of the forest model.

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Appendix A. Categories in WILIAM-TERRA

In this appendix, a description of the categories used in the WILIAM-TERRA model is provided.

A.1 Land-uses

All land-use data comes from FAO database [1], some of the WILIAM categories are derived from "land-use" classifications, while others originate from "land cover" classifications. SHRUBLAND and OTHER LAND are calculated using a mix of land-use and land cover data.

Data is taken from the land-use categories when available, but for some uses, there is no information under the FAO land use categories . The categories CROPLAND_RAINFED, CROPLAND IRRIGATED, FOREST MANAGED, FOREST PRIMARY, FOREST PLANTATIONS, and GRASSLANDS are taken from FAO "land-use" data. URBAN, SNOW-ICE-WATERBODIES, and WETLAND are obtained from "land cover" data.

SHRUBLAND and OTHER LAND (basically bare areas) are adapted, as taking them from land cover creates inconsistencies (for example, the sum of all categories is greater or smaller than the total area in some cases). To avoid these inconsistencies, all the land-uses except SHRUBLAND and OTHER LAND are subtracted from the total land area, and the remaining area is divided between SHRUBLAND and OTHER LAND based on the share obtained from land cover data.

Table A1 describes the FAO land use categories. Table A2 outlines the FAO land-uses, and Table A3 presents the combination of both sources of information used for the categories in WILIAM-TERRA model. The numbers beside the descriptions correspond to the FAO codes [2]. As pointed out by Tubiello et al. [3], there are significant discrepancies between land-use measurements from different sources, including satellite data. Therefore, the FAO database has been used as the standard data, despite these inconsistencies.

Table A1. FAO land use categories.

<table>
<tr><td rowspan="12">total area</td><td rowspan="10">Land area 6601</td><td rowspan="7">agriculture 6602</td><td rowspan="6">agricultural land 6610</td><td rowspan="4">cropland 6620</td><td rowspan="3">arable land 6621</td><td>L. temporary crops 6630</td></tr>
<tr><td>L. temporary meadows and pastures 6633</td></tr>
<tr><td>L. temporary fallow 6640</td></tr>
<tr><td>L. permanent crops 6650</td><td></td></tr>
<tr><td rowspan="2">L. permanent meadows and pastures 6655</td><td>L. permanent meadows and pastures cultivated 6656</td><td></td></tr>
<tr><td>L. permanent meadows and pastures naturally growing 6659</td><td></td></tr>
<tr><td>Protective cover (buildings in agricultura land) 6649</td><td></td><td></td><td></td></tr>
<tr><td rowspan="3">forest land 6646</td><td>primary forest 6714</td><td></td><td></td><td></td></tr>
<tr><td>naturally regenerated forest 6717</td><td></td><td></td><td></td></tr>
<tr><td>planted forest 6716</td><td></td><td></td><td></td></tr>
<tr><td rowspan="2">water bodies</td><td>Inland waters 6680</td><td></td><td></td><td></td><td></td></tr>
<tr><td>Coastal waters 6773</td><td></td><td></td><td></td><td></td></tr>
</table>

Table A2. FAO land cover categories.

LAND COVER -FAO	
Item code	**Item**
6970	Artificial surfaces (including urban and associated areas)
6971	Herbaceous crops
6972	Woody crops
6973	Multiple or layered crops
6983	Grassland
6974	Tree-covered areas
6975	Mangroves
6976	Shrub-covered areas
6977	Shrubs and/or herbaceous vegetation aquatic or regularly flooded
6978	Sparsely natural vegetated areas
6979	Terrestrial barren land
6980	Permanent snow and glaciers
6981	Inland water bodies
6982	Coastal water bodies and intertidal areas

Table A3. WILIAM-TERRA land-use categories.

WILIAM CATEGORIES	**From FAO land uses**	**From FAO land cover**	**Mixed (with calculations)**
CROPLAND_RAINFED (FAO land uses)	cropland 6620 - cropland area actually irrigated 6694		
CROPLAND_IRRIGATED (FAO land uses)	cropland area actually irrigated 6694		
FOREST_MANAGED (FAO land uses)	naturally regenerated forest 6717		
FOREST_PRIMARY (FAO land uses)	primary forest 6714		
FOREST_PLANTATIONS (FAO land uses)	planted forest 6716		
SHRUBLAND (mixed calculated)			REST1*SHARE OF SHRUBLAND
GRASSLAND (FAO land use)	L. permanent meadows and pastures 6655		
WETLAND (FAO land cover)		Shrubs and/or herbaceous vegetation, aquatic or regularly flooded 6977 (from land cover)	
URBAN_LAND (FAO land cover)		Artificial surfaces (including urban and associated areas) 970 (from land cover)	
SOLAR_LAND (historical data aprox=0)			zero (before 2015 very low value)
SNOW_ICE_WATERBODIES (FAO land cover)		(from land cover) Inland water bodies 6981 + Coastal water bodies and intertidal areas 6982+Permanent snow and glaciers 6980	
OTHER_LAND (mixed, calculated)			REST1*(1-SHARE OF SHRUBLAND)
	ALL (land+ inland waters) 6680+6601		
REST (other land+shrubland)= ALL-(C.RAINFED+C.IRRIGATED+F.MANAGED+F.PRIMARY+F.PLANTANTIONS+URBAN+GRASSLAND +SNOW ICE WATERBODIES+WETLANDS)	**REST**=6680+6601-(6620 + 6717 + 6714 + 6716 + 6655 + 6977+ 970 + 6981 + 6982+6980)		
SHARE OF SHRUBLAND (from REST) = shrub covered areas 6976 /REST			

A.2 Land product categories

Land products contain 11 types of crops (one of them, BIOFUELS_2GCROPS, is for annual cellulosic crops used for energy purposes) and two forestry products. The groups are based on FAO crop categories [4], except for the cellulosic crops for biofuels and the forestry products (from the FAO forestry database [5]). Table A4 provides an aggregation of land product categories, detailing the FAO item group, FAO CPC code, FAO item code, and crop production items.

Table A4. WILIAM-TERRA land product categories.

WILIAM-TERRA land product categories	FAO Item Group	FAO Item CPC code	FAO Item code	Item in crop production
1 CORN	Cereals Total	112	56	Maize (corn)
2 RICE	Cereals Total	113	27	Rice
3 CEREALS_OTHER	Cereals Total	115	44	Barley
	Cereals Total	1192	89	Buckwheat
	Cereals Total	1195	101	Canary seed
	Cereals Total	1199.9	108	Cereals n.e.c.
	Cereals Total	1193	94	Fonio
	Cereals Total	118	79	Millet
	Cereals Total	1199.02	103	Mixed grain
	Cereals Total	117	75	Oats
	Cereals Total	1194	92	Quinoa
	Cereals Total	F0030	30	Rice, paddy (rice milled equivalent)
	Cereals Total	116	71	Rye
	Cereals Total	114	83	Sorghum
	Cereals Total	1191	97	Triticale
	Cereals Total	111	15	Wheat
4 TUBERS	Roots and Tubers Total	1520.01	125	Cassava, fresh
	Roots and Tubers Total	1599.1	149	Edible roots and tubers with high starch or inulin content, n.e.c., fresh
	Roots and Tubers Total	1510	116	Potatoes
	Roots and Tubers Total	1530	122	Sweet potatoes
	Roots and Tubers Total	1550	136	Taro
	Roots and Tubers Total	1540	137	Yams
	Roots and Tubers Total	1591	135	Yautia
5 SOY	Oilcrops Primary	141	236	Soya beans
6 PULSES_NUTS	Pulses Total	1708	203	Bambara beans, dry

	Pulses Total	1701	176	Beans, dry
	Pulses Total	1702	181	Broad beans and horse beans, dry
	Pulses Total	1703	191	Chick peas, dry
	Pulses Total	1706	195	Cow peas, dry
	Pulses Total	1704	201	Lentils, dry
	Pulses Total	1709.02	210	Lupins
	Pulses Total	1709.9	211	Other pulses n.e.c.
	Pulses Total	1705	187	Peas, dry
	Pulses Total	1707	197	Pigeon peas, dry
	Pulses Total	1709.01	205	Vetches
	Treenuts Total	1371	221	Almonds, in shell
	Treenuts Total	1377	216	Brazil nuts, in shell
	Treenuts Total	1372	217	Cashew nuts, in shell
	Treenuts Total	1373	220	Chestnuts, in shell
	Treenuts Total	1374	225	Hazelnuts, in shell
	Treenuts Total	1379.9	234	Other nuts (excluding wild edible nuts and groundnuts), in shell, n.e.c.
	Treenuts Total	1375	223	Pistachios, in shell
	Treenuts Total	1376	222	Walnuts, in shell
7 OILCROPS	Oilcrops Primary	1447	265	Castor oil seeds
	Oilcrops Primary	1460	249	Coconuts, in shell
	Oilcrops Primary	142	242	Groundnuts, excluding shelled
	Oilcrops Primary	1449.02	336	Hempseed
	Oilcrops Primary	1499.03	277	Jojoba seeds
	Oilcrops Primary	1499.05	310	Kapok fruit
	Oilcrops Primary	1499.01	263	Karite nuts (sheanuts)
	Oilcrops Primary	1441	333	Linseed
	Oilcrops Primary	1449.01	299	Melonseed
	Oilcrops Primary	1442	292	Mustard seed
	Oilcrops Primary	1491.01	254	Oil palm fruit
	Oilcrops Primary	1450	260	Olives
	Oilcrops Primary	1449.9	339	Other oil seeds, n.e.c.
	Oilcrops Primary	1448	296	Poppy seed
	Oilcrops Primary	1443	270	Rape or colza seed
	Oilcrops Primary	1446	280	Safflower seed
	Oilcrops Primary	1921.01	328	Seed cotton, unginned
	Oilcrops Primary	1444	289	Sesame seed
	Oilcrops Primary	1445	267	Sunflower seed
	Oilcrops Primary	1499.04	305	Tallowtree seeds
	Oilcrops Primary	1499.02	275	Tung nuts
8 SUGAR_CROPS	Sugar Crops Primary	1809	161	Other sugar crops n.e.c.

	Sugar Crops Primary	1801	157	Sugar beet
	Sugar Crops Primary	1802	156	Sugar cane
9 FRUITS_VEGETABLES	Fruit Primary	1341	515	Apples
	Fruit Primary	1343	526	Apricots
	Fruit Primary	1311	572	Avocados
	Fruit Primary	1312	486	Bananas
	Fruit Primary	1355.01	552	Blueberries
	Fruit Primary	1229	568	Cantaloupes and other melons
	Fruit Primary	1359.02	591	Cashewapple
	Fruit Primary	1344.02	531	Cherries
	Fruit Primary	1355.02	554	Cranberries
	Fruit Primary	1351.01	550	Currants
	Fruit Primary	1314	577	Dates
	Fruit Primary	1315	569	Figs
	Fruit Primary	1351.02	549	Gooseberries
	Fruit Primary	1330	560	Grapes
	Fruit Primary	1352	592	Kiwi fruit
	Fruit Primary	1322	497	Lemons and limes
	Fruit Primary	1356	461	Locust beans (carobs)
	Fruit Primary	1316	571	Mangoes, guavas and mangosteens
	Fruit Primary	1323	490	Oranges
	Fruit Primary	1355.9	558	Other berries and fruits of the genus vaccinium n.e.c.
	Fruit Primary	1329	512	Other citrus fruit, n.e.c.
	Fruit Primary	1359.9	619	Other fruits, n.e.c.
	Fruit Primary	1349.1	542	Other pome fruits
	Fruit Primary	1349.2	541	Other stone fruits
	Fruit Primary	1319	603	Other tropical fruits, n.e.c.
	Fruit Primary	1317	600	Papayas
	Fruit Primary	1345	534	Peaches and nectarines
	Fruit Primary	1342.01	521	Pears
	Fruit Primary	1359.01	587	Persimmons
	Fruit Primary	1318	574	Pineapples
	Fruit Primary	1313	489	Plantains and cooking bananas
	Fruit Primary	1346	536	Plums and sloes
	Fruit Primary	1321	507	Pomelos and grapefruits
	Fruit Primary	1342.02	523	Quinces
	Fruit Primary	1353.01	547	Raspberries
	Fruit Primary	1344.01	530	Sour cherries
	Fruit Primary	1354	544	Strawberries

	Fruit Primary	1324	495	Tangerines, mandarins, clementines
	Fruit Primary	1221	567	Watermelons
	Vegetables Primary	1216	366	Artichokes
	Vegetables Primary	1211	367	Asparagus
	Vegetables Primary	1243	420	Broad beans and horse beans, green
	Vegetables Primary	1212	358	Cabbages
	Vegetables Primary	1251	426	Carrots and turnips
	Vegetables Primary	1219.01	378	Cassava leaves
	Vegetables Primary	1213	393	Cauliflowers and broccoli
	Vegetables Primary	1231	401	Chillies and peppers, green (Capsicum spp. and Pimenta spp.)
	Vegetables Primary	1232	397	Cucumbers and gherkins
	Vegetables Primary	1233	399	Eggplants (aubergines)
	Vegetables Primary	1290.01	446	Green corn (maize)
	Vegetables Primary	1252	406	Green garlic
	Vegetables Primary	1254	407	Leeks and other alliaceous vegetables
	Vegetables Primary	1214	372	Lettuce and chicory
	Vegetables Primary	1270	449	Mushrooms and truffles
	Vegetables Primary	1239.01	430	Okra
	Vegetables Primary	1253.02	403	Onions and shallots, dry (excluding dehydrated)
	Vegetables Primary	1253.01	402	Onions and shallots, green
	Vegetables Primary	1241.9	414	Other beans, green
	Vegetables Primary	1290.9	463	Other vegetables, fresh n.e.c.
	Vegetables Primary	1242	417	Peas, green
	Vegetables Primary	1235	394	Pumpkins, squash and gourds
	Vegetables Primary	1215	373	Spinach

	Vegetables Primary	1241.01	423	String beans
	Vegetables Primary	1234	388	Tomatoes
10 BIOFUELS_2GCROPS	Annual cellulosic crops used for biofuel energy use (not accounted in FAO)			
11 OTHER_CROPS	Fibre Crops Primary	1929.07	809	Abaca, manila hemp, raw
	Fibre Crops Primary	1929.06	800	Agave fibres, raw, n.e.c.
	Fibre Crops Primary	26190.01	773	Flax, processed but not spun
	Fibre Crops Primary	1922.01	780	Jute, raw or retted
	Fibre Crops Primary	1922.02	782	Kenaf, and other textile bast fibres, raw or retted
	Fibre Crops Primary	1929.9	821	Other fibre crops, raw, n.e.c.
	Fibre Crops Primary	1929.04	788	Ramie, raw or retted
	Fibre Crops Primary	1929.05	789	Sisal, raw
	Fibre Crops Primary	1929.02	777	True hemp, raw or retted
	Other Crops Primary	1654	711	Anise, badian, coriander, cumin, caraway, fennel and juniper berries, raw
	Other Crops Primary	1379.01	226	Areca nuts
	Other Crops Primary	1691	459	Chicory roots
	Other Crops Primary	1652	689	Chillies and peppers, dry (Capsicum spp., Pimenta spp.), raw
	Other Crops Primary	1655	693	Cinnamon and cinnamon-tree flowers, raw
	Other Crops Primary	1656	698	Cloves (whole stems), raw
	Other Crops Primary	1640	661	Cocoa beans
	Other Crops Primary	1610	656	Coffee, green
	Other Crops Primary	1929.08	813	Coir, raw
	Other Crops Primary	1657	720	Ginger, raw
	Other Crops Primary	1659	677	Hop cones

	Other Crops Primary	1379.02	224	Kola nuts
	Other Crops Primary	1630	671	Maté leaves
	Other Crops Primary	1950.01	836	Natural rubber in primary forms
	Other Crops Primary	1653	702	Nutmeg, mace, cardamoms, raw
	Other Crops Primary	1699	723	Other stimulant, spice and aromatic crops, n.e.c.
	Other Crops Primary	1651	687	Pepper (Piper spp.), raw
	Other Crops Primary	1930.01	748	Peppermint, spearmint
	Other Crops Primary	1930.02	754	Pyrethrum, dried flowers
	Other Crops Primary	1620	667	Tea leaves
	Other Crops Primary	1970	826	Unmanufactured tobacco
	Other Crops Primary	1658	692	Vanilla, raw
12 WOOD	Roundwood. From FAO forestry database [5]			
13 RESIDUES	Residues used for energy (own calculation based on FAO and IEA accounts)			

A.3 Food categories

Table A5 provides an aggregation of food categories, detailing the FAO categories corresponding to the classification of food items [6].

Table A5. *WILIAM-TERRA food items.*

WILIAM FOOD ITEMS categories	FAO categories
CEREALS_DIET	Wheat and products; Rice (Milled Equivalent); Barley and products; Maize and products; Rye and products; Oats; Millet and products; Sorghum and products; Cereals, other
TUBERS_DIET	Cassava and products; Potatoes and products; Sweet potatoes; Yams
PULSES_LEGUMES_NUTS	Beans; Peas; Pulses, Other and products; Soyabeans; Groundnuts (Shelled Eq); Sunflower seed; Rape and Mustardseed; Cottonseed; Coconuts - Incl Copra; Sesame seed; Nuts and products; Palm kernels
FRUITS_VEGETABLES_DIET	Roots, other; Tomatoes and products; Onions; Vegetables, other; Oranges, Mandarines; Lemons, Limes and products; Grapefruit and products; Citrus, Other; Bananas; Plantains; Apples and products; Pineapples and products; Dates; Olives (including preserved); Fruits, other; Grapes and products (excl wine)

FATS_VEGETAL	Oilcrops, Other; Soyabean Oil; Groundnut Oil; Sunflowerseed Oil; Rape and Mustard Oil; Cottonseed Oil; Palmkernel Oil; Palm Oil; Coconut Oil; Olive Oil; Sesamesseed Oil; Ricebran Oil; Maize Germ Oil; Oilcrops oil, Other
FATS_ANIMAL	Fats, Animals, Raw; Fish, Body Oil; Fish, Liver Oil
DAIRY	Butter, Ghee; Cream; Milk - Excluding Butter
EGGS	Eggs
MEAT_RUMINANTS	Bovine Meat;Mutton & Goat Meat
MEAT_MONOGASTRIC	Pigmeat; Poultry Meat; Meat, Other; Offals, Edible
FISH	Freshwater Fish; Demersal Fish; Pelagic Fish; Marine Fish, Other; Crustaceans; Cephalopods; Molluscs, Other; Meat, Aquatic Mammals; Aquatic Animals, Others; Aquatic Plants
SUGARS	Sugar cane; Sugar beet; Sugar non-centrifugal; Sugar (Raw Equivalent); Honey
BEVERAGES	Wine; Beer; Beverages, Fermented; Beverages, Alcoholic
STIMULANTS	Stimulants

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[5] Food and Agriculture Organization of the United Nations (FAO), Global Forest Resources Assessment http://www.fao.org/faostat/en/#data/FO

[6] Food and Agriculture Organization of the United Nations (FAOSTAT) http://www.fao.org/faostat/en/#data/FBSH

Appendix B

Table B1. Detailed information about the data sources used in the WILIAM-TERRA model.

DATASET NAME	UNIT	SOURCE DATA	LINK
Agricultural commodities breakdown by use (food, feed, biofuel use, other use)	thousand tonnes	OECD-FAO Agricultural Outlook 2019-2028	https://stats.oecd.org/Index.aspx?datasetcode=HIGH_AGLINK_2019#
Agricultural commodities breakdown by use (food, feed, biofuel use, other use)	%	OECD-FAO Agricultural Outlook 2019-2028	https://stats.oecd.org/Index.aspx?datasetcode=HIGH_AGLINK_2019#
Land use by category	thousand ha	Food and Agriculture Organization of the United Nations (FAO), Statistics Division (ESS), Environment Statistics team	http://www.fao.org/faostat/en/#data/RL
Land cover by land cover class	thousand ha	Food and Agriculture Organization of the United Nations (FAO), Statistics Division (ESS), Environment Statistics team	http://www.fao.org/faostat/en/#data/RL
Fertilisers for agricultural use by nutrient (Nutrient nitrogen N (total), Nutrient phosphate P2O5 (total), Nutrient potash K2O (total))	tonnes	Food and Agriculture Organization of the United Nations (FAO), Statistics Division (ESS), Environment Statistics team	http://www.fao.org/faostat/en/#data/RL
Crop yield	tonnes/ha	Food and Agriculture Organization of the United Nations (FAO), Statistics Division (ESS), Environment Statistics team	http://www.fao.org/faostat/en/#data/RL
Crop production quantity	tonnes	Food and Agriculture Organization of the United Nations (FAO), Statistics Division (ESS), Environment Statistics team	http://www.fao.org/faostat/en/#data/RL
Crop yield change	%	Food and Agriculture Organization of the United Nations (FAO), Statistics Division (ESS), Environment Statistics team	http://www.fao.org/faostat/en/#data/RL
Crop production change	%	Food and Agriculture Organization of the United Nations (FAO), Statistics Division (ESS), Environment Statistics team	http://www.fao.org/faostat/en/#data/RL
Crop area harvested	ha	Food and Agriculture Organization of the United	http://www.fao.org/faostat/en/#data/RL

		Nations (FAO), Statistics Division (ESS), Environment Statistics team	
Food supply quantity	kg/capita	Food and Agriculture Organization of the United Nations (FAOSTAT)	http://www.fao.org/faostat/en/#data/FBSH
GDP (constant 2010)	US$	World Development Indicators	https://databank.worldbank.org/source/world-development-indicators
Water availability: Internal renewable water resources	10^9 m^3/year	FAO. 2016. AQUASTAT Main Database, Food and Agriculture Organization of the United Nations (FAO)	http://www.fao.org/nr/water/aquastat/data/query/index.html?lang=ev
Water resources: Total renewable water resources	10^9 m^3/year	FAO. 2016. AQUASTAT Main Database, Food and Agriculture Organization of the United Nations (FAO)	http://www.fao.org/nr/water/aquastat/data/query/index.html?lang=en
Water resources: Exploitable water resources	10^9 m^3/year	FAO. 2016. AQUASTAT Main Database, Food and Agriculture Organization of the United Nations (FAO)	http://www.fao.org/nr/water/aquastat/data/query/index.html?lang=en
Land cover map	ha	ESA CCI-LC	https://maps.elie.ucl.ac.be/CCI/viewer/index.php
Land cover map EU	ha	CORINE Land cover	https://land.copernicus.eu/pan-european/corine-land-cover
Water use by sector and source	10^9 m^3	WIOD Environmental accounts	http://www.wiod.org/database/eas13
Roundwood removals (production) for industrial roundwood and wood fuel	m^3	Food and Agriculture Organization of the United Nations (FAO), Global Forest Resources Assessment	http://www.fao.org/faostat/en/#data/FO
Forest growing stock	million m^3 over bark	Food and Agriculture Organization of the United Nations (FAO), Global Forest Resources Assessment	https://fra-data.fao.org/
Forest expansion and deforestation	tonnes/year	Food and Agriculture Organization of the United Nations (FAO), Global Forest Resources Assessment	https://fra-data.fao.org/
Forest area	thousand ha	Food and Agriculture Organization of the United Nations (FAO), Global Forest Resources Assessment	https://fra-data.fao.org/
Annual crop yield projections at grid level	tonnes/ha	Inter-Sectoral Impact Model Intercomparison Project Repository	https://data.isimip.org/search/page/4/query/yield/tree/ISIMIP2b%2FOutputData%2Fagriculture%2Flpjml%2Fhadgem2-es%2Frcp26/tree/ISIMIP2

			b%2FOutputData%2Fagriculture%2Flpjml%2Fhadgem2-es%2Frcp60/
Temperature data at grid level used in annual crop yield projections	0K	Inter-Sectoral Impact Model Intercomparison Project Repository	https://esg.pik-potsdam.de/search/isimip/
Total dam capacity	km^3	FAO. 2016. AQUASTAT Main Database, Food and Agriculture Organization of the United Nations (FAO)	http://www.fao.org/nr/water/aquastat/data/query/index.html?lang=en
Land cover by land cover class	thousand ha	Food and Agriculture Organization of the United Nations (FAO), Statistics Division (ESS), Environment Statistics team	http://www.fao.org/faostat/en/#data/RL
Forestry production	m^3	Food and Agriculture Organization of the United Nations (FAOSTAT)	https://www.fao.org/faostat/en/#data/FO
Crop production by crop and crop group	tonnes	Food and Agriculture Organization of the United Nations (FAOSTAT)	https://www.fao.org/faostat/en/#data/QCL
Wood residues	m^3	Food and Agriculture Organization of the United Nations (FAOSTAT)	https://www.fao.org/faostat/en/#data/FO
Wood residues	tonnes	Food and Agriculture Organization of the United Nations (FAOSTAT)	https://www.fao.org/faostat/en/#data/FO
Forestry production	tonnes	Food and Agriculture Organization of the United Nations (FAOSTAT)	https://www.fao.org/faostat/en/#data/FO
Residential consumption of primary solid biofuels	TJ	International Energy Agency (IEA)	https://www.oecd-ilibrary.org/energy/data/iea-world-energy-statistics-and-balances_enestats-data-en
Crops and other commodities by use (food, feed, biofuel use, other use)	thousand tonnes	OECD-FAO Agricultural Outlook 2021-2030	https://www.oecd-ilibrary.org/agriculture-and-food/oecd-fao-agricultural-outlook-2021-2030_19428846-en
Crops and other commodities by use (food, feed, biofuel use, other use)	%	OECD-FAO Agricultural Outlook 2021-2030	https://www.oecd-ilibrary.org/agriculture-and-food/oecd-fao-agricultural-outlook-2021-2030_19428846-en
Global use of major commodities	%	OECD-FAO Agricultural Outlook 2021-2030	https://www.oecd-ilibrary.org/agriculture-and-food/oecd-fao-agricultural-outlook-2021-2030_19428846-en

Biofuels by feedstock - Biodiesel	%	OECD-FAO Agricultural Outlook 2021-2030	https://www.oecd-ilibrary.org/agriculture-and-food/oecd-fao-agricultural-outlook-2021-2030_19428846-en
Biofuels by feedstock - Ethanol	%	OECD-FAO Agricultural Outlook 2021-2030	https://www.oecd-ilibrary.org/agriculture-and-food/oecd-fao-agricultural-outlook-2021-2030_19428846-en
Biofuels by feedstock - Biodiesel	million lt	OECD-FAO Agricultural Outlook 2021-2030	https://www.oecd-ilibrary.org/agriculture-and-food/oecd-fao-agricultural-outlook-2021-2030_19428846-en
Biofuels by feedstock - Ethanol	million lt	OECD-FAO Agricultural Outlook 2021-2030	https://www.oecd-ilibrary.org/agriculture-and-food/oecd-fao-agricultural-outlook-2021-2030_19428846-en
Biofuel production ranking and major feedstocks	%	OECD-FAO Agricultural Outlook 2021-2030	https://www.oecd-ilibrary.org/sites/4777cb60-en/index.html?itemId=/content/component/4777cb60-en#section-d1e2169
Land use indicators	%	Food and Agriculture Organization of the United Nations (FAOSTAT)	https://www.fao.org/faostat/en/#data/EL
Annual afforestation	thousand ha/year	Food and Agriculture Organization of the United Nations (FAO), Global Forest Resources Assessment	https://fra-data.fao.org/
Agricultural residues	tonnes	Food and Agriculture Organization of the United Nations (FAOSTAT)	https://www.fao.org/faostat/en/#data/QCL
Crop imports	tonnes	Food and Agriculture Organization of the United Nations (FAOSTAT)	https://www.fao.org/faostat/en/#data/QCL
Crop exports	tonnes	Food and Agriculture Organization of the United Nations (FAOSTAT)	https://www.fao.org/faostat/en/#data/QCL
Crop balances	thousand tonnes	OECD-FAO Agricultural Outlook 2021-2030	https://stats.oecd.org/viewhtml.aspx?datasetcode=HIGH_AGLINK_2021&lang=en#
Area harvested by crop and crop group	ha	Food and Agriculture Organization of the United Nations (FAOSTAT)	https://www.fao.org/faostat/en/#data/LC

Crop yield by crop and crop group	tonnes/ha	Food and Agriculture Organization of the United Nations (FAOSTAT)	https://www.fao.org/faostat/en/#data/LC
Land area under organic agriculture by category (agriculture area, cropland area, land under permanent meadows and pastures)	thousand ha	Food and Agriculture Organization of the United Nations (FAOSTAT)	https://www.fao.org/faostat/en/#data/LC
Crop production breakdown in irrigated and rainfed - % of total grain production irrigated	%	AQUASTAT - FAO's Global Information System on Water and Agriculture	https://tableau.apps.fao.org/views/ReviewDashboard-v1/country_dashboard?%3Aembed=y&%3AisGuestRedirectFromVizportal=y
Crop production breakdown in irrigated and rainfed - Ratio between rainfed and irrigated yields	ratio	AQUASTAT - FAO's Global Information System on Water and Agriculture	https://tableau.apps.fao.org/views/ReviewDashboard-v1/country_dashboard?%3Aembed=y&%3AisGuestRedirectFromVizportal=y
Water use - Total water withdrawal	10^9 m^3/year	AQUASTAT - FAO's Global Information System on Water and Agriculture	https://tableau.apps.fao.org/views/ReviewDashboard-v1/country_dashboard?%3Aembed=y&%3AisGuestRedirectFromVizportal=y
Forest Biomass	tonnes	Food and Agriculture Organization of the United Nations (FAO), Global Forest Resources Assessment	https://fra-data.fao.org/
Forest Carbon	tonnes/ha	Food and Agriculture Organization of the United Nations (FAO), Global Forest Resources Assessment	https://fra-data.fao.org/
Wood fuel consumption	m^3	Food and Agriculture Organization of the United Nations (FAOSTAT)	https://www.fao.org/faostat/en/#data/FO
Total roundwood consumption	tonnes	Food and Agriculture Organization of the United Nations (FAOSTAT)	https://www.fao.org/faostat/en/#data/FO
Industrial roundwood consumption	tonnes	Food and Agriculture Organization of the United Nations (FAOSTAT)	https://www.fao.org/faostat/en/#data/FO
Wood fuel consumption	tonnes	Food and Agriculture Organization of the United Nations (FAOSTAT)	https://www.fao.org/faostat/en/#data/FO
Living animals	Number of animals	Food and Agriculture Organization of the United Nations (FAOSTAT)	https://www.fao.org/faostat/en/#data/FO

Livestock primary products	tonnes/(types of animal*year)	Food and Agriculture Organization of the United Nations (FAOSTAT)	https://www.fao.org/faostat/en/#data/FO
Producing Animals	Number of animals	Food and Agriculture Organization of the United Nations (FAOSTAT)	https://www.fao.org/faostat/en/#data/FO
Fertilizers: nutrient nitrogen N (use per area of cropland)	tonnes/ha	Food and Agriculture Organization of the United Nations (FAOSTAT)	https://www.fao.org/faostat/en/#data/FO

Appendix C. Policies of WILIAM-TERRA

Table C1. Policies applied in the WILIAM-TERRA model.

Policy Name	Brief description	Submodule Name
Protection of Primary Forest	If this policy is applied, the primary forest is protected, and its area does not fall below a certain value. If the policy switch =1, the protection starts in the policy initial year and ends in the policy final year. The policy objective is expressed as a share of the initial area of primary forest in 2015 (1 = means that an area equal to the primary forest in 2015 is protected, 0 = means that there are no limits to deforestation). If primary forest area in the policy initial year is lower than the policy objective times forest area in 2015, the area in the policy initial year is maintained.	Land Uses
Forest Plantation Growth	Policy of increase of forest plantations, this is the increase in single-species tree plantations. If policy switch=1 the policy is applied starting in policy initial year and ending in policy final year. The policy objective is achieved in policy final year and follows a lineal evolution. The policy objective is expressed as a percentage of the historical value of the area of forest plantations in 2015 (0 = 0%, means that there is no increase of plantations; 1 = 100%, means that the area planted equals plantations area in 2015).	Land Uses
Protection of Managed Forest	If this policy is applied, the managed forest is protected, and its area does not fall below a certain value. If policy switch =1, the protection starts in policy initial year and ends in policy final year. The policy objective is expressed as a share of the initial area of managed forest in 2015 (1 = means that an area equal to the managed forest in 2015 is protected, 0 = means that there are no limits to deforestation) .If managed forest area in policy initial year is lower than policy objective times forest area in 2015, the area in policy initial year is maintained.	Land Uses
Protection of Cropland	If this policy is applied, the cropland is protected, and its area does not fall below a certain value. It applies both to irrigated and rainfed cropland. If policy switch=1, the protection starts in policy initial year and ends in policy final year. The policy objective is expressed as a share of the initial area of cropland in 2015 (1 = means that an area equal to the cropland in 2015 is protected, 0 = means that there are no limits to loss) .If cropland area	Land Uses

	in policy initial year is lower than policy objective times cropland in 2015, the area in policy initial year is maintained.	
Protection of Grassland	If this policy is applied, the grassland (land under permanent meadows and pastures) is protected, and its area does not fall below a certain value. If policy switch=1, the protection starts in policy initial year and ends in policy final year. The policy objective is expressed as a share of the initial area of grassland in 2015 (1 = means that an area equal to the grassland in 2015 is protected, 0 = means that there are no limits to loss). If grassland area in policy initial year is lower than policy objective times grassland 2015, the area in policy initial year is maintained.	Land Uses
Protection of Natural Land	If this policy is applied, the land under the categories of SHRUBLAND and OTHER LAND is protected, and its area does not fall below a certain value. If policy switch=1, the protection starts in policy initial year and ends in policy final year. The policy objective is expressed as a share of the initial area of either shrubland or other land in 2015 (1 = means that an area equal to the one in 2015 is protected, 0 = means that there are no limits to loss).	Land Uses
Afforestation	Policy of increase of managed forest, this is an increase of the high-medium biodiversity forest (not the increase of tree plantations). If policy switch =1, the policy is applied starting in the policy initial year and ending in the policy final year. The policy objective is achieved in the final year and follows a lineal evolution. The objective is expressed as a percentage of the historical value of the area of managed forests in 2015 (0=0%, means that there is no increase of forests; 1=100%, means that the new area planted equals managed forest area in 2015). This policy competes with the rest of land uses; therefore, the policy objective area might not be achieved in the final year due to land use changes to other uses.	Land Uses
Change of Diet	If this policy is applied, the population starts a cultural-driven change of diet to the policy diets that starts in policy initial year and ends in policy final year. The policy objective is expressed as a share of the population that has adopted the policy diet in policy final year. The policy objective might vary between 0 and 1 (0 = means that there no dietary change, 1 = means that all the population adopts the policy diet). If policy switch=1 the policy is applied starting in policy initial year. The policy objective is achieved in policy final year and follows a lineal evolution. This policy offers the possibility to choose between three options of objective diets: Flexitarian, 50% plant-based, and 100% plant-based.	Diets and Land Products Demand

From Traditional to Industrial Agriculture	This policy consists of transitioning from traditional to industrial agriculture, with an objective that varies from 0 to 1 (0 = no change, 1 = complete transition from traditional to industrial agriculture)	Crops and Yields
Change to Regenerative Agriculture	This policy consists of transitioning to regenerative agriculture, with an objective that varies from 0 to 1 (0 = no change, 1 = complete transition to regenerative agriculture)	Crops and Yields
Soil management in grasslands	If this policy is applied, there is a change in extensive grazing techniques towards advanced ecological methods based on soil restoration with high carbon capture such as Voisin Rational Grazing or Holistic management. The change starts in policy initial year and ends in policy final year. The policy objective is expressed as a share of the pastures that have adopted the policy in its final year. And the policy objective might vary between 0 and 1 (0 = means that there no change, 1 = means that all the grasslands adopt the policy). If policy switch=1, the policy is applied starting in policy initial year. The policy objective is achieved in policy final year and follows a lineal evolution. The land that starts this transformation suffers a delay of saturation time of regenerative grasslands, years before it gets saturated, and no more carbon is captured in grazing soils.	Grassland
Forestry self sufficiency	If this policy is applied, there is a change in the allocation of the demand of forestry product to producing regions. The change starts in policy initial year and ends in policy final year. The policy objective is expressed as a share of the demand of each region that is fulfilled with the production of its own forests in policy final year. The policy objective might vary between 0 and 1 (1 = means that the regions produce all the roundwood it demands; 0 = means that historical trends of distribution are maintained). If policy switch=1 the policy is applied starting in its initial year. The policy objective is achieved in policy final year and follows a lineal evolution.	Forests
Forest loss limit	If this policy is applied the biomass forest stock that can be loss per region is limited between initial and final time. If the policy switch =1, the protection starts in policy initial year and ends in policy final year. The policy objective is the minimum value of forest stock of biomass that must remain in the forest, expressed as a percent of the 2019 value.	
Forestry self sufficiency	If this policy is applied the regions reach the desired level of self sufficiency in their wood consumption. If the policy switch =1, the protection starts in policy initial year and ends in policy final year. The policy objective is expressed as a percent of the wood (both for energy and materials) that	

	would come from the same region instead of being distributed in the international pool. .	
Solar land from others	If this policy is applied, the share (or combination) of land use types from whom solar land is taken changes to the desired values. If the policy switch =1, the protection starts in policy initial year and ends in policy final year. The policy objective is expressed as a vector that tells us thee shares among land use types where the land for solar comes.	Land Uses
Policy of land use protection from solar PV	If this policy is applied, specific land use types are protected and not changed to "solar land". If the policy switch =1, the protection starts in policy initial year and ends in policy final year. The policy objective indicates for each land use type if it is protected from solar land deployment. It ranges from 0 to 1: if it takes the value of 1, the policy allows to deploy solar PV in that land use type, and if takes the value of 0 the policy protects that type of land use to with respect solar PV occupation.	Land Uses
Priorities of land products distribution among regions	This policy has a parameter named "PRIORITIES_LAND_PRODUCTS" that allows for deciding the priorities of land product distribution among regions. It governs the distribution of crops production to the demands of the consumers of each region. This distribution is not a model of the international market of agricultural products, it is a confrontation of the final demand of the consumers of each region to the agricultural production of each region. If all the values of policy parameter are the equal, the allocation of production to regions is proportional to each region's demands. If the priority of a region is greater, this region gets its demand fulfilled before than the rest in case there is shortage. Another parameter named "WIDTH_LAND_PRODUCTS" specifies how big a gap in priority is required to have the allocation go first to higher priority with only leftovers going to lower priority: the smaller this parameter is relative to priority, and the more severe the effect of the priorities.	Land Products Availability
Priorities of crops distribution among uses	This policy has a parameter named "PRIORITIES_CROPS" that decides the priorities of crops distribution among uses. It governs the distribution of crops production to the uses of food and energy (biofuels), and other uses are kept constant. If all the values of "PRIORITIES_CROPS" are the equal, the allocation of production to use is proportional to each use demand. If the priority of a use is greater, this use gets its demand fulfilled before than the rest in case there is shortage. Another parameter named "WIDTH_CROPS" specifies how big a gap in priority is required to have the allocation go first to higher priority with only leftovers going to lower priority: the smaller this	Land Products Availability

	parameter is relative to priority, and the more severe the effect of the priorities.	
Priorities of forestry products distribution among uses	This policy has a parameter named "PRIORITIES_WOOD" that decides the priorities of wood distribution among uses. It governs the distribution of wood production to the uses of industry and energy. If all the values of "PRIORITIES_WOOD" are the equal, the allocation of production to use is proportional to each use demand. If the priority of a use is greater, this use gets its demand fulfilled before than the rest in case there is shortage. Another parameter named "WIDTH_WOOD" specifies how big a gap in priority is required to have the allocation go first to higher priority with only leftovers going to lower priority: the smaller this parameter is relative to priority, and the more severe the effect of the priorities.	Land Products Availability
Land products global pool	This policy changes the shares of the agricultural production of each region that is not subject to international exchanges, either because is produced by very small farmers based on subsistence agriculture or because of autarchy policies of the regions. If the policy switch=1, this policy is applied, and the share of agriculture out of international exchanges changes. The change starts in policy initial year and ends in policy final year. The policy objective is expressed as a share of the agricultural products protected (0 = means that all of them are traded internationally, 1 = none). The policy objective is achieved in policy final year and follows a lineal evolution.	Land Products Availability
Effect oil and gas on agriculture	If this policy is applied, farmers are forced to cultivate without chemical inputs such as pesticides and fertilizers (because of high prices, for example), causing a dramatic drop in agricultural yields (in all croplands, those under industrial as well as under traditional management and irrigated as well as rainfed). The change starts in policy initial year and ends in policy final year. The policy objective is expressed as a share of the agricultural lands that have adopted the policy in policy final year. The policy objective might vary between 0 and 1 (0 = means that there no change, 1 = means that all the cropland adopts the policy). If policy switch=1, the policy is applied starting in policy initial year. The policy objective is achieved in policy final year and follows a lineal evolution.	Crops and Yields
Manure management system	If this policy is applied, policies based on new "manure management systems" are applied. It can be defined the different distribution or combination of manure system types (percentage) by animal (dairy cattle, other cattle, buffalo, and swine), and by WILIAM-TERRA region. The "less emissions" options are solid storage, dry lot, range/paddock, daily spread,	Emissions

	and Pit storage <1month. If this policy is not applied, past trends with respect manure systems (from IPCC) continue. The manure management system options are lagoon, liquid/slurry, solid storage, dry lot, pasture/range, daily spread, digester, burned for fuel, PIT, and other.	
Urban land density	If this policy is applied, the ratio of m2 of urban land area per person reaches the given target. If it is applied the urban_land_dispersion_ratio (m2 per person) starts changing to the chosen final density, until it reaches the objective, expressed in m2 of urban land per person.	Land Uses

Appendix D. Diet evolution

In this appendix, some data relative to present diet and to the diets used as policy is presented.

Present diet

The data of historical demand of food for the year 2019 obtained from the FAO database [1] is shown in Table D1.

Table D1: Diet (kg/person/year) in the year 2019 [1]

DIETS / REGIONS	EU27	UK	CHINA	EASOC	INDIA	LATAM	RUSSIA	USMCA	LROW
CEREALS	125.60	122.67	200.56	211.09	182.98	128.56	153.53	122.16	171.10
TUBERS	61.49	86.04	69.08	37.35	29.03	66.65	89.70	47.29	94.04
PULSES_LEGUMES_NUTS	9.13	6.98	14.93	15.87	22.99	20.39	4.11	14.03	15.70
FRUITS_VEGETABLES	194.01	163.63	462.74	148.35	143.39	167.16	165.74	201.95	151.45
FATS_VEGETAL	18.20	13.73	8.54	12.05	8.36	17.28	16.37	18.10	9.97
FATS_ANIMAL	1.85	1.30	1.73	1.28	0.03	1.83	0.65	1.34	0.50
DAIRY	199.71	205.04	22.73	20.78	64.77	137.92	151.51	189.86	54.45
EGGS	13.05	11.25	20.02	12.24	2.85	9.75	16.62	16.77	4.26
MEAT_RUMINANTS	15.51	22.27	8.68	6.87	1.53	34.50	14.56	31.24	10.19
MEAT_MONOGASTRIC	67.09	60.48	57.06	34.52	3.12	52.84	66.20	75.74	15.99
FISH	23.62	19.52	50.96	42.30	6.48	10.44	21.73	20.41	10.89
SUGARS	33.90	33.71	6.82	31.79	34.24	52.22	35.92	34.87	23.76
BEVERAGES	99.24	96.75	44.52	24.92	1.86	65.53	69.63	85.34	20.32
STIMULANTS	5.39	4.34	1.18	2.02	0.78	5.11	3.28	3.97	1.41

Flexitarian policy diet:

The flexitarian diet (see Table D2) is the outcome of the Lancet-EAT Commission in the year 2019, which is primarily based on plant-based foods[2]. It is one example of a planetary health diet with a daily intake of 2500 kcal per day [3]. The highlighted foods include fruits and vegetables, legumes, cereals, and nuts, with moderate consumption of red meat and starchy vegetables recommended, and optionally including moderate amounts of meat, fish, and dairy products. By making these dietary changes, an estimated 11 million deaths per year could be prevented according to [2]. This diet has been adapted to WILIAM-TERRA food groups, as shown in Table D3. Figure D1 compares this diet with the present average diet of EU27 and India inhabitants in some of its items.

Table D2: Flexitarian Diet, result of the EAT-Lancet Commission in the year 2019.

Group of aliments	Description	Consumption per day (g/person/day)	kcal/day
Whole Grains	Rice, wheat, corn, and others	232	811
Starchy Vegetables or Tubers	Potatoes and cassava	50	39
Vegetables	In general, and seasonal ones in particular	300	78
Fruits	In general, and seasonal ones in particular	200	126
Dairy Products	Milk	250	153
Proteins	Fish	28	40
	Eggs	13	19
	Lean meats and poultry	29	62
	Pulse	75	284
	Nuts	50	291
	Beef, Lamb, and pork	14	30
Added Fats	Unsaturated oils	40	354
	Saturated oils	11.8	96
Added Sugars	All kinds of sugars	31	120
Total			2503

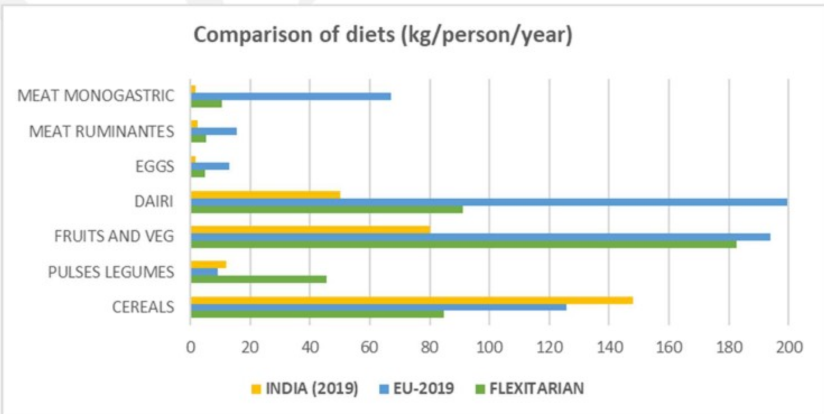

Figure D1. Comparison of present average diet in EU and India with the target diet used (Flexitarian).

Table D3: Categorization of the Flexitarian diet in the WILIAM-TERRA module.

DIETS / REGIONS	EU27	Consumption per day (g/person)	Consumption per year (kg/person/year)	Consumption per day (kcal/day/person)
CEREALS	Barley and products, Oats, Rye and products, Wheat and products, Millet and products, Sorghum and products, Maize and products, Rice and Products	232	85.77	811
TUBERS	Starchy roots	50	18.25	39
PULSES_LEGUMES_NUTS	Pulses, Groundnuts (shelled eq.), Soyabeans	100	36.50	426
FRUITS_VEGETABLES	Fruits excluding wine, vegetables	500	182.50	152
FATS_VEGETAL	Vegetable oils	47	17.15	414
FATS_ANIMAL	Fats, animal, raw	5	1.82	36
DAIRY	Milk excluding butter, Butter ghee	250	91.25	153
EGGS	Eggs	13	4.74	19
MEAT_RUMINANTS	Bovine meat, Mutton & Goat meat	7	2.55	15
MEAT_MONOGASTRIC	Pigmeat, Poultry	36	13.14	15
FISH	Fish, seafood	28	10.22	40
SUGARS	Sweeteners	31	11.31	120
BEVERAGES				
STIMULANTS				
Total				2240

50% and 100% plant-based policy diets:

In the plant-based 50% diet scenario, 50% of animal-source foods is replaced with legumes, fruits, and vegetables. The replacement assumes that 75% of the added plant-based foods are legumes, while 25% are fruits and vegetables (12.5% fruits, 12.5% vegetables). To determine the quantities of fruits, vegetables, and legumes to add when reducing animal-source foods, the kilograms are converted to calories and then back to kilograms to maintain constant calorie intake.

The following steps have been followed to determine how much fruits, vegetables, and legumes to add when reduce animal-source foods used:

1. Add calories per kg of the food groups from Table 8 in Supplementary Materials of the paper by Springmann et al. [4] (row 5 in EU).
2. Divide the kg of animal source food groups in the baseline scenario by 2 to determine the amount of animal source foods in the new 50% scenario (row 4 in EU). In the 100% plant-based scenario, they are reduced to 0.
3. In order to determine how many calories are taken away by those changes (and thus need to be replace), the number obtained in step 2 is multiplied by the kcal/kg of that food group (row 6 in EU). In the 100% plant-based scenario, this number is multiplied by the kg number in the baseline scenario instead.
4. Add all calorie contents together from the animal source foods that had been taken away to calculate the column total kcal animal difference. This is how much kcal in total is taken away from the diet and needs to be replaced by plant-based foods (row 7 in EU).
5. Following the replacement rule (that the animal source food is replaced by 75% legumes, 12.5% fruits, and 12.5% vegetables), this is multiplied by 0.75 (row 8 in EU) and 0.125 (row 9 in EU).
6. Divided these numbers by the calorie content per kg (legumes: 3500, fruits: 600, vegetables: 260). This gave the kg to be added to the new diet (row 10 in EU).
7. Finally, add the new kg of legumes to the baseline kg of legumes, and the new kg of fruits and vegetables to the baseline kg of fruits and vegetables (row 11 in EU).

The resulting diets are shown in tables D3, D4 and D5.

Table D4: Categorization of the 50% plant-based diet in the WILIAM-TERRA module (kg/year/person).

DIETS / REGIONS	EU27	UK	CHINA	EASTOC	INDIA	LATAM	RUSSIA	USMCA	LROW
CEREALS	126.39	115.68	149.41	158.02	148.46	114.90	147.90	119.00	143.90
TUBERS	69.76	104.05	67.36	37.70	30.79	63.50	113.27	47.40	81.70
PULSES_LEGUMES_NUTS	52.49	46.71	39.45	26.74	23.96	44.57	38.58	54.81	24.40
FRUITS_VEGETABLES	353.81	349.92	529.86	207.73	168.37	249.67	298.01	339.28	178.96
FATS_VEGETAL	19.59	17.43	7.46	10.18	8.67	15.50	13.75	25.03	9.47
FATS_ANIMAL	2.41	1.27	0.96	0.57	0.02	1.21	1.60	1.57	0.34
DAIRY	120.09	117.74	16.84	17.39	43.77	70.56	83.08	107.66	35.58
EGGS	6.02	5.54	9.31	4.30	1.29	4.79	7.72	7.70	2.02
MEAT_RUMINANTS	8.53	11.31	4.21	3.60	0.70	17.35	9.19	15.55	4.85
MEAT_MONOGASTRIC	32.15	29.44	26.94	14.98	1.15	24.95	28.22	34.42	7.01
FISH	11.29	10.38	17.43	17.52	2.52	5.43	11.47	9.40	5.16
SUGARS	39.60	41.28	7.53	24.24	23.43	44.40	49.02	58.70	19.80
BEVERAGES	96.20	93.14	44.69	25.57	2.02	65.60	79.80	82.80	23.30
STIMULANTS	7.50	7.80	1.35	2.98	0.81	5.50	4.41	6.00	0.54

Table D5: Categorization of the 100% plant-based diet in the WILIAM-TERRA module (kg/year/person).

DIETS / REGIONS	EU27	UK	CHINA	EASTOC	INDIA	LATAM	RUSSIA	USMCA	LROW
CEREALS	126.39	115.68	149.41	158.02	148.46	114.90	147.90	119.00	143.90

TUBERS	69.76	104.05	67.36	37.70	30.79	63.50	113.27	47.40	81.70
PULSES_LEGUMES_NUTS	96.27	85.75	67.17	44.57	31.21	74.27	73.67	96.11	35.98
FRUITS_VEGETABLES	494.60	475.45	619.02	265.07	191.69	345.17	410.83	472.10	216.19
FATS_VEGETAL	19.59	17.43	7.46	10.18	8.67	15.50	13.75	25.03	9.47
FATS_ANIMAL	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
DAIRY	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
EGGS	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
MEAT_RUMINANTS	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
MEAT_MONOGASTRIC	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
FISH	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
SUGARS	39.60	41.28	7.53	24.24	23.43	44.24	49.02	58.70	19.80
BEVERAGES	96.20	93.14	44.69	25.57	2.02	65.60	79.80	82.80	23.30
STIMULANTS	7.50	7.80	1.35	2.98	0.81	5.50	4.41	6.00	0.54

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Appendix E. Description and Equations of the WILIAM-TERRA Model

This appendix provides a detailed description of specific WILIAM-TERRA submodules and the key equations used.

The WILIAM-TERRA model works vectorially with the following categories:

- 9 regions (R_i): EU27, UK, CHINA, EASOC, INDIA, LATAM, RUSSIA, USMCA, and LROW.
- 14 food categories (F_j): cereals, tubers, pulses legumes and nuts, fruits and vegetables, vegetal fats, animal fats, dairy, eggs, meat from ruminants, meat from monogastric, fish, sugars, beverages, and stimulants.
- 12 land-use categories (L_n and L_m): rainfed cropland, irrigated cropland, managed forest, primary forest, forest plantations, shrubland, grassland, wetland, urban land, land for solar energy, snow ice and waterbodies, and other land.
- 13 land product categories (Lp_k), that include 11 crops: corn, rice, rest of cereals, tubers, soy, pulses and nuts, oil crops, sugar crops, fruits and vegetables, crops for cellulosic biofuels, other crops; and 2 other products: wood, and residues used for energy. The first 11 are also referred to as *crops* in the model.
- 8 nutritional assessment categories: calories, proteins, carbohydrate, fiber, fats, SFA, MUFA, and PUFA fats.
- 7 types of animals (for emissions): dairy cattle, other cattle, buffalo, goat, sheep, chickens, and swine.

E1. Land Uses submodule

Figure E1 shows the simplified Forester diagram of the Land Uses submodule. This submodule is responsible for allocating the land among 12 uses (see Appendix A for thethe methodology and sources). The demands of all uses are included in a vector called *Vector of land use change demand*, which is generated by adding two components:

- Historical trends of land-use changes, estimated using lineal approximations over the period from 2005 to 2019 (Source FAO).
- Land-use changes driven by various demands, including the need for additional land due to population growth (connected to the WILIAM Demography module and policies

related to urban density evolution), the expansion of land for solar energy (connected to the WILIAM Energy module), the demand for land for reforestation and the establishment of new forest plantations (driven by policies), and the need for new croplands based on the gap of the global availability of crops (calculated within the Land Products Availability submodule).

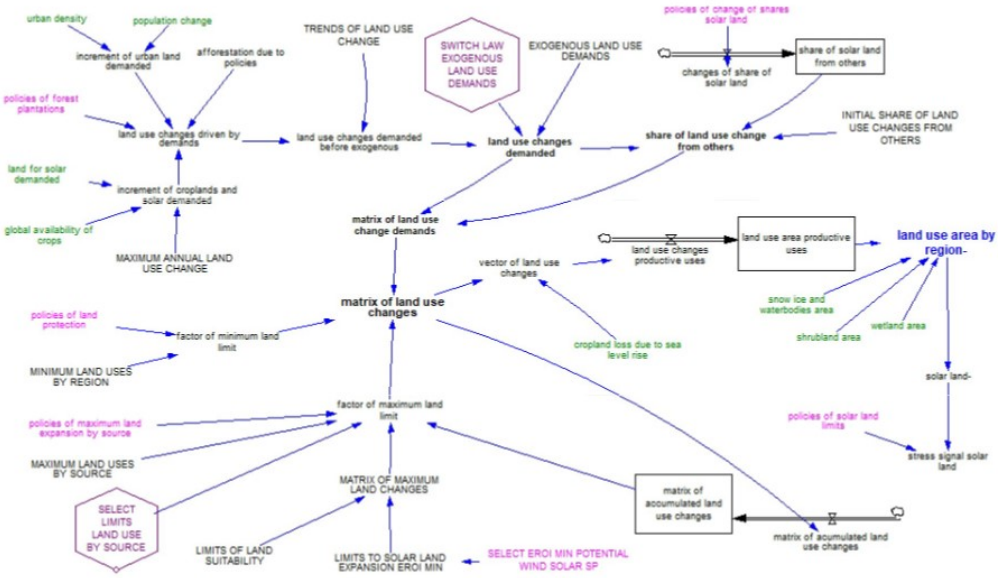

Figure E1. Simplified diagram of the Land Uses submodule; Green colour: variables from other WILIAM modules; Blue colour: principal outputs of the submodule; Purple Hexagon-shape: to (de)activate (sub)module/link switches, allowing the (sub)module to run in isolation or with disconnected links; Pink colour: policy variables.

The expansion of land-uses must be obtained from other land-uses to ensure the physical coherence of the land allocation. This is specified in the matrix of land-use change demands (see Eq. 1), which describes the demand for changes from land use L_n to another land use L_m:

$$Matrix\ of\ LUC\ Demands\ (R_i, L_n, L_m) = Share\ of\ LUC\ from\ Others\ (R_i, L_n, L_m) \cdot LUC\ Demands\ (R_i, L_m) \quad (1)$$

Where $LUC\ Demands\ (R_i, L_n)$, represents the vector of land-use change demand by region and land type; $Share\ of\ LUC\ from\ Others\ (R_i, L_n, L_m)$ represents the share of land-use L_m that is obtained from use L_n. The $Share\ of\ LUC\ from\ Others\ (R_i, L_n, L_m)$ consists of constant matrices based on the literature review described in the work of Campano Méndez, M. [1] and is calibrated with historical land-use data (see Appendix G for a detailed explanation).

For solar land, the initial shares have been obtained using Geographic Information Systems (GIS) techniques analyzing the allocation of existing solar power capacity. This analysis has been conducted for each of the nine regions in the WILIAM-TERRA model and is based on data from the "Global Database of Power Plants", combined with land cover data from Globcover Portal [2] (see [2] for a complete description).

The land-use changes demanded may not be fully implemented if land-use protection policies are activated. $Matrix\ of\ LUC\ Demands\ (R_i, L_n, L_m)$ is transformed into a $Matrix\ of\ LUC\ changes\ (R_i, L_n, L_m)$ where land-use changes that are incompatible with physical constraints or policy-imposed restrictions are excluded.

There are two types of limits on land-use changes:

- Changes from use L_n to use L_m that are impossible because use L_n cannot lose any more area (e.g., its area reaches zero or is protected by policies, such as forests protection),
- Changes from use L_n to use L_m that are impossible because use L_n cannot be transformed into use L_m (e.g., no remaining grassland with soil quality suitable for conversion into cropland).

The WILIAM-TERRA model allows for the implementation of land protection policies (first type) for primary and managed forests, grasslands, croplands, and a general natural land protection policy that safeguards shrublands and bare areas. All these policies can be activated by the user.

The limits on land-use changes due to suitability (second type) are determined by integrating the elements of the matrix of land-use changes into a stock of accumulated land-use changes, which is then compared with a matrix of land suitability limits. Currently, only some values in this suitability matrix have been obtained with sufficient precision to be used in the model as reliable physical constraints on land-use expansion, except for solar land.

Another way to set limits on land expansion Is through the variable *Select limits land use by source.* This variable allows the user to define land expansion limits based either on the matrix of land suitability limits or on a constraint that restricts the expansion from use L_n to use L_m proportionally to the initial value of use L_n, as specified in the parameter *Maximum land uses by source*. Currently, this method is applied only to cropland expansion.

The $Matrix\ of\ LUC\ changes\ (R_i, L_n, L_m)$ is collapsed into a $Vector\ of\ LUC\ changes\ (R_i, L_n, L_m)$ by summing the land-use changes allocated to each use and subtracting the changes that demand from it:

$$vector\ LUC\ (R_i, L_m) = \sum_n matrix\ LUC(R_i, L_n, L_m) - \sum_n matrix\ LUC(R_i, L_m, L_n) \quad (2)$$

The loss of agricultural land due to sea level rise is subtracted to this vector. This loss is determined in our model by adapting the method reported by Roson & Sartori [3] to the WILIAM-TERRA regions and is driven by the temperature change received from the WILIAM Climate module.

Finally, the $Land\ use\ area\ by\ region\ (R_i, L_m)$ is calculated as the integral of the $vector\ LUC\ (R_i, L_m)$, however, the model only integrates certain uses into the stock of $Land\ use\ area\ productive\ uses\ (R_i, L_m)$ and excludes wetlands, snow, ice, waterbodies, and shrubland areas. These land-uses are not calculated via the $vector\ LUC\ (R_i, L_m)$ because they are not directly driven by the policies of the rest of the model and, at present stage, are kept constant.

The Land Uses submodule is fundamentally based on maintaining trends in land evolution while incorporating policies related to demand and land protection. The competition for land among different uses follows a “all against all” dynamic, where all uses have the same priority when demanding land from others, However, land for solar energy and cropland have specific parameters that allow their use to be prioritized over the rest.

Some IAMs use functions to guide land-use changes based on the relative profitability of different uses (e.g., GCAM, GLOBIOM). For example, the GLOBIOM model at a grid scale of 10x10 degrees, and comparing land-use cost-effectiveness for changes in adjacent areas. In contrast, the WILIAM-TERRA model, operates at a much larger spatial scale, working with nine large regions Given this level of aggregation, *we do not believe that reliable prices can be found to calibrate these exchanges at this level of aggregation*. Therefore, the Land Uses submodule is primarily based on the continuation of observed trends, which can be modified through the application of policies (see Appendix G for a description of the calibration of the Land Uses submodule).

The WILIAM-TERRA model is mainly based on land-use data from FAOSTAT, supplemented with land cover data from the MapSpam database [4], trying to maintain the consistency of these sources by giving priority to FAO data (see Appendix A for more details). A significant discrepancy has been found between land-use and land cover data from different sources (as noted by other authors, such as Tubiello et *al.* [5]) and many discrepancies in data have been encountered when trying to disaggregate the data to the level of AEZ agroecological zones while maintaining data consistency. Therefore, we have opted for aggregation into 9 world regions, although do not exclude using a greater disaggregation in the future if sufficiently robust data sources become available.

At current stage of development, some approximate limits to cropland and forest expansion have been calculated based on a literature survey. The limits to cropland expansion set by the variable *Maximum land uses by source* (when the option *Select limits land use by source* is activated) are established based on a combination of the data from Bot et al. [16] and Lambin et al. [17]. Bot's data on potential arable land for the WILIAM regions is shown in Figure E1. The maximum percentage of cropland expansion relative to the data from 2019 is shown in Table E1.

Table E1. Actual and potential cropland expansion according to [16] and [17]

	total area (km2)	actual arable (km2)	potencial arable (km2)	% potential land relative to 2019	% increse relative to world	realistic increase (km2)	% realistic increase relative to actual cropland
EU27	4,166,170	1,123,670	2,641,730	135%	6.40%	341,969	131%
UK	244,180	59,890	156,590	161%	0.38%	21,783	136%
CHINA	9,349,490	957,820	2,016,470	111%	4.89%	238,479	118%
EASOC	11,624,620	1,618,240	2,962,310	83%	7.18%	302,774	121%
INDIA	3,061,400	1,696,500	2,063,270	22%	5.00%	82,621	105%
LATAM	13,258,360	882,300	7,101,420	705%	17.21%	1,400,961	222%
RUSSIA	16,741,460	1,233,020	2,825,690	129%	6.85%	358,776	129%
USMCA	21,213,030	2,580,060	5,317,940	106%	12.88%	616,753	128%
LROW	51,848,780	4,577,090	16,189,470	254%	39.22%	2,615,884	150%
world	131,507,490	14,728,590	41,274,890	180%	100.00%	5,980,000	138%

This estimate of Bot et al. [16] reaches an increase of 26 million km^2, which is criticized in [17], arguing that those high estimates are not realistic, since there are strong constraints that can only be observed when bottom-up analysis, such as the one described in [17], are conducted. Lambin et al. [17] estimate a maximum potential of 5.98 million km^2 for total world cropland expansion. Unfortunately, this bottom-up analysis is only performed for some regions in [17], but assuming Lambin's total estimate of 5.98 million km^2 is correct and dividing it among world regions as Bot et al. [16] assumed, one arrives at the potentials shown in columns 6 and 7 of Table E1. These are the approximate values to cropland expansion used in current version of the WILIAM-TERRA model.

E2. CROPS AND YIELDS SUBMODULE

Figure E2 presents a simplified Forrester diagram of the Crops and Yields submodule. Agricultural production in WILIAM-TERRA is determined within the Crops and Yields submodule. This production can be calculated using different yields for irrigated and rainfed crops or by combining both irrigated and rainfed yields. Mixed yields are obtained from the FAO database, which does not separate irrigated and rainfed production, while separated yields are obtained by combining data from the FAO and MapSpam databases [4], which estimate yields under four farming systems (irrigated, rainfed high-input, rainfed low-input and subsistence farming system) at a global 5 arc-minute grid [6].

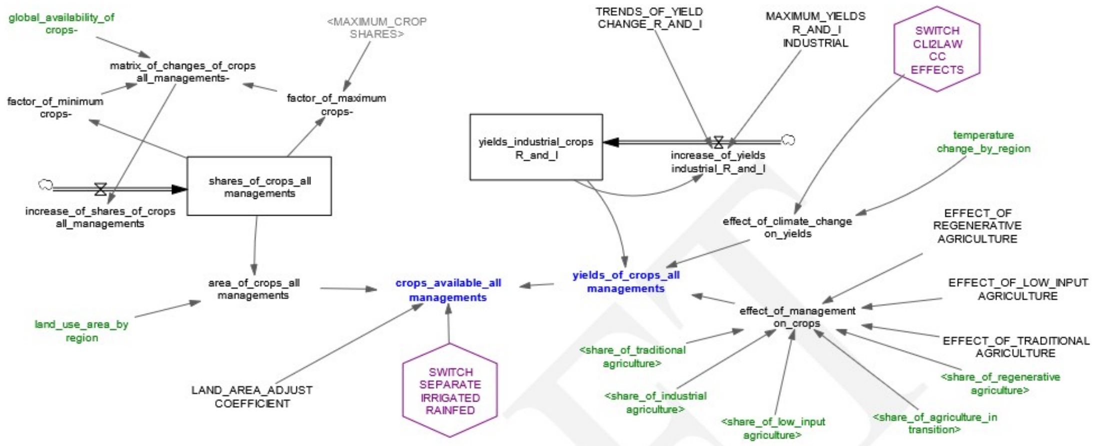

Figure E2. Simplified diagram of the Crops and Yields submodule; Green colour: variables from other WILIAM modules; Blue colour: principal outputs of the submodule; Purple Hexagon-shape: to (de)activate (sub)module/link switches which, allowing the (sub)module to run in an isolation or with disconnected links.

In the current version of the WILIAM-TERRA model, mixed yields, based solely on FAO data, are recommended due to lower confidence on the calculation of separated yields for irrigated and rainfed crops. The MapSpam data is provided only for two years and shows inconsistencies with the rest of the model's data (mainly from FAO), which will hopefully be resolved in future versions of the model.

If mixed irrigated and rainfed crops are used, the area assigned to each crop, $Area\ crop_{all}\ (R_i, Lp_k)$, is calculated by multiplying the sum of rainfed cropland area, $Area_{rainfed}\ (R_i)$, and the irrigated cropland area, $Area_{irrigated}\ (R_i)$, by a variable called *Shares of Crops All Managements,* $SHCrops_{all}\ (R_i, Lp_k)$:

$$Area\ crop_{all}\ (R_i, Lp_k) = SHCrops_{all}\ (R_i, Lp_k)\left(Area_{irrigated}\ (R_i) + Area_{rainfed}\ (R_i)\right) \quad (3)$$

The $SHCrops_{all}\ (R_i, Lp_k)$ are adapted to the relative demand of each crop (or land product) Lp_k by a mechanism of many-to-many allocation that adjusts the shares of each crop based on the relative Global Availably of Crops:

$$Global\ Availability\ Crops\ (\ Lp_k) = \frac{\sum_{R_i} crops\ available\ (R_i, Lp_k)}{\sum_{R_i} crops\ demanded\ (R_i, Lp_k)} \quad (4)$$

The changes in the dynamic shares of crops are driven by the *Global Availability of Crops* and assign more land to the crops that have less availability. It is assumed that the global shortage of crops affects all the regions in similar terms, although this hypothesis might be changed with minimal changes in the model. These dynamic shares create a balancing feedback loop that adjusts crop demand and crop production as long as there is enough cropland available. At present stage, the change in crop shares is driven solely by the relative availability of each crop, which tends to adjust demand and production of all the crops in an equal way. However, priorities based on the profitability of each crop might be included in the framework of dynamic shares.

Crop production is calculated by multiplying the area of each crop in each region by the yield (by crop and region) and the parameter LAND_AREA_ADJUST_COEFFICIENT (R_i), which adjusts production per year to production per area by considering fallow area and multiple crops per year using the FAO average data per region.

The WILIAM-TERRA model incorporates various agricultural management practices when calculating agricultural yields. These practices include industrial agriculture, traditional agriculture, low-input agriculture, regenerative agriculture, and transitional agriculture.
These are the reasons why WILIAM-TERRA model includes the share of five types of agricultural management:

- Share of industrial agriculture, $SH\_Ag_{industrial}\ (R_i, Lp_k)$: High-input agricultural techniques based on the extensive use of machinery and fossil fuel-based inputs. Data on the share of agriculture for each crop and region under this regime is taken from MapSpam [4].
- Share of traditional agriculture, $SH\_Ag_{traditional}\ (R_i, Lp_k)$: Low-input agricultural techniques based on extensive use of hand labour and farming oriented toward subsistence. Data on this share is obtained from MapSpam [4], which includes the categories referred to in MapSpam as “low input” and “subsistence” agriculture (do not confuse MapSpam “low input” with the low-input agriculture in the WILIAM-TERRA model).
- The share of low-input agriculture, $SH\_Ag_{low}\ (R_i, Lp_k)$, models the low-input agriculture that would result from the eventual lack of fertilizers due to rising oil and gas prices that would force farmers to produce without chemical inputs but before any advanced ecological techniques are applied to restore fertility through biological means.
- The share of regenerative agriculture, $SH\_Ag_{regen}\ (R_i, Lp_k)$, models agriculture that uses advanced ecological techniques to improve agricultural yields without the use of gas and oil-based chemical compounds.

- The share of agriculture in transition, $SH\_Ag_{transition}\,(R_i, Lp_k)$, takes into account the fact that regenerative agriculture requires long transition times before it is able to achieve high yields. It describes the share of agriculture that has started the transition to regenerative practices but has not completed the transition period.

The combined yields for all types of management are calculated by taking the yields of industrial agriculture as a reference and calculating the effect of each management type relative to industrial agriculture:

$$Y_{traditional}(R_i, Lp_k) = \gamma_{traditional}(R_i, Lp_k) \cdot Y_{industrial}(R_i, Lp_k) \quad (5)$$

$$Y_{low}(R_i, Lp_k) = \gamma_{low}(R_i, Lp_k) \cdot Y_{industrial}(R_i, Lp_k) \quad (6)$$

$$Y_{regen}(R_i, Lp_k) = \gamma_{regen}(R_i, Lp_k) \cdot Y_{industrial}(R_i, Lp_k) \quad (7)$$

$$Y_{transition}(R_i, Lp_k) = \gamma_{transition}(R_i, Lp_k) \cdot Y_{industrial}(R_i, Lp_k) \quad (8)$$

Where $Y_{industrial}(R_i, Lp_k)$, $Y_{traditional}(R_i, Lp_k)$, $Y_{low}(R_i, Lp_k)$, $Y_{regen}(R_i, Lp_k)$, and $Y_{transition}(R_i, Lp_k)$ are the agricultural yields for industrial, traditional, low yield, regenerative, and transition managements, respectively. The γ factors are calculated using historical data from the MapSpam yield data under traditional and industrial management, assuming that the low input and transition yields are similar to the traditional ones.

Regenerative management reaches a percentage of industrial yields that ranges between 90% and 70% of industrial agriculture, depending on the scenarios and hypotheses assumed:

$$\gamma_{traditional}(R_i, Lp_k) = \frac{Y^{hist}_{traditional}(R_i, Lp_k)}{Y^{his}_{industrial}(R_i, Lp_k)} \quad (9)$$

$$\gamma_{low}(R_i, Lp_k) = \gamma_{traditional}(R_i, Lp_k) = \gamma_{transition}(R_i, Lp_k) \quad (10)$$

Table E2 presents the relative yield values of industrial (high-input) and traditional management for several crops obtained from MapSpam data for various agroecological zones (AEZ). The yields of industrial agriculture have been rising in most regions in recent decades, although in some regions, such as the EU, the trend is unclear in recent years, and the variability is too high to observe clear trends. The WILIAM-TERRA model enables yields to evolve according to linear trends from past years, and subject to future limits.

The trends of soil degradation due to processes of desertification and inappropriate agricultural practices have been increasing to very alarming rates, as stated by [7, 8]. According to [7], the soil degradation might lead to a loss of agricultural production equivalent to 10% of the present production[1]. To mode this, we have introduced a variable called *Effect of soil degradation on yields ($F_{erosion}$)*, which varies from 1 in the initial time to 0.9 in 2050 and reduces the fertility of all crops and regions due to soil degradation.
The combined effects of all types of management on crops are determined by the following equations:

$$Y(R_i, Lp_k) = Y_{industrial}(R_i, Lp_k) \cdot Fcrops_{cc}(R_i, Lp_k) \cdot F_{management}(R_i, Lp_k) \cdot F_{erosion} \tag{11}$$

where $Fcrops_{cc}(R_i, Lp_k)$ is the factor representing the effects of climate change on the agricultural yields, calculated based on the work of Waldhoff et. *al.* [9]. The $F_{management}(R_i, Lp_k)$ is expressed as follows:

$$\begin{aligned} F_{management}(R_i, Lp_k) = 1 \cdot SH_{Ag_{industrial}}(R_i, Lp_k) + \gamma_{traditional}(R_i, Lp_k) \\ \cdot SH_{Ag_{traditional}}(R_i, Lp_k) + \gamma_{transition}(R_i, Lp_k) \cdot SH_{Ag_{tansition}}(R_i, Lp_k) \\ + \gamma_{regen}(R_i, Lp_k) \cdot SH_{Ag_{regen}}(R_i, Lp_k) + \gamma_{low}(R_i, Lp_k) \cdot SH_{Ag_{low}}(R_i, Lp_k) \end{aligned} \tag{12}$$

The shares of each type of management are stocks in the model (see Figure E3) that change based on management policies. There are three basic management change policies: transitioning from traditional to industrial agriculture, transitioning to regenerative agriculture, and transitioning to low-input agriculture.

[1] *"If there is no action to reduce erosion, by 2050, cereal losses are expected to exceed 253 million tonnes (FAO and ITPS, 2015). This is equivalent to removing 1.5 million km2 of land – equal to the total area of arable land in India – from crop production"*. Literal quote of pag 151 of reference [1]

Table E2. Relative values of yields for industrial (high-input) and traditional management for several crops obtained from MapSpam data across various agroecological zones (AEZ). Empty values correspond to crops for which there is insufficient significant data.

yield hig input management / yield traditional management												
Region	AEZ	CORN	RICE	CEREALS OTHER	TUBERS	SOY	PULSES NUTS	OILCROPS	SUGAR CROPS	FRUITS VEGETABLES	BIOFUEL 2GCROP	OTHER CROPS
EU27	Tropical											
EU27	Temperate	1.48	1.02	1.71	1.63	3.54	1.28	1.78	1.55	1.92		1.62
EU27	Arid											
EU27	Boreal				2.44							
UK	Tropical											
UK	Temperate									2.70		
UK	Arid											
UK	Boreal											
China	Tropical		2.94							1.57		
China	Temperate	1.55	4.93	2.21	1.82	1.32	1.54	1.67	2.01	1.69		1.51
China	Arid			3.44	1.47	2.43	1.43	2.67	4.74	2.59		3.02
China	Boreal			2.94				1.91				
EASOC	Tropical	1.88	2.66		1.75	1.24	2.05		1.51	0.70		1.79
EASOC	Temperate	1.11	1.78	1.98	1.81	1.42	1.23		1.85	1.88		1.88
EASOC	Arid											
EASOC	Boreal											
India	Tropical	1.81	2.41	1.11	1.17	1.03	2.92	2.30	0.70	1.25		2.23
India	Temperate	1.69	2.48	1.94	1.67	0.98	1.01	1.26	1.23	1.19		1.57
India	Arid	1.91	2.73	1.63						0.99		1.57
India	Boreal											
LATAM	Tropical	2.03	0.94	1.22	1.68	2.16	2.20	0.00	1.31	1.54		1.57
LATAM	Temperate	2.04	0.76	2.30	1.99	3.23	3.55	4.11	0.90	1.76		1.19
LATAM	Arid	3.01		2.39	2.29		4.36		0.69	2.12		1.98
LATAM	Boreal											
Russia	Tropical											
Russia	Temperate		5.85	1.18			1.24		1.19	1.94		
Russia	Arid											
Russia	Boreal			1.26								
USMCA	Tropical	3.90	1.77	3.04			3.14		2.30	1.60		1.61
USMCA	Temperate	13.71		2.19	4.55	12.45	14.89	5.78	1.89	3.35		10.51
USMCA	Arid	11.39		4.29	5.44		23.52	6.54	5.23	2.19		3.25
USMCA	Boreal											
LROW	Tropical	2.37	2.41	2.19	2.11	2.42	1.85	3.91	2.10	1.84		2.06
LROW	Temperate	1.75	1.48	1.68	1.39	2.05	1.69	1.44	1.50	1.53		1.87
LROW	Arid	2.41	1.96	1.78	1.66	2.72	1.82	3.18	3.26	1.69		2.08
LROW	Boreal			2.43	2.53							
average		**3.38**	**2.41**	**2.15**	**2.20**	**2.85**	**4.10**	**3.05**	**2.00**	**1.80**		**2.66**

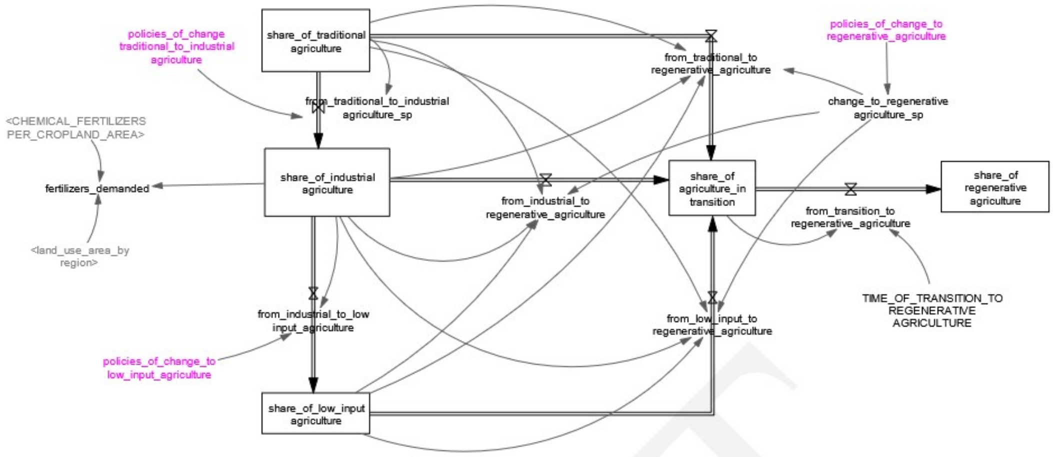

Figure E3. Connection between the different shares in the Crops and Yields submodule. Pink colour: Policy variables.

All management policies change with a coefficient that varies between 0 and 1. A coefficient of 0 implies no application of the policy (in this scenario, the shares remain unchanged from the beginning), while a coefficient of 1 denotes a complete transformation.

The shifts to industrial agriculture correspond to the transition to industrialized agriculture. The transition to low-input agriculture implies the abandonment of chemical agriculture due to a lack of profitability caused by rising prices of fossil fuel-based inputs. This shortage of fossil fuels is more likely to damage agriculture than other economic sectors, as agriculture is more dependent on oil and gas than other industries. Historical examples from Cuba and North Korea in 1990-92, when the URSS collapsed (resulting in an abrupt impact that halved yields), highlight the importance of this crisis. Nevertheless, in this initial version of WILIAM-TERRA model, this possible effect of oil and gas prices on agriculture has only been added as a policy. This feature is still very innovative in the field of IAMs, and as far as we know, WILIAM-TERRA model is the only one that incorporates it.

The policy of the shift to regenerative agriculture is also activated by the user, with a transition period. It applies proportionally to all types of agriculture, including low-input, traditional, and industrial agriculture, and results in a final decrease in yields for industrial agriculture but a net increase for the others. This policy would also impact employment, although to a lesser extent than traditional agriculture. However, this connection has not yet been established.

In this regard, this approach to modeling the ecological transition of agriculture is innovative in the IAMs domain, as is the effect of the peak oil and gas on agriculture.

E3. GRASSLAND SUBMODULE

The grassland submodule manages the policies for changing the management of permanent meadows and pastures. It is known that poor management of grasslands leads to severe degradation, but advanced regenerative techniques, such as Multi Paddock, holistic management, and Voisin's Rational Management [14, 15], are able to improve the soil of pastures by capturing large amount of carbon and increasing the productivity of extensive farming.

The Grassland submodule includes policies for gradual change to the following types of management:

- severely degraded
- moderately degraded
- improved with medium inputs
- improved with high inputs
- regenerative grazing

When the policy of soil management in Grassland submodule is activated, the stock "Share of grasslands in transition" starts growing. This stock depletes as the pastures transition into the final stock, "Share of grassland in final management". In the case of regenerative grazing, this applies to lands that are saturated with carbon and no longer absorb carbon. The carbon stored in the soil of pastures is used to estimate the carbon absorption or emissions resulting from grassland management.

Since the number of animals fed per hectare under regenerative grazing is reported to be higher than that of conventional techniques, the share of grassland under both these regimes is used to increase the animal products obtained from grasslands in the Diets and Land Products Demand submodule.

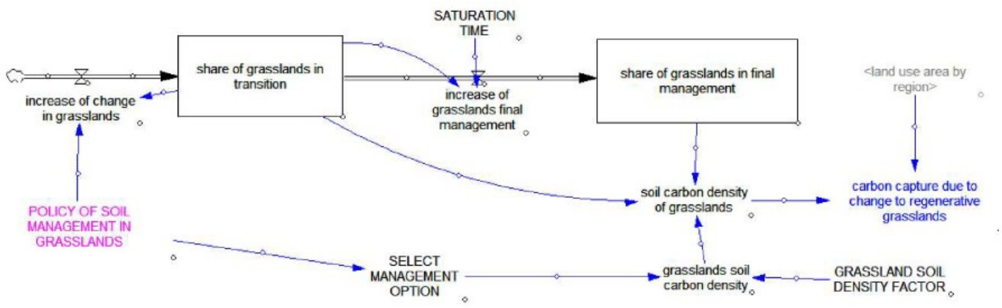

Figure E4. Simplified model of the Grassland submodule. Pink colour: Policy variables.

E4. FORESTS SUBMODULE

Figure E5 presents a simplified Forrester diagram of the Forests submodule. This submodule encompasses a model of forest biomass balance that includes growth, forest area changes and extraction of wood for human use, along with the corresponding carbon balances in forests. This comprehensive approach is applied to each of the nine regions within the model and takes into account the possibility of strong forest degradation due to human extraction, even though the forest area might not be reduced through the loss of forest area.

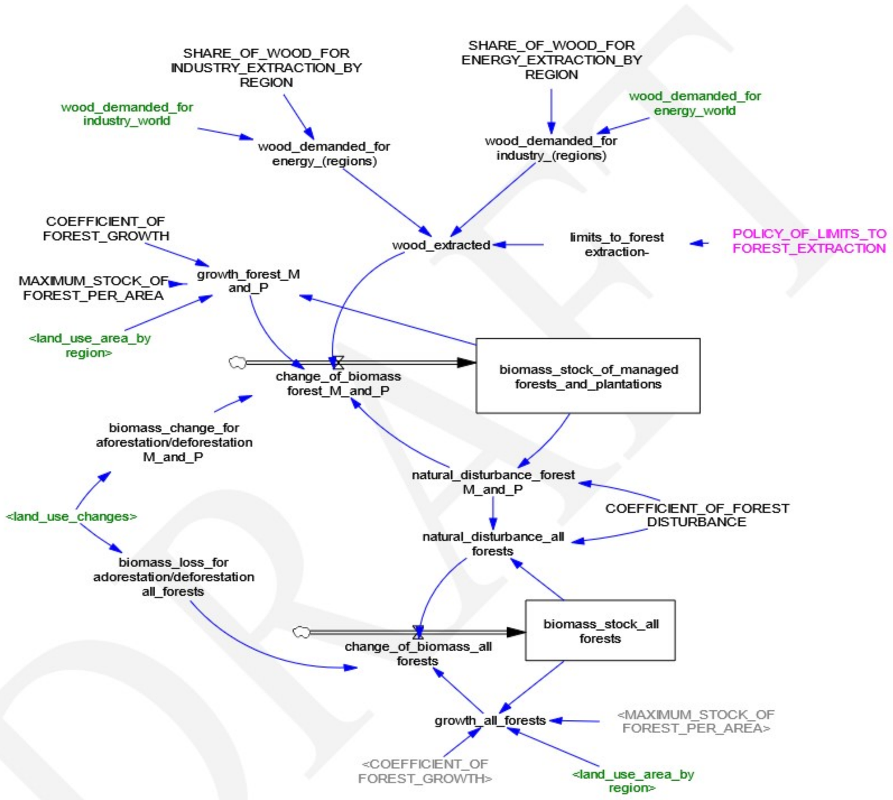

Figure E5. Simplified diagram of the Forests submodule; Green colour: variables from other WILIAM modules; Blue colour: principal outputs of the submodule; Pink colour: Policy variables.

The forest growth submodule implements, for each region, a mass balance of total forest above ground stock of biomass in all the forest ($S_{all}(R_i)$) and in managed forest and plantations ($S_{mp}(R_i)$), which considers the natural growth of forests ($G_{all}(R_i)$ and $G_{mp}(R_i)$), the biomass gained via reforestation ($Af_{mp}(R_i)$, only for managed forests and plantations, since primary forests cannot be generated by human intervention), introduced with a delay of maturation time; the biomass gained through deforestation ($Def_{all}(R_i)$ and $Def_{mp}(R_i)$), the natural disturbance of forests ($Ndist_{all}(R_i)$ and $Ndist_{mp}(R_i)$), and the biomass extraction done by human intervention ($Ex_{mp}(R_i)$, assumed only in managed forests and plantations).

Forest stock is calculated as:

$$\frac{dS_{mp}(R_i)}{dt} = G_{mp}(R_i) + Af_{mp}(R_i) - Def_{mp}(R_i) - NDist_{mp}(R_i) - Ex_{mp}(R_i) \qquad (13)$$

$$\frac{dS_{all}(R_i)}{dt} = G_{all}(R_i) + Af_{mp}(R_i) - Def_{all}(R_i) - NDist_{all}(R_i) - Ex_{mp}(R_i) \qquad (14)$$

where the natural growth of forests is calculated using a logistic function, with limits set by the maximum achievable biomass stock as determined by Roebroek et *al.* [10]. The natural disturbance is proportional to forest stock and is based on the values of Roebroek et *al.* [10].

The biomass gained through afforestation and deforestation are proportional to the area gained or lost and the average biomass in that area (with a delay in the case of reforestation to account for maturation time).

Wood extracted, $Ex_{mp}(R_i)$, results from the demand for energy and for other uses (industry), which come from the Diets and Land Products Demand submodule. The demand across all regions is summed to calculate the *Wood demanded for energy world* and *Wood demanded for industry world.* These totals are then distributed to regions using the parameters *SHARE OF WOOD FOR ENERGY EXTRATION BY REGION* and *SHARE OF WOOD FOR INDUSTRY EXTRATION BY REGION*, which reflect the international trade of wood products in a kind of pooled market where all regions contribute and each receives according to fixed shares (based on average historical data obtained from FAO). A policy, *POLICY LIMITS TO FOREST EXTRACTION,* can halt wood extraction from forests if the biomass stock falls below a desired threshold. This limits the biomass available for energy and, consequently, limits the available energy from biomass in the WILIAM Energy module.

On the other hand, the carbon cycle submodule calculates, for each region, and from the annual flow of forest volume stock, the annual flow (and stock) of biomass both above and below the soil. It also calculates the annual carbon flux (and stock) above and below soil, as well as the annual flux of CO_2, using the values from the IPCC [11] and Machado et *al.* [12].

Diet demanded $DD(R_i, F_j)$*, Diet according to GDP,* $DD_{GDP}(R_i, F_j)$, and the *Diet according to policies,* $DD_P(R_i, F_j)$. stock *Change to policy diets,* $SPC(R_i)$, that starts with 0 when the diet is only driven by GDP and reaches 1 when the full change to policy diet is achieved.

The food demanded by households $FH(R_i, F_j)$ is calculated by multiplying $DD(R_i, F_j)$ by the population of each region. The demand of fish is ignored because it does not come from the land products and our goal is to compare with the products obtained from the croplands (we assume that there are no restrictions to food obtained from the seas, although this assumption will be revised in future versions of the module). The meat obtained directly from feed obtained from pastures is subtracted as well because it does not come from products obtained from croplands (refer to Appendix B for more details about the estimation of meat obtained from grasslands).

The result is multiplied by an Agro-food transformation matrix $AM(F_j, Lp_k)$ that relates food products and the *Land products demanded for food* ($LP\ demand\ for\ food\ (R_i, Lp_k)$) and is calculated based on a 14 food items of FAO database adapted to our food and land products categories. This transformation takes into consideration the entire global farming and food industry system in order to obtain the land products demanded for food that is expressed as follows:

$$LPdemand\ for\ food(R_i, Lp_k) = AM(Lp_k, F_j) \cdot FH(R_i, F_j) \quad (16)$$

The calculation of the *Land products demanded for energy* involves adding two components: the energy demand from agricultural products (biofuels) and the energy demanded from forestry products. The first component is calculated based on the variable *Primary energy by commodity* of the Energy module that is converted from energy units to weight units using average densities of crops used for energy per region (source FAOSTAT) and assuming that the percent of each crop used for biofuels remains constant and equal to the average of past years. The second component is also calculated via the variable *Primary energy by commodity* of the Energy module, applying the corresponding conversion factors energy-weight based on world average historical data (source FAOSTAT).

The *Wood demanded for industry,* $WD_{forindustry}(R_i)$, is calculated based on data of the economic activity ($EO(R_i, s_l)$, where s_l are the economic sectors) of the industries that are more intensive on the use of wood (Wood Manufacture and Construction). The average intensity of wood for industry $I_{woodI}\ (R_i)$, is calculated using the historical values of wood consumption in year t from 2005 to 2019 (source FAOSTAT) divided by the economic output of those two sectors. Thus, the land products demanded for industry are calculated as:

$$WD\ for\ industry\ (R_i) = \left(EO(R_i, wood\ manufacture) + EO(R_i, construction)\right) \cdot I_{woodI}(R_i) \quad (17)$$

Where:

$$I_{woodI}(R_i) = \frac{\sum_t wood\ consumed\ by\ industry\ (R_i)}{\sum_t econ\ output(R_i, wood\ manufacture) + econ\ output(R_i, construction)} \quad (18)$$

The *Land products demanded* for each use, calculated in this submodule, are confronted with the *Land products available* estimated in Crops and Yields and Forest submodules and distributed to regions and uses in Land Products Availability submodule. If the demand of food exceeds the production, a signal of shortage appears, and this shortage of the availability of land products for food, [$AvailabilityLP_{food}(R_i, Lp_k)$, is expressed as follows:

$$AvailabilityLP_{food}(R_i, Lp_k) = \frac{LP\ available\ for\ food\ (R_i, Lp_k)}{LP\ demand\ for\ food(R_i, Lp_k)} \quad (19)$$

This shortage becomes < 1 when there is food stress and the *Diet Available*, the one that matches the agricultural production, is different from the desired one. Note that the *diet available* ($DA(R_i, F_j)$) is calculated as follows:

$$DA(R_i, F_j) = DD(R_i, F_j) \cdot AvailabilityF(R_i, F_j) \quad (20)$$

Where $Availability\ F(R_i)$ is the average value of $AvailabilityF(R_i, F_j)$ for all crops in each region. This is an approximate way to translate the shortage of crops to the shortage of food iterms, since all of them are restricted in the same way and the historical data show that when the GDP of the regions decreases, there is less consumption of all products in general but it is more relevant in animal products and fruits and vegetables. This approximation is used in order to maintain the physical consistency of the food and crops (consumption must equal production minus losses) and we were not able to create a stable feedback mechanism that translates the shortage maintaining the physical coherence, but hope to be able to solve it in future versions of the model.

E6. LAND PRODUCTS AVAILABILITY SUBMODULE

Figure E7 shows a simplified view of the Vensim model of *Land products availability* submodule. The *Land products Available* are distributed first to regions using one Allocate by priority Vensim function and then to uses withing each region.

The stock *Share of production protected from global pool* is the share of the production of each region that does not enter the global pool allocation and can be changed via the policy *Land Products Global Pool.*

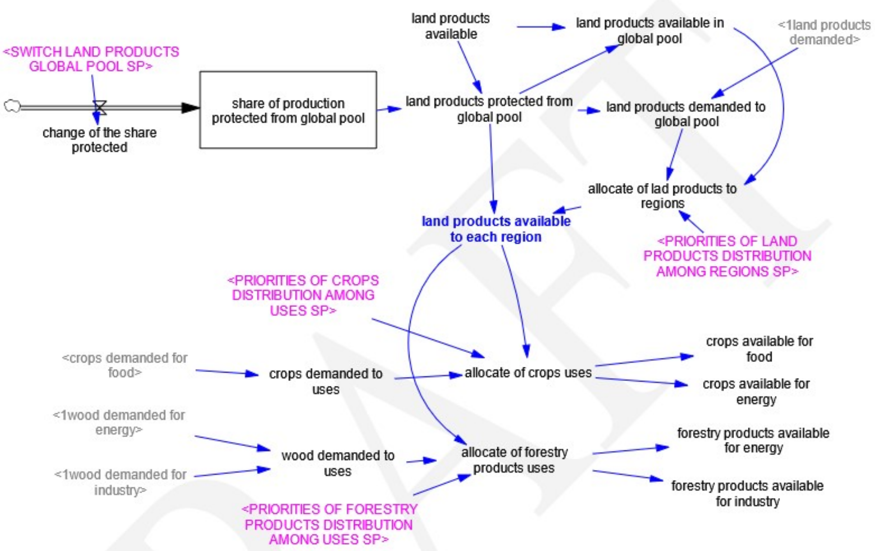

Figure E7. Simplified diagram of the Land Products Availability submodule; Green colour: variables from other modules of the WILIAM model; Pink colour: policy variables.

E7. EMISSIONS SUBMODULE

Figures E8, E9, and E10 present simplified Forrester diagrams related to the Emissions submodule. This submodule is responsible for calculating the main Agriculture, Forestry, and Other Land Use (AFOLU) GHG emissions. This includes Land Use, Land-Use Change and Forestry (LULUCF) and agriculture emissions, being this the main link between the Land related submodules and the Climate module of WILIAM model. In particular, it allows to dynamically calculate the main GHG emissions related to land use, land use changes, forestry activities, and agriculture (fertilizers, rice cultivation and livestock), over time, including the effect of the change of diets in livestock emissions.

Figure E8 shows the part of LULUCF emissions related to *Land Use Changes (LUC)*, which is directly dependent of the Land Uses submodule. In particular, the CO_2 LUC emissions is calculated based on the area changed between land use types (from one use to another), i.e., on the allocation of land use. Depending on the land use change type, the difference of carbon densities generates the emissions or, on the contrary, the increase in carbon uptake. In the case of a land use change that implies carbon uptake (carbon stock increase), as for example from grasslands to forestland, it is necessary to take into account the time needed to reach the equilibrium to a new state, i.e., to reach the new carbon stock value.

The general equation for estimating the total change transfer of carbon is as follows:

$$\Delta C_{(R_i)}(\mathrm{tC}) = \left(A\ (t_2) \times Cdensity_{t_2, L_\mathrm{m}(R_i)} - A\ (t_1) \times Cdensity_{t_1, L_\mathrm{n}(R_i)}\right) \\ = A \times Cdens._{t_2, L_\mathrm{m}(R_i)} - A \times Cdens._{t_1, L_\mathrm{n}(R_i)} = A \times Factor\ emission\ _{L_\mathrm{n} \rightarrow L_\mathrm{m}, R_i} \quad (22)$$

Where $C\ density_{t2, l2(R_i)}$ is the carbon density (tC/Mha) in the year "t" and the land use "L" in region "R_i", the land use change from use L_n $(use\ 1\ in\ t_1)$ to use L_m $(use\ 2\ in\ t_2)$, and A is the area of land that is being changed (Mha). This information comes from the $Matrix\ of\ LUC\ changes\ (R_i, L_n, L_m)$ calculated in the "Land Uses" submodule.

After applying the previous equation, afterwards it is necessary to allocate the change of carbon in time. For these, two approaches have been applied:

- Instantaneous emissions (emitted in the same year)
- Applying an exponential delay function of first order (asymptotic function) taking into account the equilibrium period (time of carbon to reach the equilibrium to a new state). In this case the form of the equation is the following:

$$C_{(t)} = \left(C_0 + a\left[1 - e^{-bx}\right]\right) \rightarrow \left(C_{stock\ 0} + a\left[1 - e^{-\frac{1}{\tau} * t}\right]\right) \quad (23)$$

being τ the time equilibrium period.

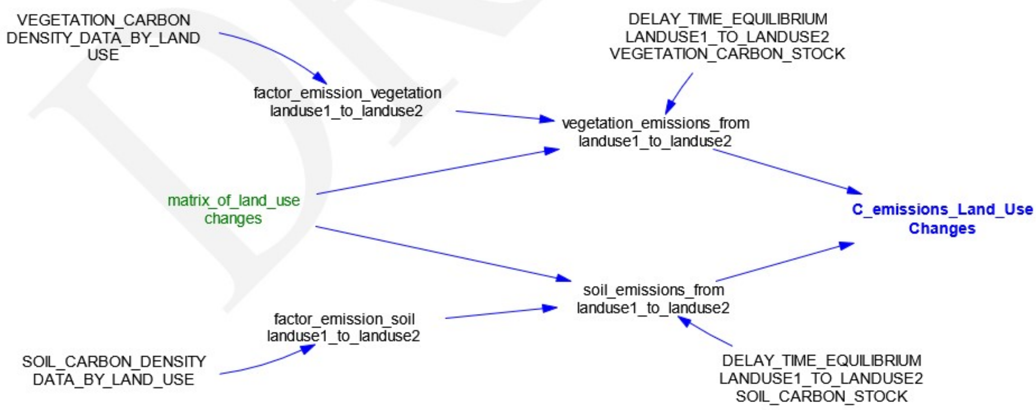

Figure E8. Simplified diagram of the calculation of emissions from LUC in the Emissions submodule. Green colour: variables from other submodules of WILIAM model; Blue colour: principal outputs of the submodule.

Secondly, the change of soil carbon stock (and related CO_2 emissions) due to different types of management in cropland are also calculated (see Figure 9). This information is based on the outputs of the Grasslands and the Crops and Yields submodules. In particular, the shares of the different types of practices *($SH\_Ag_{management\_type}$ (R_i, Lp_k)),* which can change over time in response to active policies, influence the carbon stock in soil as they imply different management and different inputs of organic matter. As listed in Section 1.2, WILIAM-TERRA module includes five different types of agricultural management: industrial $SH\_Ag_{industrial}$ (R_i, Lp_k), traditional $SH\_Ag_{traditional}$ (R_i, Lp_k), low input SH_Ag_{low} (R_i, Lp_k), regenerative SH_Ag_{regen} (R_i, Lp_k) and agriculture in transition $SH\_Ag_{transition}$ (R_i, Lp_k), which has been aligned with default management factors and estimations from IPCC guidelines [13].

The Equation to reflect the effect of the type of management in cropland on soil carbon stock following IPCC guidelines [13] is the following:

$$C_{stock-af} = C_{density-SOil-ref\,(R_i)} * FLU_{aft} * FMG_{aft} * FL_{aft}$$
$$= C_{density-SOil-be\;\;(R_i)}.* \frac{FLU_{aft} * FMG_{aft} * FL_{aft}}{FLU_{bef} * FMG_{bef} * FL_{bef}} \qquad (24)$$

Where $C_{density-SOil-r\;\;(Ri)}$ (tonC/ha) is the default reference value of carbon density (under native vegetation) for each WILIAM region; $C_{density-SOil-b\;\;(R_i)}$., carbon density under normal conditions (current carbon stock) before the new type of management is applied and FLU, FMG, and FL are the management factors which depend on the "land use system", "management regime", and "input of organic matter" respectively, i.e, on the current management options applied. The changes in the factors of management are calculated based on the shares of the five different types of practices *($SH\_Ag_{management\_type}$ (R_i, Lp_k))* from the "Crops and Yields" submodule.

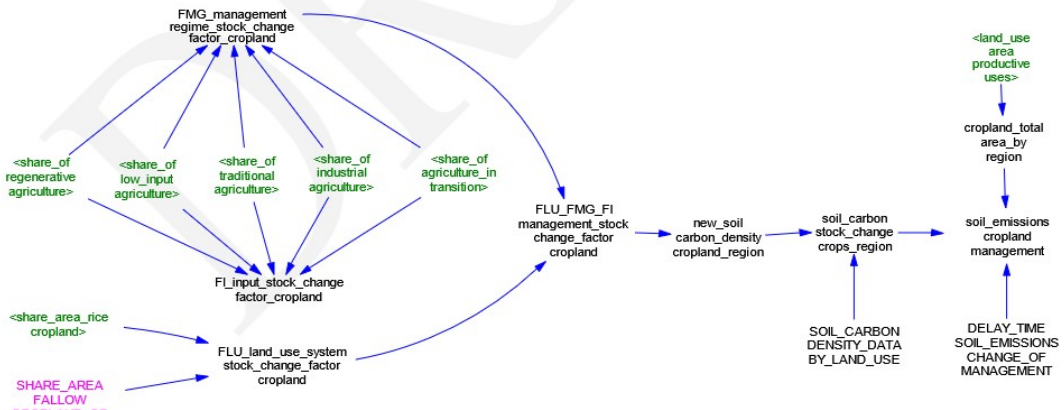

Figure E9. Simplified diagram of the calculation of emissions from changes in the management of cropland in the Emissions submodule. Green colour: variables from other submodules of WILIAM model; Blue colour: principal outputs of the submodule. Pink colour: Policy variables.

On the other hand, the emissions and carbon uptake calculated in the "Forests" and "Grassland" submodules also enter in the "pool" of emissions from LULUCF.

Finally, emissions from agriculture activities (see Figure 10) are also calculated and calibrated with information from FAO database. The general equation for calculating this type of emissions is the following:

$$Emission = EF \times A \tag{25}$$

Where EF is the emission factor, and A is the activity parameter, which depends on the type of activity. In particular, in WILIAM the emissions from the following *agriculture* activities are calculated: livestock (manure management and enteric fermentation), rice cultivation and synthetic fertilizers application:

- *N_2O and CH_4 emissions from livestock* (from manure management and enteric fermentation): These emissions depend on the number (stock) and type of living animals (activity parameter) and on the type of manure management. The number of animals is calculated based on the consumption (demand) of food (meat, dairy, eggs, etc.), which is transformed in number of production animals. This allows to analyse the effect of change of diets, that influence the consumption, on the number of animals, and therefore in livestock emissions.
The demand of food is calculated in the Diets and Land Products Demand submodule, which depends on specific policies of "diets changes" and the availability of food. Then, this demand ($food_{consumed}$) is transformed into the quantity of food that needs to be produced ($Production\left(\frac{tonnes}{year}\right)$) by animals to satisfy that consumption taking into account food losses with information from FAO database.

$$Production(\frac{tonnes}{year}) = food_{consumed} * ratio\left(\frac{food_{produced}}{food_{consumed}}\right) \tag{26}$$

Next, the production of food is distributed between the different type of animals (An_i). Finally, the stock of animals is calculated taking into account the animal the yield of each type of animal (tonnes of food produced by each live animal), and the ratio of animals producing with respect the total living animals, according to the following equation:

$$\begin{aligned} &Number\ of\ animals_{An_i} = \\ &animals\ producing(An_i)\ *\ ratio\left(\frac{animals(An_i)_{living}}{animals(An_i)_{producing}}\right) = \\ &Production(\frac{tonnes}{year}) * share(An_i)_{production}\ * (\frac{1}{yield_{An_i}(\frac{tonnes}{animal * year})}) \\ &*\ ratio\left(\frac{animals(An_i)_{living}}{animals(An_i)_{producing}}\right) \end{aligned} \tag{27}$$

On the other hand, the EF correspondent to livestock is dependent of the combination or shares of types of manure management by each WILIAM-TERRA region, which can evolve through policies. In particular, the policy allows to define the share of each of the manure system types (percentage) by animal (dairy cattle, other cattle, buffalo and swine), and by WILIAM-TERRA region. On this side, the options which produce less emissions are: solid storage (manure stored in unconfined piles or stacks), dry lot, range/paddock (manure that is allowed to lie in agricultural/pasture soils), daily spread (routinely removed and applied to cropland or pasture within 24 hours of excretion) and pit storage (storage of manure with little or no added water less than 1 month, in contrast with the "liquid/slurry" management). In case of policies not being applied, past trends of manure system shares continue, based on data from IPCC (IPCC, 2006) guidelines [13], which has been adapted to WILIAM-TERRA regions.

- *CH_4 emissions from rice cultivation*: These emissions are estimated based on the rice cultivated area ($\text{“}rice\ paddy\ annual\ harvested\ area\text{"}\ (ha)$) which is the activity parameter and is calculated in the Crops and Yields submodule. As the type of water regime influences these emissions, the irrigated and rainfed areas of rice cultivated are used for the calculation.
- *N_2O emissions from the application of synthetic fertilizers* by farmers are calculated based on the nitrogen applied (tonnes N/year) which is the activity parameter. The fertilizers demanded depends on the different types of agriculture management (traditional agriculture, industrial, regenerative, etc.), which is calculated in the Crops and Yields submodule. Then, this quantity of fertilizers (nitrogen) is transformed into direct and indirect nitrous oxide (N_2O) emissions.

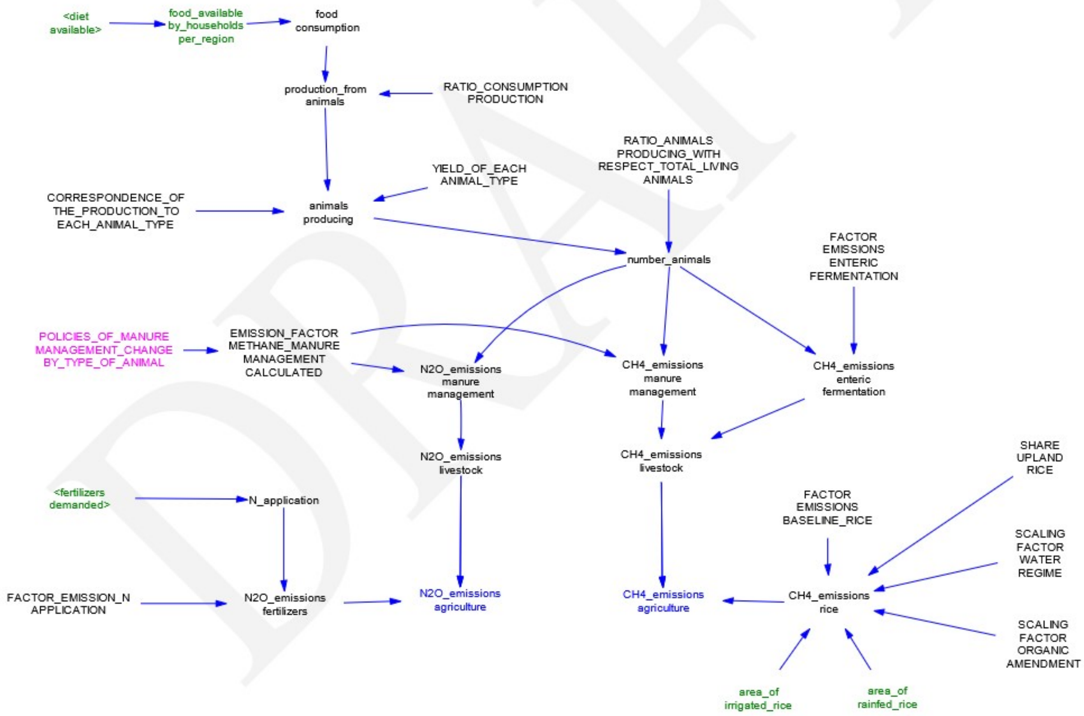

Figure E10. Simplified diagram of the calculation of emissions from agriculture activities (livestock, synthetic fertilizers and rice cultivation) in the Emissions submodule. Green colour: variables from other submodules of WILIAM model; Blue colour: principal outputs of the submodule; Pink colour: Policy variables.

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Appendix F. Exogenous Inputs

This appendix describes the inputs used in the experiments of section 3. The WILIAM-TERRA module receives inputs from various modules of WILIAM model. Since the experiments of this paper are obtained only with the WILIAM-TERRA module disconnected from the rest of WILIAM, some inputs from other modules are taken as an exogenous. The ones that are relevant for the experiments of this article are the *Population* from Demography module, the *Gross domestic product per capita* from Economy module and the demand of energy from crops and forestry products. The Appendix shows, as well, some results that are common to all the simulations of section 3: the evolution of yields and the maximum values of cropland area.

Population:

The *population* variable in the Demography Module evolves as shown in Figure F1, for 9 regions and from 2005 to 2050. From 2005 to 2020, it is calculated using historical data of life expectancy at birth and fertility rate from each studied region (data from World Bank national accounts data [1]). From 2020 to 2050, it follows an exogenous scenario based on historical data of fertility rate and life expectancy at birth.

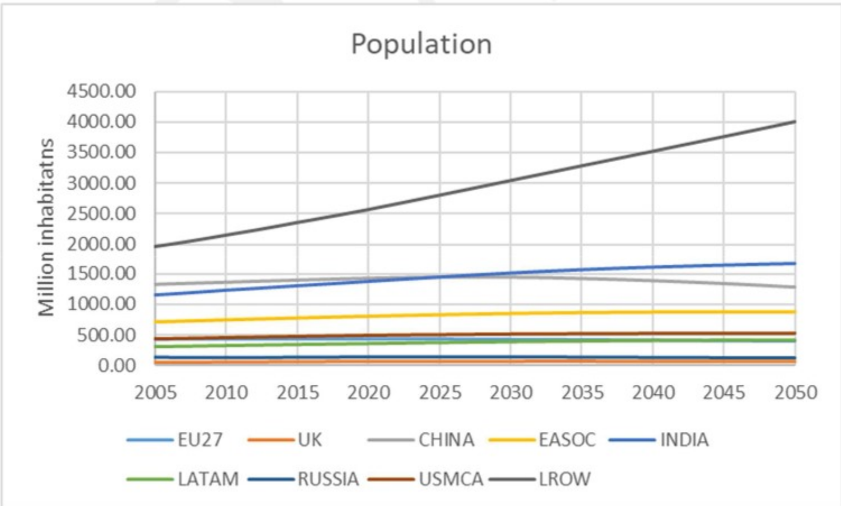


Figure F1. Population by region.

- *Gross Domestic Product per capita* (*GDPpc*):

The *GDPpc* variable is calculated in the Economy Module for the 9 studied regions and evolves as shown in Figure F2. From 2005 to 2015, the *GDPpc* data are historical data with a constant price in 2015 (data from World Bank national accounts data, and OECD National Accounts data files [2]). From 2015 until 2050 its growths at rates like those of the past that are calculated on the Economy Module in a baseline scenario of continuation of present trends.

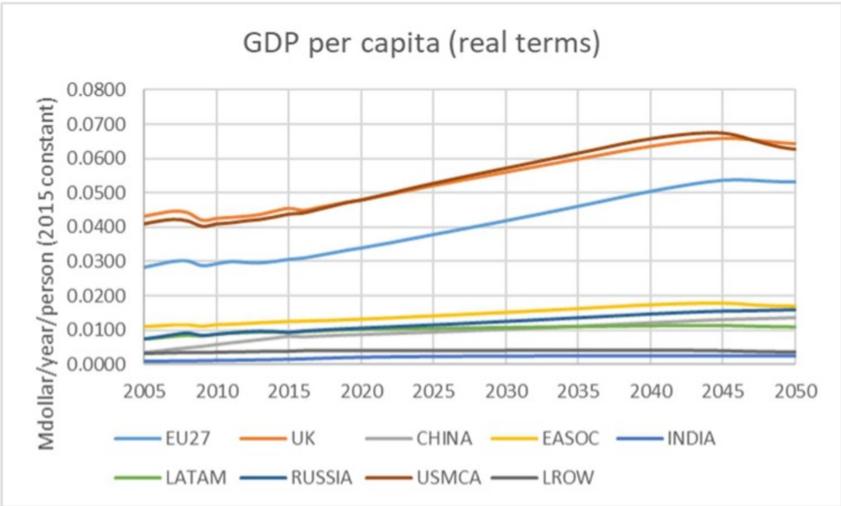


Figure F2. GDP per person by region.

- *Demand of energy from crops*:

The demand of crops for first generation biofuels is calculated for an scenario of low penetration of biofuels in the energy mix and can be seen in Figure F3.

- *Demand of forestry products for energy and materials*:

The demand of forestry products for energy is shown in Figures F4, F5 and F6 for three scenarios of low, medium and high demand. The medium scenario has been calculated in the Energy module based on a scenario of average introduction of biomass in the energy mix. The demand of LROW almost doubles as a consequence of its population growth. The demand of scenarios low and high are linear approximations. Low scenario keeps the demand constant at the value of 2005 and high scenario growths to a demand that is 50% higher than in the value of 2050 of medium scenario, except for LROW that gets in 2050 the same value of medium scenario.

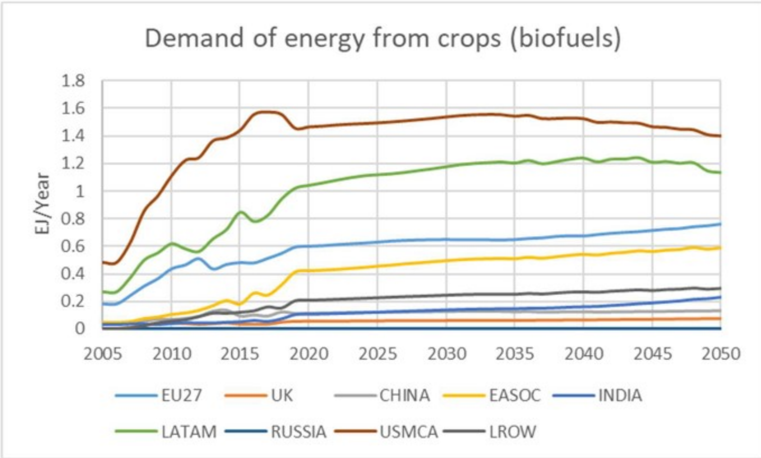


Figure F3. Demand of energy from crops.

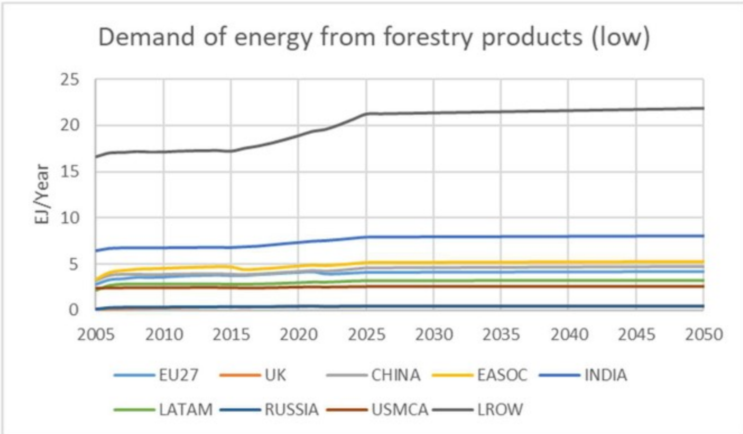
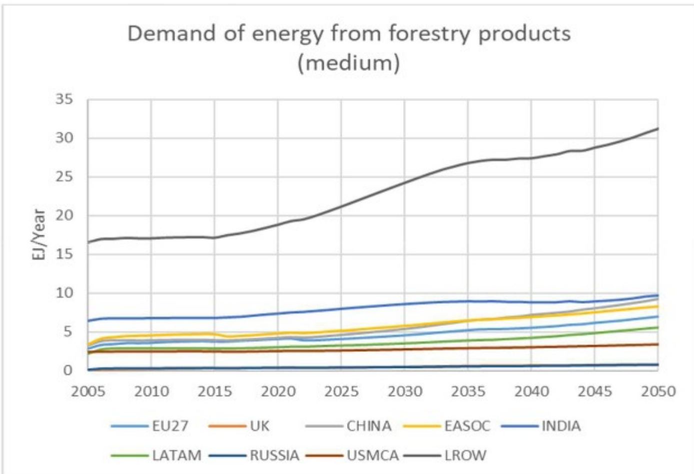


Figure F4. Demand of energy from forestry products (scenario low)



treated in future releases of WILIAM-TERRA model. In the meanwhile, a 30% increase of yields seems realistic or even optimistic, given the observed stagnation of the yields of EU27, for example, in last decade and the observed growth (limit is reached around 2035-50 for most crops). The effects of climate change are added to this and the effect of soil erosion as well (see Appendix E section 2 for more information). Figure F8 shows the evolution of the average world yields driven by all these factors.

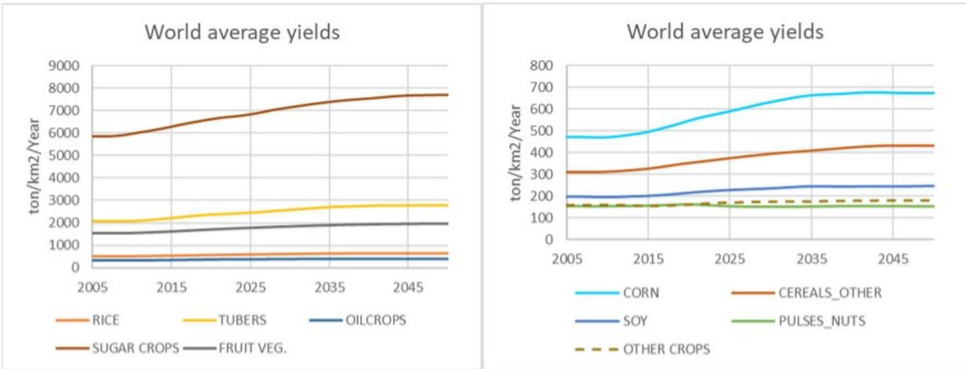


Figure F8: world average crop yields.

- *Diet change*:

Figure F9 shows the comparison of the diet used in the results of section 3 with present diet of two regions (India and EU).

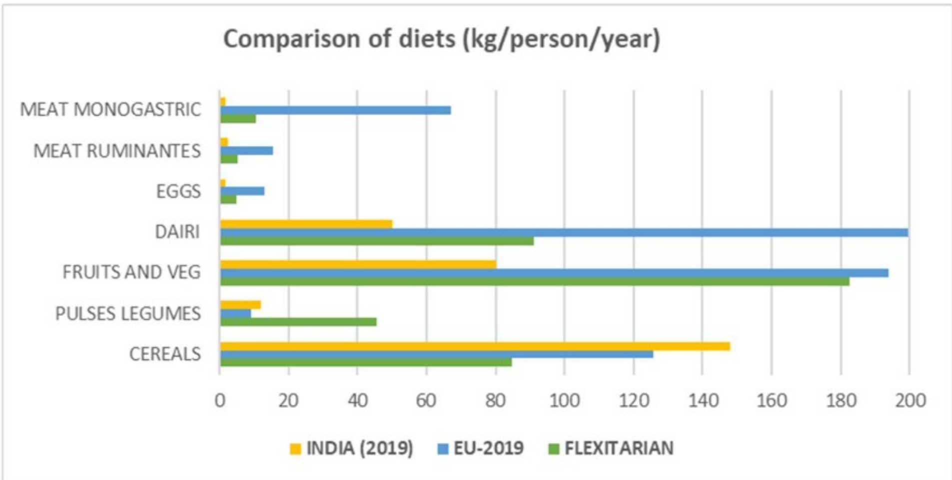


Figure F9. Comparison of present average diet in EU and India with the target diet used (Flexitarian).

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Annex I. Feedback analysis and validation of WILIAM-TERRA module

Contents:

G1. Feedbacks within TERRA module and with the rest of the WILIAM model

The WILIAM-TERRA module is interconnected with five modules of the WILIAM model [1], [2] : Energy, Economy, Demography, Society and Climate (see Figure G1). It receives the information of GDP per capita from the Economy module, population from the Demography module, temperature and climate change impacts on yields from the Climate module as well as the demand of liquid biofuels, solid biomass and land for renewable energy (mainly solar PV) from the Energy module. In return, it provides various outputs to these modules, such as data on the availability of crops and forestry products for energy and food, and a stress signal of the use of land for solar energy.

Some of these links create feedback loops withing the TERRA module and with this module and Energy and Climate modules. Five loops between TERRA and other modules are shown in Figures G2 and G3: loops 1 and 2 are relative to the effects of Climate Change on crop yields and loops 3, 4 and 5 relative to the limits of energy expansion.

Loop 1 is created because the expansion of agricultural land creates emissions due to land use changes (croplands tend to expand at the cost of land uses with more carbon content). Carbon emissions increase temperature change and have an impact on crop yields that, in most regions, is negative (the more temperature the less yields). This requires more cropland to meet demand and increases the expansion of agricultural land.

The effect of loop 2, related to fertilizers, is similar, since their consumption is proportional to cropland area under industrial management: the more area the more GHG emissions which increases climate change impacts on yields, decreases productivity and requires more cropland and more fertilizers.

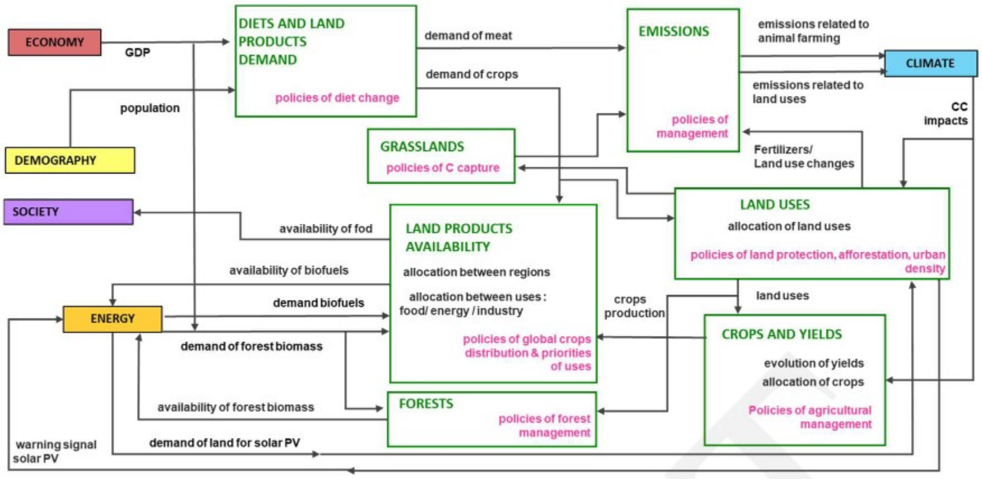

Figure G1. WILIAM-TERRA module and its connection with the rest of WILIAM modules. White-green boxes are submodules of WILIAM-TERRA, boxes in other colour belong to other modules of WILIAM. Variables in pink are exogenous policies chosen by the user.

Loop 3 is related to the expansion of solar renewable energy and its demand of land. The more demand of land for solar the more land dedicated to this use and the more pressure on landscape and society of these appliances. This creates a stress signal that limits the deployment of those infrastructures when relative limits of occupation are reached and is, therefore, a stabilizing loop.
Loop 4 is caused by the demand of forest biomass for energy: the more biomass demanded the more extraction and the more forest biomass depletion. If the biomass extraction reaches the limits imposed by the model policies (or if the forest becomes completely depleted) the biomass obtained is less than the demanded and a shortage signal appears and limits the biomass available to the Energy module. Loop 5 describes a process similar to that of loop 4 but relative to biofuel demand and to the available crops from the cropland submodule. Both loops 4 and 5 are stabilizing.
A more detailed description of these loops is provided in next section.

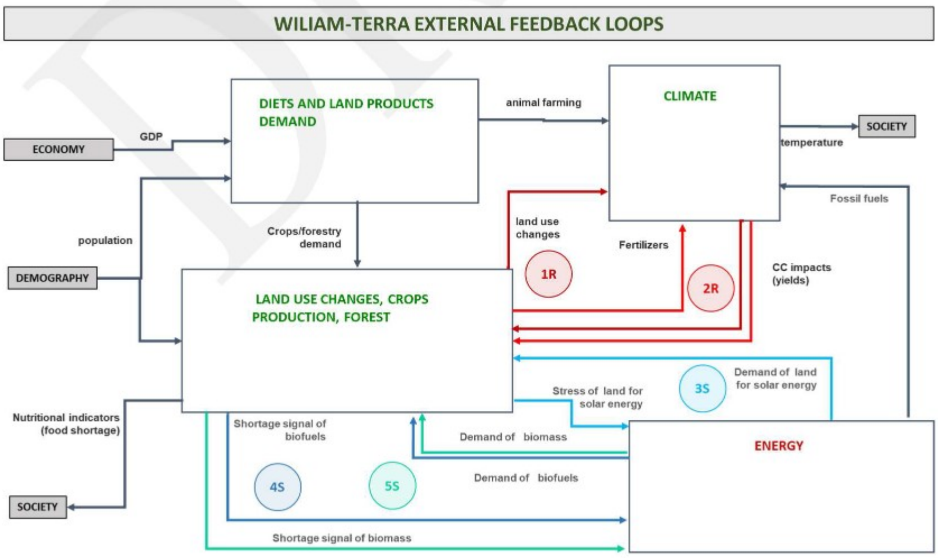

Figure G2: feedback loops of created between Land, Climate and Energy modules in WILIAM model.

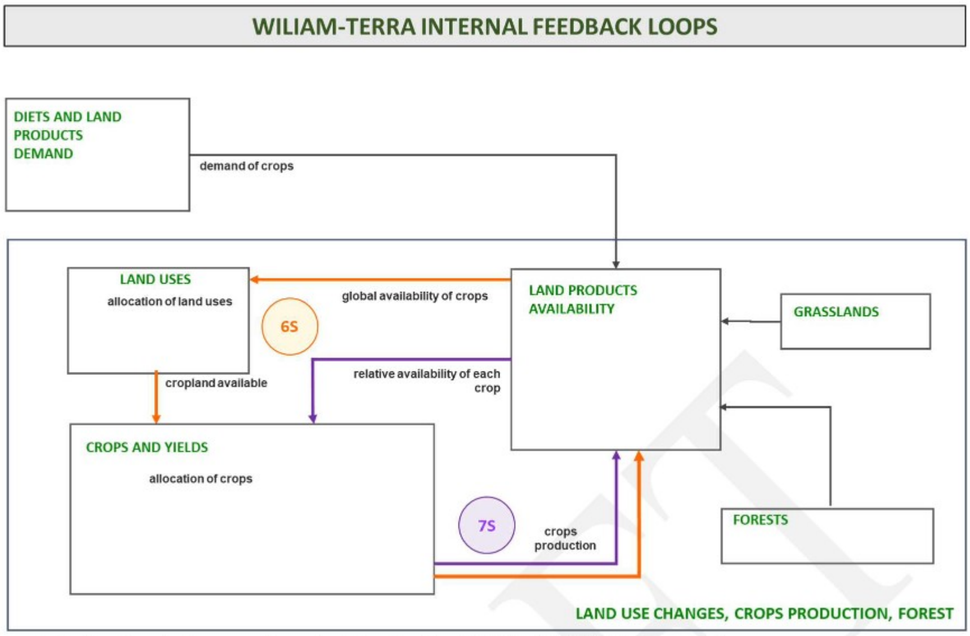

Figure G3: feedback loops of created inside the WILIAM-TERRA module.

G2. Test of the feedback loops

The stability of the feedback loops is one of the basic tests of the validation of System Dynamics Models [3], [4]. The loops identified in section G1 are tested in this section, starting with loop 7, since it is the most internal one, and its stability must be guaranteed before analysing the rest. The tests show, as well, the behaviour of the model and the performance under extreme conditions.

Loop 3, relative to solar renewable energy expansion, is analysed in [5] in detail. Loops 4 and 5 are relative to the interactions with the Energy module of WILIAM and involve complex interactions with the allocation between primary and final energies that can only be addressed if the Energy module is described in detail, which is out of the scope of this document.

Test of loop 7

The causal loop diagram of loops 7 is shown in Figure G3. In all the figures of causal loop diagrams, the arrows represents information flows and have a "+" sign if the increase of the first variable increases the second variable (direct relation) and a "-" when the increase of the first variable decreases the second (inverse relation). A loop is created when a closed chain of case-effect relations is found. It is stabilizing when it contains an odd amount of signs "-" and reinforcing when it contains an even (or zero) number of "-" signs.

Loop 7 appears when the production of a particular crop i is greater than its demand. In that case, its "availability" signal is more than one and the allocation mechanism of the Crops and Yields submodule reduces the percent of cropland given to that crop and increases the percent of the rest. This decreases the production of that crop and tends to match demand and production, creating, therefore, a stabilizing loop. This mechanism operates in all the crops at the same time, (using the many-to-many allocation of the dynamics shares mechanism [6] developed by the authors of this paper) and, therefore, tends to compensate all the relative shortages of all crops in the same way. Priorities can be added to this mechanism to prioritize one or several crops (such as the ones that would appear in a marker related to the added value of each commodity), but at this stage, they have not been introduced.

In order to test loop 7 in WILIAM-TERRA the demand of one single crop (CORN) has been increased abruptly 100 times in a single time step at time 2025 (increasing the variable called demand of crops in Figure 3). The cropland area and the population have been left constant in this run to avoid interferences with the other feedbacks of the model. One can see in Figure G4 that, initially, the availability of crops is greater than one: there is surplus of all crops, since population is constant. In 2025 the demand of corn increases abruptly because of the artificial signal added, a greater share of cropland is allocated to corn and the availability of crops becomes less than one for all crops, since production is unable to fulfil the demand.

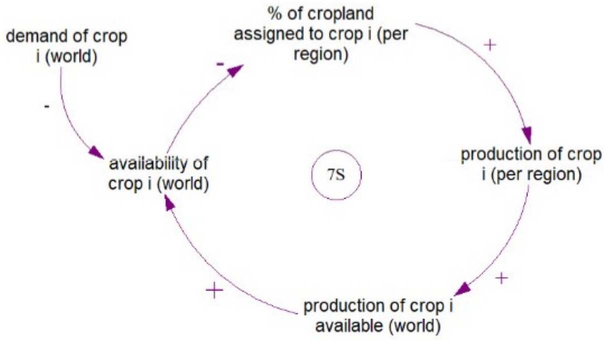

Figure G3: causal loop diagram of loop 7.

In Figure G4c and G4d the share of cropland dedicated to each crop is shown for two regions (USMCA and LROW). One can see that the share of corn grows until the limits of land suitable for it are reached (arbitrarily assigned in these runts to 100% of cropland in USMCA and 40% in LROW).

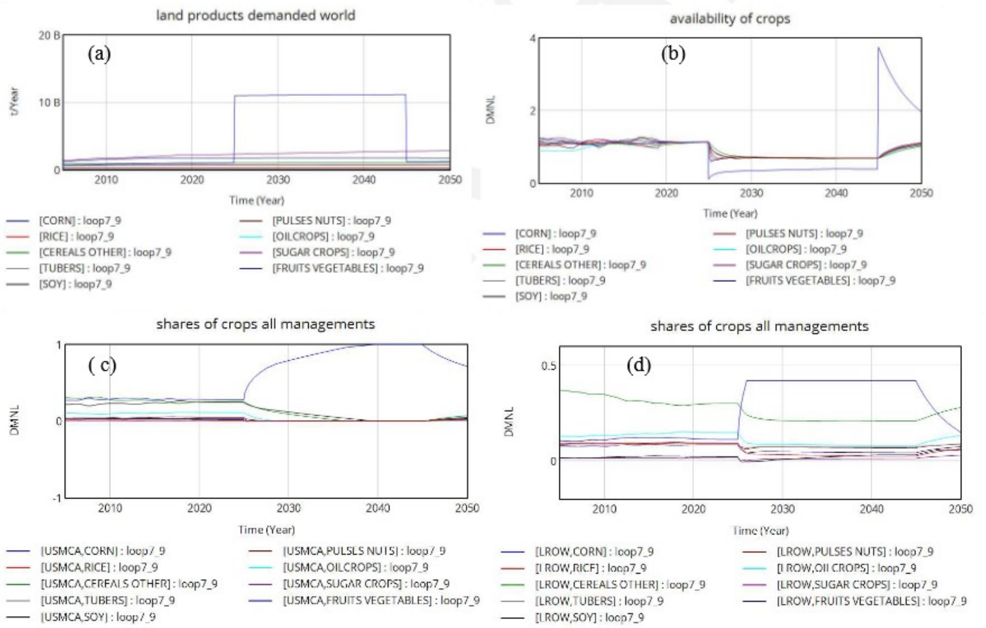

Figure G4: test of loop 7. (a) demand of crops (global) (b) signal of availability of crops, equals 1 if demand meets production, less than one means that there is shortage (c) share of cropland used for each crop in USMCA (d) share of cropland used for each crop in LROW.

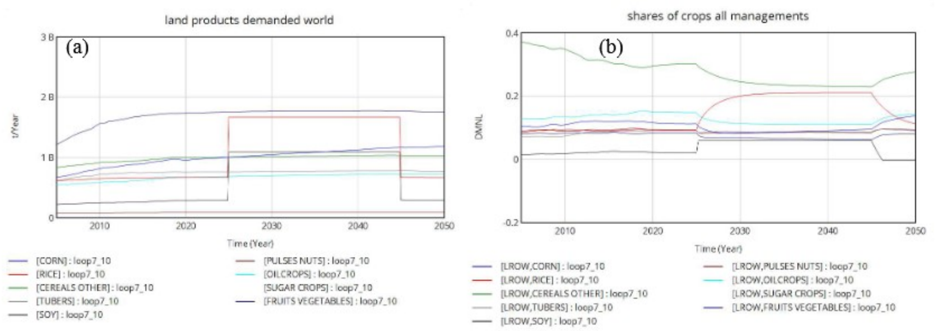

Figure G5: test of loop 7. (a) Demand of crops (global), (b) shares of crops (LROW).

Despite this huge increase of the demand of one crop the allocation mechanism based on the Dynamic Shares is very stable and the results of the allocation are the expected ones. With an increase 1000 times greater than the initial value and time step of 0.125 some problems arise, but not in the stability of the feedback loop, but on the stock of shares of crops that becomes negative. Since these conditions are very extreme, we can consider that this is a very stable and solid performance of the allocation mechanism and a very stable feedback loop.

In Figure G5 an increase of two crops is tested. In time 2025, the demand of RICE and SOY increase abruptly and in 2045 decreases abruptly. One can see that the shares of all the crops adapt at the same time to cope with these changes.

Test of loop 6

Loop 6 is related to cropland expansion due to crops shortage and its causal loop diagram is shown in Figure G6. Crops available (production) at world level are compared with crops demand to create the signal of availability of crops. If this availability grows, there is less demand of land to cropland, which ends up decreasing the production and the availability of crops. If the availability decreases the opposite is done: more land is assigned to crops production. This is, therefore, a stabilizing loop.

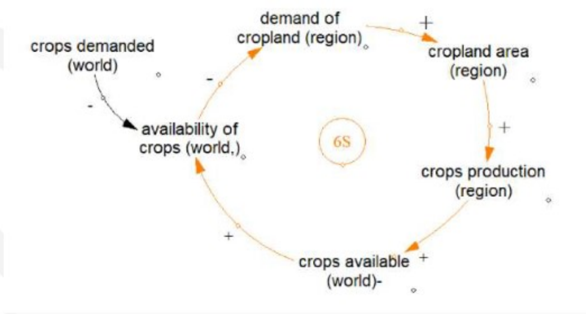

Figure G6: causal loop diagram of loop 6.

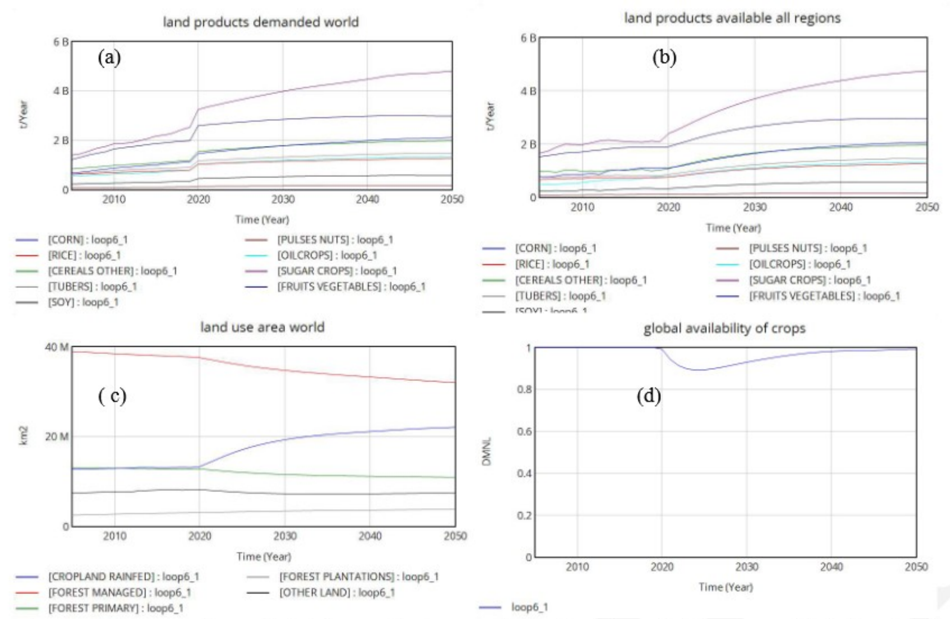

Figure G7: test of loop 6. (a) demand of crops (global), (b) available crops (global), (c) global land use area for several uses, (d) signal of global availability of crops (equals one if demand equals production, less than one means that there is shortage).

Loop 6 has been tested adding an abrupt change to *crops demanded*, in this case the same for all crops. The demands of biofuels, land for solar energy and biomass are left exogenous and, therefore, their feedbacks do not interact with this test. The effects of climate change on crop yields and the limits to cropland expansion have also been deactivated to test only loop 6 dynamics. The WILIAM-TERRA variable *Land products demanded world* (*crops demanded (world)* in Figure G6) changes abruptly in year 2020.

Figure G7 shows the results of a 30% increase of the demand of all crops in 2020. The demand of land products (a) increases more than the trend (given by the population increase) and the land products available (production) tries to follow it (b). Cropland expands in all the regions (c) at the expenses of other uses. The signal of global availability (d) of crops, that is equal to one when supply and demand match, becomes less than one in 2025 but tends to one when cropland increases.
Notice that land use changes are not fast, since the speed of land changes is limited by the model to the largest annual land use change observed in historical data which is 6%.
Figure G8 shows the results of a 30% reduction of the demand of all crops in 2020. The demand of land products (a) goes down initially, but latter grows because of the growth of population. The land products available follows it (b). Cropland decreases in all the regions (c) and other land uses gain area. The signal of global availability (d) of crops becomes positive because there is surplus of crops but tends to one when cropland decreases.

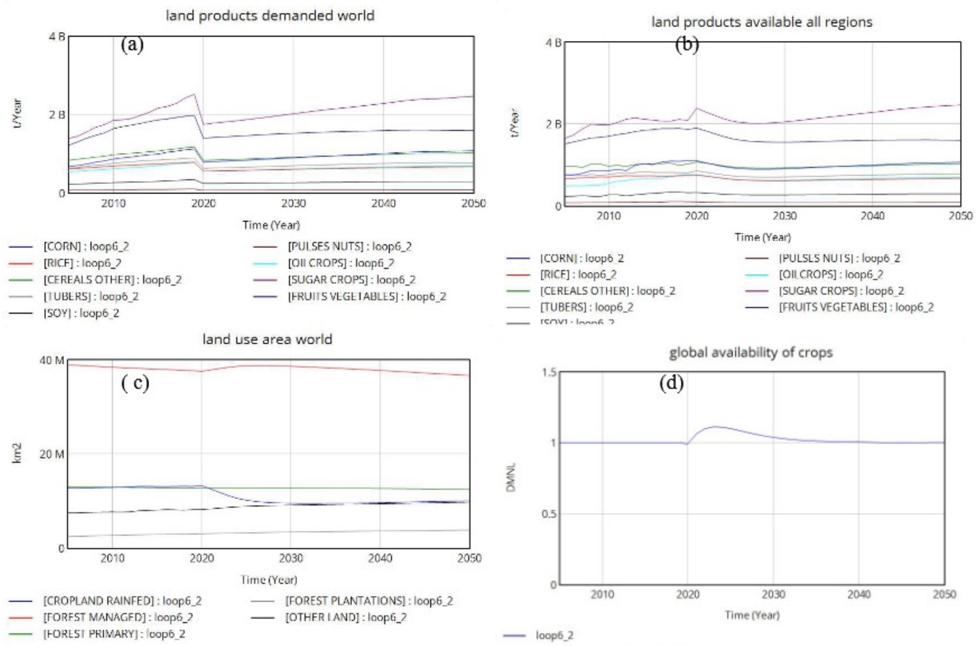

Figure G8: test of loop 6, 30% decrease of the demand. (a) demand of crops (global), (b) available crops (global), (c) global land use area for several uses, (d) signal of global availability of crops (equals one if demand equals production, less than one means that there is shortage).

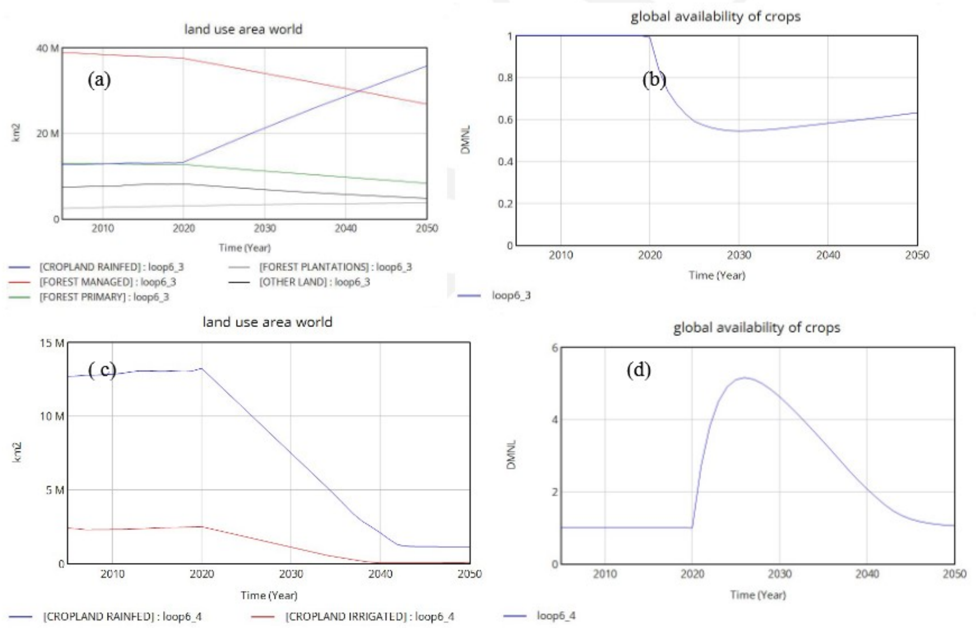

Figure G9: test of loop 6, extreme conditions. (a) global land use area for a three times increase of the demand of crops, (b) signal of global availability of crops, three times increase of the

Test of loops 1 and 2

The loops 1 and 2 are relative to climate change effects on crop yields and can be described by the feedback loop diagram of Figure G10. The increase of cropland area has two effects that increase the greenhouse gases emissions. The first one (loop 1) is due to the increase of the use of fertilizers for that cropland and the second (loop 2) is relative to the loss of forest and other land use changes needed to increase cropland. Both cause increase greenhouse gases emissions and increase the global temperature. Temperature increase tends to decrease agricultural yields at global scale, and, therefore, more cropland is required to meet the demand and more emissions are done. As one can see, these loops are reinforcing. Climate change effects in WILIAM-TERRA are calculated for each region and crop based on the data of [5] for three models (CCSM4, GFDL, and HadGEM_ES). In order to analyse these loops the results are compared with simulations with climate change effects but without feedback. For that purpose, a variable called SWITCH in Figure 9 is used. When SWITCH equals 1, climate change effects on yields are endogenous and depend on the temperature, therefore, the loop is activated; when it is 0 the climate change effects are exogenous.
Both loops 1 and 2 are very similar, since they both depend on the increase of cropland area and just add two different sources of greenhouse gases, therefore, they are analysed jointly.

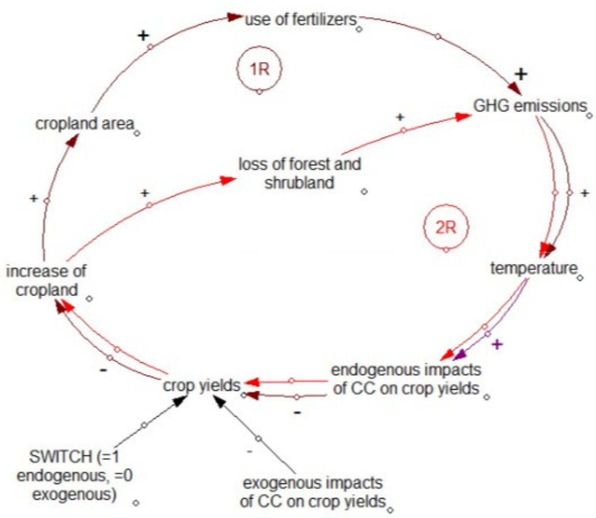

Figure G10: feedback loop diagram of loops 1 and 2.

In Figure G11 the results of three simulations are tested: "no_cc" is a run without climate change impacts on crop yields, "exo" is a run where the climate change effects on crops are exogenous and "endo" a run where climate change effects are endogenous (and create the feedback loops 1 and 2). They all use the HadGEM_ES model. The small "bumps" in the graphs of figure 10 are due to the climatic models used in [5].
One can see that the cropland area is larger with climate change effects Figure G11(c) and is slightly higher with the feedback loop activated ("endo") but the effect is extremely weak. The yields of the two crops where climate change effects are more evident are shown in Figure G11(a, b) and the figures show that the difference between the activation and deactivation of the feedback loop is negligible. The reason for this is that the temperature change in both cases is extremely small as well. Therefore, although the climate change impacts on yields create a reinforcing feedback loop, the effect of this loop is very wea. Using the climatic models that are most common in the literature, this loop cannot have an important change in the model nor create problems of instability. The other two models provided in [5] are also implemented in WILIAM-TERRA and their results are similar to those shown in Figure G11.

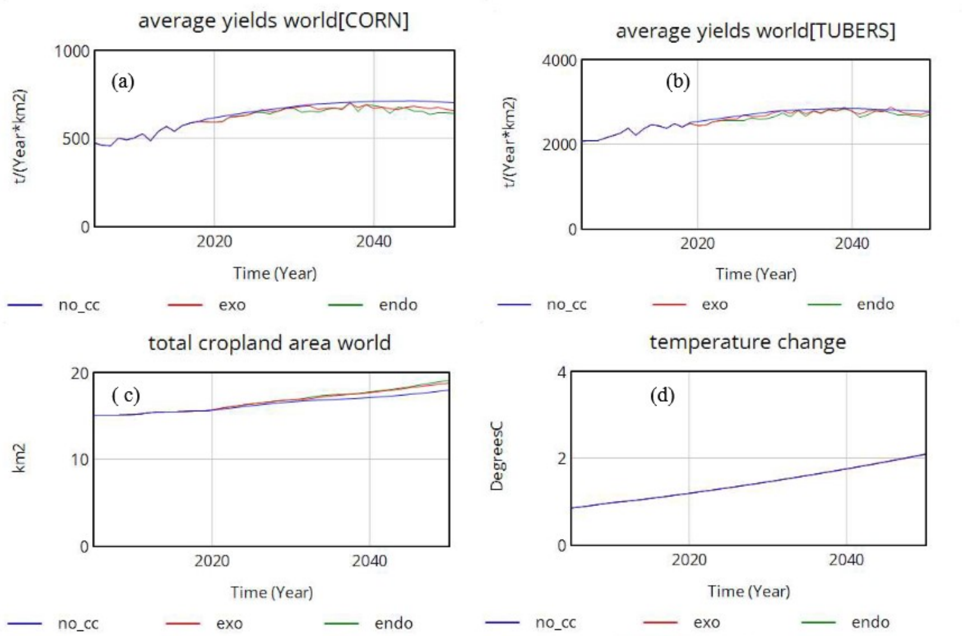

Figure G11. Test of loops 1 and 2. Exo=exogenous climate change effects on yields, endo=endogenous climate change effects on yields, no_cc= no climate change effects on yields. (a) average world yields for CORN, (b) average world yields for TUBERS, (c) total cropland area of the world, (d) global temperature change.

G.3 Other validation tests

Apart from the tests of loop stability and extreme conditions seen in previous section, some other structural tests have been performed to WILIAM-TERRA mode, following the methodology stated by Sterman [3] and Barlas [4].
The consistency of the units, the non-zero condition of variables that should not be zero such as land areas or crops production, the consistency of variables that represent shares or percentages (and should sum 1) and the correct evolution of all the policies of the whole WILIAM is constantly checked in a view of WILIAM model called Automatic Equations Check that detects those errors. In the release of WILIAM version 1.3 beta these errors were checked and reduced to zero. Figure G12 shows this Vensim view with the variables relative to TERRA module.

The standard time step used in the simulation of WILIAM model is 0.25 year and the Euler solver is normally used. This time step was elected to ensure a reasonable simulation time for all the model, given the heavy computing load of some of the modules (specially Economy). But WILIAM-TERRA module can be run isolated at much smaller simulation steps with a low computing time: using the smallest time step that Vensim provides (0.00781) the simulation time is less than 4 seconds with Euler integrator method and 40 seconds with Runge Kutta 4 fixed step solver.

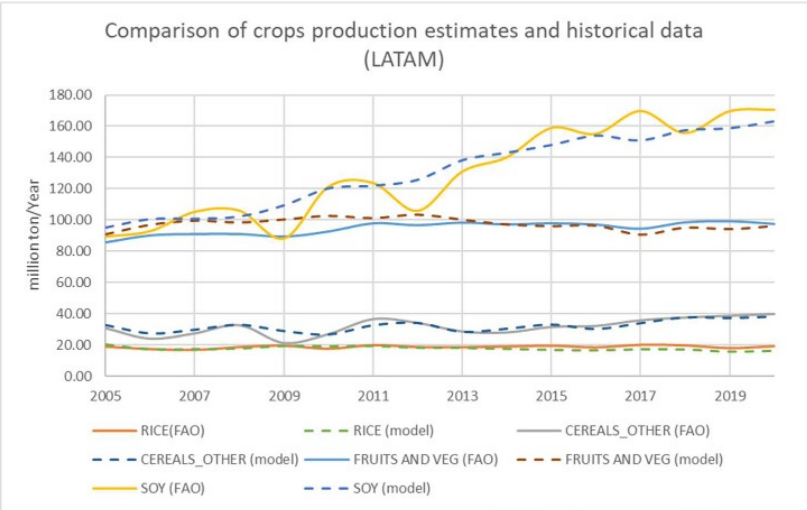

Figure G13. Comparison of the crops production in LATAM estimated by the model and the historical data obtained from FAO database.

Table G2: comparison of crops production calculated in the model and the historical data (average difference for all crops)

average difference (all crops)	
EU27	5.7%
UK	5.7%
CHINA	11.8%
EASOC	16.8%
INDIA	10.8%
LATAM	13.1%
RUSSIA	12.4%
USMCA	14.8%
LROW	12.5%

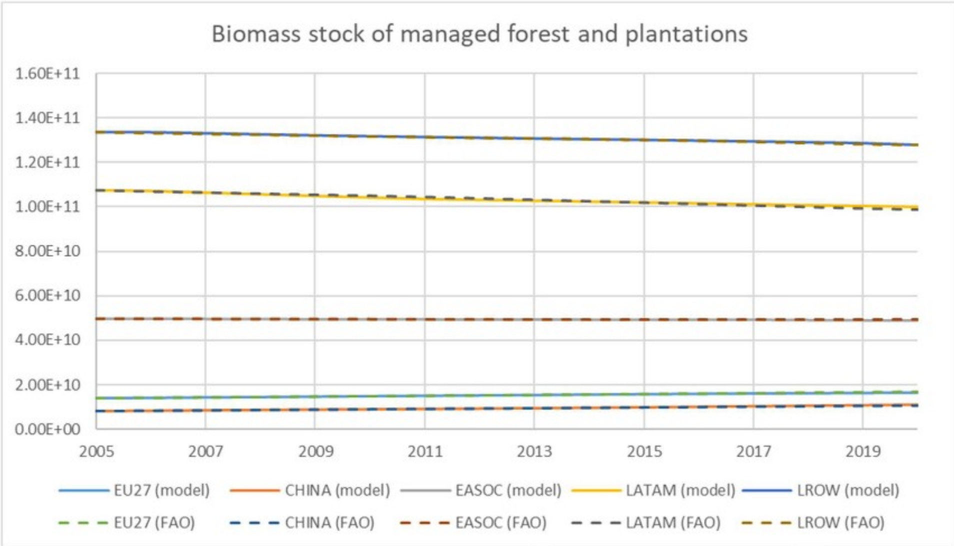

Figure G14. Comparison of the biomass stock of managed forests and plantations in several regions estimated by the model and the historical data obtained from FAO database.

Emissions

As explained in *Section 2.10 Emissions submodule* of the article, the model can calculate emissions related to the AFOLU sector, which allows to evaluate the effects of different policies in terms of mitigation. For these emissions, also, validation has been applied comparing the values with historical data. In particular:

- Global land use and land use change emissions (GtC): comparing it with historical information from the Global Carbon Budget (year 2023)[8]. This can be seen in Figure G15.

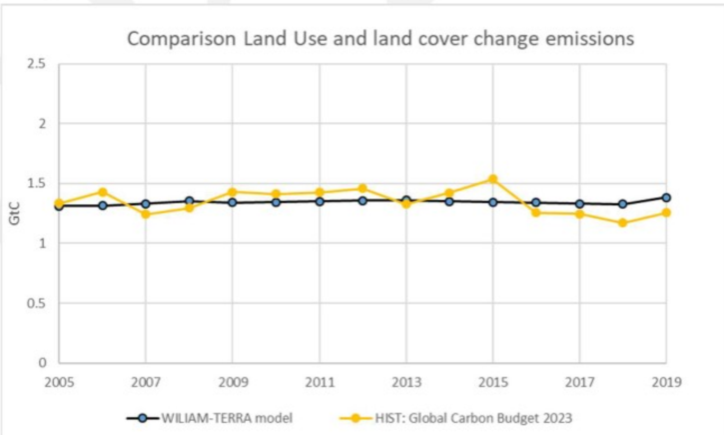

Figure G15. Comparison of the carbon emissions from land use and land use change estimated by the model and the historical data obtained from Global Carbon Budget 2023.

- Global agriculture emissions: the total emissions are compared with EDGAR database[9], but partially results from each of the subsectors are compared with historical national values of FAO (FAOSTAT database [7]) (adapted to the regions of WILIAM) . The values have an error less or around 10% on average.

- Partial outputs: Livestock emissions

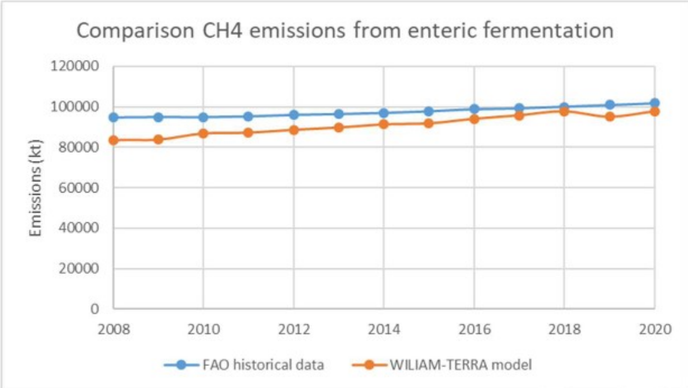

Figure G16. Comparison of the CH_4 emissions from enteric fermentation (livestock emissions) estimated by the model and the historical data obtained from FAO database.

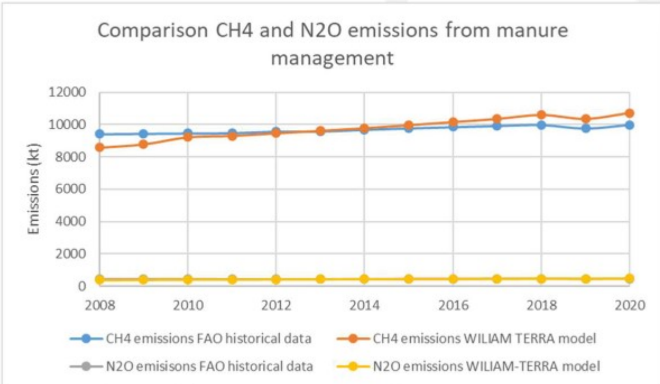

Figure G17. Comparison of the N_2O and CH_4 emissions from manure management (livestock emissions) estimated by the model and the historical data obtained from FAO database.

- Partial outputs: Fertilizers

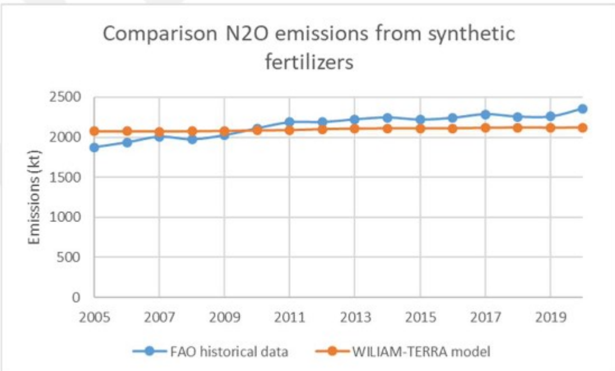

Figure G18. Comparison of the N_2O emissions from synthetic fertilizers estimated by the model and the historical data obtained from FAO database.

- Partial outputs: Rice cultivation

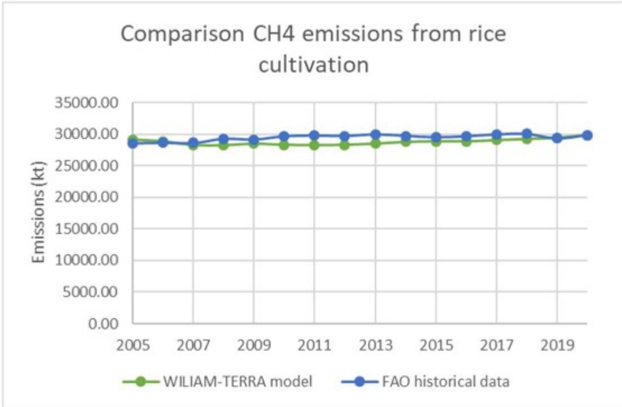

Figure G19. Comparison of the carbon emissions from rice cultivation estimated by the model and the historical data obtained from the FAO database.

G5. Calibration of the Land Uses submodule

The Land Uses submodule is the most complex part of the WILIAM-TERRA model and one of its most fundamental items, its numerical calibration is shown in this section. This section describes the obtention of the trends of the vector $Trends\ of\ \ LUC\ Demands\ (R_i, L_n)$ and the matrices of shares of land uses from other, $Share\ of\ LUC\ from\ Others\ (R_i, L_n, L_m)$, based on historical data and model calibration. The model is based on the hypothesis that there are some land use changes that are driven by demands, since they are economically or socially interesting (croplands, forests, grasslands, solar land, urban, etc.) while some other land uses are not demanded and only absorb the demand of the rest (other land and shrubland). In both cases, all the lands compete with each other and absorb the demand of other uses. Trend demands are calculated on the basis of historical land use trends, and in some cases have been adjusted to take account of evident changes in trends that cannot be extrapolated into the future (such as the loss of agricultural land in the EU in recent decades due to agricultural policies, which does not appear to be continuing).

WILIAM model spatial scale is global with a division in 9 large regions. Economic indicators such as prices or elasticities are hardly reliable at this level of aggregation, while the huge cultural and sociopolitical differences between world regions make it very difficult estimate the effect of detailed decarbonization policies. This is the reason why the approach of WILIAM-TERRA does not use demand and supply functions as the main drivers of land-use changes. Land use changes are driven by the continuation of observed trends and some basic demands plus the application of a wide range of policies. Thus, it is a policy evaluation model, not aimed at predicting the future, but at analysing the dynamic effects and interactions of a wide range of policies.

In future releases of the model, a GIS-based analysis is planned to be used to determine, based on historical data, the real historical shares of land use from other. This would determine what have really been the actual flows of land from one use to another and improve a lot the calibration of this model. In the meantime, this adjustment aims to stablish the most relevant trends of past land use changes for the most relevant uses.

It is assumed that the primary forest cannot be increased, since it is defined as very mature forests whose creation goes back to centuries ago. When forest primary increases in the historical data, we assume it is due to changes in definition and assume the greatest value as the initial one. Solar land is the land under photovoltaic and concentrated solar power electricity appliances, since its historical values are very low, we do not take it into account in the calibration. For solar land, the initial shares have been obtained applying Geographic Information Systems (GIS) techniques analyzing the allocation of current solar power capacity. This analysis has been done for each of the 9 regions of WILIAM-TERRA module and it is based on data processed from the “Global Database of Power Plants” combined with land cover data (see [5] for a complete description).

Table G3: Initial shares of land use changes from other as stated in [11]

INITIAL_SHARE_OF_CROPLAND_RAINFED_FORM_OTHER_LANDS_BY_REGION (REGIONS_I,LANDS_I)

LANDS_I	RAINFED	IRRIGATED	FOREST_MANAGED	FOREST_PRIMARY	FOREST_PLANTATIONS	SHRUBLAND	GRASSLAND	WETLAND	URBAN	SOLAR	SNOW_ICE_WATERBODIES	OTHER_LAND
REGIONS_I	[%]	[%]	[%]	[%]	[%]	[%]	[%]	[%]	[%]	[%]		[%]
EU27	0	0	0.8	0	0	0.12	0.06	0	0	0	0	0.02
UK	0	0	0.8	0	0	0.12	0.06	0	0	0	0	0.02
CHINA	0	0	0.44	0	0	0.16	0.25	0	0	0	0	0.16
EASOC	0	0	0.19	0.66	0	0.15	0.01	0	0	0	0	0.01
INDIA	0	0	0.18	0.3	0	0.24	0.18	0	0	0	0	0.11
LATAM	0	0	0.18	0.63	0	0.18	0.01	0	0	0	0	0
RUSSIA	0	0	0.2	0	0	0.52	0.25	0	0	0	0	0.04
USMCA	0	0	0.11	0.38	0	0.23	0.27	0	0	0	0	0
LROW	0	0	0.18	0.28	0	0.38	0.1	0	0	0	0	0.07

INITIAL_SHARE_OF_GRASSLAND_FORM_OTHER_LANDS_BY_REGION (REGIONS_I,L/ pondremos que grassland no tiene demanda salvo en LATAM

LANDS_I	RAINFED	IRRIGATED	FOREST_MANAGED	FOREST_PRIMARY	FOREST_PLANTATIONS	SHRUBLAND	GRASSLAND	WETLAND	URBAN	SOLAR	SNOW_ICE_WATERBODIES	OTHER_LAND
REGIONS_I	[%]	[%]	[%]	[%]	[%]	[%]	[%]	[%]	[%]	[%]		[%]
EU27	0	0	0	0	0	0	0	0	0	0	0	0
UK	0	0	0	0	0	0	0	0	0	0	0	0
CHINA	0	0	0	0	0	0	0	0	0	0	0	0
EASOC	0	0	0	0	0	0	0	0	0	0	0	0
INDIA	0	0	0	0	0	0	0	0	0	0	0	0
LATAM	0.34	0	0.12	0.44	0	0.04	0	0	0	0	0	0.05
RUSSIA	0	0	0	0	0	0	0	0	0	0	0	0
USMCA	0	0	0	0	0	0	0	0	0	0	0	0
LROW	0	0	0	0	0	0	0	0	0	0	0	0

INITIAL_SHARE_OF_FOREST_PLANTATIONS_FORM_OTHER_LANDS_BY_REGION (REGIONS_I,LANDS_I)

LANDS_I	RAINFED	IRRIGATED	FOREST_MANAGED	FOREST_PRIMARY	FOREST_PLANTATIONS	SHRUBLAND	GRASSLAND	WETLAND	URBAN	SOLAR	SNOW_ICE_WATERBODIES	OTHER_LAND
REGIONS_I	[%]	[%]	[%]	[%]	[%]	[%]	[%]	[%]	[%]	[%]		[%]
EU27	0.23	0	0.61	0	0	0.1	0.6	0	0	0	0	0
UK	0.23	0	0.61	0	0	0.1	0.6	0	0	0	0	0
CHINA	0.23	0	0.61	0	0	0.1	0.6	0	0	0	0	0
EASOC	0.23	0	0.61	0	0	0.1	0.6	0	0	0	0	0
INDIA	0.23	0	0.61	0	0	0.1	0.6	0	0	0	0	0
LATAM	0.23	0	0.61	0	0	0.1	0.6	0	0	0	0	0
RUSSIA	0.23	0	0.61	0	0	0.1	0.6	0	0	0	0	0
USMCA	0.23	0	0.61	0	0	0.1	0.6	0	0	0	0	0
LROW	0.23	0	0.61	0	0	0.1	0.6	0	0	0	0	0

INITIAL_SHARE_OF_NEW_URBAN_FORM_OTHER_LANDS_BY_REGION (REGIONS_I,LANDS_I)

LANDS_I	RAINFED	IRRIGATED	FOREST_MANAGED	FOREST_PRIMARY	FOREST_PLANTATIONS	SHRUBLAND	GRASSLAND	WETLAND	URBAN	SOLAR	SNOW_ICE_WATERBODIES	OTHER_LAND
REGIONS_I	[%]	[%]	[%]	[%]	[%]	[%]	[%]	[%]	[%]	[%]		[%]
EU27	0.75	0	0.08	0	0	0.04	0.06	0	0	0	0	0.06
UK	0.75	0	0.08	0	0	0.04	0.06	0	0	0	0	0.06
CHINA	0.76	0	0.03	0	0	0.06	0.14	0	0	0	0	0.02
EASOC	0.82950502	0	0.06475246	0	0	0.06306926	0.01297029	0	0	0	0	0.03
INDIA	0.84	0	0.03	0	0	0.07	0.05	0	0	0	0	0.01
LATAM	0.45	0	0.11	0	0	0.35	0.08	0	0	0	0	0.02
RUSSIA	0.67	0	0.08	0	0	0.12	0.09	0	0	0	0	0.04
USMCA	0.40465181	0	0.17046426	0	0	0.24418755	0.16313836	0	0	0	0	0.01244197
LROW	0.53574826	0	0.09093677	0	0	0.19739033	0.06602194	0	0	0	0	0.10978433

INITIAL SHARE_OF_NEW_SOLAR_FORM_OTHER_LANDS_BY_REGION (REGIONS_I,LANDS_I)

LANDS_I	RAINFED	IRRIGATED	FOREST_MANAGED	FOREST_PRIMARY	FOREST_PLANTATIONS	SHRUBLAND	GRASSLAND	WETLAND	URBAN	SOLAR	SNOW_ICE_WATERBODIES	OTHER_LAND
REGIONS_I	[%]	[%]	[%]	[%]	[%]	[%]	[%]	[%]	[%]	[%]		[%]
EU27	0.125	0	0	0	0	0.125	0.125	0	0	0	0	0.625
UK	0.125	0	0	0	0	0.125	0.125	0	0	0	0	0.625
CHINA	0.125	0	0	0	0	0.125	0.125	0	0	0	0	0.625
EASOC	0.125	0	0	0	0	0.125	0.125	0	0	0	0	0.625
INDIA	0.125	0	0	0	0	0.125	0.125	0	0	0	0	0.625
LATAM	0.125	0	0	0	0	0.125	0.125	0	0	0	0	0.625
RUSSIA	0.125	0	0	0	0	0.125	0.125	0	0	0	0	0.625
USMCA	0.125	0	0	0	0	0.125	0.125	0	0	0	0	0.625
LROW	0.125	0	0	0	0	0.125	0.125	0	0	0	0	0.625

These hypothesis of land use trends are used to calculate the land use changes taken from other uses in each simulation time step using initial values of the matrices of shares of land uses from other, ($Share\ of\ LUC\ from\ Others\ (R_i, L_n, L_m)$) obtained by the analysis of the literature described in [10], [11] (see Table G3) and the resulting land use changes are confronted to historical data. The discrepancy between estimated and historical data is used to accommodate the matrix $Share\ of\ LUC\ from\ Others\ (R_i, L_n, L_m)$. An initial computer calibration of these shares was done with Vensim Software calibration tools, but the final adjustment was made by hand, since the complexity of the task made automatic calibration worse than the human-made. The main efforts have been dedicated to the calibration of the most relevant and conflictive uses (croplands and forests), therefore the errors accumulate in shrubland and other land, whose historical data was not properly found (as described in section 3). Snow, ice and waterbodies and wetlands have not been calibrated at this stage of the model and they are left constant in the model.

EU27

In Table G4 one can see the historical trends of land use change in EU. EU27 has had a decrease of rainfed cropland that shows a stagnation in the last years and a similar growth of irrigated cropland that have been maintained. Forest primary grows in the historical data and has been accommodated to be zero, as explained in previous section. Shrubland, snow ice and waterbodies and other land are assumed to have no demand. The historical demand of plantations and urban is maintained. Managed forest demand is set equal to the value of annual deforestation recorded in FAO data. Grassland shows a significant loss that is coherent with the abandonment of extensive farming seen in the EU and is maintained with a small increase to adjust the rest of the uses. Table G5 shows the calibrated shares.
The error between the historical and the simulated land use areas after the calibration are shown in Figure G15. The average error is less than 0.4% and, although some land uses such as cropland rainfed and forest managed reach 4% in some years, this result is considered to be acceptable taking into account the big discrepancies that are always present in land use data at this level of aggregation.

Table G4. EU27 initial and calibrated land use trend demands

	RAINFED	IRRIGATED	FOREST_MANAGED	FOREST_PRIMARY	FOREST_PLANTATIONS	SHRUBLAND	GRASSLAND	WETLAND	URBAN	SOLAR	SNOW_ICE_WATERBODIES	OTHER_LAND
EU27 Initial trends of land demand (km2/Year)	-4471.5	517.9	-303.2	233.6	3515.1	749.0	-3280.0	0.0	691.9	0.0	23.6	2323.4
	RAINFED	IRRIGATED	FOREST_MANAGED	FOREST_PRIMARY	FOREST_PLANTATIONS	SHRUBLAND	GRASSLAND	WETLAND	URBAN	SOLAR	SNOW_ICE_WATERBODIES	OTHER_LAND
EU27 calibrated trends of land demand (km2/Year)	-4471.5	517.9	1127.0	0.0	3515.1	0,	-4000.0	0,	691.9	0.0	0.0	0.0

Table G5. EU27 calibrated matrices of shares of land use changes from others

Calibrated shares of land use changes from others (EU27)												
share of --> that comes from:	RAINFED	IRRIGATED	FOREST_MANAGED	FOREST_PRIMARY	FOREST_PLANTATIONS	SHRUBLAND	GRASSLAND	WETLAND	URBAN	SOLAR	SNOW_ICE_WATERBODIES	OTHER_LAND
RAINFED	0.00	1,	0.3,	0,	0.23	0,	0,	0,	0.75,	0.13,	0,	0;
IRRIGATED	0.00	0,	0,	0,	0.00	0,	0,	0,	0,	0,	0,	0;
FOREST_MANAGED	0.06	0,	0,	0,	0.61	0,	0,	0,	0.08,	0,	0,	0;
FOREST_PRIMARY	0.00	0,	0,	0,	0.00	0,	0,	0,	0,	0,	0,	0;
FOREST_PLANTATIONS	0.00	0,	0,	0,	0.00	0,	0,	0,	0,	0,	0,	0;
SHRUBLAND	0.80	0,	0.3,	0,	0.10	0,	0,	0,	0.04,	0.13,	0,	0;
GRASSLAND	0.12	0,	0.4,	0,	0.06	0,	0,	0,	0.06,	0.13,	0,	0;
WETLAND	0.00	0,	0,	0,	0.00	0,	0,	0,	0,	0,	0,	0;
URBAN	0.00	0,	0,	0,	0.00	0,	0,	0,	0,	0,	0,	0;
SOLAR	0.00	0,	0,	0,	0.00	0,	0,	0,	0,	0,	0,	0;
SNOW_ICE_WATERBODIES	0.00	0,	0,	0,	0.00	0,	0,	0,	0,	0,	0,	0;
OTHER_LAND	0.02	0,	0,	0,	0.00	0,	1,	0,	0.06,	0.63,	0,	0;

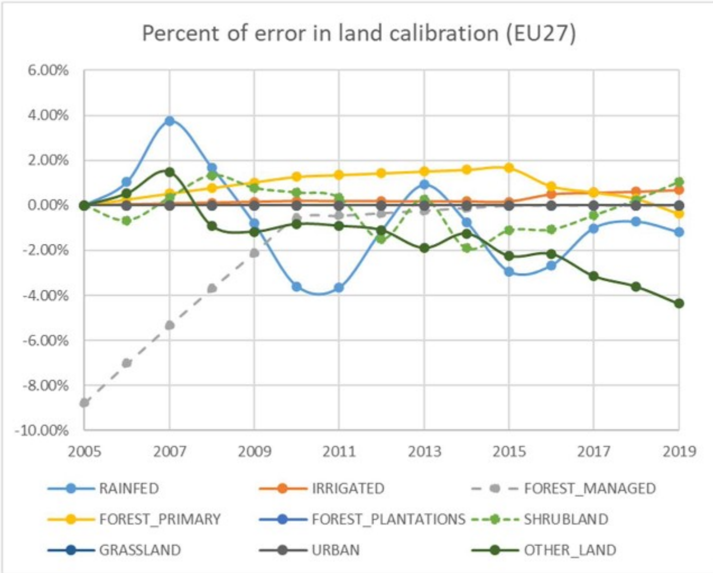

Figure G15. Percent of error between historical and simulated values of land uses in EU27 after the calibration.

UK

In Table G6 one can see the historical trends of land use change in UK. UK shows no significant change of forests and shrublands and loss of irrigated cropland (though the absolute value of irrigated cropland in UK is very small). Historical trends for cropland rainfed and plantations have been reduced a bit to adjust the loss of other land. Table G7 shows the calibrated shares. In general, land use changes are small in UK and the error between the historical and the simulated land use areas after the calibration are less than 6% for most land uses (Figure G16). The relative error of cropland irrigated is not considered important because the small area of this land use in UK makes it negligigle.

Table G6. UK initial and calibrated land use trend demands

	RAINFED	IRRIGATED	FOREST_MANAGED	FOREST_PRIMARY	FOREST_PLANTATIONS	SHRUBLAND	GRASSLAND	WETLAND	URBAN	SOLAR	SNOW_ICE_WATERBODIES	OTHER_LAND
UK Initial trends of land demand (km2/Year)	352.0	-98.0	0.0	0.0	125.0	0.0	150.0	0.0	12.0	0.0	-1.0	-540.0
UK calibrated trends of land demand (km2/Year)	254.0	0.0	0.0	0.0	94.0	0.0	0.0	0.0	12.4	0.0	0.0	0.0

Table G7. UK calibrated matrices of shares of land use changes from others

Calibrated shares of land use changes from others (UK)												
share of --> that comes from:	RAINFED	IRRIGATED	FOREST_MANAGED	FOREST_PRIMARY	FOREST_PLANTATIONS	SHRUBLAND	GRASSLAND	WETLAND	URBAN	SOLAR	SNOW_ICE_WATERBODIES	OTHER_LAND
RAINFED	0.00	1.00	0.30	0.00	0.30	0.00	0.00	0.00	0.75	0.45	0.00	0.00
IRRIGATED	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
FOREST_MANAGED	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.00	0.00
FOREST_PRIMARY	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
FOREST_PLANTATIONS	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.00	0.00
SHRUBLAND	0.92	0.00	0.30	0.00	0.30	0.00	0.00	0.00	0.13	0.12	0.00	0.00
GRASSLAND	0.06	0.00	0.40	0.00	0.40	0.00	0.00	0.00	0.06	0.40	0.00	0.00
WETLAND	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
URBAN	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
SOLAR	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
SNOW_ICE_WATERBODIES	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
OTHER_LAND	0.02	0.00	0.00	0.00	0.00	0.00	1.00	0.00	0.06	0.00	0.00	0.00

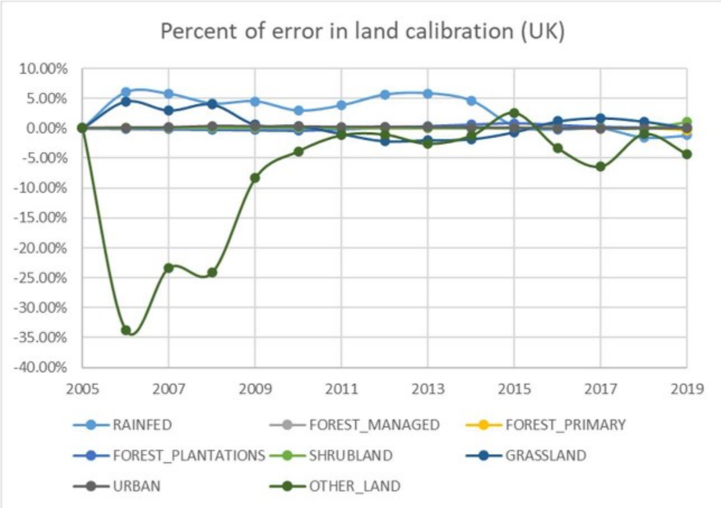

Figure G16. Percent of error between historical and simulated values of land uses in UK after the calibration.

CHINA

In Table G8 one can see the historical trends of land use change in China. China shows a large increase of forests, plantations and croplands that seems to come from other land. Irrigated land is much larger than in other regions. Urban expansion is large and irrigated land demand is increased to cope with the demands from urban. Table G9 shows the calibrated shares and the error between the historical and the simulated land use areas after the calibration are shown in Figure G17. The average error is less than 6% for all uses.

Table G8. China initial and calibrated land use trend demands

	RAINFED	IRRIGATED	FOREST_MANAGED	FOREST_PRIMARY	FOREST_PLANTATIONS	SHRUBLAND	GRASSLAND	WETLAND	URBAN	SOLAR	SNOW_ICE_WATERBODIES	OTHER_LAND
China Initial trends of land demand (km2/Year)	1336.0	0.0	6991.0	0.0	13933.0	-29.0	0.0	0.0	3876.0	0.0	149.0	-26256.0
China calibrated trends of land demand (km2/Year)	4772.1	49056.1	6990.6	0.0	13933.1	0.0	0.0	0.0	3875.9	0.0	0.0	0.0

Table G9. China calibrated matrices of shares of land use changes from others

Calibrated shares of land use changes from others (China)												
share of --> that comes from:	RAINFED	IRRIGATED	FOREST_MANAGED	FOREST_PRIMARY	FOREST_PLANTATIONS	SHRUBLAND	GRASSLAND	WETLAND	URBAN	SOLAR	SNOW_ICE_WATERBODIES	OTHER_LAND
RAINFED	0.00	1.00	0.00	0.00	0.00	0.00	0.00	0.00	0.76	0.15	0.00	0.00
IRRIGATED	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.00	0.00
FOREST_MANAGED	0.40	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.03	0.01	0.00	0.00
FOREST_PRIMARY	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
FOREST_PLANTATIONS	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.00	0.00
SHRUBLAND	0.60	0.00	0.50	0.00	0.50	0.00	0.00	0.00	0.20	0.04	0.00	0.00
GRASSLAND	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.09	0.00	0.00
WETLAND	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
URBAN	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
SOLAR	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
SNOW_ICE_WATERBODIES	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.04	0.00	0.00
OTHER_LAND	0.00	0.00	0.50	0.00	0.50	0.00	1.00	0.00	0.01	0.65	0.00	0.00

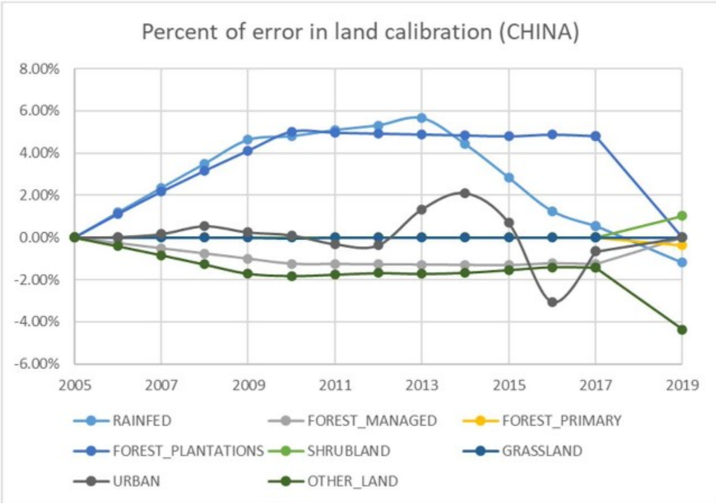

Figure G17. Percent of error between historical and simulated values of land uses in China after the calibration.

EASOC

In Table G10 one can see the historical trends of land use change in EASOC. Both croplands experiment important increases that seem to be compensated with the decrease of forest managed and primary. Table G11 shows the calibrated shares.

The error between the historical and the simulated land use areas after the calibration are shown in Figure G18. There is a relevant error for shrubland and other land that we cannot compensate with the calibration. It seems to come from the fact that shrubland and other land areas have not been obtained from real historical data but from and approximation (assuming constant proportions between them) and this assumption might not hold. In any case, these uses are of very little importance for out model.

Table G10. EASOC initial and calibrated land use trend demands

	RAINFED	IRRIGATED	FOREST_MANAGED	FOREST_PRIMARY	FOREST_PLANTATIONS	SHRUBLAND	GRASSLAND	WETLAND	URBAN	SOLAR	SNOW_ICE_WATERBODIES	OTHER_LAND
EASOC Initial trends of land demand (km2/Year)	15692.0	-155.0	-6669.0	-1477.0	3309.0	466.0	-38165.0	0.0	1341.0	0.0	-53.0	25710.0
EASOC calibrated trends of land demand (km2/Year)	15691.9	-155.0	0.0	0.0	3640.3	0.0	-30532.3	0.0	1341.3	0.0	0.0	0.0

Table G11. EASOC calibrated matrices of shares of land use changes from others

Calibrated shares of land use changes from others (EASOC)												
share of --> that comes from:	RAINFED	IRRIGATED	FOREST_MANAGED	FOREST_PRIMARY	FOREST_PLANTATIONS	SHRUBLAND	GRASSLAND	WETLAND	URBAN	SOLAR	SNOW_ICE_WATERBODIES	OTHER_LAND
RAINFED	0.00	1.00	0.30	0.00	0.30	0.00	0.00	0.00	0.75	0.63	0.00	0.00
IRRIGATED	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.09	0.00	0.00
FOREST_MANAGED	0.40	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.08	0.06	0.00	0.00
FOREST_PRIMARY	0.14	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
FOREST_PLANTATIONS	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.06	0.00	0.00
SHRUBLAND	0.46	0.00	0.30	0.00	0.30	0.00	0.00	0.00	0.04	0.06	0.00	0.00
GRASSLAND	0.00	0.00	0.40	0.00	0.40	0.00	0.00	0.00	0.06	0.08	0.00	0.00
WETLAND	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
URBAN	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
SOLAR	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
SNOW_ICE_WATERBODIES	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.00	0.00
OTHER_LAND	0.00	0.00	0.00	0.00	0.00	0.00	1.00	0.00	0.07	0.02	0.00	0.00

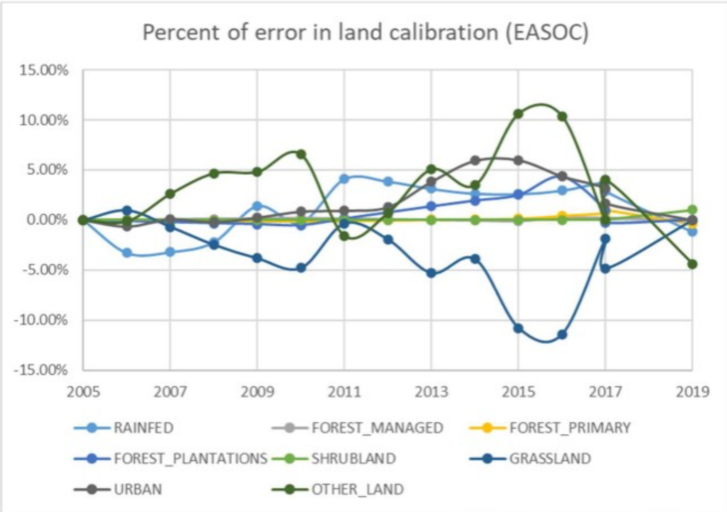

Figure G18. Percent of error between historical and simulated values of land uses in EASOC after the calibration.

INDIA

In Table G12 one can see the historical trends of land use change in India. Table G13 shows the calibrated shares. India shows an important growth of irrigated cropland and plantations that seems to come from rainfed cropland. The error between the historical and the simulated land use areas after the calibration are shown in Figure G19. The error found in forest plantations is due to the fact that we are assuming linear

Table G12. India initial and calibrated land use trend demands

	RAINFED	IRRIGATED	FOREST_MANAGED	FOREST_PRIMARY	FOREST_PLANTATIONS	SHRUBLAND	GRASSLAND	WETLAND	URBAN	SOLAR	SNOW_ICE_WATERBODIES	OTHER_LAND
INDIA Initial trends of land demand (km2/Year)	-6036.0	5781.0	860.0	0.0	1533.0	-71.0	-136.0	0.0	708.0	0.0	169.0	-2808.0
INDIA calibrated trends of land demand (km2/Year)	-3500.4	5781.4	484.0	0.0	1533.1	0.0	-136.4	0.0	708.1	0.0	0.0	0.0

Table G13. India calibrated matrices of shares of land use changes from others

Calibrated shares of land use changes from others (INDIA)												
share of --> that comes from:	RAINFED	IRRIGATED	FOREST_MANAGED	FOREST_PRIMARY	FOREST_PLANTATIONS	SHRUBLAND	GRASSLAND	WETLAND	URBAN	SOLAR	SNOW_ICE_WATERBODIES	OTHER_LAND
RAINFED	0.00	1.00	0.30	0.00	0.30	0.00	0.00	0.00	0.84	0.13	0.00	0.00
IRRIGATED	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.39	0.00	0.00
FOREST_MANAGED	0.18	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.03	0.01	0.00	0.00
FOREST_PRIMARY	0.30	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
FOREST_PLANTATIONS	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.00	0.00
SHRUBLAND	0.24	0.00	0.30	0.00	0.30	0.00	0.00	0.00	0.07	0.08	0.00	0.00
GRASSLAND	0.18	0.00	0.40	0.00	0.40	0.00	0.00	0.00	0.05	0.23	0.00	0.00
WETLAND	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
URBAN	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
SOLAR	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
SNOW_ICE_WATERBODIES	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.00	0.00
OTHER_LAND	0.10	0.00	0.00	0.00	0.00	0.00	1.00	0.00	0.01	0.14	0.00	0.00

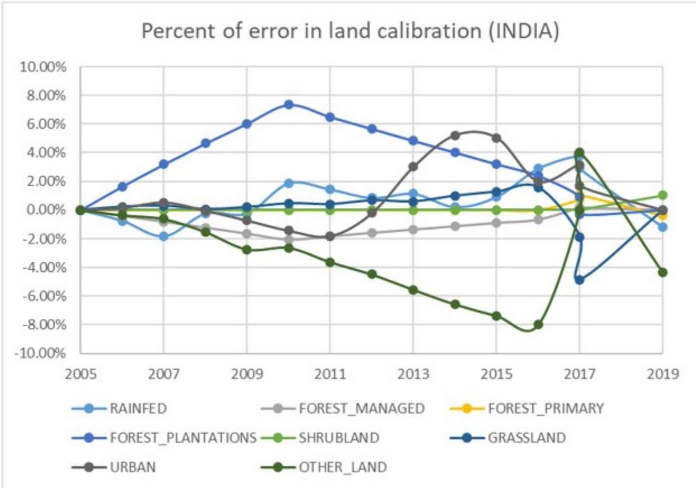

Figure G19. Percent of error between historical and simulated values of land uses in India after the calibration.

LATAM

In Table G14 one can see the historical trends of land use change in LATAM. LATAM shows a destruction of forest and grasslands that is only partially compensated by the expansion of cropland. The rest of the loss of grassland and forest has to be compensated with negative demand of these land uses. This would correspond to deforestation or desertification due to causes not related to cropland expansion (probably mining, logging, desertification and other factors).
Table G15 shows the calibrated shares. The error between the historical and the simulated land use areas after the calibration are shown in Figure G20. The large error in other land cannot be compensated, it is probably due to the fact that shrubland and other land areas have not been obtained from real historical data but from and approximation (assuming constant proportions between them) and this assumption might not hold. In any case, these uses are of very little importance for out model.

Table G14. LATAM initial and calibrated land use trend demands

	RAINFED	IRRIGATED	FOREST_MANAGED	FOREST_PRIMARY	FOREST_PLANTATIONS	SHRUBLAND	GRASSLAND	WETLAND	URBAN	SOLAR	SNOW_ICE_WATERBODIES	OTHER_LAND
LATAM Initial trends of land demand (km2/Year)	4795.0	1933.0	-32820.0	0.0	4762.0	401.0	-10665.0	0.0	631.0	0.0	-114.0	33804.0
LATAM calibrated trends of land demand (km2/Year)	8000.3	1932.5	-30000.0	0.0	4761.9	0.0	-10000.0	0.0	631.3	0.0	0.0	0.0

Table G15. LATAM calibrated matrices of shares of land use changes from others

Calibrated shares of land use changes from others (LATAM)												
share of --> that comes from:	RAINFED	IRRIGATED	FOREST_MANAGED	FOREST_PRIMARY	FOREST_PLANTATIONS	SHRUBLAND	GRASSLAND	WETLAND	URBAN	SOLAR	SNOW_ICE_WATERBODIES	OTHER_LAND
RAINFED	0.00	1.00	0.00	0.00	0.00	0.00	0.34	0.00	0.45	0.11	0.00	0.00
IRRIGATED	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
FOREST_MANAGED	0.18	0.00	0.00	0.00	0.00	0.00	0.13	0.00	0.11	0.00	0.00	0.00
FOREST_PRIMARY	0.63	0.00	0.00	0.00	0.00	0.00	0.44	0.00	0.00	0.00	0.00	0.00
FOREST_PLANTATIONS	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
SHRUBLAND	0.18	0.00	0.90	0.00	0.90	0.00	0.04	0.00	0.35	0.01	0.00	0.00
GRASSLAND	0.01	0.00	0.10	0.00	0.10	0.00	0.00	0.00	0.08	0.01	0.00	0.00
WETLAND	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
URBAN	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
SOLAR	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
SNOW_ICE_WATERBODIES	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
OTHER_LAND	0.00	0.00	0.00	0.00	0.00	0.00	0.05	0.00	0.01	0.87	0.00	0.00

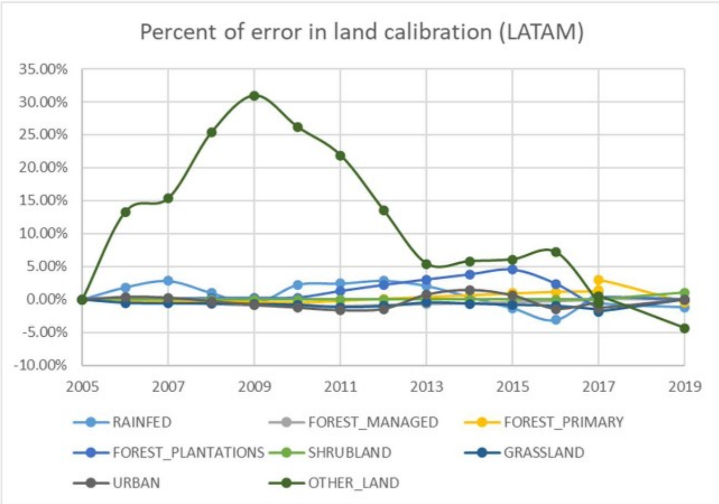

Figure G20. Percent of error between historical and simulated values of land uses in LATAM after the calibration.

RUSSIA

In Table G16 one can see the historical trends of land use change in Russia. Land areas vary very little in Russia. Table G17 shows the calibrated shares. The error between the historical and the simulated land use areas after the calibration are shown in Figure G21. Although the relative error forest plantations reaches 8%, its absolute value is very small and reaches no significance.

Table G16. Russia initial and calibrated land use trend demands

	RAINFED	IRRIGATED	FOREST_MANAGED	FOREST_PRIMARY	FOREST_PLANTATIONS	SHRUBLAND	GRASSLAND	WETLAND	URBAN	SOLAR	SNOW_ICE_WATERBODIES	OTHER_LAND
RUSSIA Initial trends of land demand (km2/Year)	63.0	-162.0	1226.0	0.0	995.0	7507.0	-34.0	0.0	341.0	0.0	-509.0	-9427.0
RUSSIA calibrated trends of land demand (km2/Year)	62.9	-162.1	1225.8	1404.0	1100.0	0.0	0.0	0.0	341.1	0.0	0 0	0.0

Table G17. Russia calibrated matrices of shares of land use changes from others

Calibrated shares of land use changes from others (RUSSIA)												
share of --> that comes from:	RAINFED	IRRIGATED	FOREST_MANAGED	FOREST_PRIMARY	FOREST_PLANTATIONS	SHRUBLAND	GRASSLAND	WETLAND	URBAN	SOLAR	SNOW_ICE_WATERBODIES	OTHER_LAND
RAINFED	0.00	1.00	0.00	0.00	0.00	0.00	0.00	0.00	0.67	0.64	0.00	0.00
IRRIGATED	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
FOREST_MANAGED	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.08	0.03	0.00	0.00
FOREST_PRIMARY	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
FOREST_PLANTATIONS	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.03	0.00	0.00
SHRUBLAND	0.50	0.00	0.50	0.00	0.50	0.00	0.00	0.00	0.12	0.02	0.00	0.00
GRASSLAND	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.09	0.02	0.00	0.00
WETLAND	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
URBAN	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
SOLAR	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
SNOW_ICE_WATERBODIES	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
OTHER_LAND	0.50	0.00	0.50	0.00	0.50	0.00	1.00	0.00	0.04	0.26	0.00	0.00

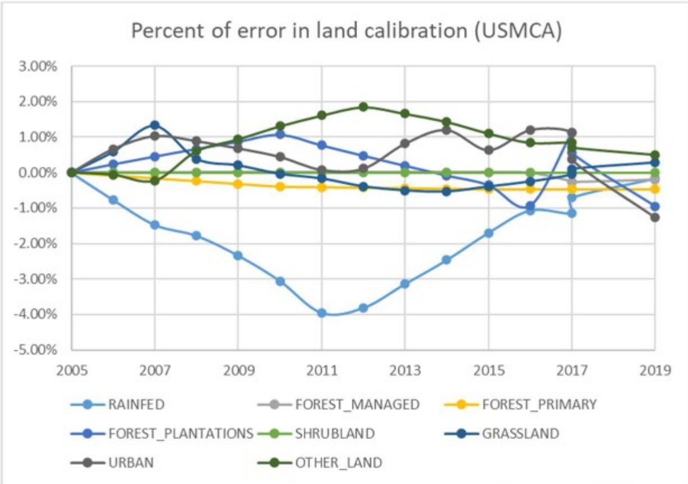

Figure G22. Percent of error between historical and simulated values of land uses in USMCA after the calibration.

LROW

In Table G21 one can see the historical trends of land use change in LROW, that shows a large cropland expansion that can explain the losses of managed and primary forests. Table G22 shows the calibrated shares. The errors are below 6% and can be assumed. Figure G23 shows the percent of error.

Table G21. LROW initial and calibrated land use trend demands

	RAINFED	IRRIGATED	FOREST_MANAGED	FOREST_PRIMARY	FOREST_PLANTATIONS	SHRUBLAND	GRASSLAND	WETLAND	URBAN	SOLAR	SNOW_ICE_WATERBODIES	OTHER_LAND
LROW Initial trends of land demand (km2/Year)	28841.0	-7048.0	-50912.0	-12302.0	3430.0	-4258.0	-25336.0	0.0	2872.0	0.0	-2231.0	66945.0
LROW calibrated trends of land demand (km2/Year)	14000.0	-7048.2	-37000.0	-7000.0	3429.7	0.0	-20000.0	0.0	2872.4	0.0	0.0	0.0

Table G22. LROW calibrated matrices of shares of land use changes from others

Calibrated shares of land use changes from others (LROW)												
share of --> that comes from:	RAINFED	IRRIGATED	FOREST_MANAGED	FOREST_PRIMARY	FOREST_PLANTATIONS	SHRUBLAND	GRASSLAND	WETLAND	URBAN	SOLAR	SNOW_ICE_WATERBODIES	OTHER_LAND
RAINFED	0.00	1.00	1.00	1.00	0.30	0.30	0.00	0.00	0.00	0.00	0.00	0.00
IRRIGATED	1.00	0.00	0.00	0.00	0.54	0.54	0.08	0.08	0.00	0.00	0.00	0.00
FOREST_MANAGED	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
FOREST_PRIMARY	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
FOREST_PLANTATIONS	0.70	0.70	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
SHRUBLAND	0.00	0.00	0.00	0.00	0.09	0.09	0.02	0.02	0.00	0.00	0.00	0.00
GRASSLAND	0.30	0.30	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
WETLAND	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
URBAN	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
SOLAR	0.00	0.00	0.00	0.00	0.00	0.00	0.02	0.02	0.00	0.00	0.00	0.00
SNOW_ICE_WATERBODIES	0.00	0.00	0.00	0.00	0.30	0.30	0.00	0.00	0.00	0.00	0.00	0.00
OTHER_LAND	0.00	0.00	0.00	0.00	0.20	0.20	0.08	0.08	0.00	0.00	0.00	0.00

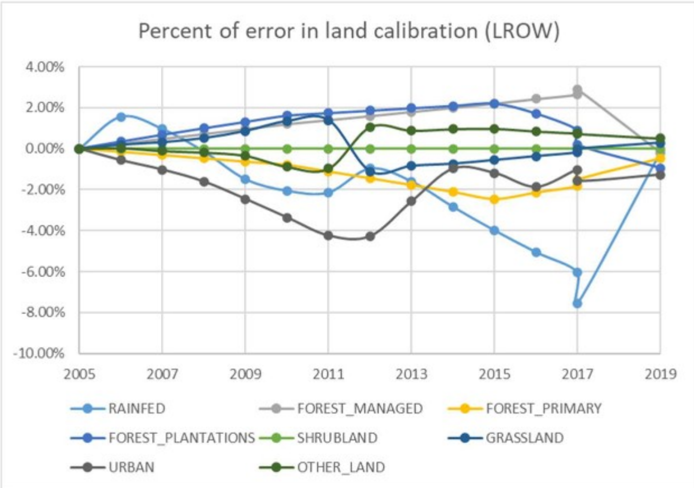

Figure G23. Percent of error between historical and simulated values of land uses in LROW after the calibration.

The future trends of land expansion used in the model when the historical period ends are not necessarily the same as the historical ones, since some uses show clear rupture of the past trends. The trends used after the historical data are shown in table G23. Table G24 shows the historical data of land uses for all the regions. Figure G24 shows that evolution of land uses in the first years after the historical period (that ends in 2020) in an scenario of continuation of trends. One can see that the trends of land evolution of past years are maintained.

Table G23. Trends of land expansion used in the simulation of the model after the historical period

TRENDS OF FUTURE LAND DEMAND BY REGION	RAINFED	IRRIGATED	FOREST_MANAGED	FOREST_PRIMARY	FOREST_PLANTATIONS	SHRUBLAND	GRASSLAND	WETLAND	URBAN	SOLAR	SNOW_ICE_WATERBODIES	OTHER_LAND
REGIONS_I|LANDS_I	[Mm2/Year	[Mm2/Year]	[Mm2/Year]	[Mm2/Year]	[Mm2/Year	[Mm2/Y	[Mm2/Y	[Mm2/Y	[Mm2/Ye	[Mm2/Ye	[Mm2/Year]	[Mm2/Yea
EU27	0	0	0.00112702	0	0.003515	0	0	0	0.0007	0	0	0
UK	0	0	0	0	0.000125	0	0	0	1E-05	0	0	0
CHINA	0.004	0.00342736	0.01	0	0.013933	0	0	0	0.0039	0	0	0
EASOC	0.015551	9.0001E-05	0	0	0.00364	0	0	0	0.0013	0	0	0
INDIA	0	0	0.000484	0	0.001533	0	0	0	0.0007	0	0	0
LATAM	0.008	0.00193252	-0.03	0	0.004762	0	0	0	0.0006	0	0	0.04
RUSSIA	6.29E-05	-0.0001621	0.00122584	0.001404	0.0011	0	0	0	0.0003	0	0	0
USMCA	0	0.00074409	0	-0.001057	0.006813	0	0	0	0.0021	0	0	0
LROW	0.028841	0	-0.0509123	-0.012302	0.001715	0	0	0	0.0029	0	0	0.044

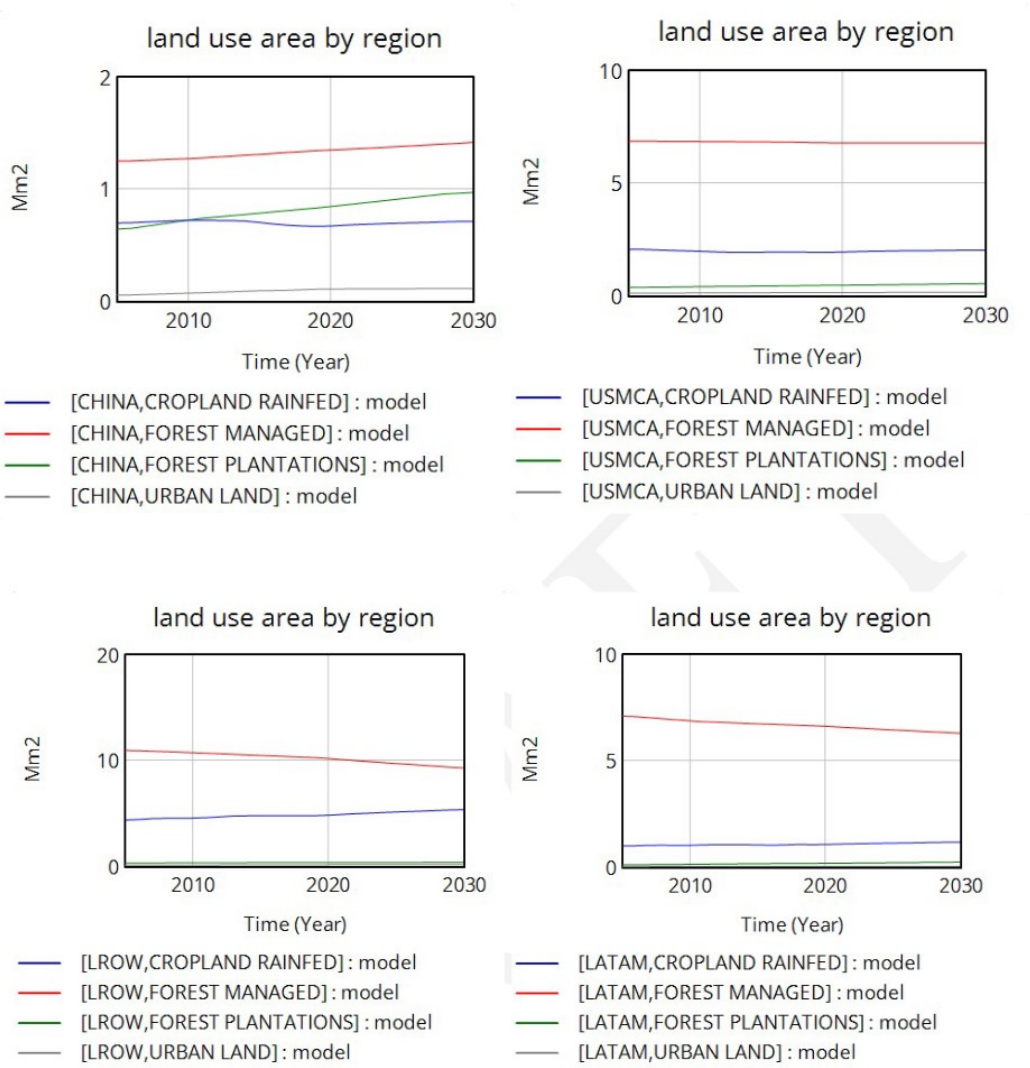

Figure G24: Evolution of the most relevant land uses in several regions. Results are calculated by the model after 2020, before that year historical data are shown.

TableG 24: historical values of land use per region

LANDS_I	CROPLAND RAINFED									
		EU27	UK	CHINA	EASOC	INDIA	LATAM	RUSSIA	USMCA	LROW
Year		1.064	0.056	0.695	1.186	1.105	0.982	1.191	2.055	4.358
2005	[Mm2]	1.053	0.060	0.701	1.162	1.086	1.007	1.189	2.030	4.487
2006	[Mm2]	1.026	0.060	0.707	1.176	1.065	1.023	1.190	2.006	4.520
2007	[Mm2]	1.034	0.059	0.713	1.201	1.071	1.010	1.192	1.991	4.530
2008	[Mm2]	1.034	0.060	0.719	1.259	1.061	0.999	1.192	1.971	4.528
2009	[Mm2]	1.026	0.059	0.718	1.251	1.073	1.034	1.192	1.948	4.562
2010	[Mm2]	1.021	0.060	0.718	1.323	1.058	1.042	1.192	1.922	4.617
2011	[Mm2]	1.023	0.062	0.717	1.333	1.041	1.053	1.192	1.915	4.729

2012	[Mm2]	1.011	0.063	0.717	1.337	1.033	1.050	1.192	1.918	4.758
2013	[Mm2]	1.011	0.062	0.705	1.345	1.013	1.038	1.192	1.922	4.759
2014	[Mm2]	1.011	0.060	0.691	1.358	1.010	1.027	1.192	1.927	4.764
2015	[Mm2]	1.005	0.060	0.678	1.377	1.020	1.014	1.192	1.929	4.772
2016	[Mm2]	1.002	0.061	0.671	1.403	1.020	1.064	1.192	1.918	4.784
2017	[Mm2]	0.997	0.060	0.666	1.404	1.020	1.052	1.192	1.917	4.773
2018	[Mm2]	1.001	0.061	0.662	1.406	1.020	1.050	1.192	1.912	4.761
2019	[Mm2]									

CROPLAND IRRIGATED

Year		EU27	UK	CHINA	EASOC	INDIA	LATAM	RUSSIA	USMCA	LROW
2005	[Mm2]	0.105	0.002	0.635	0.056	0.592	0.073	0.045	0.291	0.609
2006	[Mm2]	0.107	0.002	0.635	0.057	0.608	0.073	0.044	0.291	0.476
2007	[Mm2]	0.111	0.001	0.635	0.051	0.627	0.076	0.044	0.290	0.477
2008	[Mm2]	0.109	0.001	0.635	0.051	0.623	0.078	0.042	0.286	0.479
2009	[Mm2]	0.107	0.001	0.635	0.051	0.636	0.080	0.042	0.287	0.479
2010	[Mm2]	0.104	0.001	0.635	0.052	0.619	0.082	0.042	0.291	0.485
2011	[Mm2]	0.105	0.001	0.635	0.053	0.636	0.084	0.042	0.298	0.480
2012	[Mm2]	0.108	0.001	0.635	0.055	0.653	0.088	0.042	0.291	0.484
2013	[Mm2]	0.111	0.000	0.635	0.058	0.661	0.091	0.042	0.294	0.481
2014	[Mm2]	0.109	0.001	0.645	0.058	0.681	0.094	0.042	0.297	0.491
2015	[Mm2]	0.107	0.001	0.659	0.056	0.684	0.096	0.042	0.299	0.496
2016	[Mm2]	0.108	0.001	0.671	0.056	0.673	0.098	0.042	0.300	0.501
2017	[Mm2]	0.110	0.001	0.678	0.057	0.673	0.100	0.042	0.302	0.498
2018	[Mm2]	0.111	0.001	0.683	0.057	0.673	0.100	0.042	0.302	0.507
2019	[Mm2]	0.113	0.001	0.687	0.054	0.673	0.100	0.042	0.302	0.511

FOREST MANAGED

Year		EU27	UK	CHINA	EASOC	INDIA	LATAM	RUSSIA	USMCA	LROW
2005	[Mm2]	1.065	0.003	1.247	3.146	0.575	7.084	7.947	6.855	10.933
2006	[Mm2]	1.064	0.003	1.252	3.140	0.573	7.034	7.949	6.851	10.885
2007	[Mm2]	1.064	0.003	1.258	3.134	0.572	6.984	7.950	6.847	10.837
2008	[Mm2]	1.063	0.003	1.263	3.128	0.570	6.934	7.952	6.842	10.789
2009	[Mm2]	1.063	0.003	1.268	3.122	0.569	6.885	7.954	6.838	10.741
2010	[Mm2]	1.063	0.003	1.273	3.116	0.567	6.835	7.955	6.833	10.692
2011	[Mm2]	1.062	0.003	1.281	3.107	0.569	6.810	7.954	6.829	10.639
2012	[Mm2]	1.061	0.003	1.289	3.099	0.572	6.785	7.953	6.824	10.586
2013	[Mm2]	1.060	0.003	1.297	3.090	0.574	6.760	7.953	6.820	10.532
2014	[Mm2]	1.059	0.003	1.305	3.081	0.576	6.735	7.952	6.815	10.479
2015	[Mm2]	1.058	0.003	1.313	3.073	0.578	6.710	7.951	6.811	10.426
2016	[Mm2]	1.061	0.003	1.322	3.075	0.580	6.688	7.958	6.805	10.374
2017	[Mm2]	1.061	0.003	1.330	3.067	0.582	6.665	7.964	6.784	10.322
2018	[Mm2]	1.061	0.003	1.337	3.060	0.585	6.644	7.964	6.778	10.272
2019	[Mm2]	1.060	0.003	1.345	3.052	0.587	6.624	7.964	6.772	10.220

FOREST PRIMARY

Year		EU27	UK	CHINA	EASOC	INDIA	LATAM	RUSSIA	USMCA	LROW
2005	[Mm2]	0.037	0.000	0.116	0.770	0.157	2.812	2.727	3.158	3.238
2006	[Mm2]	0.038	0.000	0.116	0.767	0.157	2.803	2.727	3.155	3.223
2007	[Mm2]	0.038	0.000	0.116	0.765	0.157	2.794	2.727	3.153	3.208
2008	[Mm2]	0.039	0.000	0.116	0.763	0.157	2.785	2.727	3.150	3.194
2009	[Mm2]	0.040	0.000	0.116	0.760	0.157	2.776	2.727	3.148	3.179
2010	[Mm2]	0.040	0.000	0.116	0.758	0.157	2.767	2.727	3.145	3.164

2011	[Mm2]	0.040	0.000	0.116	0.756	0.157	2.768	2.727	3.145	3.144
2012	[Mm2]	0.040	0.000	0.116	0.754	0.157	2.770	2.727	3.144	3.125
2013	[Mm2]	0.040	0.000	0.116	0.752	0.157	2.771	2.727	3.144	3.105
2014	[Mm2]	0.040	0.000	0.116	0.751	0.157	2.773	2.727	3.143	3.085
2015	[Mm2]	0.041	0.000	0.116	0.749	0.157	2.774	2.727	3.143	3.066
2016	[Mm2]	0.041	0.000	0.116	0.749	0.157	2.774	2.727	3.143	3.066
2017	[Mm2]	0.041	0.000	0.116	0.749	0.157	2.774	2.727	3.143	3.066
2018	[Mm2]	0.041	0.000	0.116	0.749	0.157	2.812	2.727	3.143	3.066
2019	[Mm2]	0.041	0.000	0.116	0.749	0.157	2.812	2.727	3.143	3.066

FOREST PLANTATIONS

Year		EU27	UK	CHINA	EASOC	INDIA	LATAM	RUSSIA	USMCA	LROW
2005	[Mm2]	0.480	0.027	0.641	0.274	0.111	0.103	0.175	0.358	0.283
2006	[Mm2]	0.485	0.027	0.659	0.277	0.114	0.108	0.179	0.366	0.288
2007	[Mm2]	0.490	0.027	0.678	0.280	0.118	0.113	0.183	0.373	0.292
2008	[Mm2]	0.495	0.027	0.696	0.284	0.121	0.118	0.188	0.381	0.297
2009	[Mm2]	0.500	0.027	0.715	0.287	0.124	0.123	0.192	0.389	0.301
2010	[Mm2]	0.504	0.027	0.733	0.290	0.128	0.128	0.196	0.396	0.305
2011	[Mm2]	0.508	0.027	0.745	0.296	0.128	0.134	0.197	0.402	0.309
2012	[Mm2]	0.512	0.028	0.756	0.302	0.129	0.140	0.197	0.408	0.313
2013	[Mm2]	0.516	0.028	0.767	0.307	0.129	0.146	0.197	0.413	0.317
2014	[Mm2]	0.520	0.028	0.779	0.313	0.130	0.152	0.198	0.419	0.321
2015	[Mm2]	0.524	0.028	0.790	0.318	0.130	0.158	0.198	0.425	0.325
2016	[Mm2]	0.524	0.028	0.802	0.328	0.131	0.160	0.194	0.429	0.327
2017	[Mm2]	0.526	0.028	0.814	0.320	0.131	0.158	0.189	0.445	0.327
2018	[Mm2]	0.528	0.028	0.825	0.320	0.132	0.166	0.189	0.449	0.328
2019	[Mm2]	0.530	0.028	0.836	0.320	0.132	0.170	0.189	0.454	0.331

SHUBLAND

		EU27	UK	CHINA	EASOC	INDIA	LATAM	RUSSIA	USMCA	LROW
Year		0.558	0.017	0.227	0.949	0.531	0.000	1.570	2.484	0.202
2005	[Mm2]	0.567	0.012	0.223	0.956	0.531	0.000	1.568	2.488	0.215
2006	[Mm2]	0.578	0.013	0.219	0.993	0.531	0.000	1.566	2.489	0.223
2007	[Mm2]	0.568	0.013	0.216	1.024	0.527	0.000	1.564	2.525	0.232
2008	[Mm2]	0.571	0.015	0.212	1.034	0.522	0.041	1.562	2.543	0.240
2009	[Mm2]	0.578	0.015	0.209	1.063	0.524	0.061	1.560	2.563	0.230
2010	[Mm2]	0.583	0.015	0.206	0.983	0.520	0.080	1.560	2.580	0.239
2011	[Mm2]	0.586	0.015	0.204	1.015	0.516	0.083	1.560	2.594	0.332
2012	[Mm2]	0.586	0.015	0.201	1.072	0.512	0.087	1.560	2.594	0.337
2013	[Mm2]	0.595	0.015	0.199	1.063	0.507	0.115	1.560	2.592	0.353
2014	[Mm2]	0.593	0.015	0.196	1.160	0.505	0.144	1.561	2.587	0.365
2015	[Mm2]	0.599	0.014	0.194	1.166	0.503	0.175	1.559	2.584	0.378
2016	[Mm2]	0.597	0.013	0.191	1.049	0.499	0.172	1.558	2.591	0.386
2017	[Mm2]	0.599	0.014	0.188	1.103	0.496	0.202	1.558	2.593	0.397
2018	[Mm2]	0.589	0.013	0.186	1.092	0.493	0.213	1.557	2.594	0.413
2019	[Mm2]									

GRASSLAND

		EU27	UK	CHINA	EASOC	INDIA	LATAM	RUSSIA	USMCA	LROW
Year		0.581	0.112	3.928	4.105	0.105	3.368	0.921	3.465	16.538
2005	[Mm2]	0.574	0.117	3.928	4.114	0.104	3.343	0.921	3.479	16.543
2006	[Mm2]	0.575	0.115	3.928	4.016	0.104	3.334	0.921	3.499	16.537

2007	[Mm2]	0.577	0.116	3.928	3.916	0.104	3.326	0.921	3.459	16.545
2008	[Mm2]	0.569	0.112	3.928	3.835	0.103	3.316	0.921	3.447	16.578
2009	[Mm2]	0.564	0.112	3.928	3.770	0.103	3.305	0.921	3.432	16.633
2010	[Mm2]	0.558	0.111	3.928	3.907	0.103	3.286	0.921	3.421	16.615
2011	[Mm2]	0.544	0.109	3.928	3.815	0.103	3.284	0.921	3.407	16.178
2012	[Mm2]	0.550	0.109	3.928	3.664	0.103	3.295	0.921	3.397	16.196
2013	[Mm2]	0.534	0.110	3.928	3.684	0.103	3.283	0.921	3.390	16.188
2014	[Mm2]	0.534	0.111	3.928	3.427	0.103	3.270	0.921	3.388	16.191
2015	[Mm2]	0.530	0.113	3.928	3.380	0.103	3.257	0.921	3.387	16.196
2016	[Mm2]	0.529	0.113	3.928	3.666	0.103	3.232	0.921	3.387	16.201
2017	[Mm2]	0.529	0.113	3.928	3.533	0.103	3.217	0.921	3.386	16.203
2018	[Mm2]	0.536	0.114	3.928	3.571	0.103	3.219	0.921	3.387	16.183
2019	[Mm2]									

URBAN

		EU27	UK	CHINA	EASOC	INDIA	LATAM	RUSSIA	USMCA	LROW
Year		0.076	0.010	0.052	0.039	0.012	0.024	0.022	0.101	0.084
2005	[Mm2]	0.077	0.010	0.056	0.040	0.013	0.025	0.022	0.104	0.086
2006	[Mm2]	0.078	0.010	0.060	0.042	0.014	0.025	0.022	0.107	0.089
2007	[Mm2]	0.079	0.010	0.064	0.043	0.014	0.026	0.023	0.109	0.091
2008	[Mm2]	0.080	0.010	0.068	0.045	0.015	0.026	0.023	0.111	0.093
2009	[Mm2]	0.080	0.010	0.072	0.046	0.015	0.027	0.023	0.112	0.095
2010	[Mm2]	0.081	0.010	0.075	0.048	0.016	0.027	0.024	0.114	0.097
2011	[Mm2]	0.082	0.010	0.079	0.049	0.017	0.028	0.024	0.116	0.100
2012	[Mm2]	0.083	0.010	0.084	0.052	0.018	0.029	0.024	0.119	0.104
2013	[Mm2]	0.084	0.010	0.089	0.054	0.019	0.030	0.025	0.122	0.109
2014	[Mm2]	0.085	0.010	0.092	0.056	0.020	0.030	0.025	0.123	0.112
2015	[Mm2]	0.085	0.010	0.092	0.056	0.020	0.030	0.025	0.126	0.114
2016	[Mm2]	0.085	0.010	0.098	0.057	0.021	0.031	0.026	0.128	0.117
2017	[Mm2]	0.086	0.010	0.103	0.057	0.021	0.032	0.026	0.130	0.120
2018	[Mm2]	0.086	0.010	0.106	0.058	0.022	0.033	0.027	0.131	0.124
2019	[Mm2]									

SOLAR

		EU27	UK	CHINA	EASOC	INDIA	LATAM	RUSSIA	USMCA	LROW
Year		0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
2005	[Mm2]	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
2006	[Mm2]	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
2007	[Mm2]	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
2008	[Mm2]	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
2009	[Mm2]	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
2010	[Mm2]	0.001	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
2011	[Mm2]	0.001	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
2012	[Mm2]	0.001	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
2013	[Mm2]	0.001	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
2014	[Mm2]	0.001	0.000	0.001	0.000	0.000	0.000	0.000	0.000	0.000
2015	[Mm2]	0.001	0.000	0.001	0.000	0.000	0.000	0.000	0.001	0.000
2016	[Mm2]	0.002	0.000	0.002	0.000	0.000	0.000	0.000	0.001	0.000
2017	[Mm2]	0.002	0.000	0.002	0.000	0.000	0.000	0.000	0.001	0.000
2018	[Mm2]	0.002	0.000	0.002	0.000	0.000	0.000	0.000	0.001	0.000
2019	[Mm2]									

SNOW_ICE_WATERBODIES

		EU27	UK	CHINA	EASOC	INDIA	LATAM	RUSSIA	USMCA	LROW
Year										

2005	[Mm2]	0.119	0.005	0.187	0.110	0.057	0.271	0.661	1.490	15.302
2006	[Mm2]	0.119	0.005	0.187	0.109	0.057	0.270	0.660	1.490	15.300
2007	[Mm2]	0.118	0.005	0.187	0.109	0.057	0.270	0.659	1.490	15.297
2008	[Mm2]	0.118	0.005	0.187	0.109	0.057	0.269	0.657	1.490	15.295
2009	[Mm2]	0.118	0.005	0.187	0.108	0.057	0.269	0.655	1.490	15.289
2010	[Mm2]	0.118	0.005	0.187	0.109	0.057	0.269	0.653	1.491	15.292
2011	[Mm2]	0.118	0.005	0.187	0.109	0.057	0.269	0.653	1.492	15.290
2012	[Mm2]	0.118	0.005	0.187	0.109	0.058	0.269	0.652	1.493	15.289
2013	[Mm2]	0.118	0.005	0.187	0.109	0.058	0.269	0.652	1.495	15.288
2014	[Mm2]	0.119	0.005	0.188	0.108	0.059	0.269	0.653	1.495	15.288
2015	[Mm2]	0.119	0.005	0.188	0.108	0.059	0.269	0.653	1.495	15.288
2016	[Mm2]	0.119	0.005	0.189	0.109	0.059	0.269	0.653	1.496	15.266
2017	[Mm2]	0.119	0.005	0.189	0.109	0.059	0.269	0.653	1.496	15.266
2018	[Mm2]	0.119	0.005	0.189	0.109	0.059	0.269	0.653	1.496	15.266
2019	[Mm2]	0.119	0.005	0.189	0.109	0.059	0.270	0.654	1.498	15.271

		OTHER_LAND								
Year		EU27	UK	CHINA	EASOC	INDIA	LATAM	RUSSIA	USMCA	LROW
2005	[Mm2]	0.175	0.012	1.835	1.469	0.044	-0.050	1.840	1.418	0.635
2006	[Mm2]	0.177	0.009	1.805	1.480	0.044	-0.036	1.838	1.421	0.678
2007	[Mm2]	0.181	0.009	1.776	1.537	0.044	-0.024	1.835	1.421	0.701
2008	[Mm2]	0.178	0.009	1.746	1.586	0.044	-0.004	1.833	1.442	0.731
2009	[Mm2]	0.179	0.011	1.716	1.602	0.043	0.015	1.830	1.452	0.754
2010	[Mm2]	0.181	0.011	1.693	1.647	0.043	0.022	1.828	1.463	0.723
2011	[Mm2]	0.182	0.011	1.672	1.522	0.043	0.029	1.829	1.473	0.751
2012	[Mm2]	0.183	0.011	1.652	1.572	0.043	0.030	1.829	1.481	1.046
2013	[Mm2]	0.183	0.011	1.630	1.661	0.042	0.032	1.829	1.481	1.061
2014	[Mm2]	0.186	0.011	1.608	1.646	0.042	0.042	1.829	1.480	1.109
2015	[Mm2]	0.186	0.011	1.589	1.797	0.042	0.052	1.829	1.477	1.150
2016	[Mm2]	0.187	0.010	1.569	1.806	0.041	0.064	1.827	1.475	1.188
2017	[Mm2]	0.187	0.009	1.545	1.625	0.041	0.063	1.826	1.479	1.213
2018	[Mm2]	0.187	0.010	1.523	1.709	0.041	0.074	1.826	1.480	1.249
2019	[Mm2]	0.184	0.009	1.503	1.691	0.041	0.078	1.825	1.481	1.301

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Appendix H: How to download and use WILIAM model

The latest public version of WILIAM model can be downloaded from the LOCOMOTION project github[1]. At the time of publication of this paper, the latest public version is version WILIAM_v1.3, under Licence MIT [2]. This version is not a fully validated model and hence it is not possible to use the whole model with confidence. However, WILIAM is a modular model and enables the use of most of its modules separately. WILIAM-TERRA can be used as an independent model receiving exogenous inputs. The core group of developers is constantly developing the model and is planning to release updates in a few months. In any case, the up to date version of the model is available to external researchers who are interested upon request to GEEDS [3].

The model download contains several files, including a User's Guide for the model. Its User Guide [4] explains how to run WILIAM in Vensim software for 2 cases: (1) using the freeware Vensim Model Reader (which allows to run a model with some limitations), and (2) using the full software Vensim DSS (proprietary) which allows full transparency and flexibility. When using Vensim Model Reader, one is not allowed to make changes in the structure or equations of the model but can change some of the parameters via excel files. When using Vensim DSS one can modify the structure as well as the equations and parameters.

Both options include an Excel file which operates as an interface that allows to design and run scenarios to those users not familiar with Vensim. This User's Guide [4] explains the basic software requirements: for the Vensim DSS, WILIAM typically uses ~20 Gb of RAM memory, hence it is recommended a 32 Gb computer. In the case of Vensim Model Reader, this version is much less intensive than the DSS, so 16 Gb would be well enough.

The results of this article have been obtained with a WILIAM version in development stored in commit f1b45208e13298cffc940042a385f209e7c8e6bd of March 8th 2025.

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