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

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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 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.

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 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 like 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] and 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].

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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 Fig. 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.

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 optimization-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 Fig. 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 Fig. 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.

In WILIAM (see Fig. 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

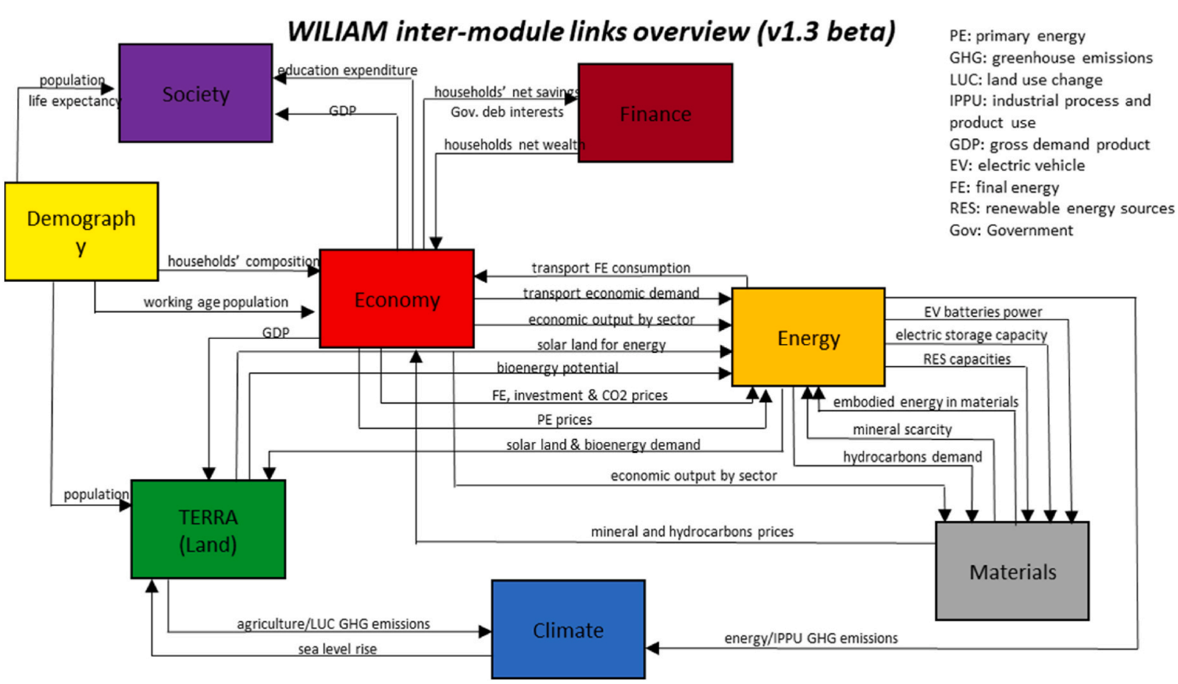

Fig. 1. Schematic structure overview of the WILIAM model, representing the main linkages between the modules: society, demography, economy, finance, land, energy, materials and climate.

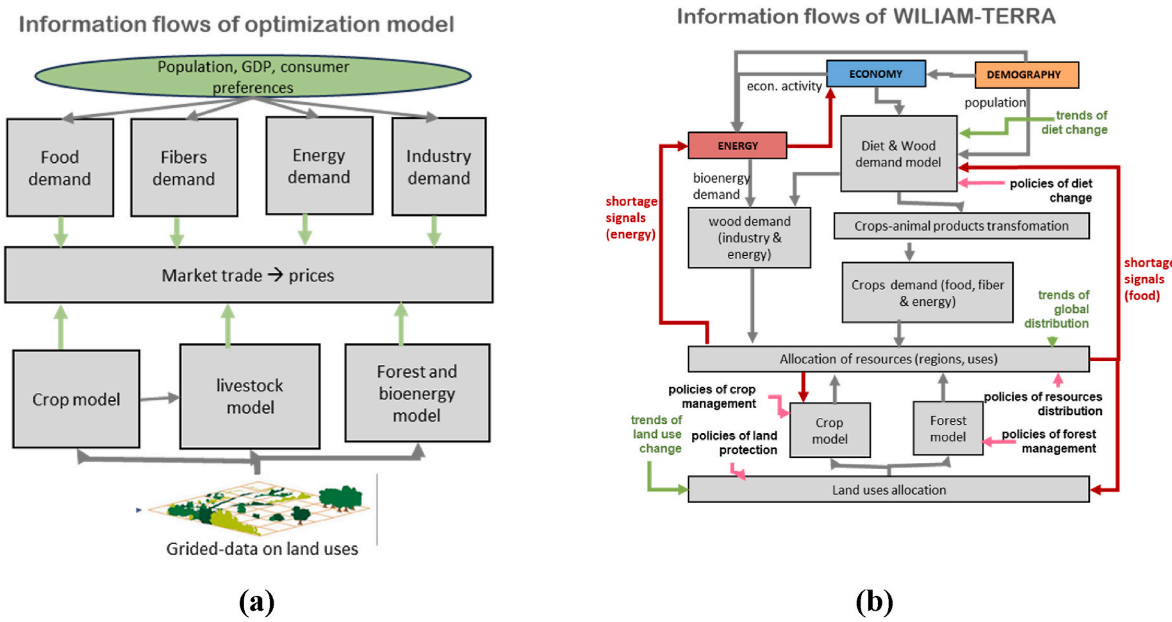

Fig. 2. Comparison of the information flows in an optimization-based model (a) and in the WILIAM-TERRA model (b).

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 Fig. 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

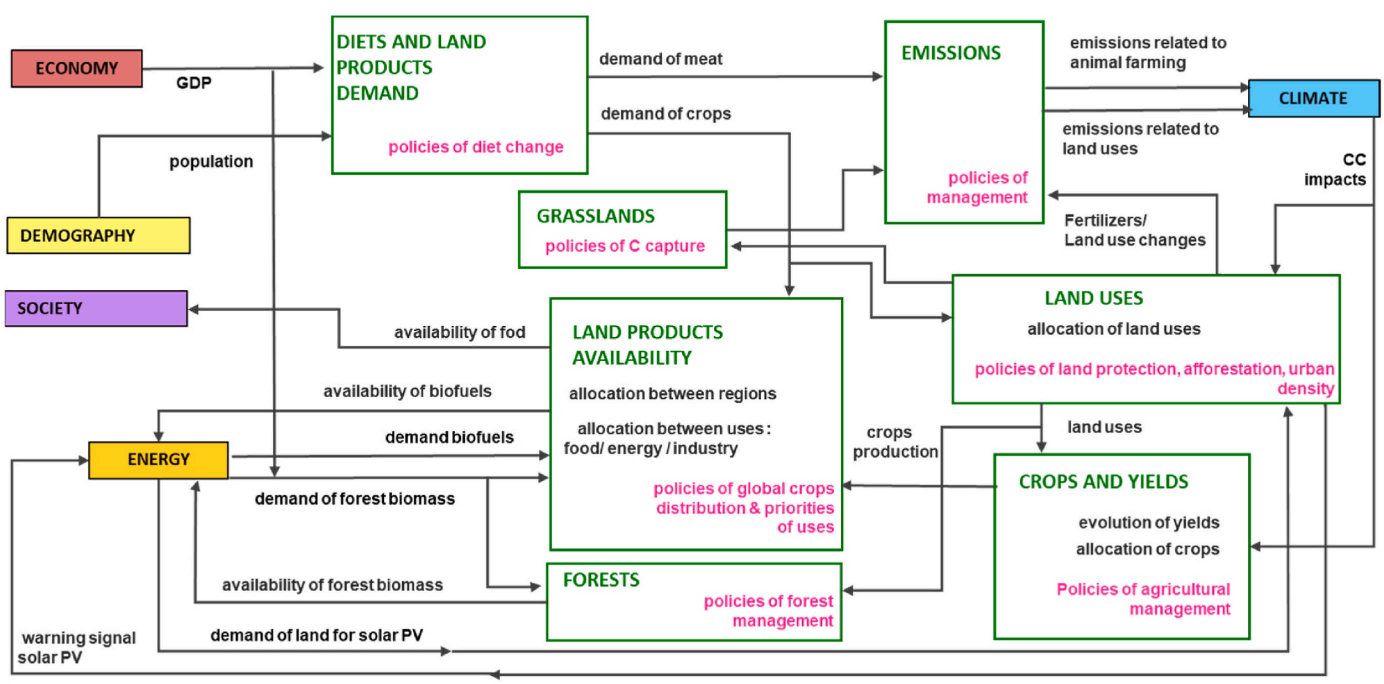

Fig. 3. WILIAM-TERRA module and its connection with the rest of WILIAM model modules. White-green boxes are submodules of WILIAM-TERRA, boxes in other colour belong to other modules of WILIAM. Variables in pink are exogenous policies chosen by the user. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

Appendix A.

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.

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).

Fig. 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)

The demand for land for cropland is governed by a feedback loop (described in the causal loop diagram of Fig. 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.

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 Appendix 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 Fig. 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 Figs. 7 and 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].

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.

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

(continued on next page)

Table 1 (*continued*)

Features of WILIAM-TERRA	Description	
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

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 to 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 Fig. 9 (see Section 3 in Appendix E for a more detailed description).

2.7. *Forests submodule*

The Forests submodule (see Fig. 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.

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 Fig. 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.

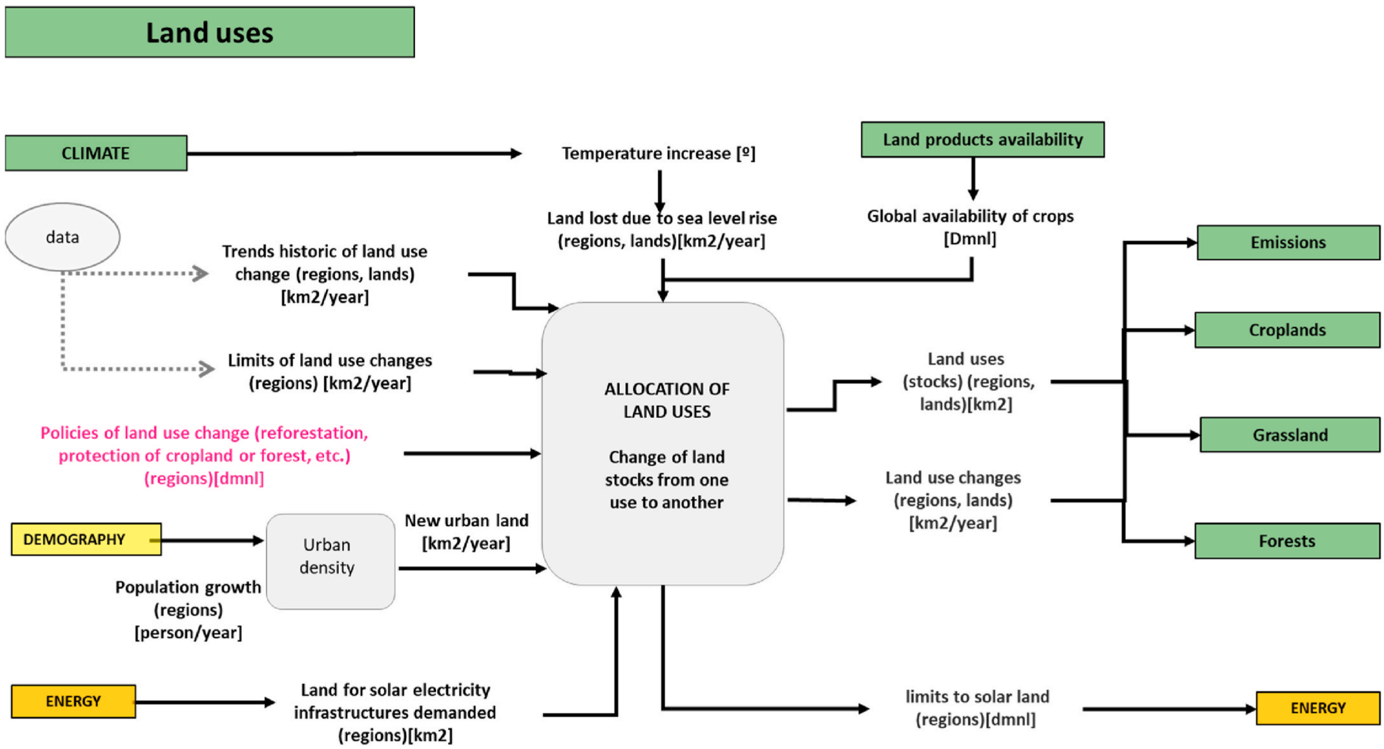

Fig. 4. Land uses submodule: information flows. Green boxes represent WILIAM-TERRA submodules, while boxes in other colours belong to other WILIAM modules. Grey boxes represent endogenous calculations. Variables in pink are exogenous policies chosen by the user. The subscripts of each variable are shown in parentheses, and the physical units are indicated in brackets. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

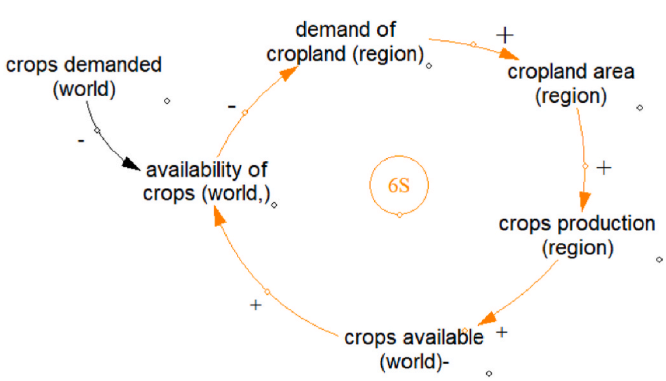

Fig. 5. Feedback that ensures that the cropland adapts to the demand in the Land Uses and Crops and Yields submodule. The stabilizing loop that appears is called 6S. (see Annex G for a detailed explanation).

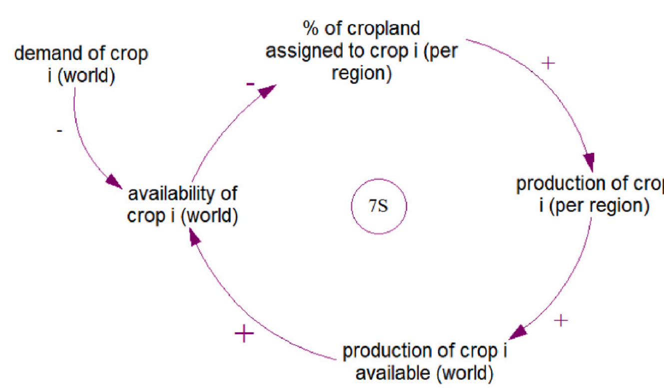

Fig. 6. Causal loop diagram of the mechanism that allocates the cropland area among crops according to its relative shortage. The stabilizing loop that appears is called 7S.

The 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).

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 Fig. 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

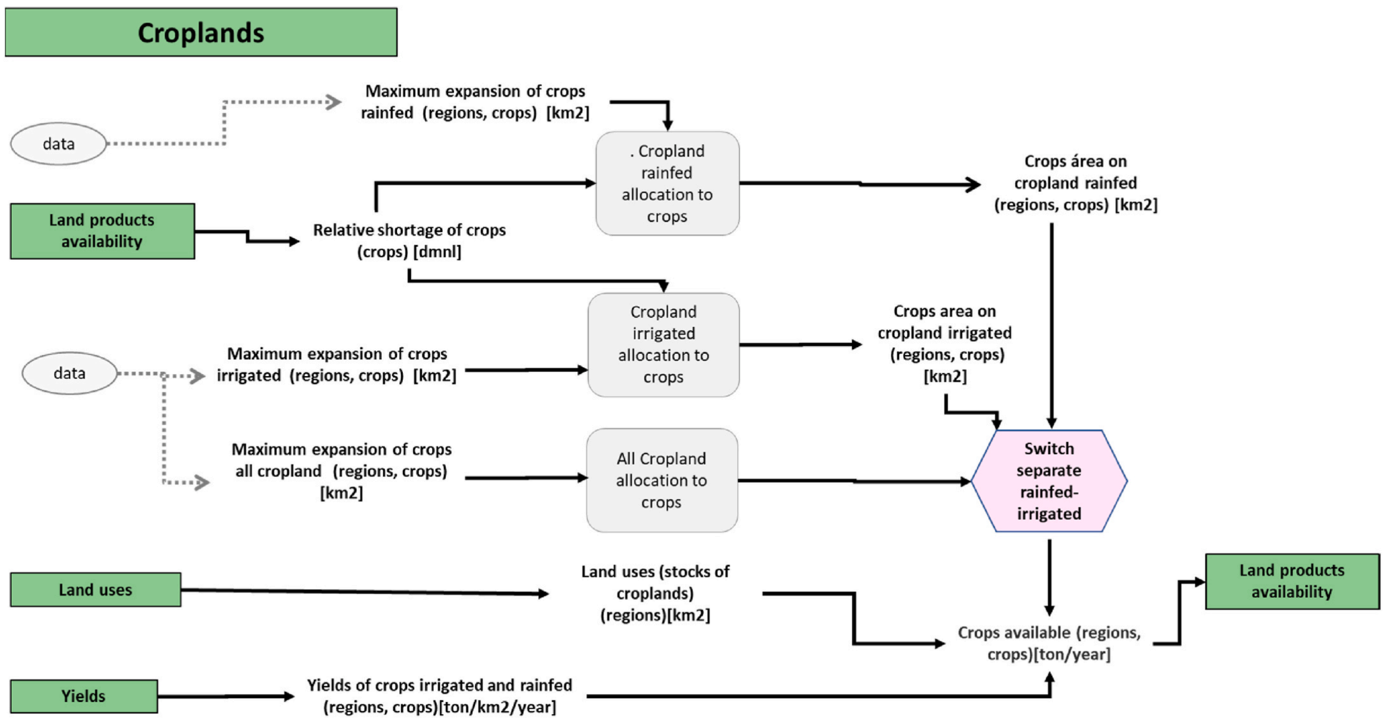

Fig. 7. Crops and Yields submodule: flows of information. Green boxes are WILIAM-TERRA submodules, boxes in other colour belong to other modules of WILIAM. Grey boxes are endogenous calculations. Pink hexagon is a selector that enables the user to choose to separate (or not separate) rainfed and irrigated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

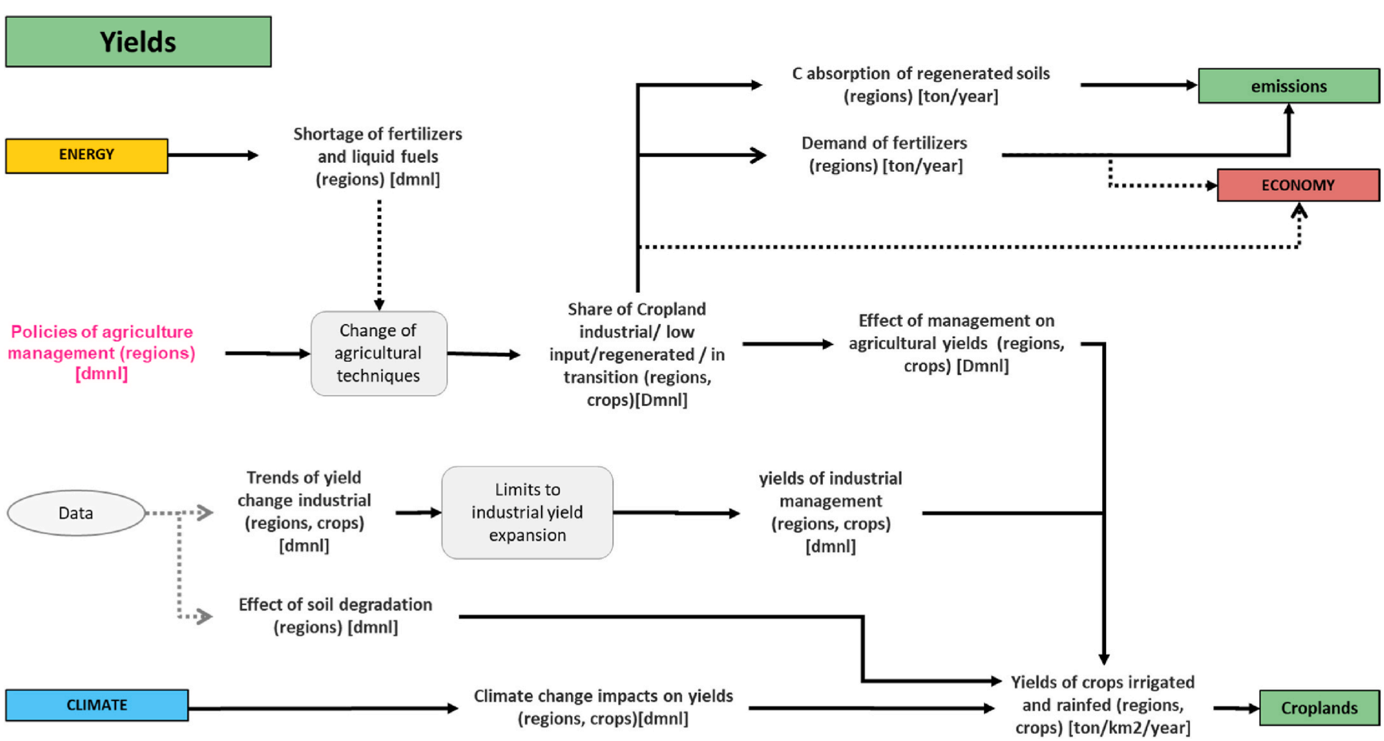

Fig. 8. Crops and Yields submodule: flows of information. Green boxes are WILIAM-TERRA submodules, boxes in other colour belong to other modules of WILIAM. Grey boxes are endogenous calculations. Exogenous policies are in pink. Doted arrows are connections not fully implemented yet. In parenthesis the subscripts of each variable are shown and in brackets the physical units. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

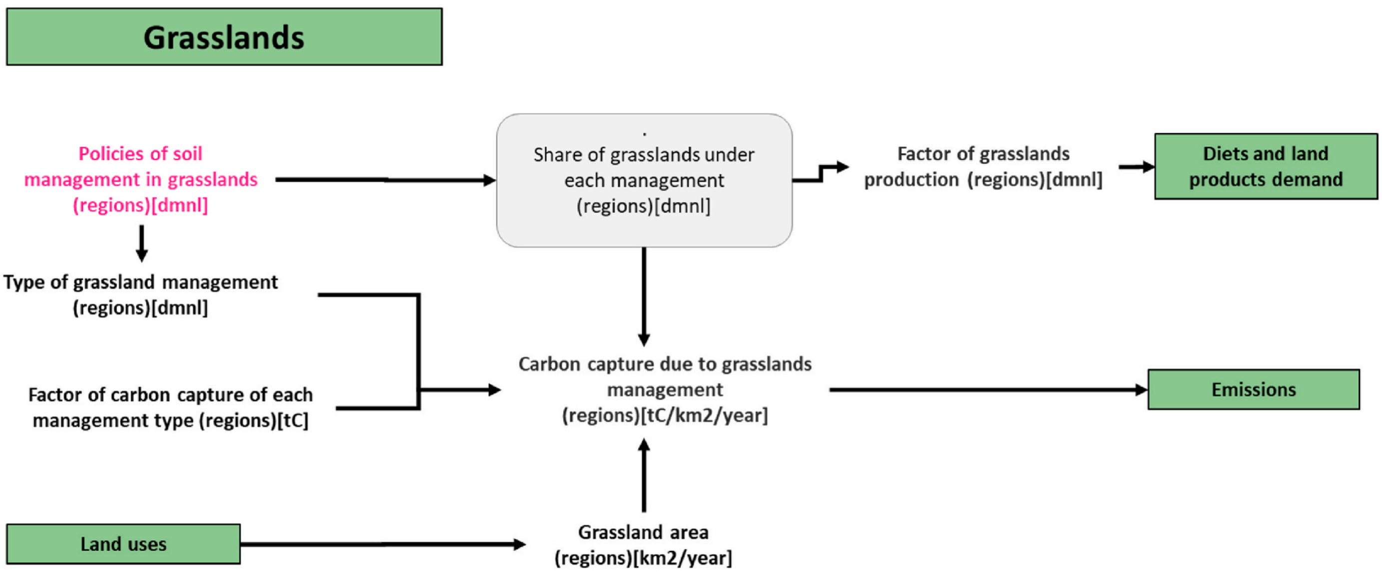

Fig. 9. Grasslands submodule: flows of information. Green boxes are WILIAM-TERRA submodules. Grey boxes are endogenous calculations. Exogenous policies are in pink. In parenthesis the subscripts of each variable are shown and in brackets the physical units. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

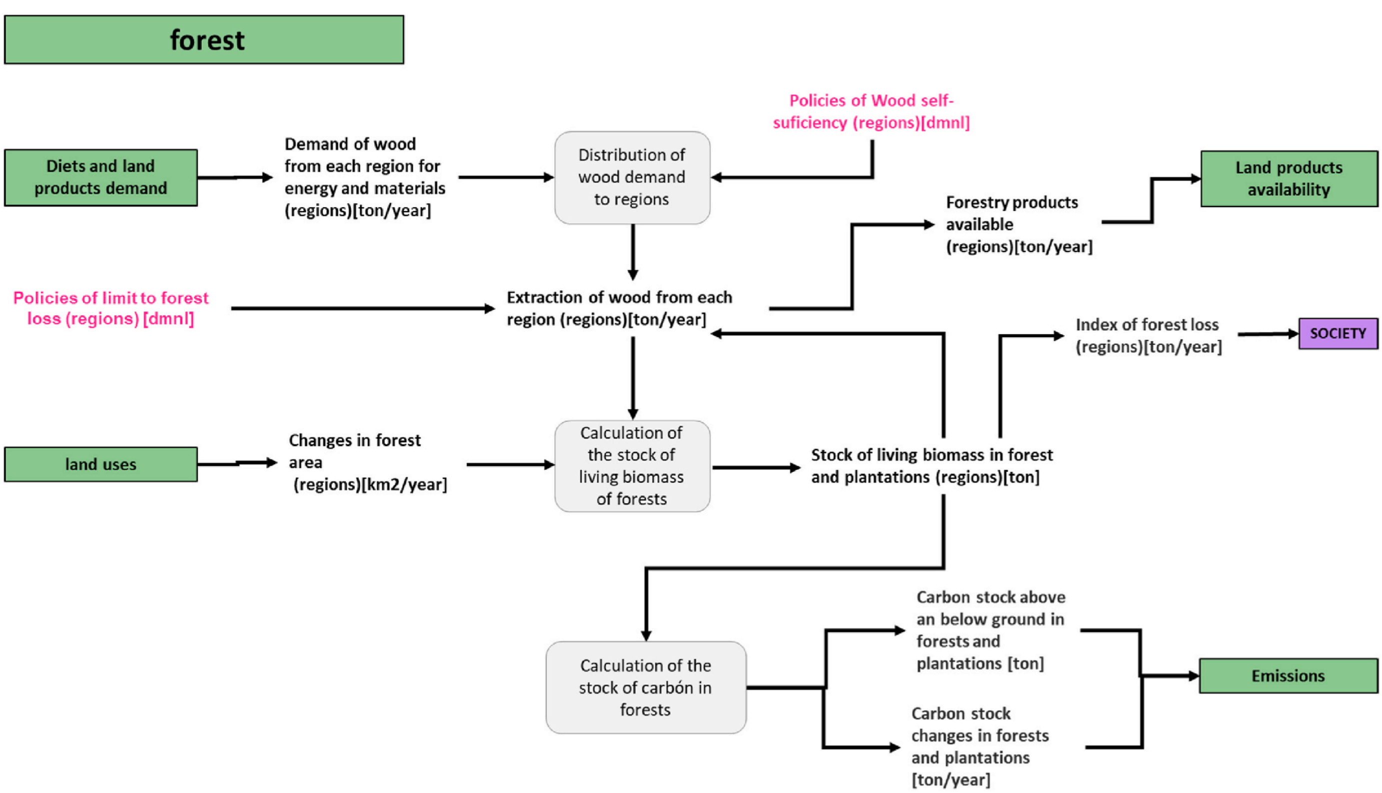

Fig. 10. Forests submodule: information flows. Green boxes represent WILIAM-TERRA submodules. Grey boxes represent endogenous calculations. Variables in pink are exogenous policies chosen by the user. The subscripts of each variable are shown in parentheses, and the physical units are indicated in brackets. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

cannot be met, a signal is sent to Energy module to reduce the consumption of energy from forestry products. See Section 5 in Appendix E for a more detailed description.

2.9. Land Products Availability submodule

In the Land Products Availability submodule (see Fig. 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

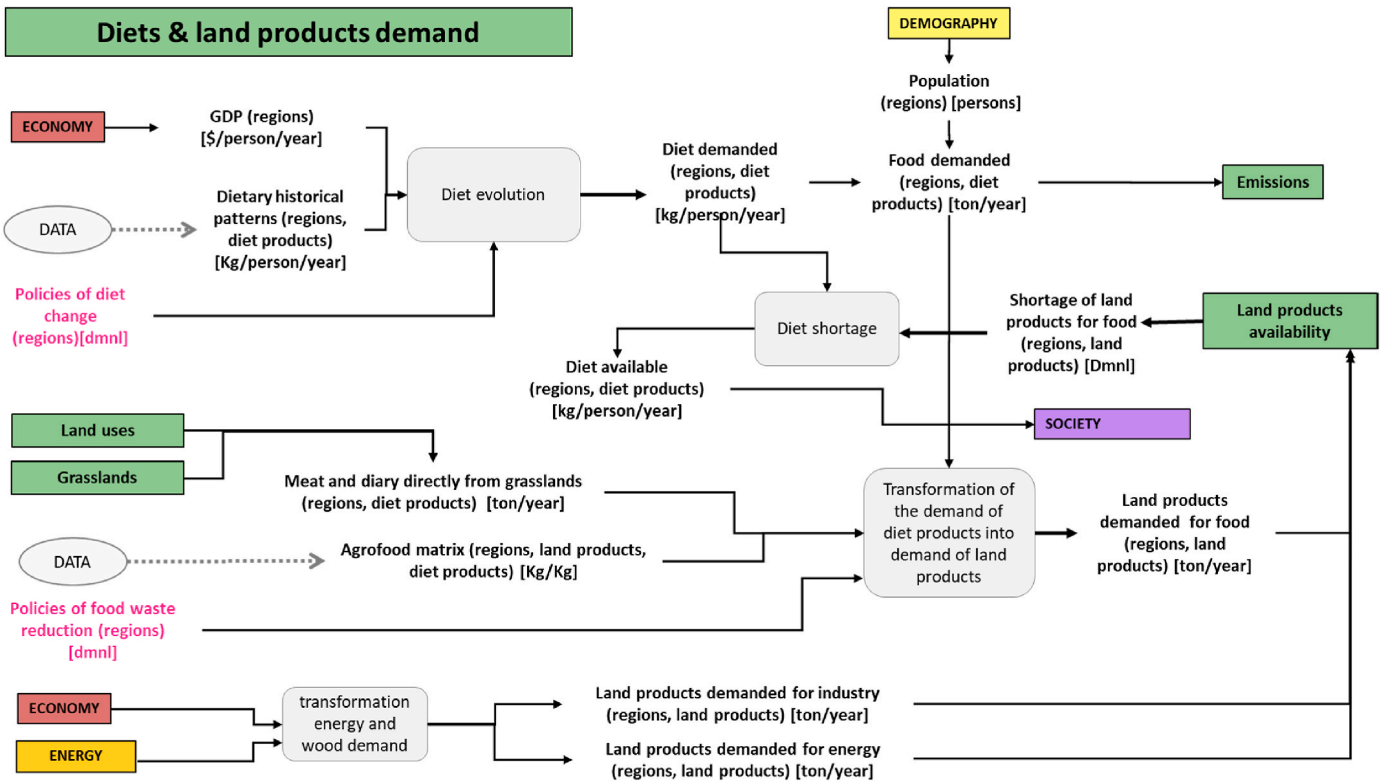

Fig. 11. Diets and Land Products Demand submodule: information flows. Green boxes represent WILIAM-TERRA submodules. Grey boxes represent endogenous calculations. Variables in pink are exogenous policies chosen by the user. The subscripts of each variable are shown in parentheses, and the physical units are indicated in bracket. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

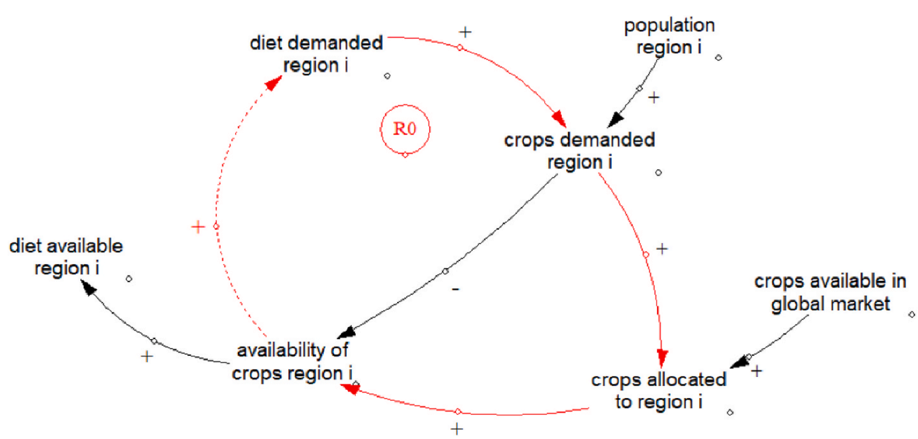

Fig. 12. Cause loop diagram of the reinforcing loop that could appear in the Diet submodule. The red arrows form the loop called R0, the dashed arrow is not included in the model to avoid this feedback which leads to unrealistic behaviour. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

production due to very small land holders that is not subject to these markets and is also considered.

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 (Fig. 14) dynamically calculates the following land-related GHG emissions.

- Agriculture, Forestry and Other Land Use (AFOLU) GHG emissions related to land use.

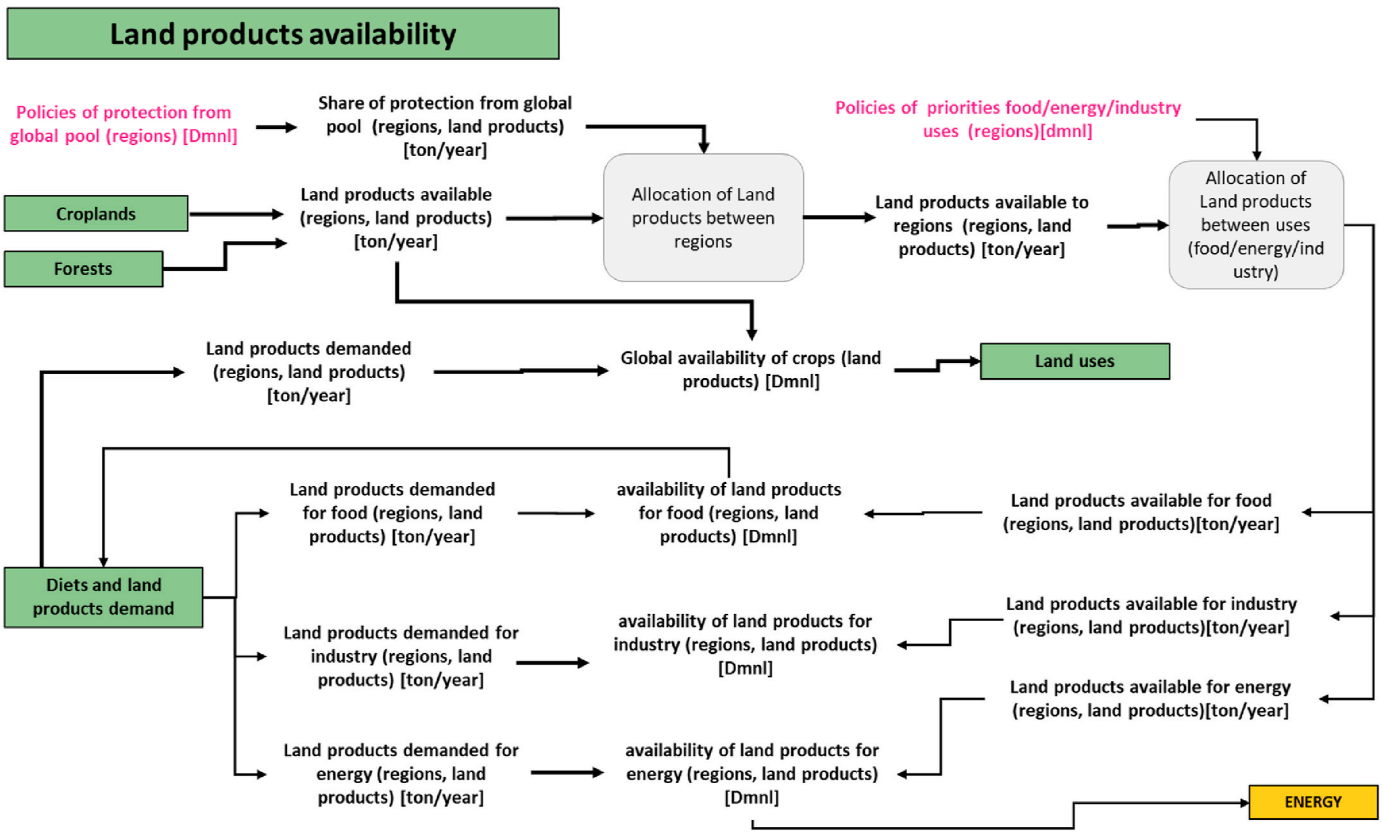

Fig. 13. Land Products Availability submodule: flows of information. Green boxes are WILIAM-TERRA submodules. Grey boxes are endogenous calculations. Exogenous policies are in pink. In parenthesis the subscripts of each variable are shown and in brackets the physical units. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

- 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.

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.

Experiment 1. Food availability under land protection and dietary changes

As sketched in Fig. 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).

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 Fig. 15 and is equal to

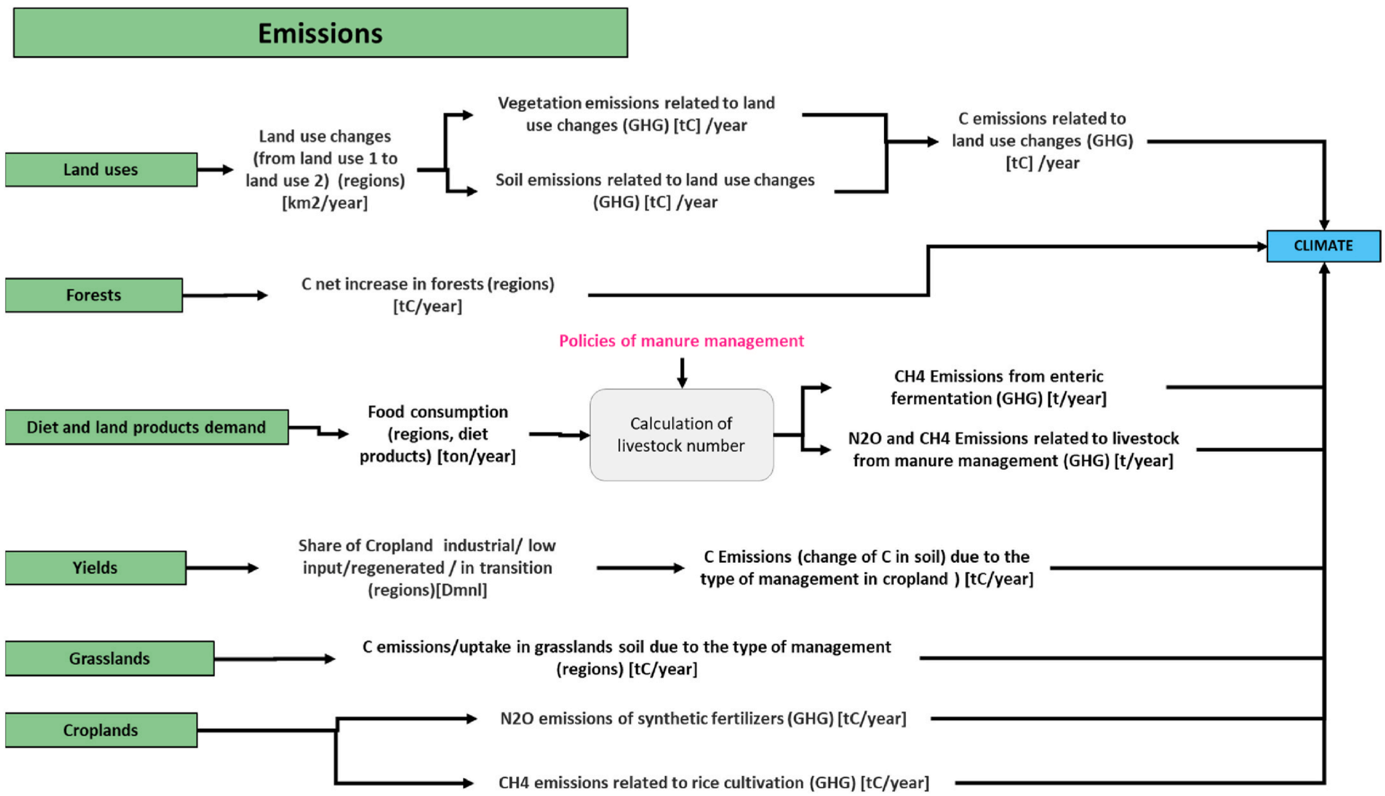

Fig. 14. Emissions submodule: information flows. Green boxes represent WILIAM-TERRA submodules. Grey boxes represent endogenous calculations. Variables in pink are exogenous. The subscripts of each variable are shown in parenthesis and the physical units in brackets. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

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)

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 Fig. 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. Fig. 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 %). Fig. 16 (d) shows the total cropland production that, as expected, is smallest in Run 1–2. Fig. 16(e) shows the reduction in methane emissions resulting from dietary change, but Fig. 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 Fig. 17. Although demand for ruminant meat is reduced in all regions except India (Fig. 17(e)), demand for monogastric meat increases in India and LROW, and in significant numbers (Fig. 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 for 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.

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.

Experiment 2. Deforestation and forest extraction

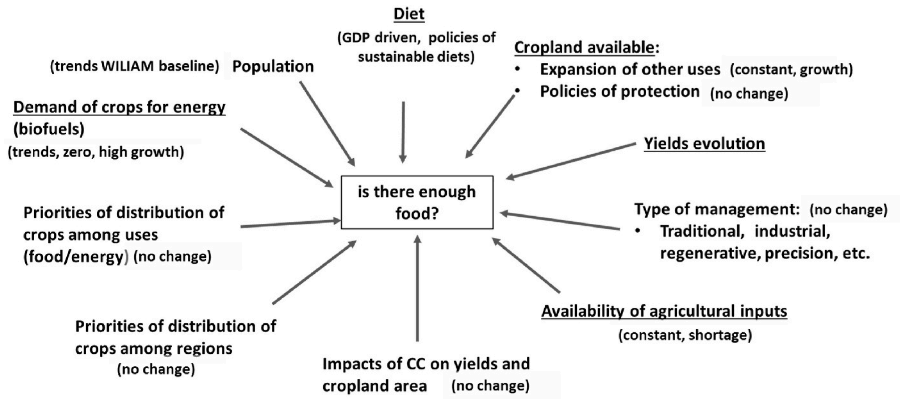

Fig. 15. Several factors impacting food availability worldwide.

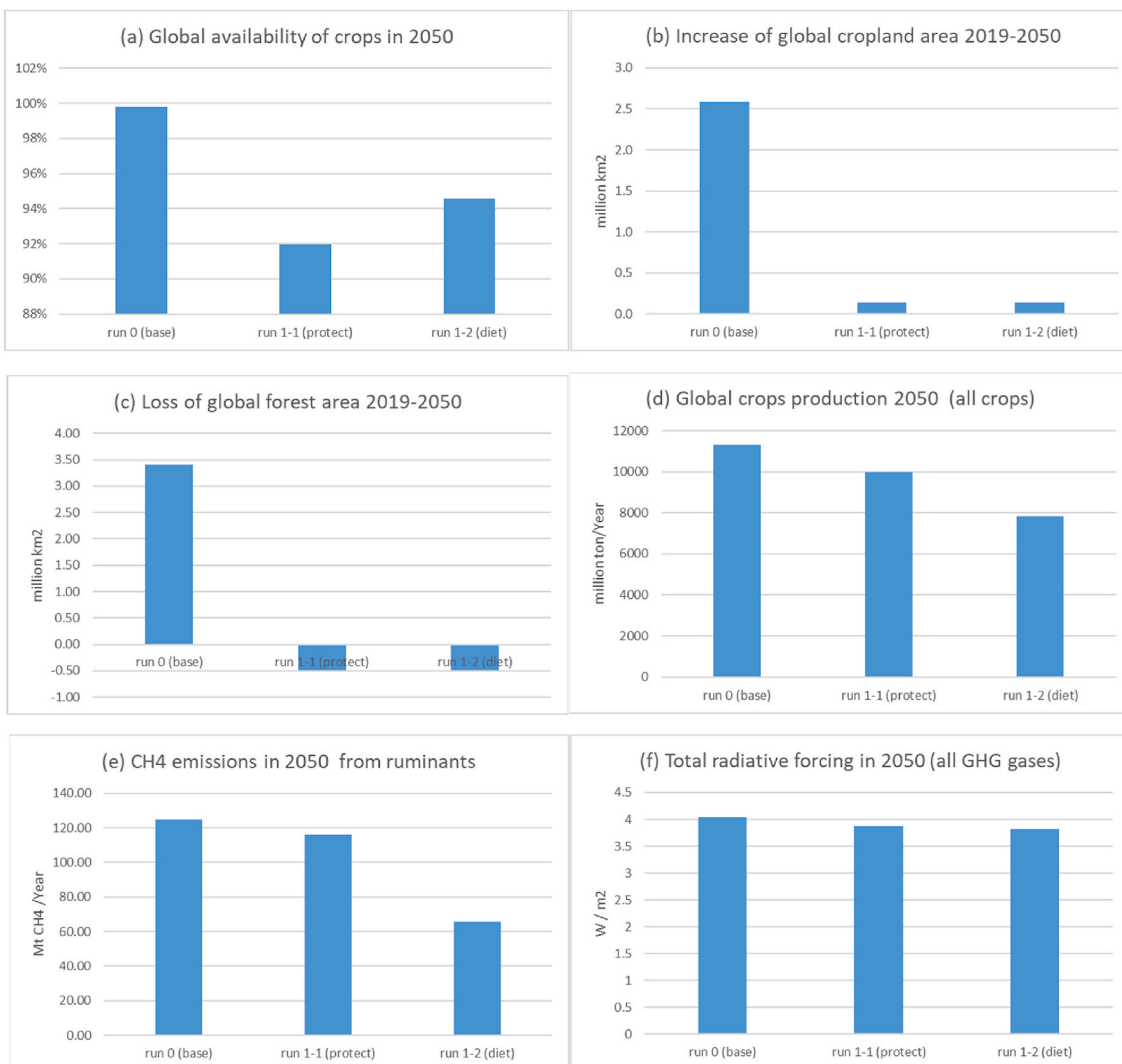

Fig. 16. Results of Experiment 1 for its three runs. (a) shows the signal of global availability of crops in year 2050, (b) the increment of cropland area and (c) the loss of forest area between 2019 and 2050. (d) shows the world crop production of all crops (added in kg) in year 2050, (e) the methane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

The runs of Experiment 2 show the effect of deforestation and forest harvesting. Fig. 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 as 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

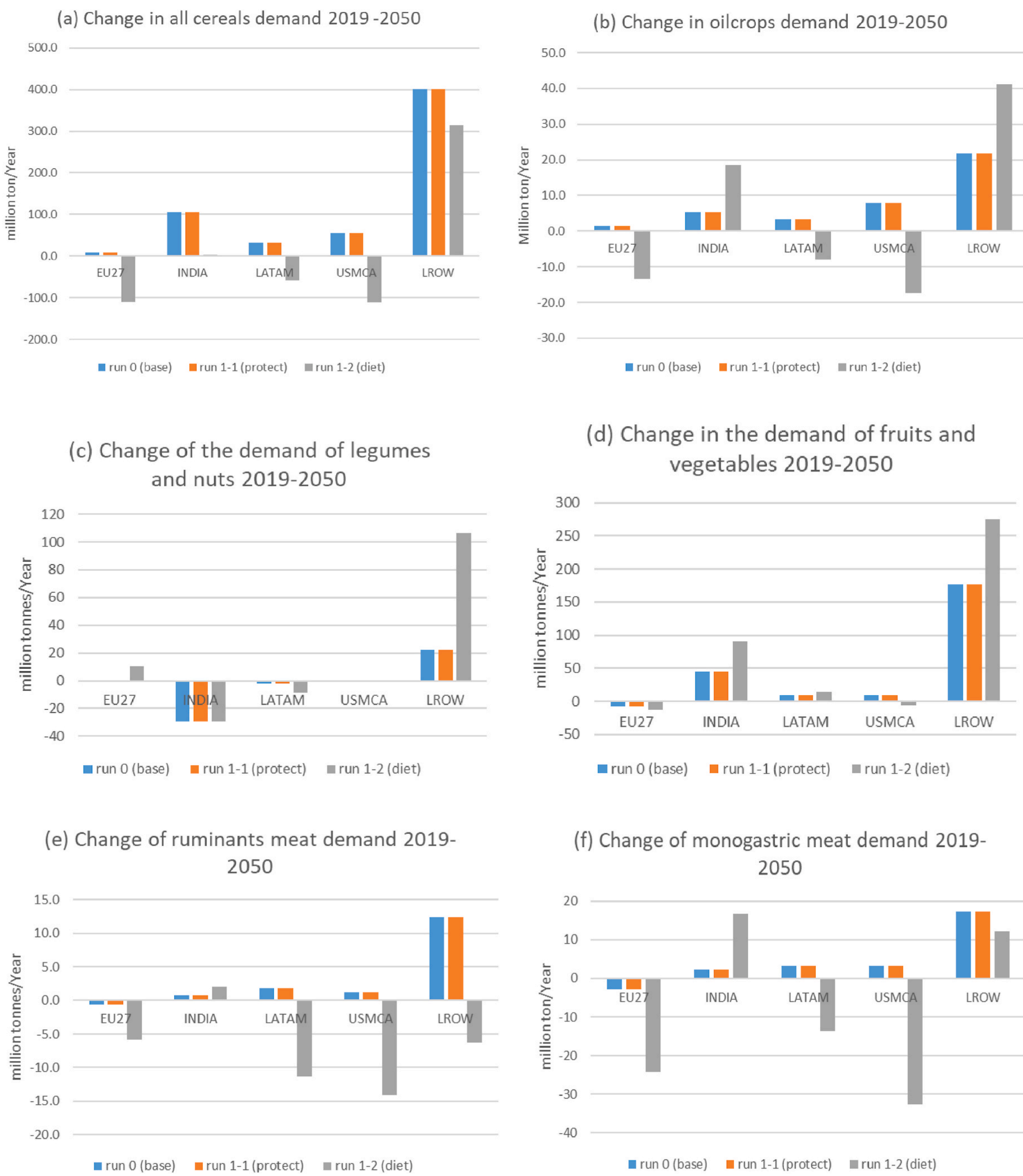

Fig. 17. Results of Experiment 1. Figures (a), (b), (c) and (d) show the demand of several crops between 2025 and 2050 for some representative regions. Figures (e) and (f) show the demand of meat from ruminants and non-ruminants for the same regions.

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 (localization), which reduces trade between forest regions, so that each region meets its demand from its forests when the policy is fully implemented.

Fig. 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 keept constant, (Run 2-1) this trend continues as well. The results of Run 2-2, without deforestation but with the same extraction as in Run 2-1, show a higher biomass stock, therefore a large part of the loss of LROW biomass is due to deforestation itself rather than to wood extraction. Nevertheless, biomass stock keeps falling in Run 2-2, even with low demand and no deforestation. As timber extraction increases in Run 2–3 and Run 2–4, the forest stock increases its annual loss although in those runs the deforetation is stopped. The loss is smaller in Run 2–4 when the localization policy is activated, as LROW produces timber for the demands of other regions.,

The same policies have 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 Fig. 18 (d) and reaches a very significant increase in Run 2-4, showing the strong dependence of China on wood from other regions. In Run 2–3 and Run 2-4, 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

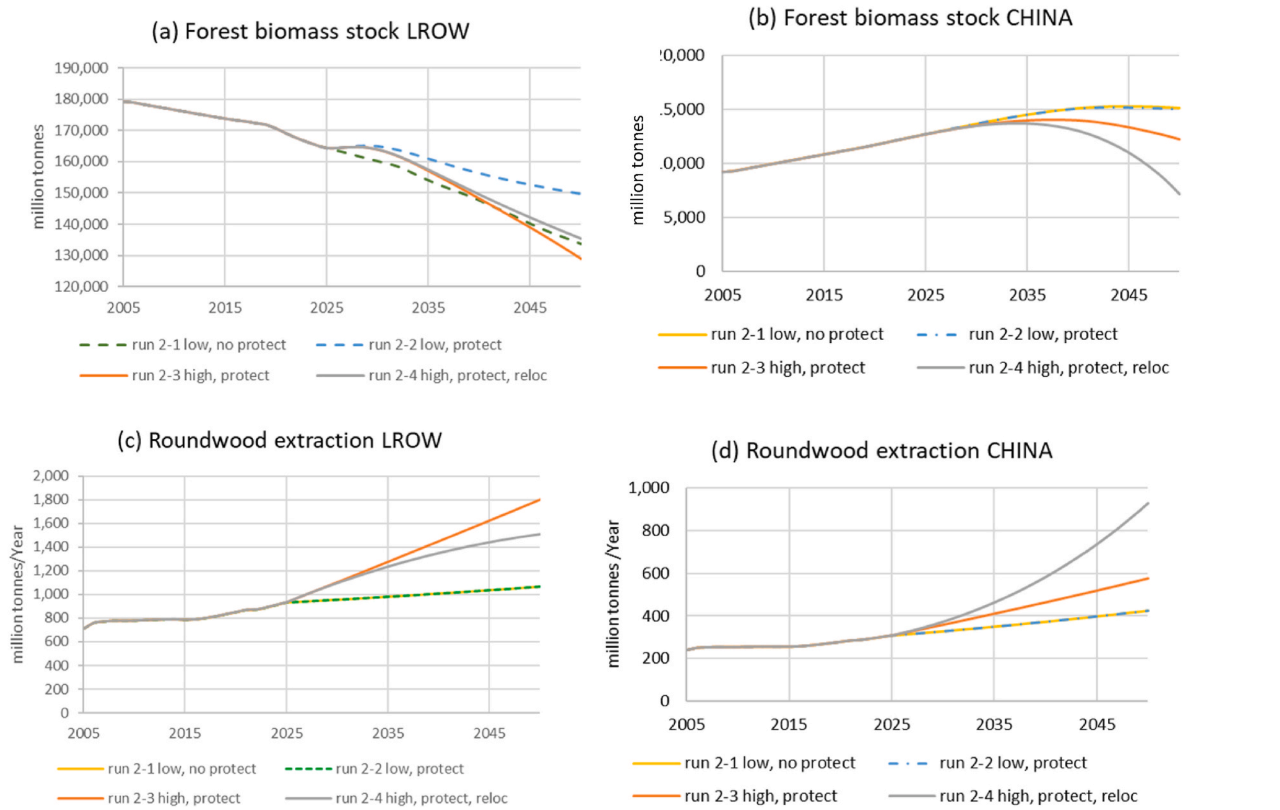

Fig. 18. results of Experiment 2. In (a) and (b) the above ground forest biomass stock is shown for LROW and China in the four runs of Experiment 2. In (c) and (d) the roundwood extraction is shown for the same regions.

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.

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.

Fig. 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 Fig. 19 (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 analysed with the WILIAM-TERRA tool. Future research will focus on

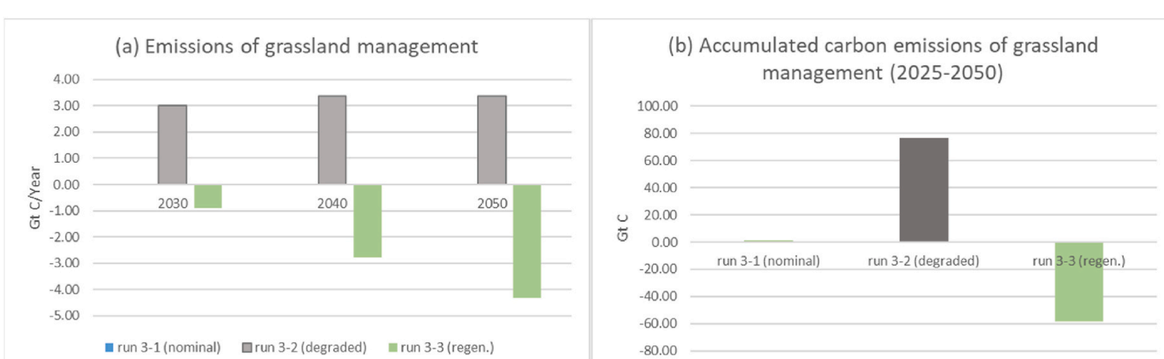

Fig. 19. results of Experiment 3. The emissions derived from the change of management in grasslands in 2050 is in figure (a). The accumulated emissions (absorptions) are in figure (b).

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 analysed 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.

CRediT authorship contribution statement

Margarita Mediavilla: Conceptualization, Data curation, Methodology, Software, Validation, Writing – original draft. **Mohamed Lifi:** Software, Writing – original draft. **Noelia Ferreras-Alonso:** Conceptualization, Software, Writing – original draft. **Luis Javier Miguel:** Funding acquisition, Project administration, Writing – review & editing. **Ignacio de Blas:** Software, Supervision, Validation, Writing – review & editing.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Margarita Mediavilla, Mohamed Lifi, Ignacio de Blas, Luis Javier Miguel, Noelia Ferreras-Alonso reports financial support was provided by European Commission. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.rser.2025.115651.

Data availability

Data will be made available on request.

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