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EU land use futures: modelling food, bioenergy and carbon dynamics

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ABSTRACT

This paper presents an original system dynamics model, which aims to assess how changes in diet, agricultural practices, bioenergy and forestry could help reduce greenhouse gas emissions. We demonstrate that changes in types and quantities of food consumed and reductions in food wastes along with sustainable bioenergy and forestry dynamics would materially assist the EU in meeting its 2050 climate mitigation obligations. We find that overall rates of EU-28 greenhouse gas emissions are highly sensitive to the food trade balance, both within and outside the EU. Land use itself is often under-represented as a major option for carbon mitigation in policy strategies, but our results show that it must become a central component aligned with energy system decarbonization if material levels of warming mitigation are to be achieved.

1. Introduction

Land use change, such as afforestation, reforestation and multiuse of land resources, has the potential to contribute substantially to reducing Europe's greenhouse gas emissions. Several models have attempted to quantify these potentials for climate change mitigation by tacking specific sectors, but often without providing a simple whole-systems perspective that could help policy makers more effectively. Our hypothesis is that to assess complex land use dynamics, including multiple uses of varying intensities and changes in dietary patterns, combinations of empirical data, mapping tools and integrated systems models are needed. Change mitigation policies have historically focused on sustainable energy transitions; however, land use management (including food, forestry and bioenergy production) and behavioural changes in dietary patterns may also substantially affect greenhouse gas (GHG) emissions trajectories [1–5].

Currently, Europe's food production is largely driven by its dietary patterns which have changed over time, including an increase in the consumption of processed food and variations in its international food trade balance. Moreover, Europe has increased crop and livestock yields, and modernised its agricultural systems. Consequently, land use in Europe has also changed, affecting land distribution for food and feed crops, livestock, forests, bioenergy, settlements and infrastructure. Futures land use dynamics for crop and livestock production can cause major impacts on biodiversity, soil conservation, water management and GHG emissions. Agriculture alone represents around 10% of the total GHG emissions in the European Union[1] (EU-28), which stood at approximately 4488 $MtCO_2eq$ in 2015, excluding land use emissions [6, 7].

In 2017, the EU-28's total land area was 424 Mha, comprising: 55 Mha (13%) of commercial forest (timber, pulp and paper), 105 Mha (25%) of natural forests and grasslands, 119 Mha (28%) of cropland, 67 Mha of land for animals (pasture), 10 Mha (2%) for settlements and infrastructure, and 68 Mha (16%) of ice, deserts and other land covers [8]. By 2017, the share of forested land has increased in the EU since 1990, although its forest sector is predominantly managed (85%) for wood supply for construction and manufacturing materials and for energy. Approximately 75% of the EU-28's forest biomass produced annually is harvest. Even so, the EU forest sector is estimated to uptake around 435 $MtCO_2eq$ per year [9], making EU forests a substantial

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[1] EU-28 means the European Union's 28 Member States combined (as in 2019): Austria, Belgium, Bulgaria, Croatia, Cyprus, Czech Republic, Denmark, Estonia, Finland, France, Germany, Greece, Hungary, Ireland, Italy, Latvia, Lithuania, Luxembourg, Malta, Netherlands, Poland, Portugal, Romania, Slovakia, Slovenia, Spain, Sweden and United Kingdom.

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carbon sink. UNFCCC [10], based on EU national inventories, reports net emissions of approximately 315 $MtCO_2$eq per year for EU-28 for its land use, land use change and forestry (LULUCF) sector, in 2012. Land for energy crops occupies approximately 10 Mha (excluding land that supplies residues for bioenergy), although there is no clear distinction between land for food or energy crops, given that energy crops are often produced under integrated multiple cropping schemes, as discussed later. Further complications arise when accounting for land for bioenergy as bioenergy feedstocks can be obtained as by-products or co-products of food crops, as well as from agricultural and livestock production residues.

In order to evaluate the sustained potential for the AFOLU (Agriculture, Forestry and Other Land Use) sector to be used for climate change mitigation, we evaluated what land use could look like in Europe by 2050. To do this effectively, we also explored the extent to which Europe could change its dependency on food and meat imports. In this paper, we ask whether potential changes in diet, crop and livestock yields, and management practices could meet Europe s anticipated food demands and avoid deforestation, as well as reduce or exacerbate GHG emissions.

Several models have already been developed to assess land use change within Europe in the context of climate change. Wolf et al. [11], for example, linked four different models (SIMPLACE, CAPRI, FSSIM and INTEGRATOR) in order to compare the potential effects of climate, price, and technological development on farming systems and future agricultural policies in Europe. More recently, Holman et al. [12] used a meta-model based on the CLIMSAVE IAP tool for assessing variations of intra-European land use change for a number of climatic and socio-economic scenarios by 2050. As a downscaling approach, Reidsma et al. [13] developed an agent-based model, based on a combination of four main models (CAPRI, RULEX, FSSIM and INITIATIOR), in order to assess the potential impacts of climate and socio-economic change on both farmland and landscape of the Baakse Beek area in the Netherlands. Some other relevant models related to land use and GHG emissions are following described: the Model of Agricultural Production and its Impact on the Environment (MAgPIE), which is a partial equilibrium model led by PIK-Potsdam in Germany [14]; the Modular Applied GeNeral Equilibrium Tool (MAGNET), which is a global general equilibrium model led by LEI Wageningen UR [15]; the Integrated Model to Assess the Global Environment (IMAGE) [16]; EC-JRC LUISA Territorial Modelling Platform [17]; and the Model for the Assessment of Greenhouse-gas Induced Climate Change[2] (MAGICC). In addition, Faber et al. [4] assessed the impacts on GHG emissions specifically from behavioural changes in dietary patterns in Europe, such as a vegetarian diet or a reduced animal protein diet, identifying a large potential for carbon mitigation over time, as well as potential indirect effects abroad.

However, despite best efforts to assess potential climate impacts on Europe s agriculture and forestry sectors, a more complete understanding is needed about the role of EU land use and its food production/consumption balances as drivers of GHG emissions to, or removals from, the atmosphere. To address this knowledge gap, we have adopted a broad interconnected systems approach which is inherently and comprehensively linked to other global dynamics, as further described in the Methods section. The proposed approach does not compete with existing models, but instead it complements them by adding a different perspective to look at the complexities involved in the EU land used dynamics and the international food trade.

To evaluate the scope and potential for Europe s land as a temporal and spatially dynamic tool for climate mitigation, we have prepared a novel integrated model, here called the EU Land Use Futures (EULUF) model, based on the land use methodology and approach previously developed for the Global Calculator.[3] Compared to other existing models, it combines into a single tool issues such as food consumption patterns, including meat consumption and type of meat (e.g. beef, chicken, pork, mutton, goat meat), crop yields, livestock yields per type of animal and production system (e.g. feedlot, free range), international food trade balance (EU imports vs. exports) and global indirect impacts, demography, bioenergy forms (solid biomass, liquid biofuels and biogas) and yields, allocation of freed-up lands (surplus areas), land multiuse (e.g. multiple cropping, and integrated systems, such as agroforestry), land degradation, and the use of wastes and residues.

By using a relatively simple system dynamics model, this paper describes the relationships between land resources, land use futures and the related greenhouse gas emissions and mitigation strategies, in order to better inform the climate change debate and encourage reflection on what sustainable European land use strategies are possible and that could be implemented. The authors recognise that many types of uncertainty are involved in the proposed model, particularly those that could result from changes in EU policies, including for bioenergy, food prices, technology innovation, agricultural practices and the accuracy of the available databases. It is worth noting that it was not the aim of this research to present an econometric analysis of carbon mitigation scenarios at a raised level of accuracy and precision, rather to understand the main vectors of land use dynamics and the potentials for carbon mitigation over time in terms of order of magnitude impacts. The uncertainty around many of these variables makes it difficult to accurately calculate the greenhouse gas emissions from European land use by 2050 and, therefore, to prioritise climate change mitigation options appropriately. Considering the uncertainties and complexities of these questions, integrative modelling approaches are fundamental components of a robust exploration of the broad range of possible different mitigation pathways. Therefore, the contribution to knowledge of this research is to propose an alternative systems tool which may contribute to the elaboration of future system models with greater resolution and accuracy. Moreover, the research follows the methodology used in the calculators initiative, which was led by the United Kingdom Department for Business, Energy & Industrial Strategy (UK BEIS, formerly UK DECC), involving several nations worldwide which already carried out their own national calculators and city level calculators; hence, it follows a method that has already been proven to be useful by several governments, business leaders and NGOs worldwide, due to its simplicity and systems perspective.

The EULUF was adapted from a pre-existing land use model developed by Imperial College London in collaboration with other institutions for the Global Calculator [1,18]. It adds to other land use assessments in Europe, such as the Volante Project [19] and the outputs from the EU Behavioural Climate Change Mitigation Options Project [4]. A European Calculator (EUCalc)[4] was recently launched by a consortium of several European institutions supported by the EU Horizon 2020 Programme. The EULUF model has contributed to the development of the EUCalc s food and land module [6]. The authors of the current article were also involved in the development of the EUCalc. Whilst the EUCalc represents land and energy use dynamics at the individual Member State and at the EU-28 aggregated levels, EULUF works exclusively at the EU-28 aggregate level and it is not based on GIS tools or mapping assessment with varying space resolutions. The EULUF uses consolidated data from official sources, such as the FAOSTAT[5] and EUROSTAT,[6] among other references cited in this article. Some data used in the EULUF model were firstly obtained and assessed per EU Member State and were then combined into a single EU-28 data matrix, given the objective of this model was to provide a relatively simple approach focused on the EU as

[2] See more about the MAGICC model at: http://www.magicc.org/.
[3] The Global Calculator is available at: http://tool.globalcalculator.org.
[4] The EUCalc is available at: http://www.european-calculator.eu/.
[5] FAOSTAT is the UN Food and Agriculture Organization s (FAO) official database, which is available at: http://www.fao.org/faostat/en/.
[6] EUROSTAT is the European Statistical Office of the European Commission, see database at: https://ec.europa.eu/eurostat.

a whole and its worldwide impacts, rather than on intra-trade dynamics. Further descriptions on how the 2050 Calculators (e.g. the Global Calculator, the EUCalc and several National Calculators) work and the respective links to access their webtools are available online in public domain.[7] In addition to the contributions for the EUCalc, the EULUF helped to inform a related assessment recently carried out by Climact (Belgium) and New Climate for the European Climate Change Foundation within its Climate Transparency Initiative [20]. The proposed approach may provide useful insights for the development of other future related projects on international carbon and land use footprint as well.

2. Methods

We used a novel whole-systems model developed by the authors, the EU Land Use Futures model (EULUF), to simulate a range of European land use scenarios to investigate what sustainable European climate change mitigation strategies might look like by 2050 and to identify critical intervention points and activities. The model allows us to investigate the potential impacts over time of a broad range of choices that affect the key drivers of land use change in Europe (EU-28).

2.1. Modelling approach

The EULUF model allows the user to assess the GHG emissions impacts arising from a wide range of possible interventions/action points, the 'levers that drive land use change. The model was adapted from the methodology used for the Global Calculator s Land Use, Food, Bioenergy and Forestry Sector [1,18]. It enables the user to assess the degree of effort with which the interventions would need to be made to generate substantive impact, with each lever having four increasing levels of ambition for climate change mitigation[8] (Fig. 1). EULUF uses aggregated weighted averages to provide representative actions across all 28 Member States and is not a 'bottom-up or process-based model. The model allows the user to develop and explore a large number of pathways arising from combinations of all levers and levels that can be chosen. For example, considering crop yield as a lever, level 1 could assumed as a pessimist scenario, in which no yield increase would be expected for all crops on average by 2050, whereas level 4 would represent an extreme effort with current yields increasing by 60% until 2050. The same rationale is applied to other levers, using different calibrations, based on literature review, and two stakeholder workshops organised by the authors at Imperial College London in collaboration with the UK BEIS and the Foreign and Commonwealth Office (FCO) in 2016, involving several international experts. Therefore, the philosophy of this methodology was already tested in previous calculators, especially the Global Calculator. The main novelty here is to implement the model at EU-28 level and combine it with the Global Calculator in order to access the indirect effects abroad (international carbon and land use footprints) from European choices in terms of imports/exports of food products by 2050.

To develop the model and calibrate all lever levels, we first investigated the current food consumption pattern in Europe and potential trends to 2050, gathering relevant related data on GHG emissions from Agriculture, Forestry and Other Land Uses (AFOLU), and other EU statistics. We then prepared datasets for main levers, such as, changes in dietary behaviour; new land use dynamics for crops, livestock and forests; changes in soil carbon; multi-cropping schemes and integrated production systems; bioenergy; wastes and residues; direct and indirect land use and GHG emissions associated with food imports/exports; among other aspects. The carbon mitigation pathways were modelled from the current to 2050, with data varying every 5 years (linearly or non-linearly, depending on the trend and data used for the calibration), i.e. 2015, 2020, 2025, 2030, 2035, 2040, 2045, and finally 2050.

Fig. 2 shows the main relationships between the levers, the underlying data and model outputs as 'results delivered to the user. The model accounts for interactions between the levers levels choices (with the endogenous baseline and historic data) and the calculated data values generated by the projections. For example, the user choices for 'calories consumed and 'meat consumed are used to derive the land demand for food production, along with relevant conversion efficiency parameters. In the EULUF model, food consumption is artificially set as a pure inelastic function as determined by the user. Food consumption and agricultural models - [21 23] - are usually based on classical assumptions, such as price-elasticity and commodity forecasts. In the EULUF model the user determines the level of food consumption, within pre-set bounds established by the modelling team, instead of using a food-price elasticity model.

As for meat consumed, the 'quantity of meat lever s level choices generate values for future demand for meat so that the necessary land area (direct and indirect) dedicated to livestock production can be calculated based on the assumed livestock and crop (for animal feed) yields. This lever can also be expanded to allow the user to select the proportion of meat types consumed by 2050 and the levels of consumption of milk and eggs. Fish consumption was modelled separately using a fixed trend adapted from the Global Calculator. The land necessary for meat production is calculated based on the user-selected dietary patterns and livestock yields, including settings for the crop yields for animal feed production. Part of the collected agricultural and food wastes are also allocated for feeding livestock under different levels of effort and animal type, as well as for bioenergy.

In order to assess the consequences of external trade, the global emission factors for the CO_2, CH_4 (methane) and N_2O (nitrous oxide) emitted as a result of supplying the plant-based food/feed and meat imported into the EU, as well as the associated land-use footprint were derived from the Global Calculator. Thus, it was necessary to conduct a sensitivity analysis of the Global Calculator (version 23) from the current to 2050. A fixed global scenario was assumed, in which the entrance variables to the model were set according to a moderate climate mitigation trend (analogous to the International Energy Agency s 4 C Scenario; 'IEA 4DS), setting the proportion of meat types similar to the EU s current diet (level 3) and changing the calories consumed (from level 2 to 3) and the meat consumption (also from level 2 to 3), obtaining emission factors for food (crops) and meat (all types under a similar EU proportion), for every five years from 2015 to 2050. In other words, by changing the levels of food and meat consumption (separately) in the Global Calculator, it was possible to estimate the impact of each lever and level change until 2050, and interpret the outputs as an approximate emission factor, in terms of CO_2eq emissions per kcal, and which vary over time.

This simulation for the global carbon and land use footprints can be easily repeated by using the Global Calculator webtool, which is available online, as already informed. Therefore, the model assumes a single international scenario in the Global Calculator for the proposed simulations, but other reference scenarios could be performed in the EULUF model by changing the global emission factors and running alternative simulations directly in the model. More progressive policies at international level, for example, could result in lower emission factors and land-use footprint for the EU imported food over time. However, for the purpose of the simulations here shown, a single international reference scenario was selected, i.e. a moderate carbon mitigation trend at global level, so that different EU scenarios could be consistently compared.

Bioenergy production and consumption estimates and allocations of biomass between end-uses are provided on a dynamic basis. Algae-based biofuels are not considered in this model, as they are not expected to

[7] See more on the calculators movement, modelling approaches and webtools at: https://www.gov.uk/guidance/international-outreach-work-of-the-2050-calculator.

[8] The model can also use intermediate levels at one decimal point through an interpolation between levels, e.g. level 1.5, 2.1, 3.2, etc.

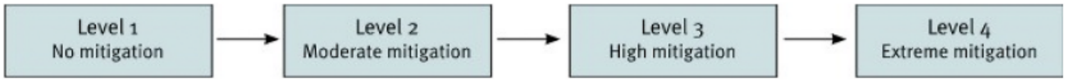

Fig. 1. Carbon mitigation effort levels for EULUF model's levers.
Source: Prepared by the authors, adapted from the Global Calculator.

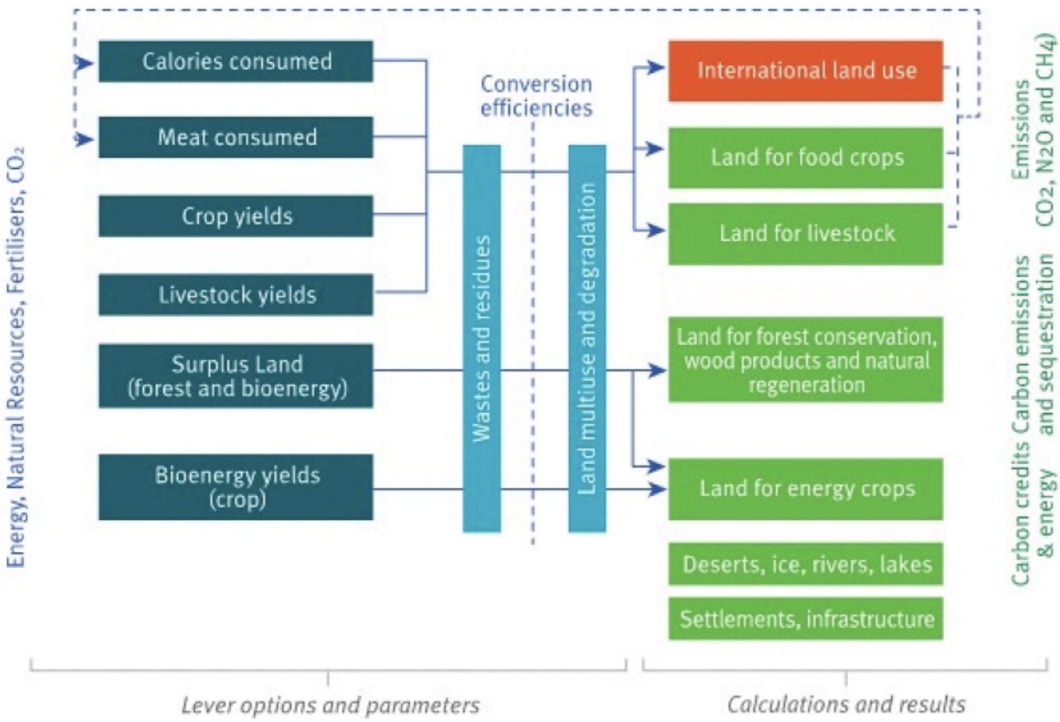

Fig. 2. Driver tree for land use dynamics, food security and GHG emissions in the EU.
Source: Prepared by the authors, adapted from GCLUC model [18].

significantly affect land use change in the coming decades. We consider it is also too speculative to make projections on the current state of the art of algae-based biofuel technologies [24], despite their high long-term potential. Crop residues are included for both bioenergy and as a source of animal feed into the model. In addition, the collection of wastes and residues also includes partial collection of sewage and animal slurry for energy purposes through the production and use of biogas.

Calculations were all made on a per capita basis. A medium fertility rate was used to estimate both global and EU population growth rates. Global population increases from 7 billion to approximately 9.6 billion by 2050, whilst the EU population remains roughly constant at the current 511 million through to 2050 [25]. The model allows further adjustment to population growth to account for other factors, e.g. migration. In terms of emissions, they are presented as lifecycle emissions for all greenhouse gases involved in Land Use, Land Use Change and Forestry (LULUCF), including average time delays for changes in soil carbon (20 years for the carbon uptake to reach equilibrium) and afforestation/reforestation (50 years for full above ground vegetation growth) [18,26,27,28].

In the case of the Global Calculator, the model was prepared using MS Excel, including all sectors of the global economy, then the database and formulas involved were converted into C language, generating a fast operational webtool. For the EULUF Model, we adapted the Global Calculator model in MS Excel, by changing all levers from the land use, food, bioenergy and forestry sector and their respective calibrations for EU standards, as well as included global emission factors for the EU food imports. We then made some scenario simulations by 2050. The two first authors of this paper also led the preparation of the original land use model in the Global Calculator, which also involved several other authors from different nations.

2.2. *Assumptions on the drivers of land use dynamics*

The approach used in this paper is based on modelling the interactions between, and impacts arising from, potential changes to the main drivers of land use dynamics, as described in the following subsections. These drivers form the basis of the EULUF model's levers.

2.2.1. *Food consumption patterns*

The quantity and type of food consumed directly influences land use. However, the nature of the environmental and social impacts of this land-food relationship is also dependent on other factors such as population growth, agricultural productivity, land ownership and investment patterns, and land use efficiency. The current daily food calorie intake in the EU is about 2596 kcal per person, which is about 20% higher than the world average of 2180 kcal [8], excluding food losses, although still lower than countries such as the United States. A higher per capita food consumption in Europe may also increase obesity problems over time. In a hypothetical scenario where the population remains constant, but per capita food consumption increases, then the land area required to meet the increased demand must also increase. However, if there is a growth in agricultural productivity, the expansion in land area for food production may not be necessary. By producing more food per unit area (yield increase and/or mixed/sequential cropping) or food in areas with other main uses (e.g. urban and peri-urban farming), the total amount of land dedicated to food production may even decrease over time, depending on the country and crop. For the EU-28, these land use dynamics were assessed in Perpiña-Castillo et al. [17], projecting a small decline in agricultural land area but also state that major dynamic is one of a significant increase in mixed cropping. Historically, due to the Green Revolution from the 1960s and 1970s, specially through plant breeding for crops like maize and rice, agricultural yields increased substantially in several nations, apart from their environmental and social impacts. This also occurred in highly populated countries, such as China and India, which were able not only to increase food security and reduce famine, but also to reduce external dependency on food imports, whilst also avoiding major deforestation rates internally and worldwide [29].

2.2.2. Quantity of meat and types of meat

The levels of consumption of meat and dairy products have substantial impacts on GHG emissions [1,30,31,32]. When raising livestock ruminant livestock, such as cattle, sheep and goats, there is a significant release of methane, a GHG with a high global warming potential (GWP), as part of the digestive process in the rumen (enteric fermentation). Depending on the livestock production system, cropland may also be required to produce specific crops (e.g. feed wheat) to feed ruminant animals, for example when livestock is raised under low-grazing or zero-grazing systems, such as in feedlots.[9] In addition, cropland is needed to produce feed for mono-gastric animals (e.g. pigs and chickens) under either feedlot or free-range systems. Imported animal feeds, such as soybean and corn, also affects EU land use and GHG emissions but moderating indigenous land demand. The use of agricultural residues and food wastes to feed animals can reduce land use impacts, particularly in the case of pig production.

The current average daily meat consumption in the EU is high: 307 kcal of meat per person compared to the global daily average of 187 kcal [8]. The average EU meat consumption is much higher than the World Health Organization s suggested daily maximum of 90g meat per person (about 152 kcal) for a healthy diet [33]. Vineis et al. [34] claim that a diet based on low meat consumption and high in pulses (legumes) would not only help reduce GHG emissions, but also prevent the incidences of non-communicable diseases (NCD), such as cancers, cardiovascular and respiratory diseases. However, the Food and Agriculture Organization (FAO) of the United Nations forecasts [35] an increase in global meat consumption of about 88% by 2050, although the consumption rates in Europe may not rise as much, given that it already has a high per capita consumption of meat and that the European consumption of animal protein has been relatively stable from 2000 to 2013 [36]. Fig. 3 shows the considerable variation in relative meat consumption levels in the EU members states and some different parts of the world, illustrating that there are many factors that determine diet choices.

2.2.3. Crop yields

An increase in agricultural productivity reduces the need for additional land resources for producing food. It is difficult to predict crop yield potentials, particularly because of the uncertainty concerning biotechnology potentials (e.g. yield, drought and pest resistance), future use of water and fertilisers, and positive or negative impacts of climate change. Positive impacts of climate change may include temperature increases in temperate regions and CO_2 effects on photosynthesis, whereas negative effects may include severe changes in precipitation and water availability, particularly a potential increase in the frequency and/or severity of droughts and floods in some regions, which may affect agricultural productivity.

Developed countries, including the EU member states, are projected by the FAO to increase their annual crop productivity by approximately 0.8% per year up to 2030, falling to around 0.3% per year from 2030 to 2050 [35]. However, speeding up crop yield gains is a challenging process, given that agricultural productivity usually grows almost steadily year upon year (linearly), instead of increasing at an annual growth rate (exponentially). There are technical limits to this growth in crop productivity, including photosynthetic efficiency and the absorption of nutrients and water by plants, although it is unlikely that these limits will be reached by 2050, even in the EU and much less so in developing countries [18,38]. For example, the world record yield for wheat is approximately 16.5 tonnes per hectare to date, while in the UK the average is about 8 tonnes per hectare [39,40]. Other limits include potential environmental drawback of an increased use of fertilizers and pesticides (e.g. biodiversity losses, GHG emissions).

2.2.4. Livestock yields

The production of meat to meet future demand poses a major challenge for land use change, given that it is necessary to produce plants first (grains and grasses) to feed the animals, which can convert only a relatively small fraction (about 10% 30% by mass for cattle and pigs respectively) of that feed intake into edible meat. An increase in the quantity of meat produced per unit area, i.e. livestock yields, would allow a smaller area to be used for livestock production. This land would then be available for other purposes, such as the production of grains, forest, energy crops or for biodiversity protection. There is a trend towards a gradual annual increase in livestock yields in developed nations, including EU countries, currently about 0.6% per year until 2030 and 0.2% per year from 2030 to 2050 [35].

Given the high degree of variation between livestock types, livestock yields cannot be assessed collectively. For example, the yield of cattle produced on pasture systems is very different from that of chickens produced in sheds, and it is therefore not appropriate to compare the number of animals per hectare in these two situations. The main parameters affecting livestock yields are the feed conversion ratio (FCR)[10], feeding system and animal density. In 2010, the animal density in the EU was estimated at about 0.98 livestock units (LSU[11]) per hectare in grazing systems and 0.77 LSU per hectare of utilised agricultural area (UAA[12]) [41]. Currently, the global average stocking density for cattle is about 0.7 cows per hectare of pasture area and approximately 3 sheep per hectare (indirectly from FAO [8]) and there is a trend for a gradual increase in livestock yields and stocking densities worldwide, possibly rising by up to 80% by 2050, particularly in developing countries. On the other hand, there are limits and concerns for livestock intensification on pasturelands in terms of animal ethics and potential environmental pollution (N content in manure). The EU Commission Regulation no. 889/2008, for example, details rules for organic farming, including recommendations for animal density, for which some countries (e.g. Poland) and regions (e.g. Wallonia in Belgium) suggest the upper limit at 2 LSU per hectare [42,43].

2.2.5. International food trade balance

The balance of food imports and exports in Europe affects the demand for land for crop and meat production. Changes in the international food trade balance may lead to land expansion or contraction within Europe, depending on other factors such as crop and livestock yields, land multiuse and degradation [17]. The EU s exports some types

[9] Feedlot also known as feed yard is here understood as an intensive animal farming operation, in which animals are raised in small plots of ground or establishment, as a factory farm instead of free-range systems, to be fattened more rapidly for market.

[10] FCR represents the amount of feed intake that is converted into edible meat, milk or eggs. The ratios may vary according to the type of animal, its genetics, age, lifetime, production system, animal health, farm management, climate conditions, and feed quality.

[11] LSU is a reference unit which facilitates the aggregation of livestock from various species and age as per convention, via the use of specific coefficients established initially on the basis of the nutritional or feed requirement of each type of animal [19].

[12] UAA represents the total area taken up by arable land, permanent pasture and meadows, land used for permanent crops and kitchen gardens [19].

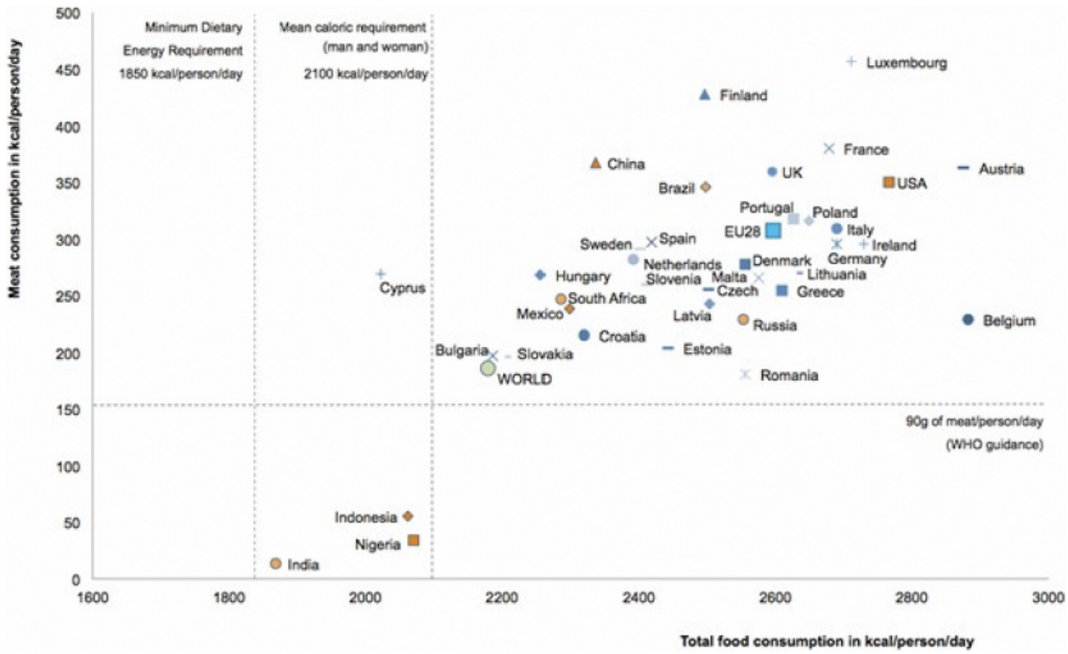

Fig. 3. Daily meat consumption vs. total food consumption (kcal per person per day as eaten) in the EU countries and other nations.
Source: Prepared by the authors, using data from FAO [8] (2011 base year) and excluding food losses [37]. Meat consumption represents all types of meat combined, except fish.

of food products and imports other types from different countries and, therefore, it is either a net exporter or a net importer, depending on the food type and price, [4]. On average, the self-sufficiency level for all plant-based food combined is approximately 81%, whereas for all types of meat combined, about 103%, as described by Noleppa & Cartsburg [44]. As such, the EU is a net food (crops) importer and a net meat exporter in terms of mass balance, but not economic value. However, there are concurrent imports and exports of different products and with different aggregated values (e.g., cocoa vs. chocolate, raw coffee vs. processed coffee, processed meat, cheese, wine, etc.), alongside imports of animal feeds (e.g. soybean) for local meat, milk and cheese production. Hence, it does not mean that the EU is at thresholds of production. EU produces, imports and exports according to economic factors, environmental constraints and trade agreements, albeit with substantial uncertainties around these data, which can vary overtime. By using FAO data [8], for example, EU is already self-sufficient in food (118%) and meat (107%) in terms of net trade balance.

Europe's food trade balance may change substantially in the coming decades due to changes in supply and competitiveness in international food markets. A detailed analysis of self-sufficiency goes beyond the scope of this assessment because it also involves food security, changes in income and jobs, purchasing power, bilateral and multilateral agreements, production costs, global power structures, trade barriers, currency impacts and consumer preferences. International food trade affects GHG emissions indirectly, because export countries to the EU would have to allocate land, energy, water and other agricultural inputs for producing food to the European population. For example, by importing more food, the EU may be able to free up some productive (or marginal) local land for the regeneration of native ecosystems or alternative land uses (forestry, recreational, urban development, etc.), but there may be a consequential land-use and GHG impact somewhere else in the world related to the crops that are imported. Besides, there are spatially differentiated intensities of agricultural production around the world. In the present assessment, we used the Global Calculator for estimating the approximate carbon and land footprints associated with possible changes in the EU imports overtime, as described in the Methodology.

2.2.6. *Bioenergy forms and yields*

Bioenergy yields are affected by three factors: crop yield, energy content of the crops, and conversion technologies. Yields of food crops used as bioenergy feedstocks (e.g., wheat, oilseed rape, soy, oil palm, sugar beet, sugar cane, etc.) might increase similarly to other crop yields, in terms of net primary production (NPP). However, it is anticipated that by 2050, a significant shift toward energy crops with high-energy efficiencies, such as short rotation coppice and several types of grasses, may occur not only in the EU, but also globally. This shift is considered possible given the progress in the large-scale deployment of new commercial technologies such as lignocellulosic ethanol, Fischer-Tropsch biodiesel (biomass-to-liquids) and hydro-treatment [45,46], although the economics remains challenging. Energy crops are also subject to technological advances in crop breeding aimed at suppling feedstocks for second-generation biofuels, such as genetic improvements for higher yields of celluloses and hemicelluloses, drought tolerance and improved nutrient use efficiencies. Industrial integration to produce biofuels is also expected to increase in the coming decades. Therefore, the resulting global average energy yield improvement is believed to be higher than that of food crop yields[1], considering all these effects combined.

According to the Renewable Energy Policy Network for the 21st Century (REN21) [47], Europe consumed about 3.1 EJ (861 TWh) in 2014 of modern biomass, including biogas, for heat generation, mainly in Sweden, Finland, Germany, France and Italy. Europe also has a substantial bioelectricity generation sector primarily using solid biomass, with approximately 36.5 GWe of installed capacity in 2014, generating approximately 81.6 TWh per year, mainly in Germany, Finland, the UK, Sweden and Poland. In addition, it has 7.9 GWe of installed capacity of biogas power plants and accounts for 62% of the total biomass pellets produced worldwide. These figures may vary depending on the reference used, nomenclature and if biomass residues are included or not in the estimates, as well as energy transformation losses. Eurostat [48], for example, presents 1520 TWh of gross inland consumption of bioenergy for 2014, including approximately 570 TWh for energy transformation (mainly electricity production) and 960 TWh for final consumption. Moreover, the EU is a major producer, importer and consumer of liquid biofuels, producing approximately 4.1 billion litres of ethanol, 11.5 billion litres of biodiesel, and 2.5 billion litres of Hydrotreated Vegetable Oil (HVO) a year, which represent, respectively, around 4%, 38% and 51% of the global production in 2015. Germany is the third largest biofuel producer, behind the USA and Brazil, with the Netherlands, France and Spain also among the top 15 largest biofuel producing countries worldwide [49].

2.2.7. Agricultural land made available for other purposes

The EU agrarian structure has changed substantially in recent decades, particularly with the globalisation of food markets, the gradual reduction of agricultural subsidies and the switch from production-based subsidies towards those that target environmental performance. Since the 1990s, there has been a continuous decline in European agricultural area which have become surplus to requirements and are continuing to alternative uses. In addition, some countries have started programmes to recover some of their historically deforested lands, including the UK, France and Germany.

Depending on the characteristics of food production and consumption and land productivity in the EU in the coming decades, more surplus land may be freed up. If such land becomes available, then forestry and bioenergy could also be expanded, including commercial plantations or natural regeneration of forest and grasslands. To date, the EU's forest-land cover has been increasing. However, changes in food demand may prevent any further land from becoming available for forests by 2050. Under such circumstances, deforestation may even occur, although it is more likely that the EU would balance its food demand with imports, given its internal legal framework for forest protection.

2.2.8. Land multiuse

When considering the use of productive land, it is important to include productivity gains by land multiuse and avoid double counting of land resources. Arable land area is the dimension of a land surface that can potentially be used for agriculture, whereas the harvested area is the area within arable land that was actually harvested. Differences arise when land planted with crops is abandoned due to severe incidences of pests and diseases, flooding, drought, for example, or when it may simply not be worth harvesting due to unexpectedly low market value. Therefore, in the EU, the harvested land area varies significantly year-on-year, whereas the total arable land area is more constant over time.

Some regions also have more than one harvest a year by producing both a summer crop and a winter crop. This practice is known as multiple cropping. Other regions will be unable to do so, due predominantly to climate constraints and/or low photoperiod (daily length of sunlight). In some cases, it is possible to have triple cropping through either favourable climate conditions, (e.g. in tropical and subtropical regions), or by using crops with short life cycles in sequential rotation. The use of greenhouses and plastic films can also help manage temperature change, moderate intensive sunlight (by providing shading) and water (and nutrient) losses, expanding the potential uses for certain areas of land. Other important types of multiple cropping are mixed-cropping, intercropping, relay-cropping and sequential cropping.

The land use efficiency, in terms of number of crops per year on a same land area, is measured in the multiple cropping index (MCI), which represents how intensively farmed a certain country or region is. The EU's total arable land area is 108 million ha, of which it harvests 81 million ha per year (excluding perennial crops) [8], with a calculated average MCI of 0.75 (no unit). Fig. 4 shows that the MCI value varies considerably at country level, but this variation is also present at the regional and even farm level. Intensity is affected by the type of harvested crops, their production cycles, regional climate variation, as well as food market, availability of funding for farmers, agricultural skills and know-how, amongst other issues. Some countries or regions may be using some of their arable lands intensively but leaving the remaining arable lands for non-productive purposes (e.g. fallow land) or for temporary pasture often integrated with crop production, therefore keeping their MCI relatively low. In addition, horticultural crops (e.g. lettuce, tomato) usually have short cycles and are often produced using greenhouses or plastic-film coverings along the year.

MCI is calculated as the sum of harvested areas with different crops during the year, divided by the total cultivated area in a certain country or region. Therefore, multiple cropping represents an increase of total production per unit of area that is additional to the potential yield gains of each harvested crop. The cultivated areas include cereals, pulses, roots and tubers, oil crops, vegetables (incl. melons) and fibre crops. Because land use classifications are often not clearly identified, there is an uncertainty associated with MCI values. Temporary pasture, for example, is not included in our calculations and this is why some countries with significant areas of temporary pasture (e.g. The Netherlands) show a lower MCI than expected, among other issues. These estimated MCIs represent national averages, which can vary overtime. It serves as a broad indicator, but a more in-depth analysis is required to understand the specificities of each nation. Double cropping, for example, occurs not only in nations with MCI >1 (e.g. Greece and

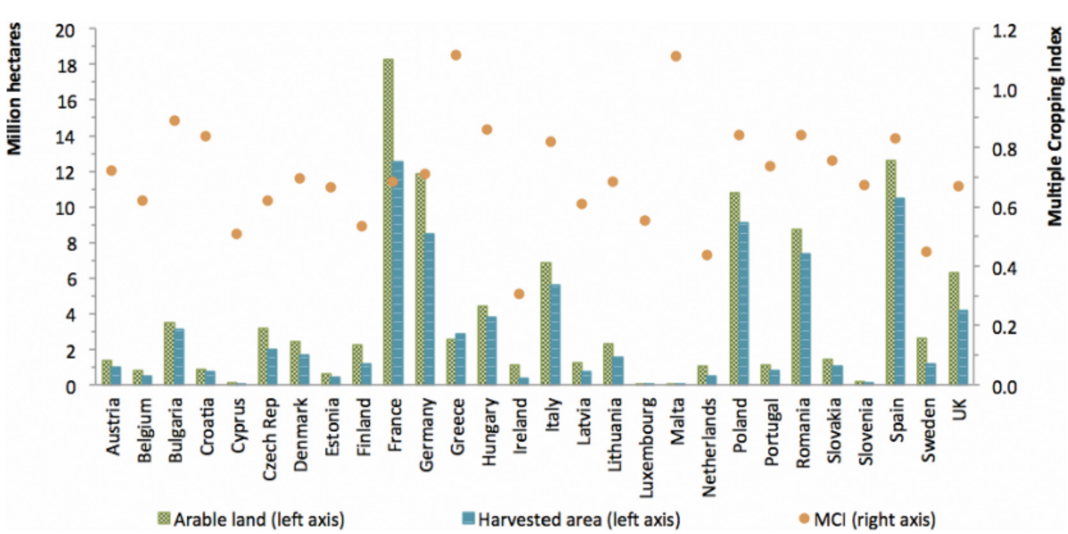

Fig. 4. Arable land, annual harvested area and multiple cropping index in the EU.
Source: Prepared by the authors, using land use data from FAO [8], including for the Multiple Cropping Index (MCI) estimates. **Note:** EU Average MCI = 0.75, in a range between approximately 0.30 and 1.10 (no unit).

Malta), but also in many locations of countries with MCI 1, given that the national average is affected by other land use types that may counter-balance the impacts from intensified areas.

Moreover, the variation of land-use nomenclatures adds complexity and uncertainties for assessing the role of multiple cropping on carbon mitigation in Europe. Perpina-Castillo et al. [17], for example, recently estimated that the EU agricultural lands represented about 42% of the total EU territory in 2015, out of which arable land covered about 56%, livestock grazing 25%, mixed crops 13.5%, and various permanent crops 5.5% (e.g. vineyards, olive trees, fruit trees), with significant differences among Member States. These authors also suggested a 1.1% reduction in agricultural land area from 2015 to 2030, being 4.0% for arable land, 2.6% for livestock grazing, 11% for mixed crops, and a minor variation in the total area dedicated to permanent crops.

Another form of land multiuse is land use integration, such as agro-livestock-forestry schemes and different combinations between them, including land-based aquaculture. Thus, in the case integration, rather than an overlap of different land use layers as in the multiple cropping schemes, there is an intersection of different land uses over time. Where land use integration is in place, it is worth noting that different land uses cannot be simply summed up as separate areas, because they may represent a common area. Consequently, less land is usually required to meet a same amount of food production, helping to free up land for other land use purposes, including bioenergy and afforestation/reforestation, or simply reducing land demands for new productive capacity. Generally, land use integration is associated with benefits for farmers, and as a source of environmental services, for example integrating productive lands with solar and wind energy systems, as well as water and biodiversity conservation via functional landscapes. The European Agroforestry Federation (EURAF) [50], for example, aspires that 50% of the European farmers could have agroforestry schemes by 2025, by combining woody vegetation, crops and/or livestock on a same farmland, under different levels of integration.

Although more complex to implement than conventional agriculture, land multiuse can offer a number of advantages to farmers, including reducing their businesses risks by diversifying the production system. Integrated schemes can also increase biodiversity on productive lands. Multi-clonal and species cropping can reduce the need for herbicides and increase soil carbon content, for example, by enabling an increase in no- or low-till systems. Using crop rotation schemes that alternate *Gramineae* crops (grasses such as wheat, rice, maize and barley) and leguminous plants (*Fabaceae*, i.e. pulses such as beans, peas, alfalfa, clover, lentils and peanuts) take advantage of the nitrogen fixation in the legumes root systems and can reduce the need for nitrogen fertilisers.

The overall productivity in integrated systems is also normally higher than in conventional ones. However, whilst land multiuse can reduce the demand for additional productive land for crop and meat production, an over-exploitation of land resources may cause land degradation, release soil organic matter and carbon to the atmosphere and ultimately damage its productive capacity resulting in lower yields and reduced water and nutrient-use efficiencies. This is why agriculture intensification, including multiple-cropping and integration, has to be properly managed with agronomical assistance.

2.2.9. Land degradation

The main causes of soil degradation are erosion, acidification, local and diffuse contamination (acidification and heavy metals), desertification, salinization, and the sealing of soil surfaces by infrastructure and urbanisation. The intensive use of heavy machinery can also lead to soil compaction, affecting water, air, and nutrient dynamics, soil biota, and root growth. Soil erosion by water and wind is particularly critical in areas with steep slopes, shallow soils, poor agricultural management, and the over-exposure of soils to weathering effects in the absence of vegetation cover. The European Environmental Agency (EEA) [51] found that the areas most impacted by soil erosion in the EU are predominantly in the Mediterranean region, with the damage in some of these areas becoming irreversible due to severe soil loss. Water-driven erosion is particularly critical in the Southern and Central European and Caucasus regions, and overall about one third of Europe is under high to very high risk of erosion. In Western and Northern Europe, the main causes of soil degradation are urbanisation and infrastructure development. Prolonged declines in water availability can also affect land degradation.

An increase in land degradation has the potential to reduce the availability of productive land for food production. Moreover, adverse effects from climate change may increase the incidence of land degradation in the EU, particularly due to changes in precipitation and flooding [51,52].

2.2.10. Wastes and residues

Wastes and residues can be grouped by their provenance: firstly, on-farm residues, as by-products of crop production (e.g. straws); secondly, the post-farm wastes, as food waste arising from the distribution system and consumption. Finally, sewage treatment and animal wastes (manure, animal slurry and tallow) are also important in terms of GHGs, environmental impacts and the potential for energy recovery. Overall, Alexander et al. [53] estimate that only 6% of globally produced agricultural biomass is ultimately consumed by humans and that 44% of dry matter in harvested crops is 'lost prior to human consumption. For each tonne of food that leaves a European farm such as in the form of cereal grain, vegetables etc., approximately another tonne remains within the farm as straw, husks, leaves, roots, etc. [54]. These on-farm residues can be partially collected, but potential trade-offs with soil carbon impacts are likely to occur in case of an excessive removal of organic material that would originally be left on soil.

Post-farm waste, which is the waste produced from the farm gate up to final disposal, represents around 30% of the mass of total food production, eventually reaching landfill/dump sites or becoming organic compost [55]. For the purpose of this article, in energy terms, we considered that post-farm waste represents approximately 24% of plant-based food and 19% of meat [37]. In the EU, the collection of waste is substantially higher than the global average, and the losses in the supply chain are usually lower than in developing nations, due to better infrastructure and storage systems. However, developed nations, including EU member countries, tend to waste more food at the consumer level than developing nations. The latter tend to discard less food once purchased for a number of reasons, including income constraints, awareness and limited access to food. Food prices can also influence these dynamics.

2.3. Model s calibration

Based on the main assumptions of land use dynamics described in the previous section, the EULUF model was calibrated according to each lever adopted in the model, as shown in Table 1. This calibration involved not only the identification of current values and historical trends, but also the use of several references from the available literature in order to estimate target values for the levels 1 to 4 of each lever by 2050. These values were also briefly discussed with international experts who participated in the two stakeholder workshops of this research.

2.4. Simulation pathways

In our simulations, we have run the EULUF model for two selected scenarios, based on assumptions and references previously cited in Table 1:

Low Emission Scenario (LES): per capita meat consumption gradually reduces towards the WHO recommendation of 90g a day (level 3), keeping the current proportion of meat types stable (level 3) whilst slowly reducing the total calories consumed per person (level

Table 1
Description of the levers and levels of the EULUF model, and ranges used of their calibration.

Levers	Current situation (actual data)	2050 (Levels 1 to 4)	Comments	Main references used for the estimates
Food calories consumed	2600 kcal/person/day	2770 2100 kcal/person/day	All types of food. Values in terms of net food intake, i.e. already excluding food wastes in energy terms (24%).	[8,21,22,35,37]
Quantity of meat	307 kcal/person/day	350 - 150 kcal/person/day	All types of meat. Values in terms of net meat intake, i.e. already excluding meat wastes in energy terms (19%).	[8,33,35,37]
Type of meat (ruminants: monogastrics)	20:80	30:70 15:85	Proportion of meat consumed from ruminant animals (cattle, sheep and goats) against monogastrics (pig, chicken and other poultry), in energy terms.	
Crop yields	100 (levelised index)	0 60% increase	Percentage of 2011 yield. Average for all crops.	[8,23,35,38,39,56]
Feedlot systems	30% for cattle 5% for sheep and goats	0 50% for cattle 0 20% for sheep and goats	Proportion of animals reared in confined systems and fed on grains, food wastes and agricultural residues.	[8,30,35,41,54, 57 59]
Livestock s feed conversion ratio	5.0% (cattle, sheep and goats), 24.4% (poultry), 27.1% (pig), 7.8% (milk), 13.0% (eggs).	5.3 7.0% (cattle, sheep and goats), 25.2 28.8% (poultry), 28.4 32.4% (pig), 8.4 9.6% (milk), 13.7 15.6% (eggs).	Percentage of feed input converted to meat/milk/egg, in energy terms.	
Animal density on pasturelands	100 (levelised index)	0 50% increase	Averages with large local variations.	
Level of self-sufficiency in food and meat	81% food 103% meat	70 110% food90 - 120% meat	Food and meat international trade balance. Consequential land and GHG emissions abroad are applied.	[42]
Land multiuse	100 (levelised baseline)	100 - 70%	Land needed to meet food demand may reduce by 30%, because of land multiuse (e.g. multi-cropping, agroforestry and agro-livestock systems).	[60 64]
Land degradation	100 (levelised baseline)	110 - 100%	Land degradation due to soil erosion and climate impact may reach 10% in the extreme scenario.	[51,52]
Surplus land	Approx. native vegetation distribution 80% forest 20% natural grasslands	Allocation of freed up lands: 80 - 16% forest 20 - 4% natural grasslands 0 80% energy crops	Preferences for land allocation of surplus lands, once attending food security. In this lever, levels 1 to 4 do not necessarily reflect increasing mitigation effort, but just different mitigation options instead.	[8,65 67]
Bioenergy yields	100 (levelised index), energy yields vary for biofuels or solid biomass	20 100% increase	Solid biomass estimated for modern bioenergy. Biofuel yields represent a weighted average between biodiesel and bioethanol.	[8,46,47,68,69]
Bioenergy types (solid: liquid fuel)	85% solid: 15% liquid	90(s):10(l) 50(s):50(l)	Proportion of solid vs. liquid fuels generated from the future expansion of dedicated energy crops. This lever includes modern bioenergy only, and levels 1 to 4 do not necessarily reflect increasing mitigation effort, but just different mitigation options instead. Biogas and traditional biomass are modelled as fixed trends based on literature.	
Wastes and residues	Production of on-farm residues: 1:1. Production of post-farm wastes: 24% food 19% meat Collection and use: 10% on farm 40% post-farm plant based food and meat 8% post-farm eggs 4% post-farm milk	Production of on-farm residues: 1:1. Production of post-farm wastes: 24 - 10% food in general 19 - 5% meat Collection and use: 10 50% on farm 45 80% post-farm plant-based food and meat 10 50% post-farm eggs 5 20% post-farm milk	Production: proportion of residues and wastes produced on farm and post-farm Collection and use: proportion of available residues and wastes (in terms of energy content) that are collected for energy generation. Part of wastes is also allocated to animal feed.	[37,55,58,70 73]

Source: Prepared and estimated by the authors, using approximate figures from the references cited within the table, the Global Calculator, Strapasson [18], and stakeholders consultation.

2), as well as achieving net self-sufficiency in both plant-based food (level 3) and meat (level 2). The use of surplus land is dedicated to the expansion of both forests (incl. natural regeneration, and natural grasslands) and energy crops, in the proportion of 60% and 40%, respectively, of the freed-up land (level 2). All other levers' levels were set to the high mitigation ambition level (level 3). Therefore, this scenario represents an optimistic mitigation pathway where European diets change in a way that reduces greenhouse gas emissions, overall calories consumed per person are reduced and mitigation ambition is high.

- ***High Emission Scenario*** (HES): little or no effort in mitigating GHG emissions. It assumes very high per capita food and meat consumption rates (both level 1), keeping approximately the same current share of meat types in the EU (level 3), increasing dependency on both food and meat imports (both level 1) and leaving all other levers set at a moderate change (level 2). Thus, HES is believed to be significantly above a business as usual trend. It exemplifies a pessimistic pathway where there is little or no concern for mitigating greenhouse gas emissions and meat consumption and total food consumption per person remains high. The allocation of potential surplus land is the same as the LES.

These two simulations above are an exercise, among many other technically possible pathways that could be simulated, to show how changes in the EU policy as well as behavioural changes of the European population could affect both GHG emissions and land use change. These scenarios were inspired in the discussions obtained from the two stakeholder workshops of this research, both held at Imperial College London in 2016, as already mentioned. However, these simulations were not aimed at representing any specific EU climate policy or to suggest a Business-as-Usual scenario, because the EULUF model was not prepared for this purpose, although some approximations may be possible to be made. For instance, the EU Green New Deal [74] may be closer to the LES simulation regarding agriculture and land use emissions, although it was not aimed to this end. The Green New Deal was recently submitted by the European Commission to the European Parliament, the European Council, the Council, the European Economic and Social Committee, and the Committee of the Regions, through an official communication (reference no. COM (2019) 640 final). Hence, these two simulations (LES and HES) are both illustrative and were prepared with the objective of estimating the magnitude of impacts on carbon emissions and land use change in both inside and outside Europe. In the occasion of the second stakeholder workshop of this research, the authors prepared a briefing paper at the Imperial College's Grantham Institute for Climate Change [75], which served as a preliminary report for the preparation of this current article.

It is also important to note that this model is exposed to several uncertainties, such as changes in the composition of the EU member countries (e.g. the recent Brexit), European policies and legal frameworks, international food prices, and the potential impacts of climate change on crop yields. Besides, the model does not show regional differences within the EU. The accuracy of the model is also dependent on the accuracy of the database and references used in the model. It does, however, provide a broad picture, but further assessments are required to understand regional dynamics within the EU as well as international changes, in combination with other existing models already mentioned.

3. Results and discussion

Using our EULUF model, we have assessed a wide range of different land use patterns that could arise through a combination of behavioural and technological choices over the coming decades. Fig. 5 shows the land use dynamics for both the LES and HES scenarios compared with current land use distribution in the EU. These outcomes highlight the potential for both enhanced self-sufficiency in food production and lower GHG emissions, combined with the potential for a significant land-based carbon sink to emerge. However, there is also the risk of a substantial impact on land use and GHG emissions arising outside the EU if dietary trends are not altered from their current course. In the HES simulation, the higher consumption of both meat and total food calories occurs without a major increase in the EU crop and livestock yields and with a slight increase in forest area and decrease in pasture area. This increased demand and static supply is balanced by higher meat imports, consequently causing an external land use impacts to meet the European market's needs.

Both scenarios show a significant impact on the EU's GHG emissions. The high emissions scenario drives the transfer of GHG emissions from Europe to countries outside the EU arising from the increased imports needed to supply the high projected demand of food and meat in the EU. HES results in a reduction of total domestic GHG emissions to about 375 $MtCO_2eq$ per year, including some negative emission for afforestation/reforestation; however, emissions outside the EU increase significantly to around 1 $GtCO_2eq$ per year by 2050 from the production of both imported meat and plant-based food (Fig. 6). This sharp increase in overall emissions includes an estimate of the emissions resulting from potential deforestation abroad as the agricultural land required to service the additional food imports expands (at least partially) at the expense of forests.

In contrast, the LES shows that it would be technically possible to reduce the total land use emissions within the EU, from 421 $MtCO_2eq$ per year in 2011 to 298 $MtCO_2eq$ per year in 2050, whilst also being self-sufficient in food production in terms of net trade balance (Fig. 7). This could be achieved mainly by having a more vegetarian diet and by substantially increasing the agricultural and livestock production and

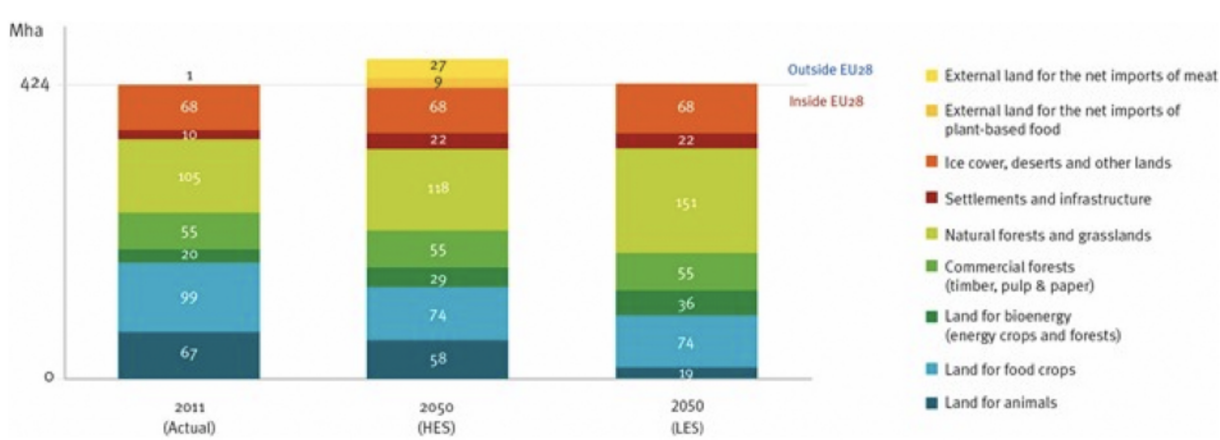

Fig. 5. Simulations of land use futures in the EU for a high emission scenario (HES) and a low emission scenario (LES).
Source: Prepared by the authors, EULUF model.

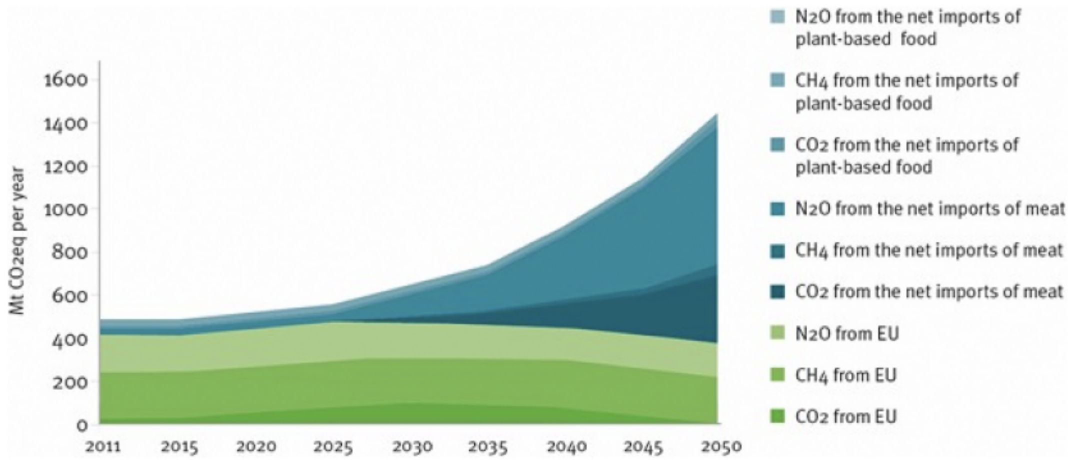

Fig. 6. High Emission Scenario (HES) for the EU AFOLU GHG emissions.
Source: Prepared by the authors, EULUF model.

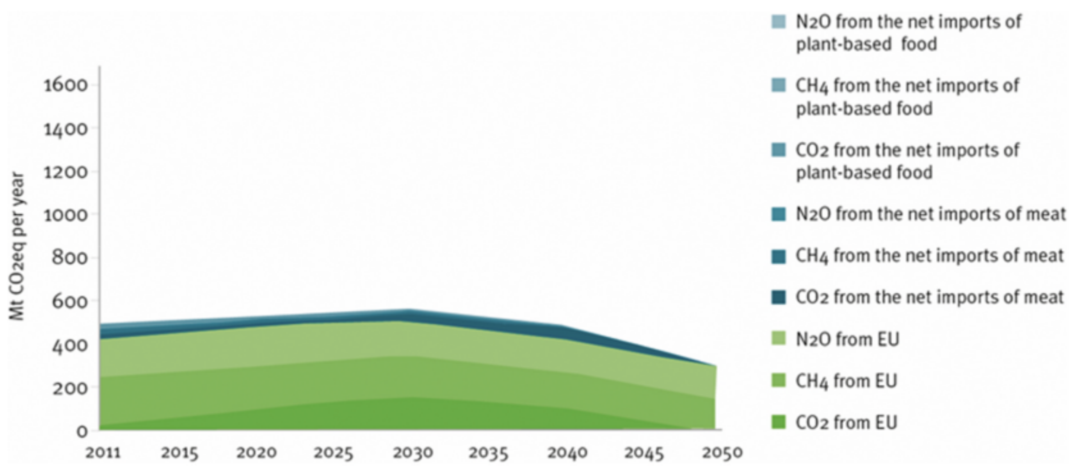

Fig. 7. Low Emission Scenario (LES) for the EU AFOLU GHG emissions.
Source: Prepared by the authors, EULUF model.

use efficiencies.

It is possible to estimate from the EULUF model that the total EU production of bioenergy, for all uses, could increase from approximately 7.1 EJ in 2011 to 9.5 EJ in 2050 in the HES simulation, or to as high as 14.3 EJ in 2050 in the LES simulation. As a comparison, the European Calculator (EUCalc) recently launched suggest that the bioenergy capacity could reach a maximum of approximately 25 EJ by 2050 under a very ambitious carbon mitigation pathway [76], and therefore the LES simulation is within this boundary.

Bioenergy could save further GHG emissions in Europe by displacing fossil fuel options at end-use, for example ethanol replacing gasoline for transport and solid biomass being used instead of coal for power generation. In a global assessment, Strapasson et al. [1] used the Global Calculator to estimate that total bioenergy supply without food competition would increase from approximately 60 EJ in 2011 to 70 EJ in 2050 under a Business-as-Usual scenario with strong land use constraints (pessimist scenario), whereas in a global high mitigation scenario, this bioenergy provision could reach 170 EJ, and in an extreme situation up to 360 EJ. Therefore, the EU could either export or import biomass energy by 2050, depending on the scenario; however, these simulations show some approximate boundaries for potential international bioenergy trade with the EU, in terms of net primary energy supply by 2050. In this context, it is important to ensure that any bioenergy feedstock imported to the EU, including vegetable oils for biodiesel production, will be sustainably produced in order to avoid potential deforestation in some biomass producing nations outside Europe [77].

The flexibility of the model allows further simulation of EU AFOLU futures which can support research and policy debates on EU decarbonization strategies. For example, Fig. 8 depicts the AFOLU GHG emissions in 2050 for four illustrative scenarios, including values for total net emissions. The mitigation impact of reducing meat consumption, using efficient cropping techniques and allocating the freed-up land mainly to forest and to carbon capture in soils (under LULUCF-others) can be clearly observed.

4. Conclusions

Dedicated integrative models, such as the EULUF model described here, are needed to assess the systems dynamics of land use, diet and food security and are fundamental to helping us understand the dynamic interactions between food, land use, and greenhouse gas emissions from a wider perspective. However, with increasing complexity comes increasing uncertainty and our outcomes should be taken as illustrative of this controversial debate rather than considered to be conclusive. A shift towards more vegetarian diets that are higher in pulses and vegetables, and lower in meat, particularly from ruminant animals, could substantially help mitigate climate change. At the same time, mitigation

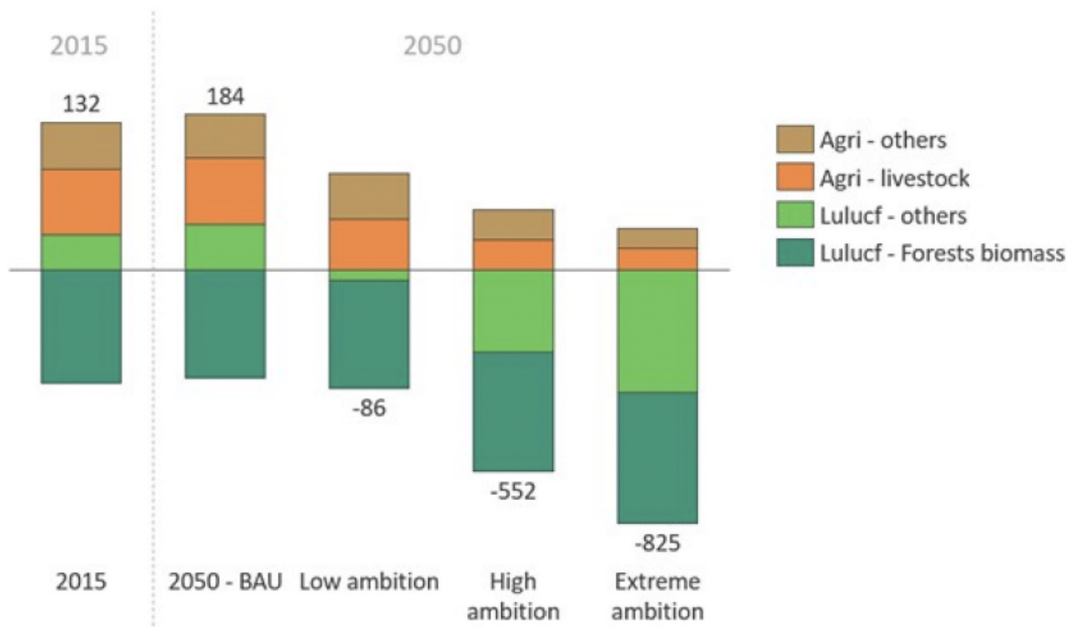

Fig. 8. EU AFOLU GHG emissions in 2030 and 2050 following 4 illustrative scenarios, in $MtCO_2eq$ per year.
Source: Prepared by the authors, EULUF model.

of GHG emissions can also be obtained in the livestock sector, but only if effective measures are taken to increase livestock yields and simultaneously raise soil carbon levels in pasturelands and croplands for the animal feed, which may contribute to reduce carbon footprint per unit of meat consumed. We show that an increase in crop and livestock yields and land multiuse, coupled with a reduction in food wastes could substantially reduce the impacts of diet and land use on GHG emissions and the associated need for additional productive land, within or outside the European Union, or both. Reforestation of surplus land also appeared a key EU lever to reduce its emissions.

The next challenge for policymakers and other stakeholders is to consider the most appropriate and effective public policies to stimulate the sustainable land use transitions and behavioural changes needed for healthy diets and climate mitigation. This paper shows the importance of looking at the global picture of emissions as well as the local (e.g. the European Union), when developing land use and climate mitigation policies and approaches.

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CRediT authorship contribution statement

Alexandre Strapasson: Conceptualization, Investigation, Methodology, Software, Formal analysis, Writing - original draft. **Jeremy Woods:** Investigation, Methodology, Writing - review & editing. **Jerome Meessen:** Investigation, Formal analysis. **Onesmus Mwabonje:** Writing - review & editing. **Gino Baudry:** Writing - review & editing. **Kofi Mbuk:** Investigation.

Declaration of competing interest

The authors 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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