Imperial College London

Grantham Institute
Briefing paper No 17

March 2016

Land use futures in Europe

How changes in diet, agricultural practices and forestlands could help reduce greenhouse gas emissions

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In partnership with the UK Department of Energy and Climate Change (DECC) and the UK Foreign and Commonwealth Office (FCO)

Foreign & Commonwealth Office

Department of Energy & Climate Change

Contents

Headlines:

- 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.
- Changes in the types and quantities of food consumed per person and reduced food wastes would help the EU meet its climate change targets by 2050.
- EU greenhouse gas emissions are highly sensitive to the food trade balance, both within and outside the EU. Choices made about the EU's level of self-sufficiency in food and food security are key determinants of net EU and global greenhouse gas emissions.
- To assess complex land use dynamics, including multiple uses of varying intensities, combinations of empirical data, mapping tools and integrated systems models are needed.
- To achieve greenhouse gas emissions reduction through land use and dietary change, the right mix of short and long-term policies is needed. In the case of dietary changes and reduced food waste, success may depend on systemic behavioural changes which would require a range of policy levers ranging from market regulations through to education and links with the health agenda.

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Introduction

Food consumption patterns and production methods have major implications for land use and greenhouse gas (GHG) emissions. Climate change mitigation policies are usually focused on energy, transport, buildings, infrastructure and industry. However, changes in our diet and associated land use for food production could substantially affect GHG emissions[1,2,3]. Europe's dietary patterns have changed over time, including an increase in the consumption of processed food and variations in its international food trade balance. In addition, Europe has increased crop and livestock yields, and has modernised its agricultural systems. Consequently, land use in Europe has also changed, affecting land distribution for crops, livestock, forests, bioenergy, settlements and infrastructure. New land use dynamics can have major impacts on biodiversity, soil conservation, water management and GHG emissions. Agriculture represents around 10% of the total GHG emissions in the European Union's 28 member states (EU28), which stood at 4,611 $MtCO_2eq$ in 2013[4].

The current balance of land use in the EU28 is illustrated in Figure 1. Perhaps surprisingly, the share of forested land has increased by 7% since 1990. The EU forest sector is predominantly managed (85%) and available for wood supply. Approximately three quarters of forest produce each year is harvested, which may have contributed to an annual uptake of around 435 $MtCO_2eq$ at the farm level[5], making EU forests a GHG emissions sink.

To evaluate the potential for the AFOLU (Agriculture, Forestry and Other Land Use) sector to be used as a tool for climate mitigation, an understanding of what land use could look like in Europe to 2050 is needed. It is also important to explore the extent to which Europe will change its dependency on food and meat imports in the future. Will changes in diet, crop and livestock yields, and management practices be sufficient to fully meet Europe's anticipated food demands and avoid deforestation as well as reduce GHG emissions?

This paper describes the relationships between land resources, land use futures and the related greenhouse gas emissions and mitigation strategies, in order to inform the climate change debate and encourage reflection on sustainable land use strategies in Europe. A range of variables such as diet, agricultural and forest productivity levels, demographics and societal demands, and the effectiveness of waste minimisation and re-use strategies drive the land use dynamics that we observe and project. These variables are interconnected and subject to complex dynamics and interactions.

To evaluate the scope and potential for Europe's land as a climate mitigation tool, we have prepared a novel integrated model referred to here as the EU Land Use Futures (EULUF) model, based on the land use approach previously developed for the Global Calculator[7]. The next section presents an overview of the key drivers of land use dynamics in Europe, followed by the key model outputs. The methodological approach used in our modelling simulations is described in Appendix 1.

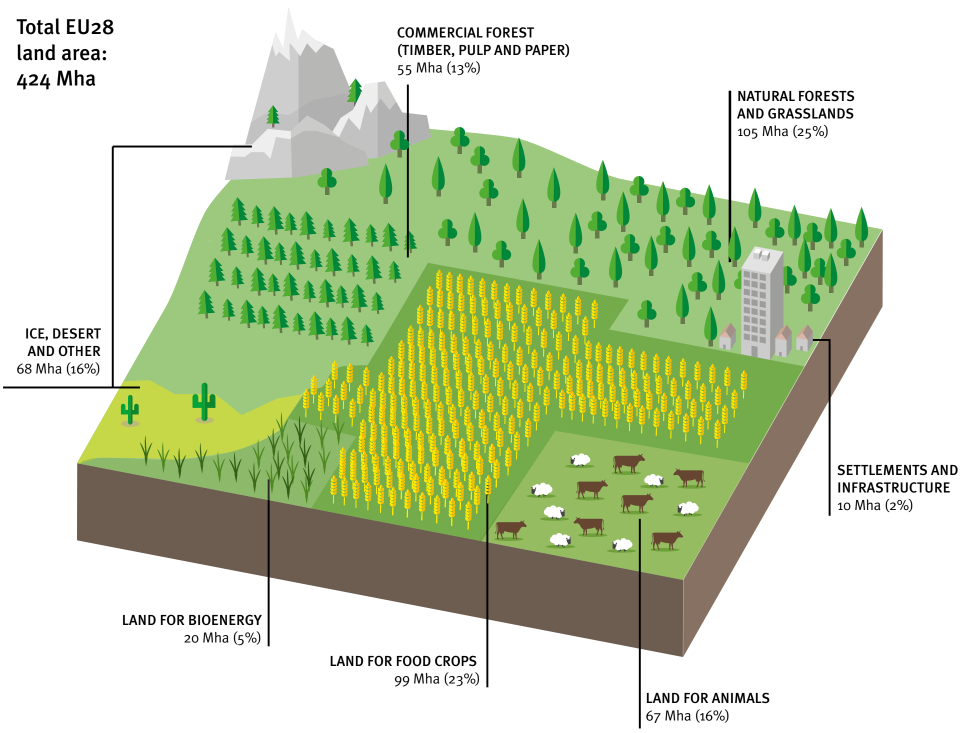

Figure 1: Illustrative representation of current EU28 land use.
Source: Prepared by the authors, using land use data from FAO[6].

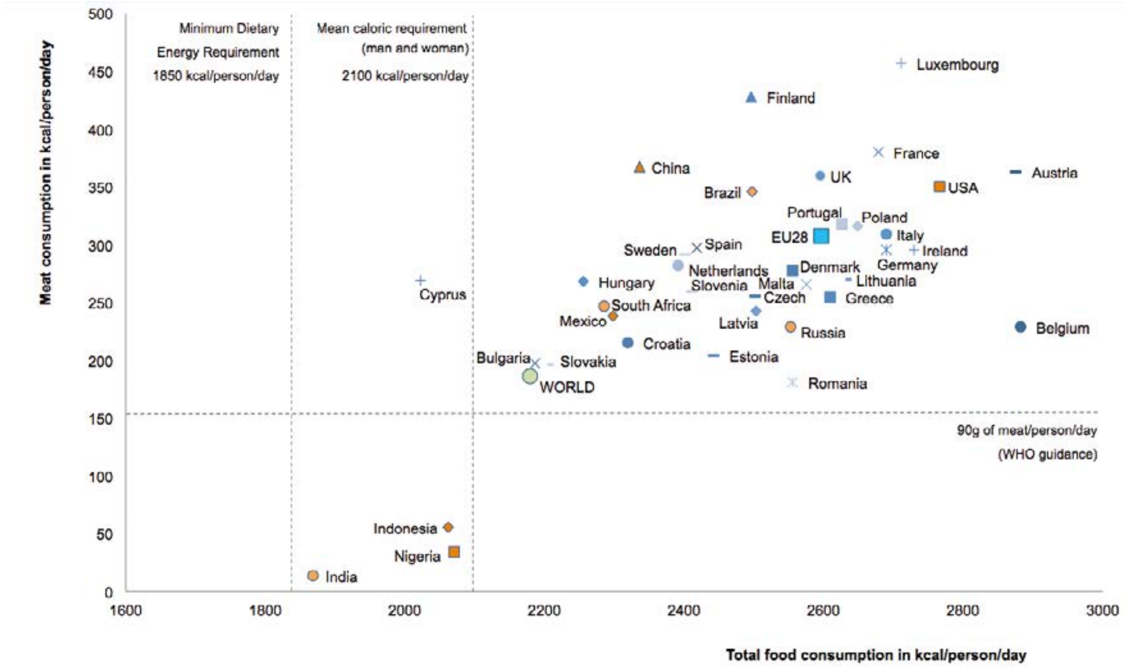

Figure 2: Daily meat consumption vs. total food consumption (kcal per person per day as eaten) in the EU countries and other selected nations.
Source: Prepared by the authors, using FAO data[6] (2011 base year), excluding 24% of food and 19% of meat wastes, in energy terms[10]. Meat consumption represents all types of meat combined, except fish.

Drivers of land use dynamics

Food consumption patterns

The quantity and type of food consumed directly influences land use. However, the nature of this land-food relationship depends on other factors such as population growth, agricultural productivity, land ownership and investment patterns, and land use efficiency. The current food daily calorie intake in the EU is about 2,596 kcal per person, which is about 20% higher than the world average of 2180 kcal[6].

Even if population remains constant, if per capita food consumption increases, then so too will the land area required to meet food demand. However, if there is an increase in agricultural productivity, the expansion of land for food production may not be necessary. By producing more food per unit area, the total amount of land dedicated to food production may even decrease over time.

Meat consumption and types of meat

The consumption of meat has substantial impacts on GHG emissions. When raising ruminant animals, 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 for the production of 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 feedlot (see glossary).

In addition, croplands are needed to produce feed for mono-gastric animals (e.g. pigs and chickens) under either feedlot or free-range systems. Importing animal feeds, such as soybean and corn, to the EU can also affect land use and GHG emissions. Conversely, 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[6]. The average EU meat consumption is much higher than the World Health Organisation's (WHO)[8] suggested daily maximum of 90g meat per person (about 152 kcal) for a healthy diet. The Food and Agriculture Organization of the United Nations (FAO)[9] forecasts an increase in global meat consumption of about 88% by 2050, whilst consumption rates in Europe are likely to rise by a smaller amount, or even decrease. Figure 2 shows the considerable variation in relative meat consumption levels in different parts of the world, illustrating that there are many factors that determine diet choices.

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 yields, whereas negative effects may include severe changes in precipitation, 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 until 2030, falling to around 0.3% per year from 2030 to 2050[9]. However, agricultural productivity usually grows steadily year upon year (linearly), instead of increasing at an annual growth rate (exponentially). There are 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 EU28 and much less so in developing countries[1,11]. For example, the world record yield for wheat is approximately 15 tonnes per hectare to date, while in the UK the average is about 8 tonnes per hectare[12].

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 fatten livestock, which can convert only a small fraction 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, of about 0.6% per year until 2030 and 0.2% per year from 2030 to 2050[9].

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 feedlots, and it is therefore not appropriate to compare the number of animals per hectare in these two situations.

The main parameters affecting different yields are the feed conversion ratio (FCR – see glossary), feedlot systems and animal density. In 2010, the animal density in the EU was estimated at about 0.98 livestock units (LSU – see glossary) per hectare in grazing systems and 0.77 LSU per hectare of utilised agricultural area (UAA – see glossary)[13]. 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[6]) and there is a trend for a gradual increase in livestock yields and stocking densities worldwide, possibly up to 80% by 2050, particularly in developing countries.

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. Currently, the EU level of self-sufficiency for plant-based food is approximately 81% and, for all types of meat combined, about 103%[14]. As such, the EU is currently a net food (crops) importer and a net meat exporter, although there are concurrent imports and exports of different products, and with different amounts of aggregated value (e.g. cocoa vs. chocolate, raw coffee vs. processed coffee etc.).

Europe's food trade balance may change substantially in the coming decades due to higher levels of competition in international food markets. The issue of self-sufficiency goes beyond the scope of this assessment, because it also involves food security, changes in rural income and jobs, bilateral and multilateral agreements, production costs, global power structures, trade barriers, currency impacts and consumer preferences. International food trade affects GHG emissions indirectly, through these impacts on land use demands. For example, by importing more food, the EU may be able to free up some productive local land for the regeneration of native ecosystems, but there may be a land-use and GHG impact somewhere else in the world related to the crops that are imported.

Bioenergy forms and yields

Bioenergy can be produced from three main forms of fuel: solid biomass (wood pellets, chips and logs), biofuels such as ethanol and biodiesel, and biogas (produced through anaerobic digestion from landfill, agricultural residues, animal slurry, or sewage treatment). In the EU, solid biomass and biofuels are usually produced under a renewable cycle through commercial production systems, also called modern biomass. Crop and forest residues and food wastes represent a significant source of bioenergy as well. In many developing nations the main source of bioenergy continues to be traditional biomass, which can be sustainable or not, for example, when firewood collection causes deforestation.

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, sugar beet, etc.) might increase similarly to other crop yields, in terms of net primary production (NPP) per unit area. However, it is expected that by 2050, a significant shift toward energy crops with high-energy efficiencies (such as miscanthus), short rotation coppice and several types of grasses may occur. 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[15,16]. Energy crops are also subject to technological advances in crop breeding aimed at second-generation biofuels, such as genetic improvements for higher yields of celluloses and hemicelluloses. Industrial integration to produce biofuels is also expected to increase in the coming decades. Therefore, the resulting global average for energy yield improvement is likely to be slightly higher overall than that of food crop yields[1].

Europe consumed about 3.1EJ (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, Europe has 7.9 GWe of installed capacity of biogas power plants. Europe accounts for 62% of the total biomass pellets produced worldwide[17].

The EU is also a major producer and user of biofuels, producing approximately 5.2 billion litres of ethanol and 11.6 billion litres of biodiesel a year, which represent, respectively, around 6% and 39% of the global production. Germany is the third largest biofuel producer, behind the USA and Brazil, with France, the Netherlands, Belgium, Spain and Poland also among the top 15 largest biofuel producing countries worldwide[17].

Agricultural land made available for other purposes

The EU agrarian structure has changed substantially in recent decades, particularly with the globalisation of food markets, and the gradual reduction of agricultural subsidies. Some productive agricultural areas in Europe have become surplus to requirements and have reverted 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 EU28 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 forestland 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.

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, for example, or when it may simply not be worth harvesting due to unexpectedly low market value. Therefore, in the EU28, 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 rotation crops with short life cycles. The use of greenhouses and plastic films can also help manage temperature change and water 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. Figure 3 shows how the annual harvested area can differ from the arable area.

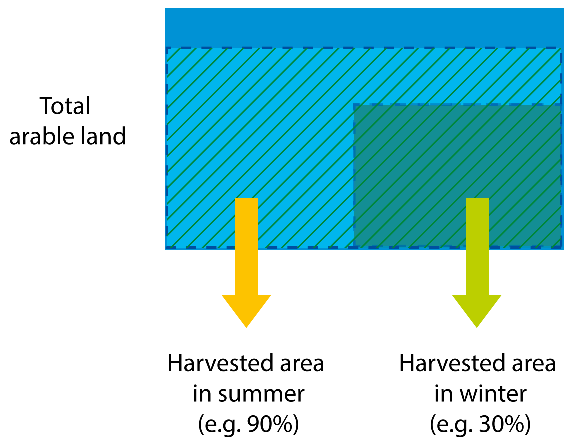

Figure 3: Illustrative multiple cropping scheme for a hypothetical arable land. In this example the total harvested area per year, i.e. all seasons combined, is equivalent to 120% of the actual arable land size.
Source: Prepared by the authors.

The land use efficiency, in terms of number of crops per year is measured in the multiple cropping index (MCI – see glossary), which represents how intensively farmed a certain country or region is. The EU28's total arable land area is 108 million ha, of which it harvests 81 million ha per year (excluding perennial crops)[6], with an average MCI of 0.75. Figure 4 shows that the MCI value varies very 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), therefore keeping their MCI relatively low.

Another form of land multiuse is land use integration. It is possible to use the same land surface for different purposes simultaneously, as shown in Figure 5, which illustrates the current proportion of different land uses in the EU. Where land use integration is in place, it is possible that land use may not sum up to only 100%, as is often the convention. 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. The European Agroforestry Federation (EURAF)[18], for example, has aspirations 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 (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 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 and ultimately lower yields.

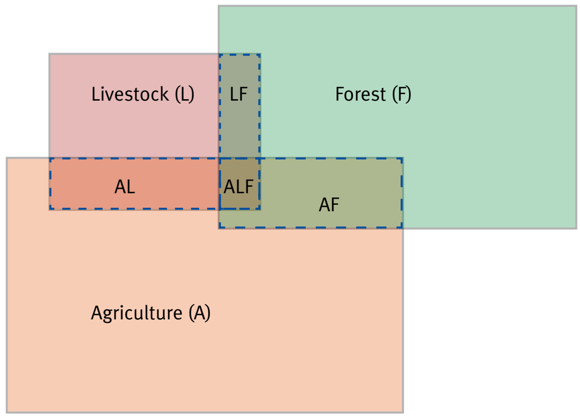

Figure 5: Illustrative land use integration schemes.
Source: Prepared by the authors.

Land degradation

The main causes of soil degradation are erosion, acidification, local and diffuse contamination (acidification and heavy metals), desertification, salinisation, 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)[19] found that the areas most impacted by soil erosion in the EU are 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. Water shortfall can also affect land degradation.

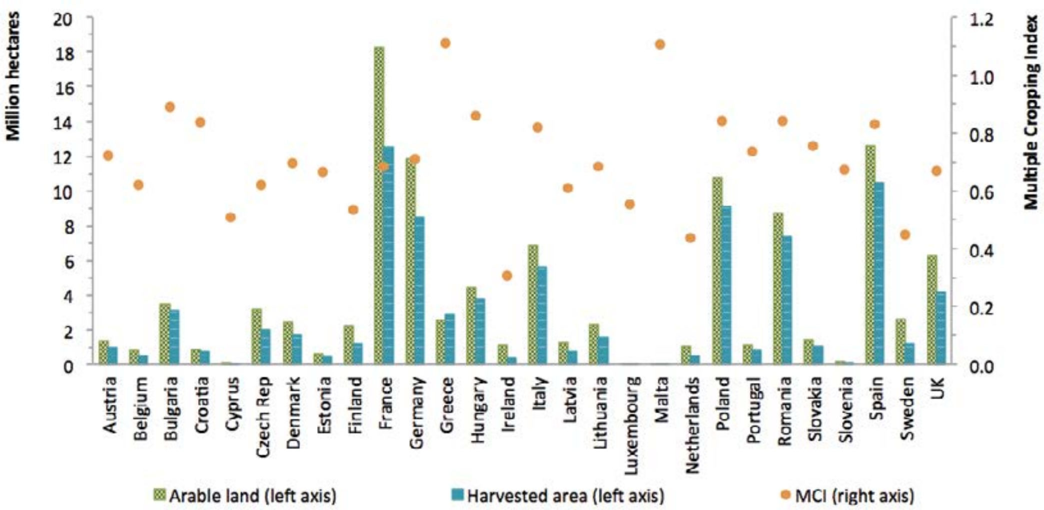

Figure 4: Arable land, annual harvested area and multiple cropping index in the EU28.
Source: Prepared by the authors, using land use data from FAO[6], including for the MCI estimates.

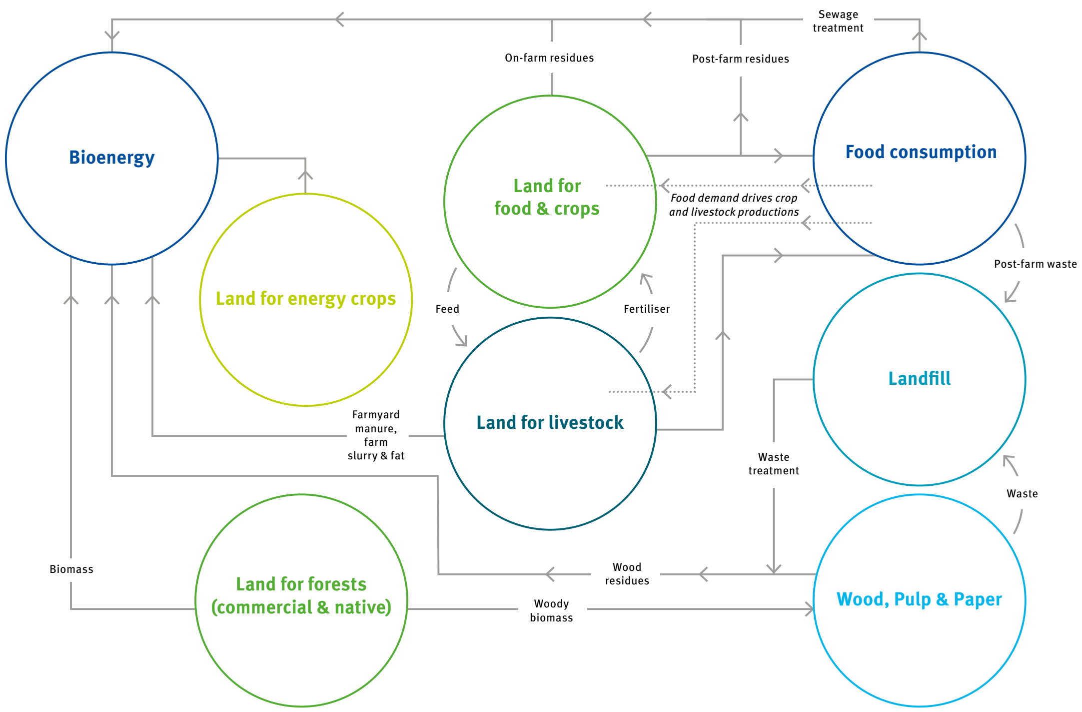

Figure 6: Energy and carbon dynamics. Source: Prepared by the authors, EULUF model.

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[19,20].

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.

For each tonne of food that leaves a European farm such as cereals, vegetables etc., another tonne remains within the farm as straw, husks, leaves, roots etc.[21]. 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[22]. 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.

What will land use in Europe look like in the future?

The wide range of variables described above will interact with each other to affect land use dynamics in Europe (see Figure 6). The uncertainty around many of these variables makes it difficult to anticipate the greenhouse gas emissions from land use in the EU by 2050, and therefore to prioritise climate change mitigation options appropriately. Considering the uncertainties and complexities of these questions, integrative modelling approaches such as the EULUF model used here are the most appropriate way to explore different futures.

This briefing paper uses two illustrative pathways for land use change in Europe based on assumptions made from the literature and stakeholders. The first scenario – the so-called Low Emission Scenario (LES) – 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. The second scenario – the High Emission Scenario (HES) – 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. See Appendix 1 for more detailed descriptions of the EULUF model.

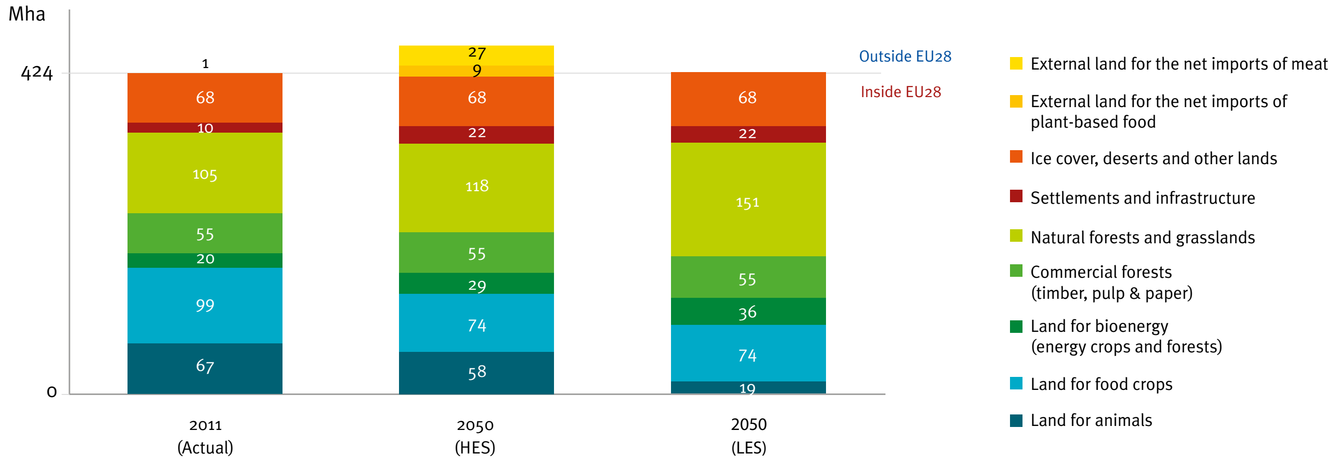

Figure 7: Simulations of land use futures in the EU28 for a high emission scenario (HES) and a low emission scenario (LES). Source: Prepared by the authors, EULUF model.

Using our EULUF model, we have assessed the full range of different land use patterns that could emerge. Figure 7 shows the land use dynamics for both the LES and HES scenarios compared with current land use distribution in the EU28. 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 patterns and GHG emissions outside the EU28 if dietary trends are not altered from their current course. In the HES simulation, the higher consumption of both meat and total food calories per capita 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 would be balanced by higher meat imports, consequently causing an external land use impact to meet the European market.

Both scenarios show significant impact on the EU's GHG emissions profile that are in line with the land use impacts. 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, while also being self-sufficiency in food production in terms of net trade balance (Figure 9). This could be achieved mainly by having more vegetarian diets and by increasing the agricultural and livestock efficiencies substantially.

A high emissions scenario implies the transfer of GHG emissions from Europe to other countries to supply the high projected demand of food and meat from the EU population. It would result in a reduction of total domestic GHG emissions to about 375 $MtCO_2eq$. per year, including some negative emission for afforestation/reforestation, but the external emissions would increase significantly by 2050, to around 1 $GtCO_2eq$. per year emissions of CO_2, CH_4 and N_2O combined from both imported meat and plant-based food (Figure 8). This sharp increase includes the potential for deforestation abroad that is required in order to service the additional food imports required by 2050.

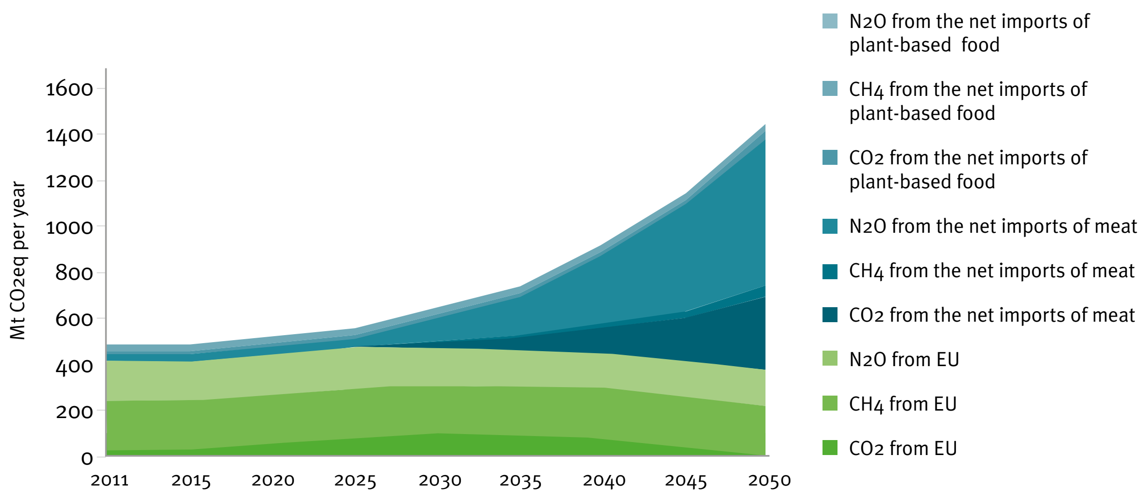

Figure 8: High Emission Scenario (HES) for the EU28 AFOLU GHG emissions. Source: Prepared by the authors, EULUF model.

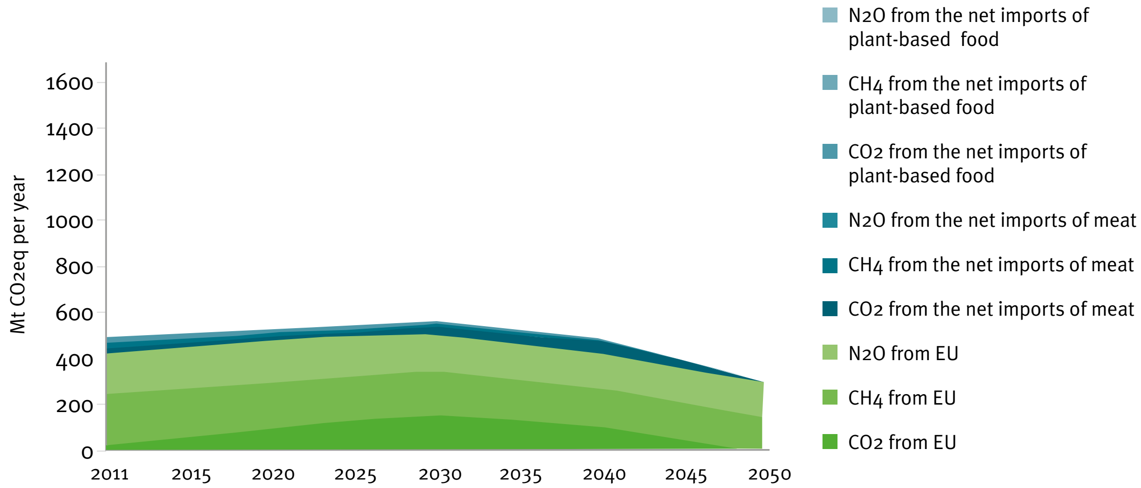

Figure 9: Low Emission Scenario (LES) for the EU28 AFOLU GHG emissions. Source: Prepared by the authors, EULUF model.

EU production of total 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. 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.

Conclusions – Food for thought

Dedicated integrated models, such as the 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. In addition, 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 climate and the associated need for additional productive land, either within or outside the European Union.

The next challenge for policy-makers and other stakeholders is to consider the most appropriate and effective public policies to stimulate sustainable land use transitions and behavioural changes for healthy diets and climate. 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.

Glossary

AFOLU – Agriculture, Forestry and Other Land Use.

EU28 – the European Union's 28 member countries as of March 2016: 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.

EULUF – European Union Land Use Futures model, which is an adapted version of the Global Calculator Land Use Change (GCLUC) model[1].

FCR – feed conversion ratio. This represents the amount of feed intake that is converted into edible meat, milk or eggs. FCRs vary according to the type of animal, its genetics, age, lifetime, production system, farm management, climate conditions, and feed quality. FCRs present large variation per animal and region.

Feedlot – also known as feed yard, is 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.

GHG – Greenhouse Gas. For the purpose of this paper, only the main GHGs from anthropogenic emissions were considered in the calculations, namely: carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O). Water vapour is the most dominant greenhouse gas, but the extent of its contribution to climate change has been debated. Other GHGs not included in the model, but relatively important for other sectors, are the chlorofluorocarbons (CFCs), hydrofluorocarbons (HFCs), perfluorocarbons (PFCs) and sulphur hexafluoride (SF_6).

LSU – Livestock Unit. This 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[13].

LULUCF – Land Use, Land-Use Change and Forestry, often used by official greenhouse gas data sources, such as the Intergovernmental Panel on Climate Change (IPCC), to group greenhouse gas emissions from these sources.

MCI – Multiple Cropping Index, which is calculated as the sum of areas planted to different crops harvested during the year, divided by the total cultivated area in a certain country or region. The cultivated areas include cereals, pulses, roots and tubers, oil crops, vegetables (incl. melons) and fibre crops.

UAA – Utilised Agricultural Area. This represents the total area taken up by arable land, permanent pasture and meadows, land used for permanent crops and kitchen gardens[13].

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Appendix 1: Using a model to tackle the complexity of land use change

The European land use scenarios simulated in this paper are based on a novel whole-system model prepared by the authors, here called EU Land Use Futures model (EULUF), in order to investigate sustainable climate change mitigation strategies at the EU level. This model was adapted from the land use model developed by Imperial College for the Global Calculator[1], and it complements other land use assessments in Europe, such as the Volante Project[23]. The land use classification used in this paper follows the same definitions adopted in the Calculator[24]. The model is based on a number of levers that drive land use change, with four increasing levels of ambition for climate change mitigation for each level (Figure A). These four levels offer a broad variation of mitigation choices, including intermediate levels. Therefore, the model can provide a large number of pathways as a combinatorics of all levers and levels that can be chosen by the user.

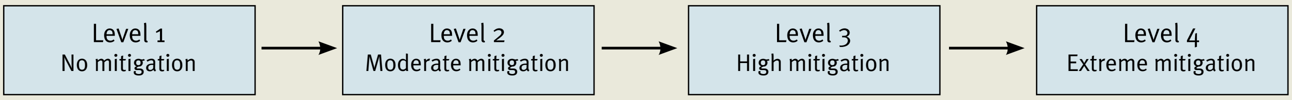

Figure A: Mitigation options for EULUF model.
Source: Prepared by the authors, adapted from the Global Calculator.

To develop the model and calibrate all levers' levels, we first investigated the current food consumption pattern in Europe and trends to 2050, gathering specific data on GHG emissions from Agriculture, Forestry and Other Land Uses (AFOLU), and other EU statistics. We then prepared data inputs for main levers, such as, changes in diet patterns; 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. Figure B describes the main interactions assessed in the model.

Driver tree for land use dynamics, food security and carbon emissions in the EU

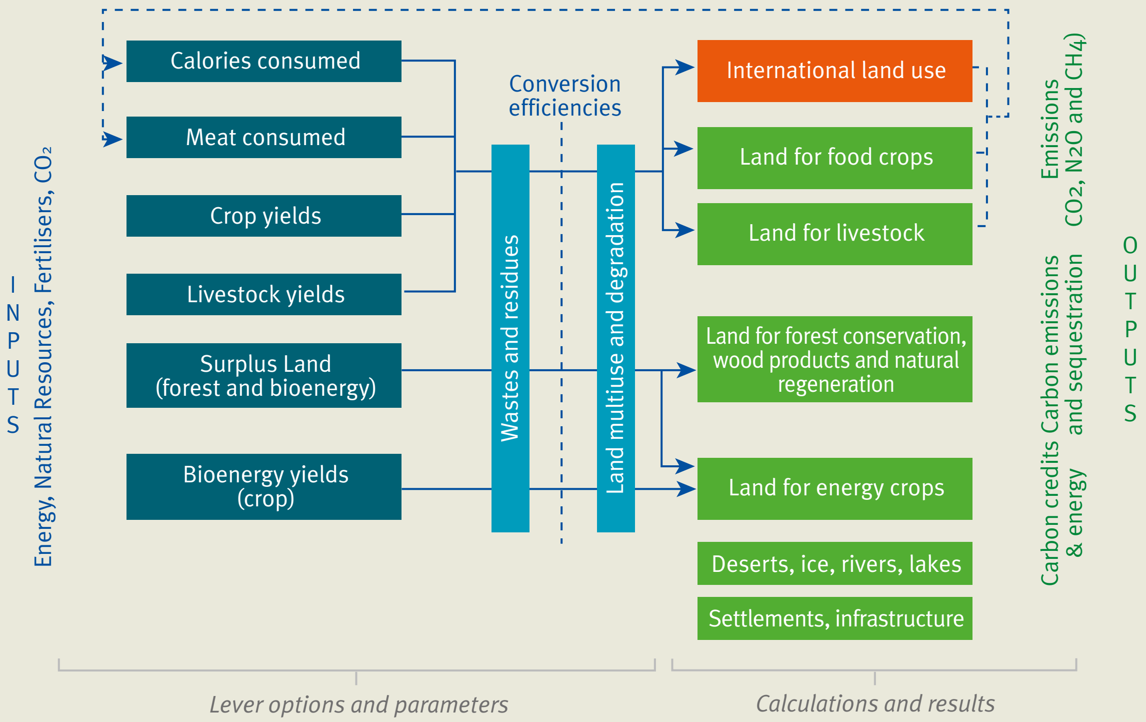

Figure B: Driver tree for land use dynamics, food security and GHG emissions in the EU.
Source: Prepared by the authors, adapted from GCLUC model[1].

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The model accounts for interactions between inputs, for example, the 'calories consumed' input models the land demand for food production, along with the 'meat consumed' and some efficiency parameters. In the EULUF model, food consumption is artificially set as a pure inelastic situation determined by the user. Food consumption and agricultural models[25,26,27] are usually based on classical assumptions, such as price-elasticity and commodity forecasts, which often brings a high degree of uncertainty to the analysis, although they can be useful for other purposes. These classical food consumption models often miss some key cultural and behavioural drivers of dietary preferences. In this model the user determines the level of food consumption instead of using a food-price elasticity model.

The meat consumption lever uses input values for future demand for meat to estimate the necessary land area (direct and indirect) for livestock production. This lever can also be changed to indicate the proportion of meat types consumed by 2050 and the 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 estimated based on dietary patterns and the livestock yield. Part of the collected wastes are also allocated for feeding livestock under different levels of effort and per type of animal, as well as for bioenergy.

The global emission factors for CO_2, CH_4 and N_2O from plant-based food/feed and meat imported into the EU were estimated using the Global Calculator. To conduct this sensitivity analysis, the inputs to the model were set according to a moderate trend (analogous to the International Energy Agency 4°C Scenario), setting the proportion of meat types similar to the EU (level 3) and changing just calories consumed (from level 2 to 3) or the meat consumption (also from level 2 to 3). Thus, it was possible to estimate emission factors for food (crops) and meat (all types under a similar EU proportion), for every five years from 2015 to 2050. Therefore, the estimated emission factors may vary over time.

Bioenergy estimates and allocations are provided on a dynamic basis. Algae-based biofuels are not considered in this model, as they are not expected to significantly affect land use change in agricultural lands in the coming decades. It is also too speculative to make projections on the current state of the art of algae-based biofuel technologies[28], despite their high potential in long term. 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 (biogas).

Further details about the calibration of the model's main levers are described in Table 1. Calculations were all made on a per capita basis. A medium fertility unit was used to estimate both the global population and EU population growth. 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 by 2050[29]. 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 reaching equilibrium). and afforestation/reforestation (50 years for full above ground vegetation growth)[1,30,31,32].

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Table 1: Description of the levers and levels in the EULUF model.

Levers	2011 (actual data)	2050 (Levels 1 to 4)	Comments	References used for the estimates
Food calories consumed	2,600 kcal/person/day	2,770 - 2,100 kcal/person/day	All types of food. Values in terms of net food intake, i.e. already excluding food wastes in energy terms (24%).	6, 9, 10, 25, 26, 27
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%).	6, 8, 9, 10
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.	6, 8, 9, 10
Crop yields	100 (levelised index)	0 - 60% increase	Percentage of 2011 yield. Average for all crops.	6, 9, 11, 12, 33
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.	6, 9, 13, 34, 35, 36, 37, 38
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.	6, 9, 13, 34, 35, 36, 37, 38
Animal density on pasturelands	100 (levelised index)	0 - 50% increase	Averages with large local variations.	6, 9, 13, 34, 35, 36, 37, 38
Level of self-sufficiency in food and meat	81% food 103% meat	70 - 110% food 90 - 120% meat	Food and meat international trade balance. Consequential land and GHG emissions abroad are applied.	14
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).	39, 40, 41, 42, 43
Land degradation	100 (levelised baseline)	110 - 100%	Land degradation due to soil erosion and climate impact may reach 10% in the extreme scenario.	19, 20
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.	6, 44, 45, 46

Appendix 1: Using a model to tackle the complexity of land use change

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.	6, 17, 47, 48, 49
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.	6, 17, 47, 48, 49
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.	10, 22, 35, 50, 51, 52, 53

Source: Prepared and estimated by the authors, using the references cited within the table.

In our simulations, we have run the EULUF model for two selected scenarios, as described below:

- Low Emission Scenario (LES), per capita meat consumption would gradually reduce towards the WHO recommendation of 90g a day (level 3), keeping the current proportion of meat types stabilised (level 3) and the total calories consumed per person slowly reducing (level 2), as well as achieving net self-sufficiency in both plant-based food (level 3) and meat (level 2). The use of surplus land would be dedicated to the expansion of both forestlands and energy crops (level 2). All other levers' levels were set as a high mitigation ambition (level 3).
- High Emission Scenario (HES), little or no concern in mitigation GHG emission. It assumes a very high food and meat consumption per person (both level 1), keeping approximately the same current share of meat types in the EU (level 3), increasing both food and meat external dependency (both level 1) and leaving all other levers under a moderate change (level 2). Thus, HES is likely to be significantly above a business as usual trend.

It is important to note that this model is exposed to several uncertainties, such as changes in the composition of the EU member countries, European policies and legal framework, international food prices, and the potential impacts of climate change on crop yields. The accuracy of the model is dependent on the accuracy of the database and references used in the model. It provides a broad picture, but further assessments are required to understand regional dynamics within the EU.

Acknowledgements

The authors acknowledge Ms Laura Aylett and Ms Kerenza McFaul from the UK DECC for commissioning this assessment, and Mr Erik Hesketh from the UK FCO for the funding support. They also appreciate the valuable comments kindly provided by the following reviewers: Dr Mairi Black from University College London (UCL); Dr Rajiv Chaturvedi from Divecha Centre for Climate Change at the Indian Institute of Science (IISc Bangalore); and Dr Frank Rosillo-Calle, Dr Lorenzo Di Lucia and Prof Martin Siegert from Imperial College London. Equally important were the contributions provided by Ms Alyssa Gilbert and Ms Alexandra Cheung in the editorial process, as well as Ms Susanne Westfold-Scott and Ms Elena Martynenko for their administrative support at Imperial. The authors also acknowledge all the participants involved in the stakeholders' consultation workshop held at the Grantham Institute, Imperial College London, in February 2016.

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