THE LIMITS OF BIOENERGY

A Complex Systems Approach to Land Use Dynamics and Constraints

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ABSTRACT

This paper summarises a PhD thesis recently defended by the author at Imperial College London. The aim is to present a novel methodology to obtain an understanding of the potential limits of bioenergy by using a complex systems approach for assessing land use dynamics and constraints. Although bioenergy is classified as a renewable energy source, land is a finite resource and its expansion limited. The anthropogenic demands on land result from a combination of multiple provisioning services. These include global food consumption, dietary preference, crop and livestock yields, land use integration, wastes and residues, and bioenergy yields and forms, as well as the allocation of surplus land for forestry and energy crops, and the potential role of negative emission technologies. Thus, bioenergy is just one part of a complex land-use system. The general hypothesis is that there are fundamental limits to the overall scale and rate of the sustainable expansion of bioenergy, which can be assessed by means of combinations of empirical data, mapping tools and complex systems models. To this end, a novel methodological approach is proposed, which is based on two original integrated models. The first one is termed the *Global Calculator Land Use Change Model* (GCLUC), developed as part of the Global Calculator project, in which land is freely allocated worldwide and food security is assumed a priority. The second considers land for dedicated energy crops as a delimited reserve, by integrating Hubbert's curve principles (originally proposed for peak oil assessments) in agro-ecological zoning schemes (as recently done for sugarcane ethanol in Brazil), resulting in a new model here termed *green-Hubbert*. The results show ranges of bioenergy potentials and expansion rates in the context of different land use futures. The potential public policies necessary to support sustainable bioenergy are also discussed. Finally, the conclusions show that, indeed, there are fundamental limits to bioenergy, and these limits are dynamic over time.

Keywords: Bioenergy; Food Security; Land Use; Global Calculator; green-Hubbert.

INTRODUCTION

The sustainable future of our society depends on how we use the natural resources available worldwide without exceeding the environmental resilience capacity. Climate change is a clear example of a complex driver that could lead to exceeding such capacity. In this context, the growing need for land-based products, such as food, feed, fibre, bioenergy, biochemicals and biomaterials, challenges us to balance their growth in a sustainable manner. This sensible balance could lead to bioenergy playing a role in either increasing or ameliorating the pressures on ecosystems by damaging or supporting regulating services. Thus, this paper summarises a PhD thesis of same title which was duly defended by the author in *viva voce* examination at Imperial College

London in November 2014 and his degree awarded in March 2015.[1] It presents a novel methodology to provide an understanding of the potential limits of bioenergy by using a complex systems approach for assessing land use dynamics and constraints.

Agriculture, livestock, forestry and bioenergy represent the main types of land allocation worldwide, after excluding deserts, ice covers, rivers, lakes, settlements, protected areas and infrastructure. Therefore, changes in the demand for land-based products can affect, either directly or indirectly, global land use dynamics. Bioenergy is just one part of this complex system, but its connections with other land uses and the energy and food sectors provide an interesting perspective for discussing development strategies. Once meeting food supply and forest conservation, for example, energy crops can contribute to reducing carbon emissions and the consumption of fossil fuels, as well as generating renewable energy, income and jobs. Energy security is strictly connected to economic and social development, and therefore moving towards modern conception of bioenergy is challenging in order to reduce the risks associated with food security and environmental management.

Bioenergy can also stimulate new investment in developing countries. The tropical region of the globe, particularly the humid zones, generally has a natural advantage in relation to bioenergy production, in terms of solar radiation and rainfall regime. Apart from the many complex issues associated with this natural potential, the tropical region is exactly where most of the developing nations are located. On the other hand, they usually lack infrastructure and access to technology, giving an opportunity for developed nations to collaborate with them to leapfrog this gap through win-win international partnerships. South-South cooperation can also play a major role in sharing experiences in this area, e.g., partnerships between Brazil and other nations in Latin America, Africa and Asia. At the same time, comparative / competitive advantages will still exist, as with food, for example, but a diverse set of global production centres to counter climate volatility and possibly political volatility will be needed. In addition, other renewable sources, such as, wind power and solar energy, have several advantages over fossil options, too, with mutual benefits for bioenergy in terms of dispatchability, intermittency, complementarity and storage.

However, the confluence of energy and food demands, the increasing scarcity of natural resources and the un-even spread of those resources impose an increasing need to find novel and more sustainable land-use management strategies. The production of bioenergy combined with food production and conservation of ecosystems and their services will depend on new policies and incentives at local and regional scales to govern the equitable use of land and the allocation of that land to different productive, extractive and non-productive uses, based on innovative modelling systems and scientific knowledge. Bioenergy presents a unique opportunity worldwide but also carries potential risks which must be carefully addressed in advance.

Energy and food securities are strategic issues for any country and they often supersede options to develop economically and environmentally sustainable bioenergy, which in turn require public policies encompassing global responsibilities, particularly in view of the growing climate risks. World population is likely to increase from about 7 billion in 2014 to 9.6 billion (in a range between 8.3 and 10.9 billion) by 2050 (UN, 2013). Associated with this United Nations' forecast, income

[1] The full thesis on the limits of bioenergy (Strapasson, 2014) includes an extensive literature review, further description of the methodology and all the calculations involved, as well as additional results and discussions. The document is in public domain and available for free download on the Imperial College's web repository (Spiral) at: http://hdl.handle.net/10044/1/19269

per capita is likely to keep increasing in the coming decades, especially in emerging economies with large populations (e.g., China, India, Brazil, Nigeria, Indonesia), which consequently would demand more per capita food and energy. Rural exodus is also a challenge for cities in developing countries, mainly in Africa and some parts of Asia and Latin America. The migration process, especially in high density countries, to metropolitan areas has been intensifying urban problems even more (e.g., slums, sewage and waste treatment, public transport, water supply) because of precarious infrastructure and education and lack of sufficient job opportunities for these excluded people, as well as damaging their rural cultures and values. Furthermore, Africa, for example, promises to have a large rural population in the coming decades (Montpellier Panel, 2014) and hence, it is essential to find new economic alternatives for the rural population, by improving their local farms, villages and towns sustainably (CGIAR, 2011; Conway, 2012).

It is clear that, in order to ameliorate these problems, bioenergy must be discussed in a broader context, involving energy, agricultural, environmental, social and political perspectives. It is not only a climate change issue, and its benefits can be significant; for example, in aiding the growth of agricultural income and resilience. In contrast, there are currently only a few countries with long experience of biofuel programmes, such as Brazil and the USA, although many others have relevant programmes, especially China, Argentina, Malawi and some countries of the European Union, such as, Germany, France, Sweden, the United Kingdom, and the Netherlands. Their experiences show that bioenergy can make a positive contribution to sustainable development and energy diversification agendas, but only if certain basic environmental, social and economic requirements are met (Woods & Kalas, 2014). However, to understand the complex dynamics of land, modelling approaches are used to simplify these dynamics, providing valuable insights.

Therefore, the dynamics of land, food and bioenergy depends on a large number of land use change scenarios, which can vary globally, regionally and locally. The elasticity effect of crops and livestock yield growth rates, for example, can distort basic linear intuitive rationale for assessing constraints on human growth without considering a complex systems approach. Hence, the use of dynamic models is essential for building sustainable policy strategies on bioenergy. See, for example, the agro-ecological zoning (AEZ) of biofuels in Brazil, which integrates several complex variables to guide public policies and regulations for a sustainable expansion of energy crops in symbiosis with other land uses (Strapasson *et al.*, 2012; Manzatto *et al.*, 2009). It is therefore imperative to find new ways of promoting efficient food and feed production in order to have sufficient land for other purposes, such as afforestation/forestation and bioenergy. What, however, are the limitations on this potential land availability for bioenergy expansion? To answer this question, an integrated approach based on complex systems dynamics is here proposed.

Land use change can be modelled as dynamic systems, in which lands are freely allocated to different uses, or as fixed systems, in which some land uses can occur only in certain delimited areas, for example, through policy or voluntary regulation. Thus, for understanding the land use complexity on global and regional scales it is necessary to look at both freely allocated and regulated system types.

For dynamic systems, this paper presents a novel global land use model for bioenergy and food security, which was prepared as part of the Global Calculator Project,[2] here termed Global Calculator Land Use Change (GCLUC) model. The Global Calculator can be used by decision-makers and the public and private sectors to inform management strategies for carbon mitigation, land use change, forest conservation, food and biomass production. The Department of Energy and Climate Change (DECC) of the United Kingdom was the project leader overall, which was co-funded by Climate-KIC. The paper's author was responsible for leading the Land Use, Bioenergy, Food Security and Forest Sector and the Greenhouse Gas Removal Technology approaches along with his colleagues from Imperial College London and other partner institutions. Similarly, the World Resources Institute (WRI, in Washington, USA) managed the Transport Sector, Ernst & Young (Delhi, India) the Electricity Sector, Climact (Brussels, Belgium) the Manufacturing Sector, and Energy Research and Development International (Beijing, China) the Building Sector. The Climate Media Factory at PIK-Potsdam developed the visuals and online version of the Global Calculator, and the Grantham Research Institute on Climate Change and the Environment at the London School of Economics and Political Science (LSE) managed the climate science contribution.

For fixed land systems (i.e., constrained areas), the paper also presents a novel approach, aimed at places with regulated land use (e.g., a country or a state), proceeding from the Brazilian experience of sugarcane agro-ecological zoning, by proposing a new model adapted from the famous Hubbert's oil curve, here termed the *green-Hubbert* (gH) model. The classical Hubbert curve shows the trend for oil exploitation and its peak in a certain oil basins, country or worldwide. Its use is rather controversial, because of the uncertainties associated with the proven-reserve lifetime, and potential discoveries not yet listed as probable and possible reserves in the geological records. However, when the reserves are well known, the Hubbert curve is a consistent model for explaining peak oil. Therefore, the proposal here is to use an adapted approach for cases in which land "reserve" for bioenergy expansion is a well-delimited area (e.g., because of law or market decisions through agro-ecological zoning schemes), which is the green-Hubbert model. The logistic curve of the classical Hubbert curve is now the land use change curve in the gH model.

Thus, these two integrated approaches, i.e., GCLUC and gH models, form the methodology of this research, and can be used for discussing sustainable land use planning, and reflecting on our current choices and actions as a society, in the context of climate change, forest conservation, food and energy.

Research hypothesis

The research hypothesis of this work is that '*there are fundamental limits to the overall scale and rate of the sustainable expansion of bioenergy, which can be assessed using combinations of empirical data, mapping tools and complex systems models'.* The null hypothesis is, therefore, that there are no limits, in practice, to the scale and rate of bioenergy expansion in order to meet both the international targets for reducing CO_2 emissions and the human need for food, feed, fibre, wood, bio-chemicals and nature conservation (ecosystem service provision).

Hence, in the context of the current global fossil fuel dependency, growing agricultural demands and climate change effects worldwide, the confirmation of this

[2] To access the Global Calculator, play its interactive webtool, download its spreadsheet and all supporting documents visit: www.globalcalculator.org

hypothesis may result in novel insights and an original scientific contribution to the research topic by offering a new methodology for land and bioenergy modelling which combines dynamic and fixed approaches through complex systems. The model may help to forecast a reasonable rate of bioenergy production between the two extremes of no bioenergy expansion and unlimited use of land for bioenergy without concerns of supplying food and other bio-products to meet human needs. It may also help assess the implications of scenarios in between these two extremes.

Research problem

This research was proposed because the current modelling approaches are not sufficient for guiding public policies on the large-scale expansion of bioenergy. This is notorious in developing countries, which could benefit substantially from bioenergy expansion, especially in Africa. In fact, there are many models available which estimate land use change and bioenergy production worldwide, as discussed by Van der Horst (2001), Solberg *et al.* (2007), and Bauen *et al.* (2009), including models that use global agro-ecological zones (IIASA, 2014). However, the current models normally use top-down approaches and present static scenarios, with results often subject to a large number of uncertainties and fixed assumptions about events which may never occur. Thus, a new integrated dynamic model is important for exploring not just a single scenario, but ranges of possible pathways. In addition, bottom-up approaches can help understanding the real agronomical potential of a certain crop in a specific region, by using dedicated agro-ecological zonings for bioenergy, for example.

The problem is how to develop a dynamic model that could integrate land use systems for food, feed, fuel and forest on a global scale and, complementary, propose a regional model which combines top-down and bottom-up approaches that could be used to estimate curves of land use change and to develop sustainable bioenergy strategies. To address this problem, system dynamics based on the methodology proposed for the Global Calculator Project is used as a basis for global modelling. The calculator can project several pathways to meet carbon targets, with or without bioenergy, according to the options chosen by the user. For the regional model, a top-down approach is proposed in this research which is based on Hubbert's curve model for oil reserves, but as a conceptual reference for biomass, i.e., a "green" Hubbert model. The bottom-up approach builds upon the use of agro-ecological zoning, as developed in Brazil for sugarcane and oil palm.

Aims and objectives

The aim is to understand the limits of bioenergy by investigating the complex relationships among sustainable land use, food security, forest conservation and bioenergy, for the purpose of making a scientific contribution to the international debate on bioenergy futures and climate change.

Main objective

The objective is to deploy a robust methodology to prove / disprove the stated hypothesis, based on a complex systems approach for assessing constrained versus freely accessed resource exploitation. With this approach, it should be possible to model bioenergy futures according to different land use dynamics by integrating the availability of natural resources to food security, bioenergy and environmental services, including agro-ecological zoning schemes and land use curves. Consequently, the limits of bioenergy could then be assessed for discussing sustainable policy strategies.

Specific objectives

In order to meet the main objective above, some intermediate steps were necessary. Hence, the following items summarise the specific objectives of this research:

- Adapt the Hubbert Curve model for oil reserves and develop an analogue approach for bioenergy (green-Hubbert) to be used when land availability is a well delimitated resource according to agro-ecological zonings and regulations;
- Collect and adapt the results of the Brazilian Sugarcane Agro-ecological Zoning for further modelling analysis with the green-Hubbert approach;
- Construct a dynamic model that synthesises complex land systems for food, forestry and bioenergy, including carbon and energy flows;
- Estimate the potential yield growths for food crops, livestock and energy crops, as well as the impacts of land use integration (e.g., multi-cropping schemes, agro-forestry systems) and the production and use of agricultural wastes and residues;
- Deploy a whole-systems modelling approach for land use, food security and bioenergy, i.e., the Global Calculator Land Use Change model (GCLUC).

METHODOLOGY

The methodology developed as part of this doctoral research comprises two main modelling approaches: the Global Calculator Land Use Change (GCLUC) model, and the green-Hubbert (gH) model. The GCLUC model aims at assessing the global dynamics of land and bioenergy limits against food consumption, crop and livestock yields, forestry, land use integration and the use of agricultural residues and food wastes, as well as potential contributions to negative emissions through BECCS and biochar. Therefore, all the results from this model are presented on a global scale. The green-Hubbert model, in contrast, focuses on cases in which land for bioenergy expansion is artificially constrained by a legal enforcement or regulation based on agro-ecological zonings. It aims at assessing bioenergy limits and expansion rate against land use potentials determined by zoning schemes, which can be implemented in a certain country or region. The only country with an agro-ecological zoning for biofuels on a national level to date is Brazil, which was taken as a reference for testing the gH model.

The Global Calculator Land Use Change (GCLUC) model

The GCLUC model was co-developed with the Land/Food/Bioenergy module of the DECC & Climate-KIC Global Calculator. The Global Calculator Project presents a novel methodological approach for modelling both carbon and land use dynamics on a global scale for the following sectors: Transport; Manufacturing; Electricity; Land, Bioenergy and Food (“Land/Bio/Food”); and Buildings. It also considers climate change impacts, different rates of population growth and urbanisation, and scenarios for the inclusion of developing Greenhouse Gas Removals (GGR) technologies (e.g., direct air capture, enhanced weathering terrestrial and oceanic, ocean fertilisation, biochar and Bioenergy with Carbon Capture and Storage (BECCS)), which are still rather speculative to date. All sectors and variables are interconnected in a dynamic model, like a network, and allows users to generate a large number of GHG emission reduction trajectories online. In addition, all calculations are estimated on a per capita basis and hence 2050 pathways can vary according to different scenarios of population growth, under the three main UN (2013) population growth scenarios. The medium scenario of population growth (9.6 billion people by 2050) is set as default.

The following section describes how the GCLUC model was structured and calibrated. It reflects the latest updates made of the spreadsheet version V3.99.2. This spreadsheet was used to prepare the final version of the global calculator webtool (V23), which was preliminary launched at COP20 of the UNFCCC in Lima in December 2014, with official launch in January 2015 at the Royal Society in London. As an international open tool, the Global Calculator may be subject to future periodical updates, and, therefore, the GCLUC results here presented reflect its version publically released and duly peer reviewed until the publication of the thesis in the Imperial College system. Both the spreadsheet and webtool are in the public domain and already available online on the Global Calculator website. Therefore, more detailed descriptions about the calculations and assumptions taken can be found on the spreadsheet and the original thesis (Strapasson, 2014).

The approach employed in the land/bio/food module of the Global Calculator applies a mathematical model for balancing the necessary expansion in the production of food crops, livestock, biofuels and other bio-based products with resources conservation. It allows users to simulate a number of trajectories of land use change and its associated greenhouse gas emissions, according to different demands for land-dependent products and services by 2050. Users can then develop their preferred pathways to 2050 by varying the weight of a selected set of parameters (‘levers’) according to their GHG mitigation objectives (‘levels’ 1 to 4, with several intermediate levels, and increasing levels of ambition). These include:

- food calories consumed per person per day;
- meat consumed per person per day, which is split into meat calories and meat types;
- crop yields;
- livestock yields, which include changes in feed conversion ratio, the share of feedlot systems, and animal density in pasture systems;
- bioenergy yields;
- bioenergy types, i.e., solid biomass and biofuels (biogas was modelled as a fixed estimate);
- surplus land for forest and/or energy crops;
- wastes and residues; and
- land use efficiency (or land use integration), i.e., multi-cropping effects and integrated farming schemes, such as agro-forestry and agro-livestock systems.

The model also considers several additional variables for the calculations, including the use of fertilisers, agricultural losses, GHG emission factors, feed conversion ratios, the proportion of animals raised in intensive production systems (feedlots), animal density (i.e., concentration of animals in grazing systems) and limiting factors for land distribution. A number of additional levers for assessing such complex issues could potentially improve the accuracy of the results obtained. However, it was important to use a restricted number of levers, given the complexity involved in other sectors of the Global Calculator, which also requires several levers and sub-levers. Hence, an excessive number of levers would result in a calculator too detailed and difficult to manage by non-experts.

The accuracy of each trajectory is limited by the availability of and uncertainty associated with data for global scale estimates and the restricted number of input parameters in the calculator, given the high complexity and uncertainty of all these levers. The model draws on several data sources, primarily statistics from the UN Food and Agriculture Organization (FAO), the International Energy Agency (IEA) and Intergovernmental Panel on Climate Change (IPCC), and other representative international references on land use modelling, for the purpose of providing not only a robust and credible methodology but also a simple and user-friendly calculator for the lay user.

The Global Calculator is presented as a webtool, and was built on a database generated by a C language programme (Ruby) from a comprehensive model in MS Excel format. The model has several input parameters and variables, which are used for estimating future land use distributions, as well as the associated CO_2, N_2O and CH_4 emissions. Land use change is determined by a hierarchy of land use types. Priority is given to food production (croplands and pasturelands), and the remaining land area is allocated to forestation, natural regeneration, and/or energy crops. Figure 1 presents the driver tree of the Land/Bio/Food methodology.

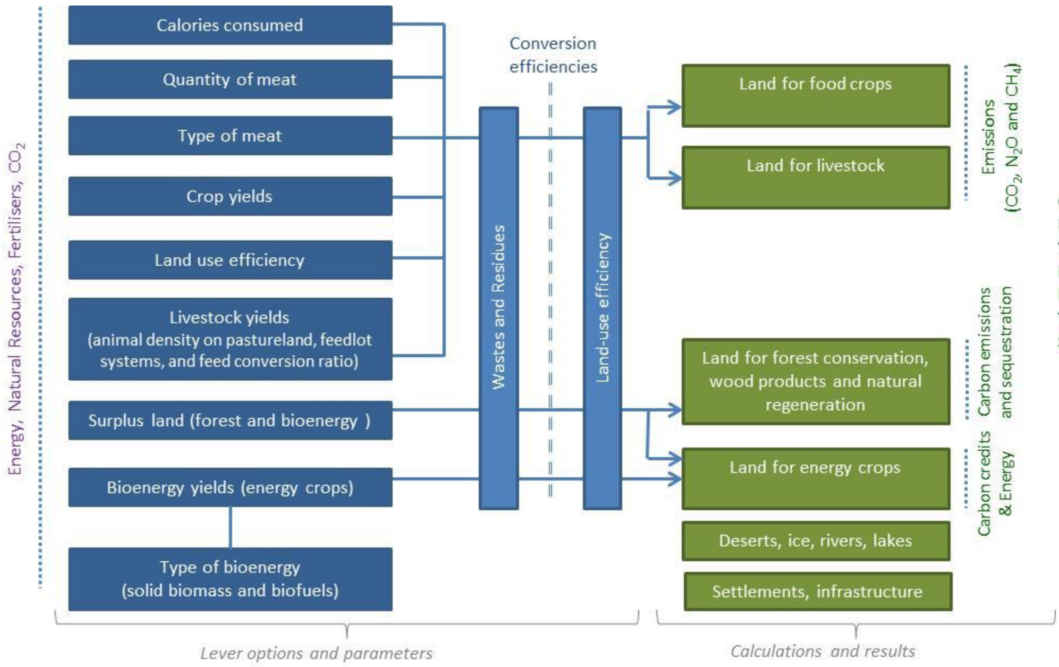

Figure 1: Driver tree for land, food and bioenergy in the global calculator

Source: Global Calculator (Strapasson *et al.*, 2014)

Thus, with the global calculator it is possible to simulate a large number of trajectories for food, bioenergy and forest land by 2050, and as a result also assess the respective land use potential for sustainable biomass, depending on the user's choice. The land use dynamics represented in the calculator include both direct and indirect Land Use Change (dLUC and iLUC), given that it is based on a global balance of several land use allocations. Figure 2 illustrates the dynamics of bioenergy, wastes and residues.

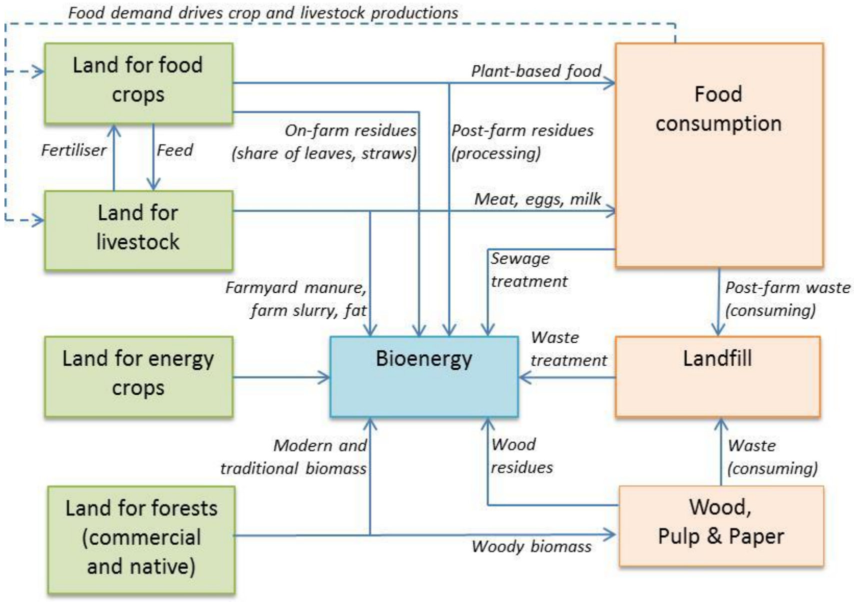

Figure 2: Dynamics of bioenergy, residues and wastes in the global calculator

Source: Global Calculator (Strapasson *et al.*, 2014)

The following sections provide a brief description of the key 'levers' and definition of "Levels" adopted in the Land/Bio/Food module of the Global Calculator tool for modelling land use change, bioenergy, forestry, and food supply and demand. These are further refined through several underlying sub-levers and fixed parameters, which are used to improve the accuracy of this module and its integration with other sectors. All the equations and calculations are available in the Global Calculator spreadsheet, and a full description of all lever's levels is also reported in the thesis (Strapasson, 2014). However, the fundamental steps of the methodology are also here presented and briefly explained, although. The definitions and estimates of all levels were discussed with several stakeholders in two workshops[3] carried out at Imperial College: one on Land/Bio/Food issues; and the other on Greenhouse Gas Removals (GGR). Some numbers were recalibrated accordingly after these consultations.

Calories consumed

This lever models the land demand for food production, along with the 'meat consumed' lever and some efficiency parameters. The user of the GCLUC model determines the level of food consumption, instead of using a food-price elasticity model. Thus, in the GCLUC model, food consumption is artificially set as a pure inelastic situation, against the assumptions used in classical approaches (Ewers *et al.*, 2009; Rudel *et al.*, 2009; Villoria *et al.*, 2013). Actual time series from FAO (2014) on calorie consumption and its forecast (FAO, 2012) were used for estimating future trajectories according to assumptions adopted in the calculator. In 2011, the global average calorie consumption was 2,180 kcal/capita/day (excluding 24% food losses in energy terms, as suggested by Lipinski *et al.* (2013)), with extremes of obesity and undernourishment worldwide in terms of dietary energy intakes.

Meat consumption (meat calories and types)

This lever is aimed at obtaining input values for the future demand for meat to estimate the necessary land area (direct and indirect) for livestock production. There

[3] See both workshops' notes at: www.globalcalculator.org

are significant differences in meat types (e.g., beef, mutton, goats, poultry, pork and fish) in terms of production systems, feed conversion ratios (FCR) and the necessary land for producing the respective meat type. The proportion of meat types by 2050 also varies according to the level selection. This lever also includes the consumption of milk and eggs. The current global average meat consumption is 187 kcal of meat/capita/day (excluding meat losses, 19% in energy terms, based on Lipinski *et al.* (2013)), but growing income in developing countries tends to stimulate an increase in meat consumption. FAO (2012) forecasts a total increase in global meat consumption of approximately 88% by 2050. Besides, a higher consumption of meat from ruminant animals (cows, sheep and goats) is usually associated with higher GHG emissions than monogastrics (pigs and chickens). The main source of data used for estimating each level was FAO (2012 and 2014). Fish consumption was modelled in separate using a fixed global trend. The calculator provides lever choices on quantity of meat and type of meat, including recommendations from the WHO (2008).

Crop yields

This lever affects the need for land resources for producing food, i.e., the greater the productivity, the smaller the area necessary for producing a certain amount of food, such as grains, fruits and vegetables. It is sensible to predict crop yield potentials, particularly because of the complexity regarding biotechnology, future use of water and fertilisers, and potentially positive or negative impacts of climate change. Positive impacts assume temperature increases in temperate regions and CO_2 effects on photosynthesis yields, whereas negative effects include severe changes in precipitation, particularly a potential increase of drought seasons in some regions, which may affect the global agricultural productivity.

The main references used for estimating crop yields in each level of effort were the FAO (2012) statistics, which predicts, for example, that they may increase about 1.3% a year until 2030 and then 0.8% a year by 2050 globally. Therefore, the current situation shows that crop yields tend to substantially increase, particularly in most of the developing countries where there is a significant productivity gap. The global trend of agricultural productivity usually follows a linear growing pattern, instead of an annual growth rate (exponential trend), and hence the lever ‘crops yields’ was linearly calibrated, using data from FAO (2012), IPCC (2014a), Grassini *et al.* (2013), among other references.

Livestock yields (FCR, pasture animal density, and feedlot)

The production of meat to meet future demand poses a major challenge for land use change. The land necessary for meat production is estimated based on the basis of dietary preferences, which provide the amount of meat needed for the projected consumption, and the livestock yield growth. Thus, with substantial livestock yield increase, a smaller area would be used for livestock production and a larger area would be available for other purposes, e.g., the production of grains, forest or bioenergy crops. There is a trend towards a gradual annual increase in livestock yields worldwide, particularly because of a significant yield gap in developing countries and the prevalence of extensive production systems. FAO (2012), for instance, estimates an annual livestock production growth of 1.4% by 2030 and 0.9% from 2030 to 2050.

However, livestock yields cannot be grouped in a single yield growth, given the high complexity involved. For example, cattle produced on pasture systems are very different from chickens produced under feedlot, and therefore it is not appropriate to compare the number of animals per hectare in these two situations. Thus, it is important to split the yields into different parameters, in order to increase the accuracy of the proposed pathways. The main issues involved are the feed conversion ratio (FCR), feedlot systems (intensification of animals), and animal density.

FCR represents the conversion efficiency of meat, i.e., the amount of feed intake (e.g., grain, grass) that is effectively converted into edible meat. FCRs vary according to the type of animal, age, lifetime, region, genetics, production system and feed quality. Approximate FCRs per type of animal and their potential increases were estimated from several references (FAO, 2006; Galloway et al., 2007; Best, 2011; Wirsenius, 2000; Searchinger et al., 2013) and experts' consultation.

The feedlot systems approach means the proportion of animals raised in intensive livestock systems, i.e., feedlot, including confined and semi-confined schemes, representing an approximate average. From this proportion it is possible to estimate the pasture and crop land (for feed grain production) necessary for the production of meat, using data adapted from FAO (2006, 2012).

The animal-density variable represents the potential increase in the number of ruminant animals (e.g., cows, sheep and goats) per unit of area in grazing systems (pasturelands), i.e., the concentration of animals. The current concentration rate may increase up to 80% by 2050, depending on the level of mitigation. There is a trend for a gradual annual increase in livestock yields worldwide, particularly due to a significant yield gap in developing countries and the prevalence of extensive production systems. Currently, the global average stocking density for cattle is about 0.7 cows/ha and approximately 3 sheep/ha (estimated from FAO (2014)). For methodological reasons in the global calculator, everything is factored in energy terms in order to keep the whole energy balance consistent throughout all estimates, according to the first law of thermodynamics. FAO (2014) presents numbers of meat production in energy terms, and total pasture area, and hence it is possible to have a kcal of meat/hectare which can be extrapolated for different pathways.

Therefore, the GCLUC model includes two levers for livestock yields, namely: *Livestock (grain/residues fed)*, which includes FCRs and the proportion of feedlot system per type of animal (cattle, sheep, goat, pig, chicken); and *Livestock (pasture fed)*, which includes FCRs and the animal density per type of animal (in this case for ruminants only) on pasturelands.

Bioenergy yields

Bioenergy yields are affected by (1) crop yield (2) energy content of the crops, and (3) technological advances. Yields of food crops used as bioenergy feedstocks (e.g., wheat, maize, sugarcane, oilseed rape, etc.) were assumed to be the same as in the 'crop yields' lever. However, it is expected that by 2050, a significant shift toward energy crops with high energy efficiency (e.g., switchgrass, elephant grass, sugarcane, miscanthus, eucalyptus, oil palm) will occur, particularly given the potential progress in the large-scale deployment of new commercial technologies such as lignocellulosic ethanol and Fischer-Tropsch biodiesel (biomass-to-liquids). Energy crops are also usually more subject to intensification schemes and agronomic supervision than conventional agricultural systems. They are also subject to technological advances in crop breeding aiming at second-generation biofuels (e.g., genetic improvements for higher yields of celluloses and hemicelluloses). Industrial integration to produce biofuels could be expected; for example, new technological advancement on the industrial level could induce greater use of certain species and agronomical characteristics. The conversion efficiencies of bioenergy into electricity, light, heating, etc. are modelled by the end-use sectors (i.e., transport, buildings, manufacturing, and power generation).

Therefore, the resulting global average for bioenergy yields is assumed to be slightly higher overall than that of (food) ‘Crop yields’ in the Global Calculator in terms of net primary production (NPP) of energy per unit of area. From Woods *et al*. (2014), IEA (2011c), and FAO (2014), it is possible to indirectly estimate that the global bioenergy area in 2011 was about 98 Mha, and that on average modern solid biomass produces about 6.5 odt/ha (heating value for dry-matter biomass: 18.5 GJ/t) and biofuels about 83.3 GJ/ha, which represents 2.7 t/ha (heating values: ethanol 28.2 GJ/t, and biodiesel 39.7 GJ/t), as a weighted average for ethanol and biodiesel. However, these values may significantly vary according to the energy crop and producing country.

Bioenergy type

The bioenergy produced globally is consumed by different sectors in two main forms: solid biomass (e.g., wood logs, pellets and chips) which amounts for approximately 92% (including traditional biomass); and liquid fuels (e.g., bioethanol and biodiesel), equivalent to about 8% of the total bioenergy consumption globally (Woods *et al.*, 2014; REN21, 2014). Excluding traditional biomass, solid biomass currently represents approximately 60% and biofuels 40%. This lever's trajectories decrease the use of traditional biomass by 2050, because of environmental concerns, rural development and technology transfer, whereas modern bioenergy tends to increase its global proportion.

This lever relates to the bioenergy form at the end-use level, hence solid biomass that is converted into liquid fuels (e.g., lignocellulosic process, biomass-to-liquids) is here considered as liquid. Bioenergy here includes only modern bioenergy which would be expanded on surplus land. Therefore, it does not include traditional biomass, farm residues and food wastes, which are modelled separately through the ‘wastes and residues’ lever. The lever is used to estimate the proportion of bioenergy types for the future expansion of dedicated energy crops. Thus, in this specific lever, the level of effort, from 1 to 4, does not necessarily mean that level 4 would be a better option for reducing GHG emissions than level 1. This is because the carbon reduction would depend on the type of displaced energy in the calculator, which is also an interactive process, e.g., solid biomass could displace coal, whereas biofuels could substitute gasoline or diesel. This lever can be alternatively described in terms of levels A to D instead of 1 to 4. Biogas is included in 'wastes and residues' too (e.g., slurry gas and anaerobic digestion), although it can also be produced from the conversion of solid biomass through the gasification process.

The bioenergy produced is then allocated to different end-uses, in accordance with different levels of demand that are possible to be chosen in other sectors of the global calculator; for instance, biofuels for the transport sector, traditional biomass for cooking, a fraction of biofuels for chemical industries, modern solid biomass for power and industry (with or without CCS) and so forth. Therefore, bioenergy estimates and allocations are provided on a dynamic basis. Algae-based biofuels are not considered in this lever, as they may not significantly affect land use change in agricultural lands. It is also rather speculative to make any projections in the current state of the art of their technologies, because the technological trends are still tentative, as suggested by IEA (2011a, 2011b, 2011c), although their high potential.

Surplus land (forest and bioenergy)

The land use dynamics in the calculator and potential increase in land use types (e.g., agriculture, pasture, forestry, energy crops, and other lands) are restricted to the total land available on Earth, and therefore, it is necessary to have a zero-sum equation to match all land uses. It was assumed that food security had priority over other uses, which were then adjusted in the calculator to fill the surplus lands. Hence, depending on the agricultural and pasture dynamics worldwide by 2050, there may (or may not) be land for additional forest and energy crop expansions. Thus, this lever allows the user to decide how any freed up land is used.

Current data (FAO, 2014) indicate that deforestation is likely to continue in the coming years worldwide, not only because of livestock and agricultural expansion, but also because of timber extraction and land tenure issues. However, if this trend is reversed in the coming years/decades, as suggested by OECD (2012), remaining land may become available, e.g., because of a reduced need for crop/pasture area. Thus, forestry and bioenergy could also be expanded in such land, including natural regeneration of forest and grasslands, i.e., not only in commercial plantations. In 2011, around 6 million ha of land were deforested, not only because of livestock and agricultural expansions, but also because of wood extraction and land grabbing issues. If cropland and pasturelands expand over forest, the GCLUC model alerts the user and issues at warning when the deforestation surpass even the protected areas (7.7 to 13.5% of the world's forest area, Schmitt *et al.* (2009)).

Bioenergy accounts for about 55 EJ of the world energy mix, which includes both traditional and modern biomass, representing a significant renewable energy source for several nations (IEA, 2011a). Countries like Brazil, for example, increased their sugarcane area by more than 10% a year in some years and simultaneously reduced the production costs of both the biomass feedstock and the biofuel (MAPA, 2011; Pacini & Strapasson, 2012), but it is unlikely that such expansion rates will be observed on a global scale in the coming decades. See, for example, bioenergy projections in the Chum *et al.*(2011), Slade *et al.* (2011, 2014), Shah *et al.* (2013), van Vuuren *et al.* (2009).

On the other hand, if an extreme increase of global crop/pastureland is necessary to meet potentially high calories and/or meat demands, there may not be any land available by 2050, either for additional forest area or for energy crops. Under such circumstances, even more deforestation may occur to meet the food security assumptions set in the calculator. Furthermore, the land currently classified as 'deserts, ice covers etc.' by FAO (2014) may include some marginal lands that could be used for the expansion of agriculture, livestock and energy crops. However, because of the uncertainties of what could be considered as potentially productive land, and rather speculative assumptions, they were not included in the GCLUC model as a potential expansion area for commercial purposes.

It is assumed that the maximum expansion rate of bioenergy would not be higher than 12 million hectares per year, in order to avoid an unrealistic expansion if substantial surplus land is available by 2050, as a kind of theoretical upper limit. Such a limited rate was estimated based on the current bioenergy area globally (approximately 98 Mha, including solid biomass and biofuel crops), and extreme expansion rates of new dedicated energy crop lands that have been already observed in countries like Brazil in its peak of biofuel investments (circa 12% a year). It was considered that the bioenergy sector would not be able to cope with rates over such a rate by 2050 for several reasons, e.g., manufacturing capacity for new industrial plants, availability of seeds, new crop varieties, harvesters, funding, storage limitations and infrastructure. This is an uncertainty of the model, but the maximum bioenergy potentials would meet about 300 to 400 EJ by 2050, which is also in line with numbers suggested by Akhurst *et al.* (2011b) and Chum *et al.* (2011) for an extreme situation.

Land use efficiency

This lever presents a novel concept for characterising different land use interactions in the Global Calculator. It was introduced to capture potential land use efficiency gains associated with agro-livestock-forestry schemes (and any combinations of them), dual-cropping (e.g., a summer crop followed by a winter crop in the same year), triple-cropping (e.g., starting with a summer crop, then a second summer crop of short cycle, followed by a winter crop), use of climate-smart technologies (e.g., no tillage systems), among other similar positive interactions from land multiuse. Conversely, over-exploitation of land resources because of inappropriate integrations and mismanagement can lead to land degradation. Generally, land use integration is associated with benefits for farmers.

Ideally, these integrated management practices would be represented by a larger number of levers to more accurately reflect the complexity of land use change. However, given the underlying structure of the model, the inclusion of additional levers was not recommended, and the lack of comprehensive datasets may not have allowed users to obtain sufficiently robust results. Thus, to simplify this complexity, and account for effects of land use integration, this lever presents four levels of land use abatement potentials, i.e., less or more land would be necessary than calculated based on the food (calories & meat consumed, crop & livestock yields) and bioenergy yields alone. In other words, it acts as a deflating factor, like a land bonus (or penalty), depending on the level of effort in agriculture maximisation selected. This lever was calibrated using experts' consultation and literature (FAO, 2013; Langeveld *et al.*, 2013; Byerlee & Deininger, 2013; Cox *et al.*, 2009; Okorio, 2006).

Wastes and residues

This lever involves three sub-levers: one for the amount of food wasted from production to consumer (post-farm waste), a second for on-farm residues, and a third for the percentage of waste and residues collected. Each of them has four levels of effort, which were subsequently combined into a single lever, 'Waste and residues'. In addition, two supporting parameters were included: waste from animals (e.g., manure, animal slurry and tallow); and human waste (e.g., sewage treatment and landfill).

Currently, there is substantial production of wastes and residues worldwide, but collection rates remain low. Post-farm waste production is around 30 to 40% of total food production, eventually reaching landfill/dump sites (Modak, 2010; Partiff *et. al.*, 2010; Foresight, 2011; Themelis, 2014). In contrast, on-farm residues equate approximately 100% of the total food amount produced, as roughly estimated by Woods (2007). This 1:1 ratio means that, on average, for each tonne of food that leaves the farm (e.g., cereals, vegetables etc.), another tonne remains within the farm as straws, leaves, roots etc. The 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 materials originally left on soil. In the calculator, part of the collected wastes is also allocated for feeding livestock under different levels of effort and per type of animal (estimated using Galloway *et al.* (2007) and Smeets *et al.* (2007)), as well as for bioenergy. The collection of wastes and residues also includes partial collection of sewage and animal slurry for energy purposes (biogas), as a sub-lever of this lever, but in different proportions and magnitudes.

Other methodological issues for land, bioenergy and food dynamics

Energy calculations are based on data from energy consumption and production from food, livestock and bioenergy, energy conversion efficiencies, and land use distributions and also consider wastes/residues. The emissions are estimated from the respective emission factors from food, meat and bioenergy production, and the associated land use allocations, by type of greenhouse gas, based on FAO (2014) and IPCC (2007a, 2007b) data. Thus, it is possible to estimate the emissions by type of land and greenhouse gas considered in the calculations (CO_2, CH_4, N_2O).

As regards forests, deforestation results in CO_2 emissions, whereas afforestation/reforestation means net CO_2 sequestration from the atmosphere through photosynthesis, particularly during the forest establishment stage. Mature forests act as carbon sinks, but they have temporal variations in terms of accumulating carbon over time. For the purposes of the GCLUC, it was assumed that new forests, as a global average, accumulate carbon on a linear basis for 50 years (IPCC, 2000). In the case of deforestation, the carbon in vegetation above ground is assumed to be released back to the atmosphere within a year, given that deforested areas are often subject to burning practices, and the logs usually burned as traditional biomass.

Similarly, soil carbon is assumed to accumulate linearly for up to 20 years (ECCP, 2003) when a land use change occurs in an area, transitioning from low to high soil carbon content. Conversely, when land use change causes a reduction in soil carbon, the carbon content of such variation ('carbon delta') is assumed to be immediately released (i.e., within the same year), because of rapid oxidation of the surplus carbon when soil is ploughed, burnt or drained for example. All the calculations were made for 1 m depth for consistency with adopted literature (IPCC, 2000; Pan *et al.*, 2011).

With regard to bioenergy emissions, GHG inventories usually account for the bioenergy emissions indirectly. In theory, growing biomass capture equivalent levels of CO_2, which are released back to the atmosphere upon combustion. However, there are other fugitive emissions associated with this cycle, which are indirectly accounted for in broad GHG assessments (i.e., also including transport, building, power and industrial sectors). Therefore, although some fossil fuel inputs are usually required in the bioenergy production, distribution and consumption chain, these are accounted for elsewhere in different sectors. This is necessary to avoid double counting of carbon emissions of bioenergy in lifecycle assessments. Thus, the same approach has been applied in the Global Calculator through the strong interconnection of levers across all sectors, i.e., the emissions from the bioenergy combustion are measured by different end use sectors in the calculator. Therefore, the calculator generates a CO_2 credit from bioenergy, which is then consumed by different sectors, e.g., transport (liquid fuels), heating and power (buildings, manufacturing and electricity sectors), resulting in a low carbon alternative (not zero) when fossil options are replaced. Part of the bioenergy can also be allocated for GGR, e.g., for Bioenergy with Carbon Capture and Storage (BECCS) or biochar, resulting in 'negative emissions'. Carbon removals from afforestation/reforestation are also considered in the calculations.

Concerning water management, the GCLUC model does not address this issue directly, but water was taken into account when indirectly calibrating two levers: 'crop yields' and 'land use efficiency'. In the crop yield lever, level 1 includes adverse effects of climate change on agriculture (e.g., changes in precipitation patters), and levels 2, 3 and 4 assume that it would be possible to increase the use of irrigation systems, among other assumptions. Likewise, in the land use efficiency lever, level 1 assumes that an over-exploitation of land resources would cause a reduction in the availability of land resources for agricultural purposes, which includes water scarcity, erosion and desertification processes.

The green-Hubbert (gH) model

The gH model is here proposed as a novel methodological approach for describing the exploitation of a renewable reserve over time through an S-curve and a derived logistic curve (bell curve), i.e., the land use change for producing bioenergy. Sugarcane is considered as reference crop for modelling, but the model can be applied to any crop, not only energy crops, but also food crops, pasturelands, forests and other types of land use potentially constrained. In this approach, the limiting factor is no longer the oil reserves, as in the classical Hubbert curve, but the land availability for energy crops. Hence, in order to estimate a green-Hubbert curve, it is necessary first to describe the new methodological model and its assumptions, and then to discuss what the results could indicate and the public policies which could be recommended for the sustainable expansion of bioenergy.

The method assumes that land is a finite resource and its agronomical potential to produce bioenergy depends fundamentally on type of soil, topography, climate and latitude (solar radiation and day length), which results in different photoperiods (seasonality). For the timescale of this research, it has been considered that the Earth is a closed system and solar radiation is infinite. As a consequence, it is possible to consider land as a finite resource, yet one capable of exploiting the infinite (but constrained) solar radiation resource to produce renewable energy.

The gH model also assumes that land use needs to be guided by public policies towards sustainable land use planning in order to meet the human needs for food, feed, fibre, fuel and chemical products as well as the delivery of ecosystem services. It is mostly applied in cases in which the expansion areas for bioenergy, or, more specifically biofuels, are defined through a normative approach in order to guide investments and avoid damaging fragile ecosystems by market pressures for example. Thus, market decisions would be restricted to the best land use options established through national legislation, and according to the sovereign decisions and priorities of each nation, as Brazil has done by means of its sugarcane and oil palm agro-ecological zonings.

Proposed equations for the gH model

This model builds on the classical Hubbert curve (Laherrere, 2000 and 2009). Adapting the Hubbert approach for land use and bioenergy, i.e., the green-Hubbert model, means the S-curve can then be described in terms of land availability as a finite resource (although its use can be renewed), instead of oil. Similarly to oil depletion, the expansion of energy crops would tend towards the limit of suitable land availability (asymptote), reducing the rate of land use change (speed) when reaching the Expected Ultimate Recovery (EUR). In the green-Hubbert model, the EUR is the land area determined by the agro-ecological zoning as suitable for the expansion of energy crops (Z), as shown in Equation 1. The green-Hubbert S-curve (gH) is, therefore, the land used for energy crops.

$$gH_s = \frac{Z\,.EXP\ (b(t - tm))}{1 + EXP\ (b(t - tm))} \quad (1)$$

gH_s = green-Hubbert S-curve
Z = land suitable for sustainable bioenergy production
t = reference date (year)
tm = date at midpoint (year)
b = factor describing the slope of the curve

This model could also be applied to any other energy crop, with respective crop-specific *Z*, *tm* and *b* values. However, an accurate estimate of land use potentials cannot be based only on simplistic surveys or general top-down land use models, given that if the input data are not reliable, then the output will not be, however robust the modelling behind the calculations. It is necessary to verify in loco what is effectively happening in the field of study, and then to integrate this information in a top-down approach, although it is not easy to find and estimate accurate bottom-up data. Nevertheless, in Brazil, the results of the national sugarcane agro-ecological zoning give a substantial database that can be integrated into the green-Hubbert model, and so they can be used to estimate a kind of 'sugarcane EUR' (Z) for Brazil.

The sugarcane EUR may be subject to future updates, either by incorporating new potential areas or excluding areas from the AEZ. Then, inputs to the model would have to be updated, too, in order to maintain accuracy. For example, the soil and climate maps used in this zoning were limited to the best scales available until its publication. The production of new varieties adapted to different soil qualities in the future could make it possible to explore lands not currently suitable for sugarcane under this zoning. Any substantial modification in this zoning would be subject to sensitive environmental debates and political concern, but the gH model could readily be updated for a new *Z* value, i.e., a new sugarcane EUR (or another energy crop). Thus, with the green-Hubbert S-curve, it is also possible to estimate the potential production of bioenergy, according to the estimation of the land potential (*Z*).

To estimate the changes in land use, it is necessary to derive of gH S-curve, which results in Equation 2. The peak of the green-Hubbert LUC curve represents the point at which the use of land would reach 50% of the total suitable land established by the agro-ecological zoning, assuming a symmetric bell curve. It may offer a way for policy-makers to understand the behaviour of the land use for bioenergy and the level of land scarcity to meet bioenergy demands. The second derivative of this equation describes the acceleration of this land use change (e.g., Mha/yr^2), but it would result in a rather speculative curve, given the high uncertainties already associated with the speed variations.

$$gH_{LUC} = \frac{Z}{(1 + COSH(b(t - tm))} \quad (2)$$

gH_{LUC} = green-Hubbert Land Use Change curve

Considering that there is both a maximum rate of expansion of bioenergy crops (Mha/yr new land) and ultimate gross land area dedicated to bioenergy crops, the more precise the evaluation of the land potential (Z) is, the more accurate the green-Hubbert model will be in projecting these figures. However, this variable (Z) depends on a number of other variables and has to be estimated for a specified bioenergy crop in a specified region, otherwise the accuracy of the model will be compromised and the result potentially spurious. This variable has to represent not only the technical potentials in terms of yields, but also the territorial planning constraints resulting from the need to obtain both bioenergy and meet other needs (i.e., food, feed, fibre, forest, biochemical, amenity and ecosystem services). Therefore, the AEZ acts as a bottom-up input to support the green-Hubbert model.

RESULTS

This section presents some results of the Global Calculator Land Use Change model in order to discuss the limits of bioenergy. This model can generate a very large number of results from the combination of all lever's levels, and therefore only a selection of results is presented. In addition, the results of the green-Hubbert model are shown, and the Brazilian sugarcane agro-ecological zoning is used as a case study for testing the model.

Results from GCLUC model on a global scale

The GCLUC simulations evaluated are consistent with the global calculator's spreadsheet version 3.63.0. Each simulation presents different levels of effort (i.e., levels 1 to 4, with intermediate levels whenever necessary) for all the GCLUC levers, as previously described. All simulations assume the 'medium population growth' forecast by the UN (2013), whereby the global population increases from approximately 7 billion in 2011 to 9.6 billion in 2050. However, emission pathways for either lower or higher UN population scenarios can also be modelled online, given that all calculations are provided on a per capita basis. Soil carbon accumulation from LUC and carbon sequestration from new forests are subject to temporal adjustments to represent the transient dynamics of these changes. A partially-subjective annual limit to the rate of expansion of energy crops (12 Mha/year) is used in order to avoid unrealistic levels of expansion over time, as further explained in the thesis (Strapasson, 2014).

The first simulation is a pseudo Business as Usual (BaU) scenario that maps the IEA 6^oC Scenario (IEA, 2014) on a Global Calculator 'IEA 6DS pathway'. To model it, all levers from other sectors (i.e., buildings, transport, manufacturing, and power generation) were set in the calculator as an equivalent energy scenario to IEA6DS, and the levers associated with the GCLUC model were estimated analogously, given that the IEA does not model land use. In this pessimist scenario, the land/bio/food sector worsens global warming. The global population keeps increasing per capita food consumption, including higher meat consumption, as it is more likely to occur in a business-as-usual scenario with low mitigation efforts. The results show a net deforestation and therefore no net surplus land by 2050. Bioenergy expansion would be marginal, based on the use of residues and low productivity gains. Similarly, the second simulation is an analogy to the IEA 2^oC scenario (IEA, 2014), but for the land/bio/food sector (high mitigation pathway), with all other sectors remaining as in IEA6DS to ensure a high bioenergy demand in the model. Finally, the third simulation is an extreme mitigation pathway, as an illustration of what it would be technically possible to achieve in terms of reducing global GHG emissions related to land use, including a substantial reduction in meat consumption and a high increase in crop and livestock yields. See further details about these estimates in Strapasson (2014).

Figure 3 shows the three GCLUC simulations regarding the consequential production of bioenergy by 2050 (without competing with food security and forest conservation), as well as the respective land area and emission reduction of expanding energy crops on part of the surplus lands instead of natural vegetation (sensitivity analysis).

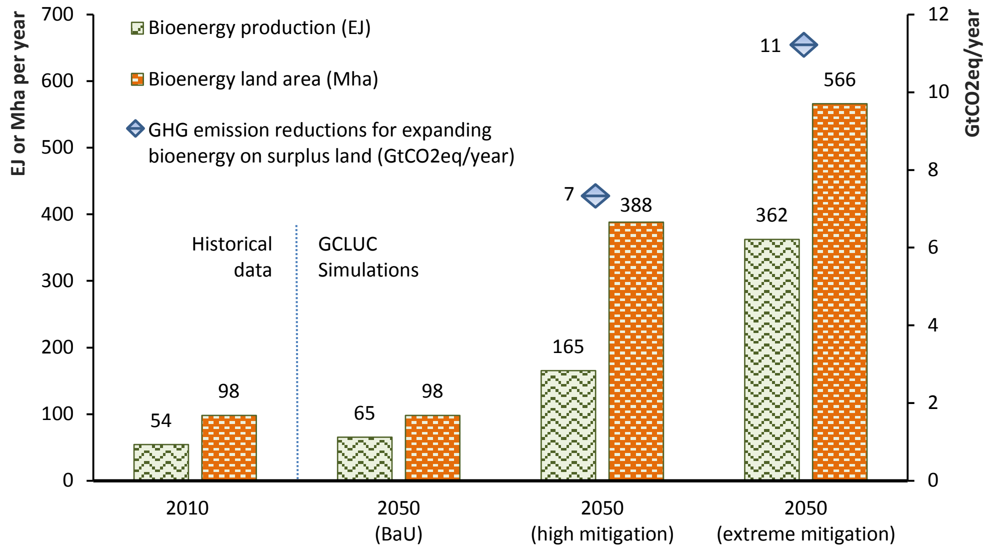

Figure 3: Global bioenergy production, land and emission reductions

These three simulations present different patterns of land use and GHG emissions by 2050. This includes emissions from deforestation, afforestation and reforestation, changes in soil carbon, as well as the agricultural emissions of CH_4 and N_2O (including food and non-food crops), livestock for CH_4 and N_2O (from pasture and all types of animals). Total emissions from AFOLU are shown in Figure 4.

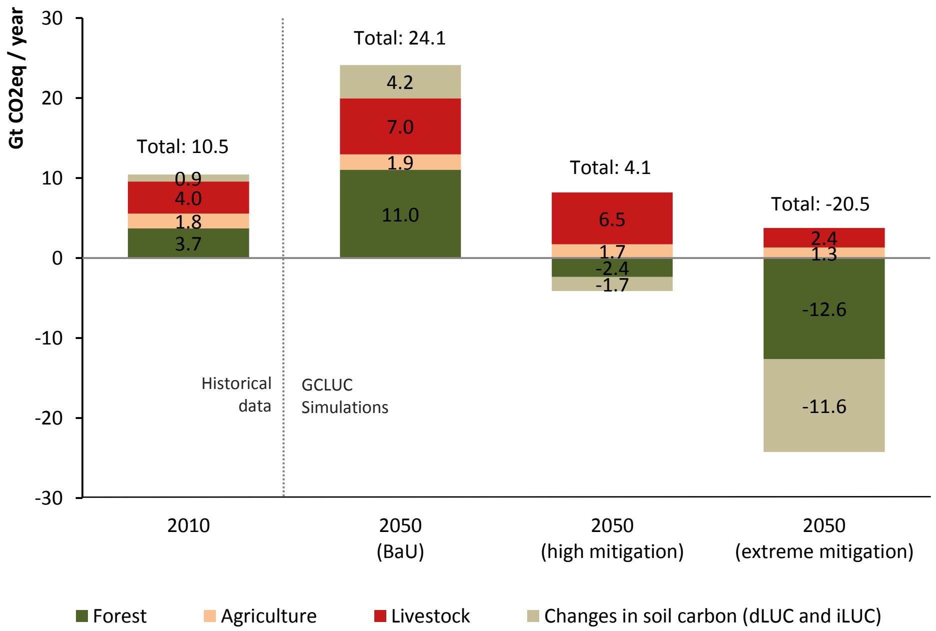

Figure 4: Global GHG emissions from Agriculture, Forest and Other Land Uses

Results from the green-Hubbert Model for Brazil

The green-Hubbert model is an integration of a top-down approach (a theoretical adaptation of the classical Hubbert curve) with a bottom-up approach (practical Agro-ecological zoning for bioenergy expansion). Thus, it provides a useful complementary approach to the GCLUC model for assessing land use for bioenergy when land availability is a resource constrained by law or market regulation. To test the model, Brazil was taken as a case study, because of the availability of its agro-ecological zoning for sugarcane expansion, which is a major crop for ethanol production, and as

Brazil is the world’s second-largest biofuels producer, just behind the USA. Thus, the numbers of such zoning were consolidated as an input to the gH equations 1 and 2.

The sugarcane EUR (Estimated Ultimate Recovery), which is the variable *Z* in gH Equations 1 and 2, is assumed to be the ultimate capacity of land ‘reserve’ for such crop expansion in Brazil, here termed as ‘*Land Use Peak*’ (LUP). This was formally fixed by the agro-ecological zoning with a robust legal framework for enforcement, as the sum of different suitable land types (64.7 million hectares, as a total of Al (livestock), Ag (agriculture-livestock) and Ac (agriculture)). Therefore, the sugarcane EUR (here called variable *Z*) is the land limit for sugarcane expansion in Brazil, which as a result indirectly limits the capacity to produce bioenergy, too, because of several technological and natural constraints, e.g., photosynthesis efficiency (Strapasson, 2014). It is assumed that the future demand for ethanol worldwide would exceed supply, and therefore all this area could be theoretically occupied. The GCLUC, for example, shows that this would be possible in many emission pathways. However, it is also possible simply to adjust the model to a lower *Z* value for a more conservative scenario if needed, e.g., if there is likely to be a reduction of land availability because of soil erosion or changes in climate. For example, the sugarcane AEZ also provides a moderate limit for expansion (40.3 Mha), comprising mostly pastureland (Al + Ag categories only), and excluding cropland (Ac category).

The gH S-curve depends on how the sector would theoretically increase if on a linear basis in order to adjust the line to logistic behaviour, which is usually more consistent with actual changes in land use and other types of finite natural resources (e.g., oil, gas and coal). Thus, three scenarios were modelled with different trends for long-term expansion rates, an upper curve for a fast expansion rate, and a medium and low rates, in order to show a range of potential sugarcane expansions (Figure 5).

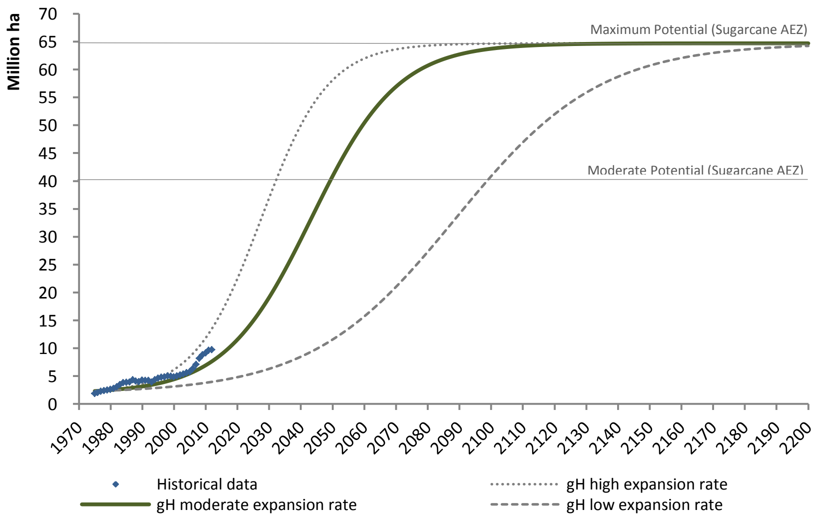

Figure 5: green-Hubbert land use curves for the expansion of sugarcane in Brazil

To assess the land use change (LUC) from the land expansion shown above in Figure 5, it is necessary to derive the obtained curves over time, as shown in Figure 6. The annual historical LUC data are usually very volatile, particularly due to changes in bioenergy policy and crop shortfall, and therefore a 12-year moving average reflects the annual variations spread over the long term, which seem to gain momentum over time. This momentum may reach a maximum (here termed ‘*Land Use Change Peak*’ (LUCP)) and then decelerate until the land is no longer available for further expansion, although not necessarily presenting a symmetric bell curve, and possibly having periods of market crisis. Therefore, if ethanol becomes a commodity with an abundant global demand, and sugarcane remains the most efficient bioenergy crop in the long run, then there is a possibility that the sugarcane sector may have a LUC peak in a long-term moving average perspective. This peak may also vary if the total land availability for this energy crop is reduced by market, legal or environmental reasons, including competitive uses with other crops and livestock. In this case, updated new gH curves should be generated.

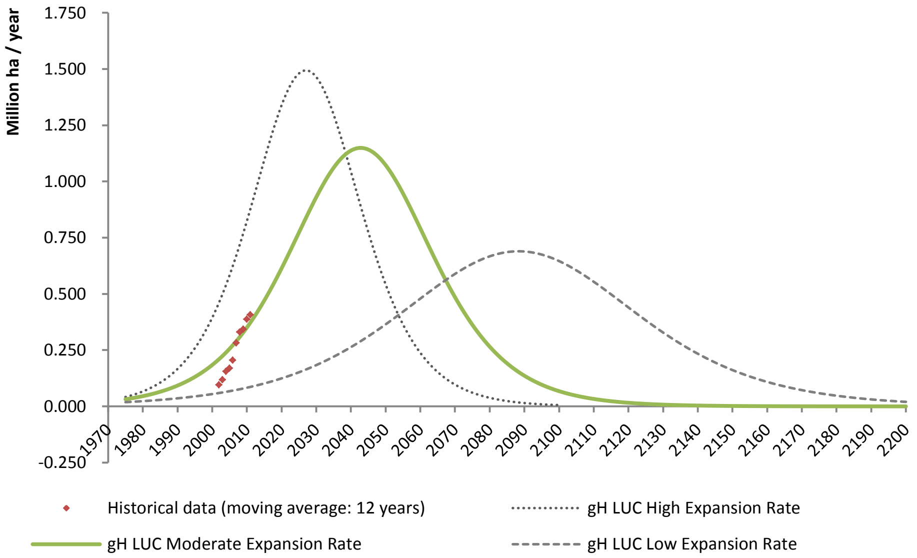

Figure 6: green-Hubbert land use change curves for the expansion of sugarcane in Brazil, with historical moving average data (12 years)

KEY FINDINGS

The single most important outcome of this research is that ‘there are certainly limits to bioenergy and these limits are dynamic over time’. The key message here is ‘change for bioenergy’. Scientific rationale and social and political rationality are about you and the world we want to live. To blame bioenergy as a single entity and without properly understanding its complexity may be a good strategy to promote a higher consumption of fossil fuels and increase global warming. The results here obtained clearly show that the sustainable production of bioenergy is not only possible, but also desirable to tackle climate change and improve energy security worldwide. At the same time, the expansion of bioenergy also presents some risks, which need to be responsibly addressed.

The original hypothesis stated that ‘there are fundamental limits to the overall scale and rate of the sustainable expansion of bioenergy, which can be assessed using combinations of empirical data, mapping tools and complex systems models’. This was duly proven by applying the integrated models proposed here along with agro-ecological zoning schemes and actual data sets from reputable sources. Thus, it was shown that the proposed methodology can provide a large number of meaningful results, and act as a *strategic vision tool*. The main messages and findings obtained from selected modelling simulations are described below.

Bioenergy potentials should be assessed using dynamic models and integrated approaches

The complexity of bioenergy is associated with a large number of variables, which can change in time and space. By testing the GCLUC model, it was shown that the limits of bioenergy can range from a marginal increase in bioenergy supply, from 54 EJ in 2010 to 65 EJ in 2050 (including traditional biomass), or instead to around 360 EJ/year in 2050, as a theoretical upper limit, with an area equivalent to 566 Mha for dedicated energy crops. This extreme bioenergy potential would be equivalent to 41% of the total primary energy supply by 2050 (886 EJ/year, under business as usual) through extreme mitigation efforts in the land/bio/food sector. Thus, a number between these two extremes is more likely to occur and depends on climate change mitigation ambitions, supporting policies and investments. For example, in a high mitigation simulation, similar to the IEA2DS, the amount of bioenergy produced would reach approximately 165 EJ/year by 2050 on 388 Mha of land used for dedicated energy crops, meeting around 18% of the total primary energy supply forecast by 2050 (895 EJ/year, under business as usual). If other sectors (transport, power generation, manufacture and buildings) also reduce their growing energy demand, particularly from fossil fuels, bioenergy could be even more representative in the global energy mix. IRENA (2014), for example, envisages that bioenergy could account for 20% of the total primary energy supply by 2030.

In addition, these models show that it is not scientifically robust to estimate global iLUC factors accurately, because land use changes are subject to complex agricultural dynamics and potential changes in lifestyle. Besides that, each bioenergy project has its own characteristics and local conditions, and consequently any attempt to generalise bioenergy under deterministic approaches is usually misguided. In other words, simplistic approaches often lead to wrong answers. Even IPCC (2014b, p. 95), in its recent attempt to assess global iLUC factors, stated that they are ‘highly uncertain, unobservable, unverifiable, and dependent on assumed policy, economic contexts, and inputs used in the model’.

In fact, the complex-systems models proposed here also present uncertainties and limitations for some types of analysis. They are useful for discussing policy strategies in a broad sense, by showing a number of possible pathways concerning the balanced use of land resources. However, they also require supplementary in loco assessments for more detailed estimates and business decisions, as well as comparative analyses with other integrated bioenergy models. Hence, GCLUC and gH models are very useful to show directions towards sustainable land use pathways, but fail to present very accurate estimates for a certain specific scenario, although this is not the purpose of these two models. Nonetheless, given their different assumptions and scopes they can complement each other nicely. The GCLUC model works as a dynamic, integrated approach, which cannot be directly applied for local assessments, but is invaluable for the assessment of global sustainable strategies instead. In contrast, the gH model is not suitable to conduct global assessments, but can help to understand regional and local changes in land use for the expansion of energy crops when land resources are duly assessed and regulated via agro-ecological zonings.

Bioenergy can play a major role as a source of GHG reduction and removals

As shown in the GCLUC simulations, in an extreme situation, bioenergy could provide up to approximately 11 $GtCO_2eq$/year of GHG savings by 2050. This would represent approximately 13% of the total projected emissions for all sectors under a business as usual scenario with no bioenergy increase, in the same period. This reduction could be even higher with the use of BECCS, and biochar integrated with bioenergy. Even for a non-extreme scenario (GCLUC for high mitigation scenario only in the land/bio/food sector), these emission reductions would be very significant, approximately 7 $GtCO_2eq$/year by 2050. Therefore, bioenergy is not an insignificant measure for reducing global GHG emissions, but a major source for this environmental service.

In addition, afforestation/forestation could sequester around 13 $GtCO_2eq$/year, and soil carbon stocks could take up about 12 $GtCO_2eq$/year from the atmosphere, which is higher than the speculative forecasts for most of GGR technologies. Consequently, as an overall balance, the net GHG emissions from (AFOLU), including changes in soil carbon, could be reduced from approximately 10 $GtCO_2eq$/year in 2011 to a negative emission of 20 $GtCO_2eq$/year in 2050 in an extreme simulation.

'Food AND Fuel' should be the norm and not 'Food VERSUS Fuel'

Although it is possible to have a direct competition between food and fuel, in most cases a symbiosis is the norm. The possible conflicts can be avoided by sustainability policies and market regulation when land availability is not a limiting factor. Thus, food *versus* fuel is often a false dilemma, and bioenergy should be seen as an integral part of agricultural production rather than a competing factor. The term 'agro-energy' emphasises this positive integration between agricultural and energy systems. Other positive integrations can be likewise explored, for example, biofuels and biochemicals.

Therefore, a major paradigm shift is required to understand crops as complex chemical structures with multiple and integrated applications, which include not only food, feed and fibre, but also bioenergy, biochemicals, carbon stock, among others, i.e., a large variety of bio-based products and environmental services. For this reason, the use of the terms 'food crops vs. non-food crops' is also a false dilemma, because, in practice, what matters is the energy efficiency of the crop and its economic feasibility, since land is the basic parameter, not the type of crop. For instance, the fact that jatropha is not a food crop does not make it better than oil palm or sugarcane from the perspective of a farmer aiming at obtaining the maximum return from the land resource. As shown in this research, NPP per unit of area is a key performance parameter for choosing the most suitable energy crop for a certain area, and for minimising LUC impacts.

Increases in productivity and changes in lifestyle can help to tackle climate change

To meet the growing demand for food, and meat consumption in particular, it would be necessary to keep increasing crop and livestock yields, in order to promote bioenergy, food security and forest conservation. In this sense, livestock productivity is a central element for reducing land demand, mainly by increasing animal density in grazing systems, improving livestock management, and animal breeding. Therefore, designing bioenergy programmes requires promoting increases in agricultural efficiency as a whole, which means to identify potentials and limitations of different regions, and give appropriate technical support for farmers to explore these potentials through agricultural extension and technology outreach.

In fact, the current food supply meets the demand partially because there are more than 800 million people undernourished worldwide. However, the hunger problem persists not because of lack of food availability in the world, but because of the lack of sufficient income in poor populations to purchase them in adequate amounts.

Therefore, producing more food without poverty alleviation would only add more pressure on the environment. GCLUC model suggest that the current world food supply could be sufficient to alleviate under- and malnutrition in poor countries without the need of land expansion for agriculture, if specially rich nations reduced, for example, their meat consumption and food wastes and tackled their obesity epidemic. Nonetheless, this is unlikely to occur, at least not on the required scale, and therefore it will be necessary to address three issues simultaneously: (i) to reduce poverty globally, (ii) increase agricultural productivity, while also (iii) adopting more sustainable lifestyles. Livestock intensification, particularly an increase of animal density on pasture systems could make a major contribution.

Bioenergy should never precede food security and forest conservation

Bioenergy can be either a renewable or non-renewable energy source, depending on how and where it is produced and used. For example, if bioenergy leads to deforestation or poses risks to food security, it will never promote sustainable development. Thus, energy crops should only expand over supply-side residual land, rather than be driven by a bioenergy demand shock. This is an important caveat to avoid exceeding the carrying capacity of Earth, particularly in a world with growing food consumption and land scarcity.

Most of the available models simply estimate bioenergy expansion according to energy scenarios (i.e., demand-driven approach), whereas the GCLUC and gH models do the opposite. In a first instance, they allocate land to food production and calculate the residual. Subsequently, some of this residual land is allocated to forest conservation (as a proxy for biodiversity). Thus, only after having met the human demand for food and taken into account the land requirements for forest conservation, bioenergy potentials that would be feasible without jeopardising food security and forest conservation are derived. Hence, these two models are based on the principle that food and forest should come first. However, in practice, this may not be necessarily the case, because there may be countries that would expand energy crops regardless of food security issues or forest conservation concerns globally. A random large-scale expansion of energy crops worldwide in a scenario of growing land scarcity is a potential threat, but which can be mostly avoided by using landscape planning and integrated public policies.

Agro-ecological zoning should be a basic platform for sustainable bioenergy expansion

As discussed in greater detail in the thesis (Strapasson, 2014), agro-ecological zoning for energy crops can be an important tool for sustainable land use planning towards a harmonious co-production of food, fuel and forest conservation. However, to achieve this, policy regulation is essential, given that *laissez-faire* policies are usually not sufficient to drive investments towards a sustainable land use in a broad context. The maximisation of profit margins is what usually drives business investments, and this is not necessarily connected to major social and environmental benefits, even less on a global scale, which is affected by complex transboundary interactions of land use dynamics. The Brazilian experience with the sugarcane and oil palm AEZ, for instance, could be *adopted and adapted* by several other nations with sufficient lands available for the production of bioenergy, particularly in tropical regions of Latin America, Africa and Asia, which generally have naturally favourable conditions for the production of biomass feedstocks. Conversely, even this pioneering Brazilian experience could go much further, by integrating new variables in their AEZs for energy crops, such as ecological corridors, integrated water resources management

(IWRM), climate change effects on agriculture (overlaying potential impacts), and interactions with other agribusiness chains and small production systems. AEZ could also be downscaled for a certain region in order to present better results for guiding regional integrated policies of land use planning.

There is no single recipe for producing sustainable bioenergy worldwide, but many lessons from current producer countries could be shared effectively with other nations. This type of cooperation could be multi-beneficial to these countries, by opening new markets, raising bioenergy to a global commodity level, and reducing GHG emissions. In spite of some international initiatives to commoditise bioenergy trade (e.g., Chicago Board of Trade (CBOT), BM&F Bovespa, Biomass Commodity Exchange (BCEX) and Port of Rotterdam), the spot market and the use of long-term contracts are still dominant, and usually regionalised. Thereby, to increase the international trade of bioenergy as a commodity and with a reliable supply, it is necessary to have more countries concomitantly supplying and demanding more bioenergy globally. In this regard, the AEZ schemes may help new players to promote this market on a sustainable basis.

Bioenergy can reshape the current energy and agricultural geo-politics

As estimated using the GCLUC model, bioenergy production could become a major source of energy in the global energy mix, displacing fossil fuel sources in many end uses. It may represent by 2050 from 65 EJ/year to 360 EJ/year in primary energy terms. Bioenergy is already part of the international energy agenda, but its vast potential can influence the global geo-politics, in most cases in a positive way. For example, bioenergy can act as a vector for rural development, increasing local income and energy security, and therefore contributing to a more equitable geopolitical relationship worldwide, besides mitigating global warming.

Furthermore, in contrast to fossil fuels, bioenergy can be produced in almost any country, albeit on different scales, whereas oil, gas, coal and even shale gas reserves are often very restricted to certain regions/countries. Thus, comparatively, bioenergy can be considered as a “democratic” energy source, representing a major breakthrough towards energy access and carbon reduction worldwide. It can be produced under different schemes and at different scales, from cooperatives of small farmers to vertical business models using plantation systems. At the same time, the production of energy crops depends on scale, competitive costs, and capacity of regular supply to sustain it as a profitable activity in the long term, and hence capacity development is requirement for the promotion of sustainable bioenergy programmes worldwide. This paper was not intended to cover these specific issues, but they represent some potential benefits that a significant expansion of bioenergy simulated in the paper could provide.

Land use is a relativistic concept

Global productive land use can be understood as a relativistic concept. Consider, for example, an illustrative mosaic, where its pieces can virtually curve and transform over time, changing their size and format, and even overlap each other, according to their use and allocation. At the same time, the overall size of the mosaic remains the same. As demonstrated in the GCLUC simulations, the size of land use types (e.g., pasturelands, croplands, forestlands) can significantly vary over time, particularly because of changes in food demand patterns and productivity gains (physical and economic elasticity effects). In addition, the way that these different land use types match up can also change over time, not only modifying the current pattern of land use, but also exchanging equivalent land area (as mosaic pieces) with other regions and countries. For example, if the USA uses more maize as an energy crop, an equivalent land area, which was originally dedicated to food production, may be moved elsewhere, e.g., another country may increase its maize production to counter-balance the food/feed market, i.e., an iLUC effect, except if this is compensated by productivity gains. This equivalent land area ('mosaic piece') can have different formats or be split into small ones.

The land use pieces of this global mosaic can also intersect, because of integration schemes, e.g., agro-forestry, agro-livestock, multi-cropping effects, etc. In fact, land is a finite resource on Earth, i.e., a zero sum equation in the limit ('first law': *conservation of land*) and, furthermore, land use can also be constrained by legal framework, as shown in the green-Hubbert model. However, the same area of a certain mosaic piece can be either totally or partially occupied by more than one piece, thereby making more space for another piece elsewhere ('surplus land'). For example, using integration schemes, such as agro-forestry, agro-livestock, etc. can free up space for forests and/or energy crops. Empty spaces, e.g., deserts, ice caps, and damaged pieces, e.g., land degradation ('second law': *entropy as degraded land*), although potentially reversible) are also part of this illustrative land use mosaic.

Bioenergy should operate as a closed-loop system

The carbon released from bioenergy combustion can potentially be entirely recycled in a global framework, assuming that new plantations will be produced to recapture the carbon emitted through photosynthesis elsewhere, closing the loop from 'cradle-to-cradle', including the energy balance, and the energy-carbon dynamics in the GCLUC model, as further explained in the thesis. Entropy losses can potentially be 'counter-balanced' at the production field level by sunlight inflow, as an external radiation source entering the atmosphere, and by increases in photosynthetic efficiency for the direct conversion of sunlight into fuels and chemicals. In other words, solar radiation can bound and organise chemical structures in plants by generating more entropy elsewhere. Thus, the challenge towards a fully sustainable bioenergy system relies on reducing and even eliminating the use of fossil fuels in its production chain, as well as on recycling the plant nutrients used by the energy crops. The same rationale can also be applied to food systems to some extent, particularly if implementing zero-waste strategies.

Therefore, technically, the limits of bioenergy are fundamentally dependant on land availability, photosynthesis constraints, the sustainable management of nutrients and water resources, and the nature of investments towards these ends. In addition to these environmental aspects, social and economic constraints should be taken into account for the sustainable development of bioenergy.

ACKNOWLEDGEMENTS

The author acknowledges all those who have contributed to this research become a reality, particularly Jeremy Woods, Nicole Kalas, Frank Rosillo-Calle, Nilay Shah, and Richard Templer from Imperial College London; Sophie Hartfield, Tom Bain and Anna Stephenson from the UK Department of Energy and Climate Change (DECC) and all the Global Calculator team; Helena Chum from the US National Renewable Energy Laboratory (NREL); Richard Murphy from the University of Surrey; Murilo Tadeu Werneck Fagá from the University of São Paulo (USP); and the CAPES Foundation, Ministry of Education of Brazil, for the funding support.

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