On the global limits of bioenergy and land use for climate change mitigation

ALEXANDRE STRAPASSON¹,², JEREMY WOODS², HELENA CHUM³, NICOLE KALAS², NILAY SHAH⁴ and FRANK ROSILLO-CALLE²

¹Belfer Center for Science and International Affairs, Harvard University, 79 JFK Street, Mailbox 117, Cambridge, MA 02138, USA, ²Centre for Environmental Policy, Imperial College London, 14 Prince’s Gardens, London SW7 1NA, UK, ³National Renewable Energy Laboratory (NREL), U.S. Department of Energy, 15013 Denver West Parkway, Golden, CO 80401, USA, ⁴Department of Chemical Engineering, Imperial College London, ACEX 304/5, 3rd Floor, ACE Extension, London SW7 2AZ, UK

Abstract

Across energy, agricultural and forestry landscapes, the production of biomass for energy has emerged as a controversial driver of land-use change. We present a novel, simple methodology, to probe the potential global sustainability limits of bioenergy over time for energy provision and climate change mitigation using a complex-systems approach for assessing land-use dynamics. Primary biomass that could provide between 70 EJ year⁻¹ and 360 EJ year⁻¹ globally, by 2050 was simulated in the context of different land-use futures, food diet patterns and climate change mitigation efforts. Our simulations also show ranges of potential greenhouse gas emissions for agriculture, forestry and other land uses by 2050, including not only above-ground biomass-related emissions, but also from changes in soil carbon, from as high as 24 GtCO₂eq year⁻¹ to as low as minus 21 GtCO₂eq year⁻¹, which would represent a significant source of negative emissions. Based on the modelling simulations, the discussions offer novel insights about bioenergy as part of a broader integrated system. Whilst there are sustainability limits to the scale of bioenergy provision, they are dynamic over time, being responsive to land management options deployed worldwide.

Keywords: biomass, biofuels, food security, GCLUC model, Global Calculator, system dynamics

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Introduction

The sustainable future of our society depends on how we use the natural resources available worldwide without exceeding the environmental resilience capacity (Steffen et al., 2015). Climate change substantially exacerbates the risks of exceeding such capacity, including for the multiple uses of biomass, unless global policies for sustainable development (UN, 2016) and climate change (UNFCCC, 2015) are implemented in an integrated manner for a wide range of specific geographic conditions and contexts. The growing need for land-based products, for example food, feed, fibre, bioenergy, chemicals and materials, challenges us to balance the growth in their markets in a sustainable manner. One critical global trend is the evolution of the integrative bioeconomy, that is, the production, conversion and use of renewable biomass (organic materials in general) as part of a broad economic development in different sectors (e.g. agriculture, food, energy, industry, transport and building), which is actively being implemented in several countries (GBS, 2015). Without an interlinked and integrated approach across multiple sectors, bioenergy’s role can either increase or ameliorate the pressures on ecosystems by damaging or supporting regulating services (Strapasson, 2014).

The aim of this paper is to understand the global sustainability limits of bioenergy by developing a novel rational, dynamic, quantitative framework to investigate the complex relationships between sustainable land use, food security, forest dynamics, bioenergy and climate change. The main objective was to assess the limits of bioenergy production over time against the availability of land resources and technology innovation, whilst also offering new insights on the role of bioenergy and land use for climate change mitigation. To this end, we deployed a novel complex-systems approach to resource exploitation from which the methodology enables the user to explore a wide range of bioenergy futures according to different land-use dynamics, by integrating the availability of natural resources with food security, changes in dietary patterns and agricultural yields, and environmental services, adopting

Correspondence: Alexandre Strapasson, tel. +1 617 495 1187, fax +1 617 495 8963, e-mail: alexandre_strapasson@hks.harvard.edu

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various commonly used global scenarios of the economy. However, how can the global limits to biomass for energy be determined in a complex framework involving all these dynamic changes under technological and sustainability constraints?

**Materials and methods**

To answer this research question, the potential limits of bioenergy were assessed using an original integrated systems model applied to sustainable policy strategies. Thus, we address the communication gap among science and policy and between science and society, as the model is incorporated into a public, open source, tool, the Global Calculator (DECC, 2016). Through this tool, experts and civil society actors can exercise various levers to choose the levels and metrics of interventions, including social behaviour and technological innovation and deployment. We have carried out a systematic synthesis of the full diversity of options captured by the model and have used the outputs to inform the design of potential sustainable policy strategies. Termed the ‘Global Calculator Land Use Change’ model (GCLUC), it addresses the main biomass, food and land-use dynamics as part of the Global Calculator.

The entire GCLUC model, including all its equations, interlinks among variables and additional references, is available as a Appendix S1 to this article. The Global Calculator was initially prepared in MS Excel, so that anyone can easily access the original spreadsheet and check the entire model in detail. The results presented in this paper are consistent with the web-tool version 23 and spreadsheet version 3.99.2, which is also available online. This spreadsheet includes all sectors of the economy (transport, buildings, manufacturing, electricity and fossil fuels, land use, bioenergy and food) and a glossary for the land-use classifications; the GCLUC model is fully detailed in its worksheets. Once concluded, the spreadsheet was converted into a multiparadigm programming language (Ruby) to publish the model as an interactive web-tool online, with a relatively simple interface, and in public domain. The program source code is also available on the Global Calculator website, which also includes some complementary methodological documents and further explanations on how to use the web-tool. Therefore, the spreadsheet available as a Appendix S1 is the modelling structure behind the Global Calculator web-tool.

This article offers some selected representative simulations, but several alternative scenarios can be simulated by running either the detailed model directly or using the web-tool interface. However, by using the spreadsheet version, the user is also able to change basic assumptions and the calibration of variables, which is not possible to be done using the web-tool. In this article, we offer a basic explanation about how the GCLUC works and its main assumptions, before showing some simulation results and discussions.

The GCLUC operates as a system dynamics model based on stocks and flows of energy, carbon and land, as illustrated in Fig. 1, using 12 levers, which are the main ‘parameters’ used in the model for the mitigation of greenhouse gas (GHG) emissions. The two arrows from ‘land for food crops’ to ‘bioenergy’ mean that the model includes the use of both on-farm biomass residues (e.g. leaves, straws) and postfarm residues and wastes (i.e. from the farm gate to the consumers).

Thus, users can develop their preferred pathways to 2050 by varying the weight of a set of levers across different levels of climate mitigation ambition. For each lever available in the model, for example changes in per capita calories consumed, crop yields or animal density on pastur elands, there are four levels (with intermediate decimal levels also available, for example levels 1.1, 1.2, 1.3, etc.) of increasing ambition to reduce GHG emissions over the coming decades, as shown in Fig. 2. The interactions of all levers’ levels result in a large number of technically possible scenarios for GHG emissions, bioenergy production and land-use distribution patterns worldwide by 2050.

A brief description of the levers used in the calculator and the main references used to calibrate their respective levels are available in Table 1. In addition, the detailed variation of each lever’s level (e.g. if linear or nonlinear) until 2050 is described in the Appendix S1. The dynamics of biomass, wastes and residues availabilities for energy use depend on the demand for food, feed, fibre, and residues. Changes in land use, such as for the production of grains, meat and energy crops, settlements and infrastructure, and forestry, including changes in soil carbon, are also considered over time, as later explained in this section.

The Intergovernmental Panel on Climate Change (IPCC) usually ensembles the many issues shown in Table 1 as part of the so-called Agriculture, Forestry and Other Land Use (AFOLU) sector (Smith et al., 2014). This sector is unique compared to other sectors of the global economy, because AFOLU is able to mitigate emissions not only by increasing GHG removals from the atmosphere, but also by reducing emissions through better agricultural management of land and livestock.

In addition, land resources under certain levels of soil degradation can, in many cases, have their productivity restored by fallow crops, perennial crops or agro-livestock-forestry systems, resulting in an increase in soil carbon content over time (Benedes & Frische, 2016).

Therefore, AFOLU emissions in the GCLUC model are derived from deforestation and afforestation/reforestation (CO₂), changes in soil carbon (C), as well as the CH₄ and N₂O emissions from both agriculture (including from food and non-food crops), and livestock (from pasture, and per type of animal). Livestock emissions comprise enteric fermentation (CH₄), manure management (CH₄ and N₂O) and manure left on pasture (N₂O), whereas agricultural emissions include rice cultivation (CH₄), burning crop residues (CH₄ and N₂O), synthetic fertilizers (N₂O), manure applied to agricultural soils (N₂O), crop harvest leftovers (N₂O) and cultivated organic soils (N₂O). The use of energy in agriculture is also included. Uncertainties in AFOLU emissions are high because of their complexity and large heterogeneity in sources of emissions and GHGs. The
Main assumptions of the GCLUC simulations

In this article, we played three representative simulations of GHG mitigation pathways by 2050, using the GCLUC model, namely: business-as-usual (BaU) scenario, high mitigation scenario, and extreme mitigation scenario. These pathways are based on scenarios previously prepared by the International Energy Agency (IEA), in which they suggested different pathways for the energy sector by 2050 that would increase global mean surface temperature by approximately 6 °C, 4 °C and 2 °C, a.k.a. IEA 6DS, IEA 4DS and IEA 2DS, respectively, as described in IEA (2012). A representation of these scenarios is also available on the Global Calculator’s web-tool under ‘example pathways’. Further explanations
| Levers                                      | 2011 (actual data)                                      | 2050 (Levels 1–4)                      | Comments                                                                 | References used for calibrating the levers                  |
|---------------------------------------------|--------------------------------------------------------|----------------------------------------|-------------------------------------------------------------------------|----------------------------------------------------------------|
| Food calories consumed                      | 2180 kcal person\(^{-1}\) day\(^{-1}\)                 | 2520–2100 kcal person\(^{-1}\) day\(^{-1}\) | All types of food. Values in terms of net food intake, that is, already excluding food wastes in energy terms (24% of the apparent food consumption). | Ewers et al. (2009), FAO (2012, 2016), Lipinski et al. (2013), Rudel et al. (2009), Villoria et al. (2013) |
| Quantity of meat                            | 187 kcal person\(^{-1}\) day\(^{-1}\)                 | 211–14 kcal person\(^{-1}\) day\(^{-1}\) | All types of meat. Values in terms of net meat intake, that is, already excluding meat wastes in energy terms (19% of the apparent food consumption). | FAO (2012, 2016), Lipinski et al. (2013), WHO (2008)          |
| Type of meat (ruminants: monogastrics)      | 22:78                                                  | 28:72–10:90                            | Proportion of meat consumed from ruminant animals (cattle, sheep and goats) against monogastrics (pig, chicken and other poultry), in energy terms. |                                                                  |
| Crop yields                                 | 100 (levelized index)                                  | 0–200% increase                        | Percentage of 2011 yield. Global average for all crops.                  | FAO (2012, 2016), Grassini et al. (2013), IPCC (2014), Scurlock (2013) |
| Feedlot systems                             | 6% (cattle), 1% (sheep and goats)                      | 0–30% (cattle), 0–10% (sheep and goats) | Proportion of animals reared in confined systems and fed on grains, food wastes and agricultural residues. | Best (2011), FAO (2006, 2012, 2016), Galloway et al. (2007), Searchinger et al. (2013), Wirsenius (2000) |
| Livestock's feed conversion ratio           | 5.0% (cattle, sheep and goats on feedlot), 2.0% (cattle, sheep and goats on pasture), 24.4% (poultry), 27.1% (pig), 7.8% (milk), 13.0% (eggs) | 5.3–7.0% (cattle, sheep and goats on feedlot), 2.1–2.8% (cattle, sheep and goats on pasture), 252–28.8% (poultry), 28.4–32.4% (pig), 84–96% (milk), 13.7–15.6% (eggs) | Percentage of biomass input converted to meat /milk/egg energy. |                                                                  |
| Animal density on pasturelands              | 0.6 animal ha\(^{-1}\) (cattle) 3.1 animals ha\(^{-1}\) (sheep and goats) | 0.7–1.1 animal ha\(^{-1}\) (cattle) 3.4–5.5 animals ha\(^{-1}\) (sheep and goats) | Global averages with large local variations. |                                                                  |

(continued)
| Levers                              | 2011 (actual data) | 2050 (Levels 1–4) | Comments                                                                 | References used for calibrating the levers |
|-------------------------------------|--------------------|-------------------|--------------------------------------------------------------------------|--------------------------------------------|
| Bioenergy yields                    | 6.7 odt ha\(^{-1}\) for solid biomass (heating value 18.5 GJ t\(^{-1}\) and liquid fuels about 83.3 GJ ha\(^{-1}\) or approx. 2.7 t ha\(^{-1}\). Total estimated area 98 Mha. | 20–200% increase | Solid biomass estimated for modern bioenergy. Biofuel yields represent a weighted average between biodiesel and bioethanol (heating values: ethanol 28.2 GJ t\(^{-1}\), and biodiesel 39.7 GJ t\(^{-1}\)). All values on global average, which may significantly vary according to the energy crop and producing country. Odt stands for oven dry tons of biomass. | FAO (2016), IEA (2011a,b), REN21 (2015), Woods \textit{et al.} (2015) |
| Bioenergy types                     | 60% solid: 40% liquid | 80(s):20(l)–20(s):80(l) | Proportion of solid vs. liquid fuels generated from the future expansion of dedicated energy crops worldwide. Modern bioenergy only. Small proportion of gases also distributed (biogas). Traditional biomass was modelled as a fixed trend based on literature review. | |
| Wastes and residues                 | Production: On farm: 1:1 | Production: On farm: 1:1 | On farm: amount of food produced (e.g. grains) against the amount of residues (e.g. leaves, straws). | Foresight (2011), Galloway \textit{et al.} (2007), Lipinski \textit{et al.} (2013), Modak (2010), Partiff \textit{et al.} (2010), Rosillo-Calle \textit{et al.} (2007), Smeets \textit{et al.} (2007), Themelis (2011) |
| Waste production:                   | 24% plant-based food 19% meat | 24–10% plant-based food 19–5% meat | Postfarm: percentage of wastes produced from the farm’s gate to the consumption and disposal. Percentage of available residues and wastes (in terms of energy content) that are collected for energy generation. Part of the wastes are also allocated to animal feed. | |
| Collection and use:                 | 10% on farm | 10–30% on farm | | |
| 1% postfarm plant-based food and meat | 5–30% postfarm plant-based food and meat | | | |
| 0.1% postfarm milk                  | 0.5–10% postfarm milk | | | |
| Surplus land                        | Approx. global 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 to food security. | FAO (2016), Lambin (2012), OECD (2012), Schmitt \textit{et al.} (2009), Bringezu (2012), EEA (2011) |
| Land-use efficiency                 | 100 (levelized baseline) | 110–70 | Land needed to meet food demand may increase 10% (due to climate impacts, desertification and erosion) or decrease 30%, because of land-use integration (e.g. multi-cropping, agro-forestry and agro-livestock systems). | Byerlee & Deininger (2013), Cox \textit{et al.} (2009), FAO (2013), Langeveld \textit{et al.} (2013), Okorio (2006) |

Prepared by the authors. Values used for the Global Calculator estimated from international references cited in the table, and stakeholders’ consultation.
about the simulations shown in this paper are following described.

The BaU scenario represents a null or low GHG mitigation pathway, which consists of a pseudo-business-as-usual scenario that maps the ‘IEA 6DS’ pathway onto a Global Calculator. In BaU, total energy use (in terms of primary energy) grows by almost two-thirds by 2050 (compared with 2012) and total GHG emissions rise even more. Here, an increase in the global mean surface temperature, above pre-industrial levels, is projected to reach almost 5.5 °C after 2100 and almost 4 °C by the end of this century. To develop the IEA 6DS pathway, all levers from the relevant sectors (i.e. buildings, transport, manufacturing, and power generation) were set in the Global Calculator to mirror an equivalent IEA 6DS energy scenario. The levers associated with the GCLUC model were estimated analogously to the assumptions used by the IEA for their 6DS scenario (i.e. a pessimist scenario with zero or low mitigation efforts in general), given that the IEA scenario does not include an explicit land-use module. Therefore, per capita food consumption continues to increase, including higher levels of per capita meat consumption worldwide, which is more likely to occur with the low level of GHG mitigation efforts assumed.

As a result in the BaU scenario, there is net deforestation and no net surplus land by 2050. Bioenergy expansion is minimal, occurring with the low level of GHG mitigation efforts assumed. As a result in the BaU scenario, there is net deforestation and no net surplus land by 2050. Bioenergy expansion is minimal, based exclusively on the use of residues, low productivity gains, and declining land availability for energy crops. In this pessimistic scenario, the land/food/bioenergy sector exacerbates climate change.

Similarly, the simulation for high GHG mitigation scenario also uses the IEA 6DS scenario as a reference, but for the land/food/bioenergy sector alone it uses an analogous scenario to the IEA’s 2 °C scenario (i.e. assuming a high global effort to mitigate GHG emissions), as mapped into the Global Calculator’s ‘IEA 2DS’ pathway, keeping the ‘surplus land’ lever at level 2.5. Hence, this simulation represents a BaU for all sectors, except the land/food/bioenergy, which implements a high mitigation effort. For comparison, in the original IEA 2 °C scenario, total global primary energy supply reaches roughly 700 EJ by 2050, with bioenergy providing around 150 EJ and with all sectors contributing to climate change reductions, as the scenario sets the target of cutting energy- and process-related CO2 emissions by almost 60% by 2050 (compared to 2012).

Finally, the ‘extreme mitigation’ simulation is also a BaU for all sectors, but this time with an extreme mitigation pathway for land/food/bioenergy alone, with all its levers set to level 4 except meat consumption, which was set at level 3. Thus, this simulation illustrates what 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 an extremely high increase in crop and livestock yields.

These scenarios imply that behaviour/lifestyle changes occur in diet and highly efficient use of biomass for associated industries takes place. Here, no effort was made to add other sectors’ efficiency improvements, increased penetration of renewable energy and increased overall resource productivity, although this is also possible to be simulated in the Global Calculator. If other sectors (transport, power generation, manufacturing and buildings) also reduce their growing energy demand, particularly from fossil fuels, bioenergy could provide an even greater share of the global energy mix.

The model also includes several additional variables, such as the use of nitrogen fertilizers and associated GHG emission factors, estimated from FAO (2016) and other references available in the Appendix S1. A number of additional levers and sub-levers could be exercised with those in the AFOLU sector in the Global Calculator, such as those in transport, buildings, manufacturing and energy, but the AFOLU sector is already interconnected with some elements of these sectors. So, in this paper, we restricted the analysis to the AFOLU dynamics to manage the degrees of freedom in the evaluation. Simultaneously varying a large number of levers would result in potentially chaotic outcomes and reduce the utility of the Global Calculator.

In regard to land-use dynamics, there are two main types of land-use change (LUC), as following described (Strapasson, 2014):

- Direct land-use change (dLUC), which occurs when crops for biofuel production are planted on land that has not previously been used for that purpose; for example, the conversion of pasture into an energy crop plantation for biofuel production. The effects of dLUC can be directly observed and measured as the effects are localized to a specific plantation;
- Indirect land-use change (iLUC), which may occur when, as a result of the switching of agricultural land to biofuel crops, a compensating land-use change occurs elsewhere to maintain the previous level of agricultural production, if crop yield gains are not sufficient to avoid this land conversion. These effects are typically the unintended consequence of land-use decisions elsewhere and, because the effects are not limited by geographical boundaries (e.g. the complex dynamics of food commodities worldwide), often are not directly observable or measurable.

For the purpose of the GCLUC model, land-use change is determined by a hierarchy of land-use types, given that in a global land-use change model the sum of land sizes (in terms of physical area) of all land-use types (productive and nonproductive lands, including deserts and ice covers) in any projected year always has to match the total existent land on Earth. Thus, there is a need for determining which land-use type is the dominant over the other ones. By assuming that food security always comes first, instead of forest conservation or the use of land for energy crops, priority is given to food production (croplands and pasturelands) in the model. Thus, for meeting the projected food consumption pattern determined in the model, the land use for agriculture and livestock is adjusted over time, including potential agricultural yield gains and the possibilities of increasing land multiuse, such as crop–live- stock-forestry integration and multiple cropping. Once food security is met, if any freed-up land (remaining land area) is available, it is then allocated to afforestation and reforestation, natural regeneration and/or energy crops, according to different options available in the model (‘surplus land’ lever).
Thus, with the Global Calculator it is possible to simulate a large number of trajectories for food consumption, and land-use dynamics for agriculture, livestock, energy crops and forests, and as a result also assess the respective land-use potential for sustainable biomass provision for energy, according to the user’s choice. By sustainable biomass, we mean biomass produced without causing deforestation or soil degradation over time. Besides, one of the objectives of a global analysis is the simultaneous determination of all land-use categories, hence avoiding the need for assumptions around dLUC and iLUC caused by a single sector.

The model includes both traditional and modern biomass. Traditional biomass stands for biomass obtained from extractive processes usually for firewood and charcoal, or agricultural residues and manure for heating or cooking. It is also commonly associated with the use of native forests, which can be either a sustainable (e.g. extraction of woods under the forest carrying capacity) or an unsustainable practice (e.g. illegal logging causing forest loss), depending on the management system, whereas modern biomass stands for the biomass produced under a renewable process, for example, through reforestation or by planting energy crops (Strapasson, 2014). The expansion of bioenergy in the model is only associated with modern biomass, whilst traditional biomass keeps gradually decreasing overtime, except the use of agricultural residues, which may increase according to the chosen pathway.

The latest year available for compiling a large historical data set of all sectors of economy at global scale during the development of the Global Calculator was 2011. Bioenergy, for example, accounted for about 54 EJ in the model’s 2011 base-year. For comparison, the world supply of bioenergy in 2015 was approximately 60 EJ in primary energy (REN21, 2016), although there are several uncertainties around bioenergy historical data. Woods et al. (2015) estimated total annual bioenergy production at 62 EJ in 2010, which represented about 12% of the world primary energy production, mostly in the form of traditional biomass (40 EJ, mainly for cooking and heating) obtained from residues, wastes and harvesting parts of living trees, with modern bioenergy accounting for 21.5 EJ (4.2 EJ as liquid biofuels, mainly for transport; 13.0 EJ as biomass for heating; and 4.1 EJ as bioelectricity). These slight variations are assumed to be normal for the agricultural sector, given the high complexity to obtain this information via surveys, satellite images and official reports, particularly in developing nations.

With respect to population, all simulations assume the ‘medium population growth’ forecast prepared 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. The proportion of people living in urban areas worldwide is also assumed to reach a medium growth, from 52% in 2011 to 66% in 2050, which has implications for land associated with settlements and infrastructure.

Soil carbon accumulation from LUC and carbon sequestration from new forests are subject to temporal adjustments to represent the transient dynamics of these changes. As a global average, changes to soil carbon are assumed to take approximately 20 years until stabilizing (EC, 2003), whilst above-ground vegetation in forests may take about 50 years (IPCC, 2000; Pan et al., 2011). In addition, a partially subjective annual limit to the rate of expansion of energy crops (12 Mha year−1 globally) is used to avoid unrealistic levels of land-use change for bioenergy over time, particularly when extreme simulations are exercised, as further described by Strapasson (2014), using several studies (Lambin, 2012; van Vuuren et al., 2012; Shah et al., 2013; Slade et al., 2014a,b).

The model also assumes some changes in transport system, mode and automotive technologies (e.g. hydrogen, electric and hybrid vehicles) by 2050, as described in the travel and transport levers of the Global Calculator. On the other hand, as earlier explained, bioenergy production was not estimated here based on demand shock, but instead on land-use availability for a supply shock. Moreover, algae-based biofuel was not included in our simulations, because of significant uncertainty on the maturity of technologies from published work to date, for consistent estimates by 2050, particularly in terms of its economic feasibility, industrial scale, environmental impacts and potential impact on land-use change (O’Connor, 2011). Algae-based products, such as food supplements, value-added chemicals and pharmaceuticals, are made commercially, but algae biofuels industry is just starting to scale up some processes.

**Results**

The GCLUC model can generate a large number of simulations of land-use change and bioenergy potentials by 2050 from the combination set across all the levers’ levels. We present only a selection of results, in the form of three main pathways: business-as-usual (BaU), high mitigation, and extreme mitigation scenarios. However, several other alternative simulations can be conducted by the Appendix S1.

Figure 3 shows the consequential bioenergy provision by 2050 from these three GCLUC scenarios, without competing with food security and forest conservation, which are also part of the model. The bioenergy production results from the variation of available land for dedicated energy crops, productivity gains and the use of residues and wastes. Here, any expansion of energy crops is directed onto surplus land arising from declining land demand for food/feed, instead of onto areas of natural vegetation (e.g. native forests and natural grasslands). Also accounted in the projections was a gradual reduction in the use of traditional bioenergy over time, and this is why more area would be needed to produce an equivalent amount of bioenergy (in terms of modern biomass), apart from productivity gains. This figure also shows the emission reductions achieved by expanding energy crops versus natural regeneration on surplus land (freed-up areas) by conducting a sensitivity analysis. Although the model uses 2011 as a base-year for all sectors, the historical data for bioenergy in this figure

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were already updated for 2015 using REN21 (2016), with no significant changes observed in its total land area, due to productivity gains in this period.

Declining land use for food/feed can result from, for instance, context-specific optimization of land-use efficiency by mixing energy and food crops (e.g. multiple cropping, rotations, crop–livestock–forestry integrated systems), cascading uses of biomass (e.g. biogas from livestock manure), technological progress and innovation in biomass production and conversion to all uses, and integrated management of land and water use. Multiple cropping can provide a larger total crop production per unit of area, in addition to the plant productivity growth, by harvesting more crops (e.g. summer and winter crops) in a same year, that is an overlap of land use, whereas integrated systems can help free up land by intersecting different land use, usually achieving similar or higher gains than via separate land uses. In contrast, an over exploitation of soils can cause soil loss and even desertification process, which can also be affected by potential climate change impacts. These issues were also considered in the calculations, as described in the Appendix S1.

Consequently, these three modelling simulations also present different land-use patterns and GHG emissions by 2050, as shown in Fig. 4, using historical data derived from FAO (2016) and Tubiello et al. (2014). Changes in soil carbon include not only those from direct land-use change, but also from indirect land-use change, given that all land-use dynamics are modelled on a global scale as a closed system (zero-sum situation).

The results obtained are also consistent with the bioenergy potential ranges by 2050 recently compiled by IPCC in its 5th Assessment Report (Smith et al., 2014), which assessed the level of agreement in the literature based on different modelling approaches (Creutzig et al., 2015). The GCLUC simulations for total bioenergy production by 2050 are comparable with those of the IPCC high and medium levels of agreement in the literature for a maximum bioenergy potential, 170 EJ year\(^{-1}\) and 250 EJ year\(^{-1}\) in 2050, respectively, from different bioenergy sources (Fig. 5). IPCC shows low agreement in the literature for potentials above 250 EJ y\(^{-1}\) in 2050, which is also in line with the extreme mitigation pathway.

**Discussion**

As initially stated, the main objective of this article was to assess the global sustainability limits of bioenergy production over time against the availability of land resources and technology innovation, whilst also offering new insights on the role of bioenergy and land use for climate change mitigation. The most important finding is that whilst there are limits to bioenergy expansion which are dynamic over time, despite these limits, we show that the sustainable production of bioenergy is not only possible, but also desirable to tackle climate change and improve energy security. At the same time, although we find little evidence for competition to date, if food security is not considered a priority, the expansion of energy crops also presents some risks, given the potential scale of land use for energy crops in the...
future. Therefore, bioenergy policies in the context of broader agricultural and energy strategies are needed to promote sustainable expansion of energy and bio-based products without jeopardizing food security and forest conservation, and in many areas contributing to energy security and diversification. Thus, results of dynamic models with detailed characteristics of land use, as presented in our modelling outputs, are fundamental to inform effective policymaking, and an integrated approach to land management over multiple scales is

Fig. 4 Global GHG emissions from Agriculture, Forestry and Other Land Use (AFOLU), including both direct and indirect land-use change.

Fig. 5 Global bioenergy potentials by 2050, using GCLUC and comparison with the experts’ assessment maximum potential from IPCC 5th Assessment Report.
Bioenergy potentials should be assessed using dynamic models and integrated approaches

The complexity of bioenergy is associated with a large number of variables, which vary over 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, 54 EJ in 2011 rising to approximately 70 EJ in 2050 (including traditional biomass), or to around 360 EJ year\(^{-1}\) in 2050 as a theoretical upper limit requiring an estimated 570 Mha of energy crops, which is equivalent to approximately 12% of the current agricultural land globally. Although physically possible under the assumptions used, we consider this upper scale of expansion as unlikely to occur. This level of bioenergy provision would be equivalent to 41% of the total primary energy supply (890 EJ year\(^{-1}\) by 2050 under business as usual) and could only be achieved through extreme mitigation efforts in the land/food/bioenergy sector. Thus, the actual level of bioenergy provision is considered more likely to lie between these two extremes and is sensitive to the level of climate change mitigation ambition, supporting policies and investments (IRENA, 2016). For example, in our high mitigation ambition, supporting policies and investments could only be achieved through extreme mitigation efforts in the land/food/bioenergy sector. Thus, the actual level of bioenergy provision is considered more likely to lie between these two extremes and is sensitive to the level of climate change mitigation ambition, supporting policies and investments (IRENA, 2016).

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

Under the extreme mitigation scenario, bioenergy could provide up to 11 GtCO\(_2\)eq year\(^{-1}\) of GHG savings by 2050, representing approximately 13% of total emissions for all sectors compared to a business-as-usual scenario in which there is no significant increase in bioenergy over the same period. In addition, the GHG savings could be higher if bioenergy was enhanced with the use of negative emissions technologies, for example bioenergy with carbon capture and storage (BECCS) and biochar. Under the high mitigation scenario, the projected emission reductions would be very significant, approximately 7 GtCO\(_2\)eq year\(^{-1}\) by 2050. Furthermore, the use of efficient crops in terms of energy and carbon balances, such as high-productivity sugarcane (Nogueira et al., 2013) and fast-growing grasses and forestry crops, could alleviate land demand for bioenergy. The advancement of alternative technologies for combustion engines (e.g., hydrogen, electric and hybrid vehicles) may also stimulate other uses for liquid biofuels, such as the production of bioplastics in the chemical industry.

As shown in the results from the GCLUC simulations, afforestation/reforestation could sequester up to 13 GtCO\(_2\)eq year\(^{-1}\) in terms of above-ground vegetation and, additionally, soil carbon stocks sequestering up to 12 GtCO\(_2\)eq year\(^{-1}\) by 2050, which combined would be higher than some speculative forecasts (The Royal Society, 2009; POST, 2013) for most of greenhouse gas removal (GGR) technologies in the same period. Consequently, as an overall balance, net GHG emissions from AFOLU, including changes in soil carbon, could be
reduced from approximately 11 GtCO₂eq year⁻¹ in 2011 to a negative emission of 21 GtCO₂eq year⁻¹ in 2050 in an extreme simulation. We note that the recently agreed Paris climate mitigation targets that aim to limit global warming to no more than 2 °C will require mitigation options currently perceived as ‘extreme’ to be adopted. Should emissions continue to increase over the next 10–20 years, negative emission options will become a necessity.

*Increases in agricultural productivity and changes in lifestyle can help tackle climate change*

As explained in the methodology, the GCLUC model prioritizes land for food production over other types of land use, and therefore to meet the growing demand for food, and specially for meat consumption, it would be necessary to keep increasing both crop and livestock yields, to avoid deforestation, as well as to free up productive land for other uses, such as afforestation/reforestation and the expansion of energy crops. Increases in agricultural productivity are potentially subject to environmental impacts, which need to be minimized to reduce its total impacts in a broader context that encompasses all land-use dynamics. Ideally, a low meat consumption should be encouraged (WHO, 2008), particularly in countries where meat consumption is already high, and especially from ruminant animals with low feed conversion ratio. Vineis et al. (2016), for example, identified a substantial cobenefit for climate and health by shifting protein consumption from meat to legumes ( pulses). On the other hand, according to the FAO (2012), world meat consumption tends to keep increasing by 2050, mainly in developing nations.

Therefore, to halt net deforestation and free up productive land for other purposes, increasing livestock productivity (i.e. more meat and milk per unit of area) is fundamental, given that pasturelands and croplands for the production of animal feed (e.g. corn and soya bean) altogether are by far the dominant uses of productive land resources to date. The GCLUC’s lever related to changes in animal density on pasturelands, for example, demonstrated to have a significant impact in the reduction in global GHG emissions by 2050. Equally important is to improve livestock management and pasture productivity, and animal breeding, whilst also reducing food wastes. It is worth noting that statistics on global animal density are highly uncertain, given that the actual use of pasturelands is usually not clearly defined in the available global datasets, so that some areas may have livestock, whilst others may not. Our calculations represent an approximation of these values as global weighted averages.

Recent efforts to reduce these uncertainties, particularly on rangeland and pasture productivity, have been made by GEO (2017).

Therefore, based on the high bioenergy potentials demonstrated in the modelling simulations by 2050, we recommend that effective design of bioenergy programmes should at least partly enable increased agricultural efficiency as a whole. An important first step is the identification of the potentials and limitations of different regions for biomass production (in terms of net primary production – NPP), followed by the provision of appropriate and targeted technical support for farmers to exploit these potentials through agricultural extension and technology outreach (Strapasson et al., 2015). To establish sustainable global land-use patterns, it will be necessary to address three issues simultaneously: (i) to reduce poverty globally, (ii) increase agricultural and livestock productivity, whilst also (iii) adopting more sustainable lifestyles and reducing food wastes at all levels of the supply chain and including consumers. Not included in this study is the potential of aquatic biomass still under investigation.

*Bioenergy should be developed in conjunction with food security and forest conservation*

Despite providing the largest global renewable energy source to date, bioenergy can be considered either sustainable or unsustainable, depending on how and where it is produced and used. For example, if bioenergy leads to material levels of deforestation or poses risks to food security, it cannot promote sustainable development. Thus, as modelled in the GCLUC, energy crops should only expand when a supply-side residual land (free-up areas) is possible to be obtained, or in integrated food and bioenergy production using perennial plants or short rotation trees using marginal agricultural productivity land that often occurs alongside productive lands.

Therefore, bioenergy potentials should not be estimated as a simple consequence of higher bioenergy demand in the market (demand shock), as usually modelled by the energy sector, without properly considering the availability of land resources for bioenergy supply with no competition over food and forest conservation. Besides, it is important to recognize the potential role of bioenergy in terms of rural development and environmental services, such as by reducing the global reliance on fossil fuels and mitigating greenhouse gas emissions, as shown in the GCLUC simulations, as well as other types of environmental services not directly assessed by the model. For example, energy crops can help restore degraded lands, improve water quality and quantity by
removing excess fertilizers and restore habitats for wildlife, also contributing to climate change adaptation (Smith et al., 2014). Therefore, identifying energy cropping strategies that support ecosystem health, crop productivities and resilience is an emerging key constraint to calculating bioenergy potentials and for their sustainable implementation (Woods et al., 2015). Data from actual bioenergy and bio-based project developments in appropriate contexts on their economic, environmental and social performance are beginning to emerge, which will help develop a sustainable bioeconomy (Lamers et al., 2016).

Although it is possible to have a direct competition between food and fuel (food versus fuel), in most cases a symbiosis is hitherto the norm (food and fuel) (Rosillo-Calle & Johnson, 2010; Kline et al., 2016; Rosillo-Calle, 2016). Potential conflicts can also be reduced and even avoided by sustainability policies and market regulation when land availability is considered to be a limiting factor. Thus, ‘food versus fuel’ is often a false dilemma, and bioenergy should be seen as an integral part of agricultural production and land use, and as an opportunity rather than a competing factor. In this context, bioenergy agro-ecological zoning schemes (Strapasson et al., 2012) and system dynamics approaches (Warner et al., 2013) can be important tools for sustainable land-use planning towards a harmonious co-production of food and fuel, biomaterials and forest conservation.

The agro-energy perspective can therefore help optimize land-based services for food, energy and carbon reductions, whilst also contributing to improve local infrastructure and new business opportunities in rural areas. This is particularly important for developing nations located in tropical zones and with land availability, which may represent a natural advantage for the production of biomass. In Africa, for example, a large population is expected to remain in rural areas in the coming decades (Montpelier Panel, 2014) and, hence, it is essential to find new economic alternatives to combat rural poverty, by improving their local farms, villages and towns sustainably (CGIAR, 2011; Conway, 2012). In fact, for competitive gains, modern energy crops are often produced in large farming systems using mechanization, following the example of other agricultural commodities. However, the use of farmers’ cooperatives and associations equipped with technical agronomical assistance, as successfully seen in many agricultural sectors worldwide, including in the biofuels industry, could help small farmers remain competitive in these new rural markets. In addition, there are jobs associated with other stages of the bioenergy production chain, such as agro-industry and services.

Bioenergy can reshape the current energy and agricultural geo-politics

Bioenergy is already part of the international energy agenda, but its vast potential can influence geo-politics, in most cases in positive ways. For example, bioenergy can act as a vector for rural development, increasing local income and energy security, and therefore contributing to more equitable geopolitical relationships, alongside climate mitigation. Furthermore, in contrast to fossil fuels, bioenergy can be produced in most countries on different scales, whereas oil, coal, natural gas and shale gas reserves are restricted to certain regions/countries, which is also the case for uranium reserves. Hence, comparatively, bioenergy can be considered as a ‘democratic’ energy source, representing a major breakthrough towards energy access, equity and climate mitigation. It can be produced under different business schemes and at different scales, from cooperatives of smallholder farmers to vertical business models using large-scale plantation systems. International trade of bioenergy has increased, and hence, liquid biofuels and more recently also biomass pellets are emerging commodities, as a result of policies being revised in some countries. More countries concomitantly supplying and demanding bioenergy globally could increase the resilience of the overall system and energy security, as countries learn from the collective experiences (Geels et al., 2016) and enact more integrative policies, for instance, by combining results from integrated assessment models with insights from sociotechnical transition analysis and practice-based action research, learning by doing (Smith et al., 2015).

Productive land use is a relativistic concept

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 area of the mosaic remains the same. As demonstrated in the CCLUC simulations, the area of the main land-use types (e.g. pasturlands, croplands, forestlands) can vary significantly over time, particularly because of changes in food demand patterns and productivity gains (physical and economic elasticity effects), and a current pattern of land use can be exchanged in equivalent land areas (as mosaic pieces) in other regions and countries to supply global needs.

The land-use pieces of this hypothetical mosaic can also intersect, because of integration schemes, for example agro-forestry, agro-livestock, multiple-cropping systems. Although land is a finite resource, that is a zero
Bioenergy should operate as part of a broad circular economy in the biosphere

Bioenergy and bio-based products should operate towards a closed-loop system with the other biomass use systems and land conservation. They should be implemented with the aim of transitioning to a circular economy, which builds on the principle of ‘cradle-to-cradle’, as a looping scheme, instead of the classical ‘cradle-to-grave’ approach (Braungart & McDonough, 2009) or as an example of industrial ecology, already operating in some countries (Chum et al., 2015; Blomsma & Brennan, 2017). In this context, the GCLUC model allows us to visualize the entire bioenergy system as a closed-loop system on a global scale within certain temporal variations. This is because the carbon released from bioenergy combustion can potentially be entirely recycled in a global framework that assures that regrowth and new plantations will use photosynthesis to recapture the carbon emitted, closing the loop from ‘cradle-to-cradle’ within a favourable thermodynamic balance (Strapasson & Fagã, 2007; Alvarenga et al., 2013a,b; Strapasson, 2014).

As demonstrated in the GCLUC model’s energy-carbon dynamics, the timing of these dynamics is also important, because dedicated energy crops should expand onto freed-up land, which may only be released gradually. Thus, the challenge of implementing 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 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 dependent on land availability, photosynthetic constraints, the sustainable management of nutrients and water resources, and the nature and rate of investments towards these ends. In addition to these environmental aspects, social, political and economic constraints should be taken into account for the sustainable development of bioenergy worldwide.

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