

## REVIEW

# How can land-use modelling tools inform bioenergy policies?

Sarah C. Davis<sup>1,2,\*</sup>, Joanna I. House<sup>3</sup>, Rocio A. Diaz-Chavez<sup>4</sup>,  
Andras Molnar<sup>5</sup>, Hugo Valin<sup>6,7</sup> and Evan H. DeLucia<sup>1,2</sup>

<sup>1</sup>Energy Biosciences Institute, and <sup>2</sup>Department of Plant Biology, University of Illinois at Urbana-Champaign, Urbana, IL, USA

<sup>3</sup>QUEST, Department of Earth Sciences, University of Bristol, Bristol, UK

<sup>4</sup>Centre for Environmental Policy, Imperial College, London, UK

<sup>5</sup>Research Institute for Agricultural Economics, Budapest, Hungary

<sup>6</sup>Forestry Program, International Institute on Applied Systems Analysis, Laxenburg, Austria

<sup>7</sup>UMR Economie Publique/Public Economics Research Unit, Institute National de Recherche Agronomique (INRA), Paris, France

Targets for bioenergy have been set worldwide to mitigate climate change. Although feedstock sources are often ambiguous, pledges in European nations, the United States and Brazil amount to more than 100 Mtoe of biorenewable fuel production by 2020. As a consequence, the biofuel sector is developing rapidly, and it is increasingly important to distinguish bioenergy options that can address energy security and greenhouse gas mitigation from those that cannot. This paper evaluates how bioenergy production affects land-use change (LUC), and to what extent land-use modelling can inform sound decision-making. We identified local and global internalities and externalities of biofuel development scenarios, reviewed relevant data sources and modelling approaches, identified sources of controversy about indirect LUC (iLUC) and then suggested a framework for comprehensive assessments of bioenergy. Ultimately, plant biomass must be managed to produce energy in a way that is consistent with the management of food, feed, fibre, timber and environmental services. Bioenergy production provides opportunities for improved energy security, climate mitigation and rural development, but the environmental and social consequences depend on feedstock choices and geographical location. The most desirable solutions for bioenergy production will include policies that incentivize regionally integrated management of diverse resources with low inputs, high yields, co-products, multiple benefits and minimal risks of iLUC. Many integrated assessment models include energy resources, trade, technological development and regional environmental conditions, but do not account for biodiversity and lack detailed data on the location of degraded and underproductive lands that would be ideal for bioenergy production. Specific practices that would maximize the benefits of bioenergy production regionally need to be identified before a global analysis of bioenergy-related LUC can be accomplished.

**Keywords:** indirect land-use change; biofuels; greenhouse gas; ecosystem services; environmental economics; feedstocks

## 1. INTRODUCTION

Bioenergy provides an opportunity for mitigating climate change and improving energy security by replacing both liquid and solid fossil fuels. However, concerns about land availability, competition with

food production and environmental impacts must all be addressed when defining suitable land-use practices for bioenergy. This paper explores the characteristics of land-use change (LUC) scenarios that should be considered when making land management decisions that affect bioenergy production. It also evaluates whether current land-use data and models contain the necessary information and processes to assess the consequences of expanding bioenergy production throughout the world.

There are many possible scenarios of bioenergy production, and the options vary with geographical

\*Author and address for correspondence: Institute for Genomic Biology, 1206 West Gregory Drive, Urbana, IL 61801, USA (davissc@illinois.edu).

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location. Bioenergy feedstocks range from oil and sugar crops to grasses and trees, and conversion pathways range from direct combustion to chemical processing for liquid transportation fuels (e.g. biodiesel, bio-ethanol). New conversion technologies for second-generation biofuels allow more diverse feedstocks, including lignocellulosic biomass and residues, and advanced conversion systems to high-density energy carriers [1]. These new feedstock opportunities are likely to encourage expansion of biomass production globally in the future, but the magnitude and localization of LUC are highly dependent on the region of production and the type of feedstock used.

Because the bioenergy sector interacts with other ecosystem services, a holistic approach to assessment of land management is required. With increasing competition for land resources, there is a need for comprehensive tools that will identify the best ways to optimize many agricultural resources in an integrated way. A few studies have recently addressed this challenge in the context of specific regions (e.g. [2–4]). There are also global models that aim to characterize LUC (e.g. [5,6]), but the macro-level view of these models can overlook some dimensions of potentially beneficial land-use options. Delineation of positive and negative scenarios for bioenergy is therefore necessary to complement global approaches and highlight local opportunities.

There has been much recent concern about indirect land-use change (iLUC) as a result of bioenergy crops being grown (e.g. [7]). Many modelling studies that estimate LUC produce widely varying results as to the degree of iLUC (see [8] for a review and [9] for discussion on uncertainty). Considering the large confidence intervals of model estimates, it remains unclear how these results can be used for legislation. At the same time, it is increasingly being recognized that, for certain crops, integrated multiple-use land management can reduce the risk of unintended iLUC. For example, bioenergy can be produced as a waste product or as a co-product with food, feed or fibre. Thus far, tools for carrying out proper assessments of multiple-use opportunities have not been developed.

We will first present a typology that characterizes desirable and undesirable effects of LUC associated with feedstock crops, then provide examples of positive and negative LUC scenarios for bioenergy production. Next, we will explore how existing datasets and models characterize new LUC scenarios and the risks of iLUC. We conclude with a discussion of how scientific tools that evaluate bioenergy-related LUC might be improved for informing policy decisions.

## 2. CRITERIA FOR EVALUATING BIOENERGY SCENARIOS

Different feedstock crop species bring different costs and benefits with respect to economic development, food security, climate mitigation, biodiversity and other land services. A clear typology of positive and negative effects is needed for a comprehensive evaluation of these different options. For example, planting

bioenergy crops on lands with high carbon stocks, such as peatlands and forests, has negative net greenhouse gas consequences and other costs [10]. On the other hand, deploying high-yielding bioenergy crops that require low inputs (fertilizers, irrigation) can improve ecologically degraded and economically under-productive landscapes [4,11–13]. In this section, we will first introduce the dimensions of bioenergy production that must be addressed in an evaluation of bioenergy-related LUC. We then discuss LUC scenarios that optimize biofuel benefits regionally, highlight scenarios of integrated land management for multiple uses and finally provide contrasting examples of scenarios that risk multiple negative impacts.

### 2.1. Dimensions of bioenergy

To assess different LUC scenarios, including those for bioenergy, some common rules must be applied to ensure systematically consistent evaluations. In the case of bioenergy, some dimensions that appear particularly critical for evaluation of costs and benefits are system boundaries, counterfactual possibilities and externalities. When evaluating iLUC, these definitions are broad, as system boundaries extend to land use in the whole world, and there is little agreement about how externalities at this scale are best regulated internationally.

System boundaries define the start and end points of the production chain (e.g. cradle-to-grave), the geographical space and the temporal limits that apply to a given analysis. System boundaries are one of the key sources of difference in estimates of overall costs and benefits of a biofuel production chain among various life-cycle analyses [14]. Results of any estimate of bioenergy-related impacts should be considered in the context of the system boundary that was selected for analysis.

The counterfactual possibilities should be defined relative to the condition of land if a biofuel project in question is not implemented. This ‘business-as-usual’ trend can vary over time according to profitability of biomass for other uses, future demand, effects of climate change on yield and other temporally dynamic factors. The costs and benefits of a land-use scenario with business-as-usual (that continues for the same length of time as a bioenergy production scenario) are the minimum counterfactuals that should be considered when evaluating impacts of LUC caused by bioenergy. The bioenergy scenario would displace the business-as-usual case, and therefore offset expected costs and benefits with new temporally dynamic costs and benefits. The difference between a bioenergy land-use scenario and its counterfactual is sometimes considered in ‘payback times’ as in estimates of carbon debts resulting from LUC [10].

Externalities are positive or negative effects of an economic activity that are not embodied in the price of products and consequently cannot be optimally managed through pure market arbitration. Effects can be diverse across bioenergy LUC scenarios because they depend on feedstock species and regional management requirements. Externalities of bioenergy production

Table 1. Effects of biofuel production scenarios across three dimensions: (i) benefits versus costs, (ii) local versus global, and (iii) internalities versus externalities.

	local	global
benefits	<p><i>direct economic benefits (internalities)</i></p> <ul style="list-style-type: none"> <li>— agricultural support to biofuel producers</li> <li>— higher prices for farmers</li> <li>— subsidization of meat sector through cheaper co-products</li> </ul> <p><i>positive social and environmental externalities</i></p> <ul style="list-style-type: none"> <li>— rural development, e.g. biofuel projects in areas with degraded land and declining resources</li> <li>— landscape management, e.g. plantation in degraded land</li> <li>— biodiversity, e.g. rotation culture in monoculture areas</li> <li>— soil quality, e.g. cultivation of degraded land</li> <li>— water quality and quantity, e.g. lower inputs in areas previously under intensive management</li> </ul>	<p><i>direct economic benefits (internalities)</i></p> <ul style="list-style-type: none"> <li>— higher prices for world farmers</li> </ul> <p><i>positive social and environmental externalities</i></p> <ul style="list-style-type: none"> <li>— fossil fuel substitution and associated emissions savings (partly internalized)</li> <li>— carbon sequestration in land and biomass (partly internalized)</li> </ul>
costs	<p><i>direct economic costs (internalities)</i></p> <ul style="list-style-type: none"> <li>— increase price for fuel consumer and/or burden for taxpayer</li> <li>— higher food price for consumer</li> <li>— higher feed price for meat producers</li> </ul> <p><i>negative social and environmental externalities</i></p> <ul style="list-style-type: none"> <li>— landscape management, e.g. maize cultivation in grassland areas</li> <li>— biodiversity, e.g. palm plantation instead of primary forests</li> <li>— soil quality, e.g. expansion of monoculture crops under intensive management used for biofuel cultivation (corn, soya beans)</li> <li>— water quality and quantity, e.g. annually fertilized crop on grassland</li> </ul>	<p><i>direct economic costs (internalities)</i></p> <ul style="list-style-type: none"> <li>— increase price for fuel consumer and/or burden for taxpayer</li> <li>— higher food price for consumer</li> </ul> <p><i>negative social and environmental externalities</i></p> <ul style="list-style-type: none"> <li>— direct carbon and GHG emissions</li> <li>— carbon and GHG emissions from iLUC</li> <li>— food insecurity and world hunger</li> </ul>

are characterized in table 1. Change in biodiversity is an example of an externality that is infrequently quantified when bioenergy scenarios are analysed but is nevertheless an important driver of economic, social and environmental impacts [15]. Soil quality is another externality that has effects on the value of bioenergy (e.g. production) as well as the potential benefits of carbon sequestration from new feedstock crops (e.g. perennial grasses on degraded lands). Some of these effects can be partially internalized through intervention in markets that tend to correct a price signal to account for the additional cost or benefit (e.g. carbon pricing in the EU for electricity required for the transformation of biofuels). Such intervention can influence the perceived value of a bioenergy cropping system within regions.

To frame a discussion about LUC associated with bioenergy, we can classify impacts of scenarios along three dimensions: (i) local/global, (ii) cost/benefits, and (iii) internalities/externalities (table 1). These effects are measured as differences between the scenario and its counterfactual within the system boundaries chosen. Specific scenarios with benefits that outweigh costs will be defined first, and then followed by a description of scenarios where cumulated costs across the three dimensions outweigh the expected benefits. It should be noted that there are costs and benefits in all scenarios of bioenergy, but ‘positive LUC scenarios’

have greater benefits than costs, while ‘negative LUC scenarios’ have greater costs than benefits.

## 2.2. Positive land-use change scenarios

Generally, land use for bioenergy is considered positive if an additional ecosystem or social service is provided as a result of the establishment of a bioenergy crop (table 1). The new benefits should outweigh the costs and could be realized in the form of increased resources (biomass, feed co-production, co-generation, etc.), improved water quality, reduced greenhouse gas emissions, increased soil carbon sequestration or increased biodiversity. Social welfare benefits include increased production capacity that diversifies and stimulates local economies. Not all of the benefits listed above can be accomplished simultaneously, but those that can be achieved should outweigh the costs that might occur. Realistic evaluations of bioenergy scenarios should provide transparent accounting of risks that would occur in the context of the benefits expected.

Highly productive crops with low input requirements are ideal for bioenergy crops because they have the potential to restore environmentally degraded land. Intensive land management for agricultural products leads to a reduction in soil quality over time (e.g. [16,17]). If more productive crops that require less intensive management (reduced tillage, herbicide,

pesticide and fertilizer) can supplement agricultural production without damaging food supplies, it is possible that land quality can be restored with bioenergy crops.

Perennial grasses used in advanced second-generation energy conversion pathways can lead to positive benefits compared with land use for intensively managed first-generation crops. For example, *Miscanthus x giganteus* (miscanthus) has the potential to triple the biomass that is currently available for ethanol feedstock from corn grain in the midwestern USA [11–13,18]. In a scenario that assumes the same land area that is currently used for grain ethanol, the agricultural landscape can be changed from a net source of greenhouse gases to the atmosphere to a net sink of greenhouse gases to the land [1,12,13]. There are some trade-offs in this scenario because corn seed markets would be affected, benefiting seed consumers (farmers) but causing a net loss for companies that sell corn seed. Another side effect of this scenario is increased water use because of the greater evapotranspiration that occurs with the high photosynthetic rates and the longer growing season of miscanthus [18–20]. In regions where rainfall is abundant as in much of the midwestern USA, this cost of water is sustainable, but such a cost would be intolerable in regions that are water-limited.

In a different scenario, the conversion of pasture land to high-producing grass crops can result in minimal losses of ecosystem services while adding resource productivity in the form of biofuel feedstocks. In Brazil, for example, it is estimated that a small increase in cattle stocking density from the current one head of cattle per hectare of pasture (versus two in France and Ireland according to FAOSTAT) can yield additional land for feedstock production [1,21]. In this way, there is no cost in displaced land use even though LUC occurs. A caveat of this scenario is that the welfare of nomadic cultures could be compromised if this land-use practice was implemented in some regions of the world (e.g. Africa); this risk is low, however, in other regions (e.g. Brazil).

High-producing feedstocks that grow in arid or semi-arid regions also exemplify a bioenergy scenario of LUC for biofuel crops that maximizes production while minimizing losses of other resources and ecosystem services. Plants that have high water-use efficiency and drought tolerance, like those that use a photosynthetic pathway known as Crassulacean acid metabolism (CAM), have recently been introduced for such scenarios [22,23]. Specifically for areas of Mexico, Africa and Australia where water is an extremely limiting resource for food and crop production, CAM plants like *Agave* may be a viable option to maximize efficient production without losing other land-based resources [24,25].

The scenarios described above indicate that there are already opportunities for positive bioenergy outcomes with existing crops, technologies and land resources. While the scenarios we provided are regionally specific, they each exemplify the use of second-generation cellulosic feedstocks. Second-generation bioenergy production chains (advanced conversion systems to high-density energy carriers) have a much lower land footprint per unit of energy than current biofuel

feedstocks that were selected for high sugar or oil contents. Some of the benefits described above will only be fully realized when the infrastructure is in place to support cellulosic ethanol production. Thus, the timeline established by policies can affect the temporal system boundary that is most relevant for these scenarios. A more detailed discussion of the effects of timescales follows in §5.4.

Cellulosic ethanol facilities are already being built in the USA, and are an indication of the future second-generation bioenergy market that is emerging. Vercipia Biofuels, for example, is initiating a commercial-scale facility that will produce 36 million gallons annually from cellulosic feedstocks that will be grown on an estimated 20 000 acres in Highlands County, Florida. Other companies, such as Dupont Danisco Cellulosic Ethanol LLC and Verenium BP, are optimizing demonstration-scale facilities and anticipate a near-term transition to commercial-scale production. These examples are indicative of a near-term temporal system boundary that can be applied for cellulosic feedstock crops in some regions of the USA.

Species composition interacts strongly with biogeochemical cycling and other ecosystem services and the potential impacts of LUCs associated with an expanding biofuel industry on biodiversity remain largely unexplored [26]. Biodiversity is greatly diminished as native ecosystems give way to intensively managed agriculture. However, reinserting perennial feedstocks, particularly if it becomes practical to use species mixtures or mixed landscapes, has enormous potential to restore some of this diversity [1,27].

### 2.3. Integrated land management

The objective of integrated land use is to find a balance between economic, social and environmental objectives [28]. Land is limited, and the fertility, productivity and functionality of lands are widely variable across space. In the case of degraded or abandoned lands, LUC may contribute to improved utilization of available resources that support local and global environmental sustainability. Accomplishing such sustainable utilization, however, can be problematic and often requires complex and well-balanced incentives. The needs of stakeholders must be balanced with the costs and benefits to the environment and societal welfare.

Competing interests at the local and global scale can complicate decision-making about integrated land use [29], but iLUC risk can be reduced with an integrated approach to land resource management. The scenario of cattle intensification in Brazil that was described above is an example of an integrated approach because two needs are being met on the same amount of land that previously had a single purpose. Another kind of integrated land use is exemplified by the use of *Jatropha curcas* L. on small-scale plantations in Zambia, where crops in some cases serve both as exports and resources for the local community (other side effects like invasiveness notwithstanding).

There also are many scenarios of integrated land use where crop residues can be used as biofuel feedstocks. In Mexico, 38 per cent of the biomass in *Agave tequilana*

Table 2. Illustration of US corn ethanol with respect to a baseline without biofuels. (Plus symbols for positive effects and minus for negative effects, italic for externalities).

corn ethanol versus no biofuels baseline (USA)	local cross-sectoral boundaries	global cross-sectoral boundaries
benefits	farm support to corn producers (++) energy security (++)	higher price for world cereals farmers (+++) <i>direct GHG savings</i> (- or +)
costs	cereal prices in the USA (---) burden for tax payer (---)  <i>intensification of cultivation</i> ( <i>water stress, nitrogen</i> ) (---)	<i>food security in the world</i> (---) <i>indirect land-use change</i> ( <i>carbon, biodiversity</i> ) (---)

plants that are harvested for the purpose of fermentation and distillation to tequila is in the leaves [30,31], which are not used to make tequila. This leaf biomass could serve as biofuel feedstock. Additionally, bagasse and vinasse from the tequila-making process can be used as feedstocks for heat and power [32]. If all of the resources are used, three products can be produced on the same land that previously yielded only one. This in theory maximizes the efficiency of the land-based resources within a finite regional boundary without compromising existing benefits.

#### 2.4. Negative land-use change scenarios

Generally, LUC can be considered negative if there is a loss of ecosystem or social services that outweighs the bioenergy benefits that could be gained. Considered alone, a small-scale bioenergy project may appear not to have an impact beyond the local vicinity. However, since the US and EU policies resulted in a significant reallocation of croplands to the production of biofuels, a body of literature has emerged that attempts to evaluate the market-mediated effects of land diversion.

From the perspective of climate mitigation, conversion of land with large carbon stores to high-input, annually tilled crops can degrade or eliminate the potential advantages of bioenergy. The climate services of an ecosystem can be summarized as its greenhouse gas value, quantified by summing its net uptake of greenhouse gases (CO<sub>2</sub>, N<sub>2</sub>O, CH<sub>4</sub>) with the losses of these constituents when the ecosystem is replaced by another. Replacing a tropical peat forest, for example, with pasture greatly reduces the capacity of this landscape to store GHG and mitigate climate change [33]. In some cases, it can take centuries to recover. The net losses of GHG to the atmosphere caused by converting large-stature ecosystems with large carbon stocks such as forests to low-stature herbaceous feedstocks with high rates of carbon turnover may negate the potential for climate change mitigation. It would take in excess of three centuries for example to repay the carbon debt associated with the conversion of tropical rainforest to palm or soya bean biodiesel [10].

While converting forests to herbaceous vegetation clearly demonstrates a large loss of above-ground biomass, the net losses of soil organic carbon (SOC) associated with LUC also can be significant. Conversion of prairie with its dominant perennial grasses to annually tilled row crops, mostly soya bean and maize in the USA, has contributed to substantial losses of

SOC and reduced soil fertility [34,35]. While losses of above-ground biomass can be repaid by converting annually tilled land to perennial feedstocks such as switchgrass, miscanthus or native prairie, the payback time for SOC losses can be very long in some soils. Restoring SOC following conversion of native forest to sugarcane is measured in decades to centuries [36].

The net effect of LUC on greenhouse gas emissions is of primary concern because greenhouse gas reduction is one of the main justifications for transitioning from petroleum to biofuels, but a myriad of ecosystem services probably will be affected by LUC associated with the widespread deployment of biofuel crops. Corn agro-ecosystems, for example, are notorious for inefficient nitrogen cycling; expanding the use of corn for ethanol production will increase nitrate contamination of ground water and N<sub>2</sub>O emissions to the atmosphere [37–39]. Because of its high input costs, low energy yield and negative effects on the environment, ethanol from corn grain is not a sustainable energy source in the long term. The economic and energy benefits of corn-ethanol are outweighed by the negative societal and environmental costs (table 2).

### 3. LAND-USE MODELS AND DATA

#### 3.1. How do land-use models represent land-use change and bioenergy?

The nature of land use at a macro-scale makes it particularly difficult to represent in a model of LUC dynamics. In a recent review of competing land-use interests globally, Smith *et al.* [40] concluded that policies governing production and markets affect land-use practices more than land-use competition affects the markets for terrestrial products. Competition for land, in itself, is not a driver affecting food and farming in the future, but is an emergent property of other drivers and pressures. There is considerable uncertainty over projections of competition for land in the future and the regional distribution of this competition. This means that models used for land-use assessment need to incorporate a wide range of drivers, from macro-economic indicators to local policy specifications.

Different families of models are presented in Smith *et al.* [40]. Some models are top down, such as the general equilibrium macro-economic model, EPPA, which projects the effects of economic growth on five land types, including bioenergy cropland, at 5 year intervals

(e.g. [6]). This model assumes that conversion of land back to a 'natural state' has no cost, an assumption that overlooks the need to assess counterfactual conditions. Two other models that categorize bioenergy as a unique land use, IMAGE and MiniCAM, are both integrated assessment models [41–44]. IMAGE includes clear geographically delineated land-use categories, but must be coupled with a separate economic model to simulate dynamics of LUC over time [40,41]. MiniCAM, however, simulates the feedbacks between profitability margins and land allocation to different categories [40,42–44].

Feedbacks to ecosystem services are the least represented (relative to effects on production and economics) in integrated assessment models like MiniCAM, and are more often modelled regionally without considering interactions with the global market. Connections between regional responses of ecosystem services, including greenhouse gas mitigation and carbon sequestration, and LUC must be made in order to assess global scenarios of biofuel-related LUC.

To properly evaluate scenarios of LUC as positive or negative, we must integrate results from different types of regional models that collectively include a wide variety of essential indicators and approaches. This does not mean that more models are needed, but rather that a wide variety of existing tools must be used in aggregate to assess LUC. A combination of productivity, biogeochemistry, economics, environmental impact and social impact models must be employed to clarify the potential consequences of bioenergy in different regions of the world. These modelling tools have already been developed and are subject to ongoing critique within specialized disciplines that define each of these model classes. The combined results of multidisciplinary state-of-the-art models should be informative for assessing LUC outcomes. These models should ideally subscribe to similar criteria in all regions, relying on data sources analogous to a global unified database and ground-truth verifications of projections (through data collection and monitoring).

### 3.2. Do we have the data we need to address the impact of land-use change?

Model inputs depend on land cover information (agriculture/forestry/grassland). This is available from various products at different resolutions. Products are improving with satellite technology, but there are still differences among datasets that are partly due to classification (e.g. per cent coverage of trees that classifies land as a forest can vary from 20% to 60%). For example, when we compare two widely used schemes for land-use classification (table 3), the categories are inconsistent. How can a global comprehensive model of LUC reconcile different classification schemes that are applied to different regions or scenarios? Standardization of land-use categories would increase the relevance of LUC models for global analysis, and should be inclusive of subdivisions with varied management practices that are employed throughout the world.

Bioenergy cropland is not explicitly identified in most internationally recognized land-use classification

Table 3. Classification schemes for land use. The Global Land Cover (GLC 2000) scheme is recognized by most European nations, and the Good Practice Guidance for Land Use, Land Use Change and Forestry (GPG-LULUCF) is recognized by the Intergovernmental Panel on Climate Change (IPCC) and the United Nations.

model	GLC-2000	GPG-LULUCF
classifications	pristine forest	forest land
	managed forest	
	short rotation tree plantation	
	cropland (IIASA— subsistence, low input, high input, irrigated)	cropland
	grassland	grassland
	other natural vegetation	wetlands settlements other land

schemes (e.g. table 3) because it has historically represented a very small amount of land that is distributed between several land categories (cropland, short rotation plantations). The amount of bioenergy cropland has grown substantially in recent years, and in 2009, 11 per cent of US cropland was devoted to corn for ethanol and 5 per cent of EU cropland to rapeseed for biodiesel. Obviously, this would be a key category for explicit analyses of LUC for bioenergy.

Another limitation of the present categorical definitions is the lack of information about productivity potentials of biofuel crops relative to the existing production in each of these land-use types. Global estimates of ecosystem productivity under different land uses are available from the Agro-Ecosystem Zoning project (International Institute for Applied Systems Analysis, Laxenburg, Austria) and other sources, but without a parallel characterization of the production potential, both in a natural state and for biofuel crops, the criteria that define positive versus negative scenarios cannot be assessed. Databases such as GLASOD and GLADA characterize the degraded nature of croplands [45,46], and may be a source of data for assessing the production potential of different regions.

Other examples of categories that are not distinguished by either the Global Land Cover (GLC) or the Good Practice Guidance for Land Use, Land Use Change and Forestry (GPG-LULUCF) classification system (table 3), but are relevant to societies that may be regionally confined, include livestock (intensive pasture/rangeland), subsistence, abandoned croplands, urban, protected, high biodiversity and peatland. A database for abandoned croplands has been compiled by the Center for Sustainability and the Global Environment in Madison, Wisconsin, USA [47], and the protected and high-biodiversity classifications are reported by the United Nations World Conservation Monitoring Center [48,49].

Lastly, more information on carbon stocks of ecosystems is necessary for accurate model predictions. Changes in land use (primarily deforestation) have been responsible for about 20 per cent of all anthropogenic emissions of CO<sub>2</sub> to the atmosphere over the past two

and a half decades, but this term is the most uncertain variable in the global carbon budget (IPCC Fourth Assessment Report; [50]). The estimated emissions from LUC for the 1990s in the IPCC Fourth Assessment Report (a negligible part of it being related to the biofuel sector that was only present in Brazil at the time of assessment) were  $1.6 \text{ Gt C y}^{-1}$  ( $5.9 \text{ Gt CO}_2 \text{ y}^{-1}$ ) with a range of  $0.5\text{--}2.7 \text{ Gt C y}^{-1}$  across different estimates. The wide range is primarily due to differences in quantification of the area, the fate of the carbon and the nature of the LUC. Some elements that are critical for calculating a complete LUC-related flux of carbon include:

- the type of vegetation change (e.g. deforestation, afforestation, shifting cultivation, logging, cropland and pasture establishment and abandonment);
- the amount of carbon present in vegetation and soils before and after the change;
- the method used for the clearing event (e.g. logging versus slash and burn);
- the fate of biomass following clearing (e.g. paper versus long-lived wood products);
- regrowth of vegetation following clearing; and
- the dynamics of soil carbon following clearing.

While there is a growing wealth of data that describe land use globally, there is still a need for a globally comprehensive categorization, international standardization and inter-disciplinary aggregation of those data with the variables that define sustainability.

#### 4. ASSESSING INDIRECT LAND-USE CHANGE

The US environmental agencies (Environmental Protection Agency (EPA) and California Air Resource Board) were the first to attempt incorporating the iLUC dimension in legislation that defines which biofuel crops should be supported for future domestic use. These agencies relied on various agricultural, energy and economic models to evaluate the effects of iLUC [51,52]. Although all models predict some iLUC associated with bioenergy expansion, policy makers had to face a large variation in the estimates because of the inherent difficulty of tracking the interactive variables that contribute to iLUC. Nevertheless, it was clear that all crops were not equal in causing iLUC. Different initial yields, differences in the sensitivity of areas where land competition takes place and trade configuration can induce significant variation in computed results [53,54]. The incorporation of these effects in legislation sparked strong controversies between various interest groups during public consultations, and the EPA position was attacked in Congress. The final EPA assessment presented a more moderate impact of iLUC than in the 2009 draft and in the end qualified all major biofuel pathways even though several corn ethanol processes had initially been disqualified.

In the EU, the European Commission received with the 2009 Renewable Fuel Directive the responsibility of writing a report to the European Parliament on the question of iLUC by the end of 2010. This was intended to open the way to legislative options for mitigating the impact of biofuel policies. The Commission ordered several studies and literature reviews on the topic in 2009

and 2010 [9,55–57]. Although there was considerable controversy about the interpretation of a few selected figures, these reports, when analysed in detail, did not depart from the US findings. High variation in the estimates of iLUC were presented with figures ranging from acceptable values to disqualifying ones, raising questions but not offering conclusions on the environmental efficiency of biofuel policies. Interestingly, like in the US studies, impacts depended on the crop considered, suggesting that a beneficial regulation should generally promote high-yielding feedstocks and second-generation biofuels [7,58].

The use of macro-sectoral models for computation of iLUC in life-cycle assessments is now deemed premature because of the uncertainties of parameters in a field that is still in its early development. Modelling efforts have however succeeded in illustrating the rationale of iLUC and the need for market intervention to mitigate side effects of biofuel policies. These side effects include leakage owing to the feedback from biofuel consumption mandates on fuel prices and subsequent increases in fossil energy consumption in the rest of the world [59,60]. Another side effect can be shuffling on the production side between inefficient and efficient production units, without real eviction from the market of undesirable production processes [61]. Sustainability criteria would remain partially ineffective as long as biofuel policies and land-use decisions are not integrated in a more general economic instrument of carbon regulation [62,63]. Modelling approaches reveal different crops and different types of biofuels that vary in their potential for climate change mitigation. Measures limited to the project scale would be ineffective in addressing macro-scale impacts if applied only to a few regions or products.

In summary of the issues associated with modelling iLUC, recent studies find that iLUC is a problem that must be considered (e.g. [64]) but there is a significant amount of uncertainty in projecting iLUC. Part of this uncertainty results from complex economic factors that are difficult to measure. Generally, we can say that iLUC is important and should be considered, but large confidence intervals prevent precise figures that can serve as regulatory guidelines. Models are however appropriate to identify trade-mediated externalities and hierarchical relationships of low- and high-risk options. There are regionally specific datasets that characterize LUC interactions, and policies that address the production of multiple resources within a regional boundary will reduce externalities and lower the risk of iLUC.

#### 5. HOW CAN MODELS BE IMPROVED FOR POLICY DECISIONS?

##### 5.1. Regional details of land management

Regionally detailed costs and benefits of LUC for bioenergy must be further explored to identify more integrated bioenergy management choices. For example, in Europe, very little land is actually unused. In contrast, there are regions in the USA that comprise relatively unused land, some of which has previously been in agriculture and abandoned. In Africa, there are areas of open rangeland for subsistence livestock, communal grazing

Table 4. Illustration of a US cellulosic ethanol with respect to a baseline without biofuels. (Plus for positive effects and minus for negative effects, italic for externalities).

cellulosic ethanol versus no biofuels baseline (USA)	local cross-sectoral boundaries	global cross-sectoral boundaries
benefits	farm support to feedstock producers (++) energy security (++)	higher price for world cereals farmers (+) <i>direct GHG savings</i> (++)
costs	food prices in the USA (-) burden for tax payer (---)  <i>intensification of cultivation</i> ( <i>water stress, nitrogen</i> ) (-)	<i>food security in the world</i> (-) <i>indirect land-use change</i> ( <i>carbon, biodiversity</i> ) (-)

Table 5. Illustration of a US cellulosic ethanol with respect to a baseline with biofuels (= table 4 – table 2). (Plus for positive effects and minus for negative effects, italic for externalities).

cellulosic ethanol versus corn ethanol (USA)	local cross-sectoral boundaries	global cross-sectoral boundaries
benefits	farm support to feedstock producers (++) food prices in the USA (++) <i>lesser intensification of cultivation</i> ( <i>water stress, nitrogen</i> ) (+)	<i>direct GHG savings</i> (+ to +++) <i>food security in the world</i> (++) <i>indirect land-use change</i> ( <i>carbon, biodiversity</i> ) (++)
costs	farm support to corn producers (--) burden for US tax payer (-)	lower price for world cereals farmers (--)

land, collection of wood fuel, traditional medicines, un-protected nature reserves, etc. The opportunities associated with these regions are unique and should be treated as such in analyses of bioenergy options, while still acknowledging potential externalities.

Common to all regions and economies are crop areas that are underproductive relative to the potential terrestrial yield. Biofuel markets may become a strong economic driver to do something on land that is not being used efficiently or where people currently have low earning power. For bioenergy development, it will be essential to identify places where improvements can be made in husbandry practices, biological productivity and the local economy.

### 5.2. Toward integrated assessment

The concept of integrated assessment is often misrepresented in models because co-benefits of production practices are not fully evaluated. This limitation does not disqualify modelling but instead calls for a better characterization of possible co-benefits in any assessment exercise. Biofuel co-products, for example, were inadequately represented by the first models addressing LUC for biofuels [65]. After the importance of co-products was identified, it became a prerequisite for any reliable modelling exercise. On the other side, many other mechanisms and co-benefits are still badly represented in models, as emphasized by Babcock & Carriquiry [66] in an evaluation of the potential for double cropping or the use of idle or degraded land. There remains room to improve models in this respect and measures of iLUC might be substantially modified as a result.

In order to determine good and bad scenarios of LUC related to bioenergy policies, it is therefore necessary to make a holistic assessment where all externalities are

taken into account. The challenge is to set boundaries that make the assessment tractable and at the same time exhaustive enough and relevant to the most realistic business-as-usual baseline. If we take the case of US ethanol as an example, we propose in table 1 a possible assessment grid that comprehensive studies should consistently and completely address. Table 2 illustrates a qualitative evaluation of corn ethanol that is currently produced in the USA.

The case of cellulosic ethanol from miscanthus is framed in table 4 similar to the corn ethanol case in table 2. Alternatively, to accurately reflect current biofuel agriculture in the USA, one could establish the baseline business-as-usual counterfactual to include biofuels that are presently based on a first-generation technology (e.g. corn grain). Assessing biofuel scenarios based on these current conditions leads to different results (table 5) than if one ignores the current baseline and the multiple products from a landscape with mixed uses (table 4).

The EPA attempted a quantitative and comprehensive cost–benefit analysis of the US biofuel programme [52], finding some benefits to the policy if current markets are ignored, but negative effects are evident if they are included in the assessment. The methodology for such assessments remains highly controversial, but the most practical framework for evaluating impacts of new biofuel feedstocks includes a baseline that reflects current real-world conditions (as in table 5) and multiple resources that would be produced within a well-defined geographical boundary.

### 5.3. Uncertainty and gaps in knowledge

Models are only as good as the data used to parametrize them. It is fair to assume that model uncertainty for

land-use analysis is high because there are inconsistent types of data collection and incomplete process descriptions. Nevertheless, models can serve as tools to estimate broad outcomes or unexpected trends. For example, the magnitude of projections calculated by Searchinger *et al.* [8] is now considered closer to the upper range of estimates [10], but the calculations described in the study led to more awareness about potential iLUC. Different models are fit for different purposes, may be only regionally appropriate and may be specific to particular processes. Combinations of complementary models and integrated approaches may yield valuable information that can direct policies and land management, as long as prudence remains the rule with respect to any exact estimates of effects produced.

We need to develop more comprehensive information on actual land use and management, carbon stocks and ecosystem services that are consistent and comparable globally. Even for categories of land use that are broadly agreed upon (e.g. agriculture or forests), there is a substantial variation in ecosystem services. For example, there can be very different biomass, different soil carbon, different rotations and management, all of which can affect the overall greenhouse gas balance of changing land use. Each of these characteristics further introduces uncertainty about the relative loss of services that the land was already providing (food, timber, biodiversity). We need this information to judge how much land might be 'available', which land could be converted and what the consequences would be for ecosystem services (e.g. greenhouse gases).

Consistent data monitoring is essential for comparison of LUC criteria at varied scales. Global datasets and national datasets differ because of measurement resolution, techniques and analyses. More complete national datasets will allow validation of global datasets and improve detail. Datasets based on high-resolution satellites and country-level reporting achieve consistency for some land variables, but there are others that must be measured on site even if only for validation. FAO and EUROSTAT are examples of international data reports that may inform international LUC questions—but even in Europe, these are not always consistent. Some land areas will soon be more accurately characterized as many countries are carrying out ecosystem assessments in response to the Millennium Ecosystem Assessment [67]. Other country-level data may exist from national statistics, scientific surveys, etc. In sum, the varying quality and quantity of data by a country/region must be addressed.

For near-term developments in bioenergy, we suggest an emphasis on a smaller number of low-risk opportunities in regions where varied land use and multiple benefits can be managed and evaluated in an integrated way and within a clear geographical boundary. Developing countries, often with the least data, may have the greatest opportunities for positive LUC for bioenergy and will rely most heavily on models with minimal data. For these opportunities to be realized, tools must be developed to measure the actual use of land and ecosystem services. Policies should ensure

that identified positive scenarios are realized and not reshaped for purely opportunistic purposes that could compromise the expected benefits.

#### 5.4. *Scenarios and time-scale issues*

Time scale is of critical importance when assessing the overall impact of bioenergy projects, particularly with respect to net greenhouse gas balances and pay back times for initial impacts that can be weighed against the lifetime of bioenergy production. Politicians are most interested in 2020 targets and 2050 targets, but the best options are likely to depend on whether a 10 year or 40 year perspective is adopted. In evaluating the costs of LUC for bioenergy, variables to consider include how long a particular land management lasts, time of establishment, the permanence of ecosystem services lost or gained and the variability of impacts and services over time.

In the near future, second-generation technologies are likely to advance substantially. It is important that policies do not get locked into first-generation biofuel chains that might fail to promote or even inhibit the development of second-generation fuels. Indeed, first-generation biofuels from cereals are expensive and their benefits are limited relative to second-generation biofuels [52].

Policy makers have mandated very ambitious targets for biofuel incorporation up to 2020 in the EU and 2022 in the USA. This might be accomplished by using resources more efficiently; this could include waste conversions and improvement of management practices to optimize production. Since cellulosic feedstock production is expanding (as demonstration by Vercipia Biofuels, Dupont Danisco Cellulosic Ethanol LLC, etc.), there is likely to be an opportunity to use agricultural residues that are low in sugar or oil, increasing the amount of biomass that can be used from existing crops. These are possibilities that require very little LUC and could be achieved by 2020.

There are many differences in the temporal assumptions of LUC models and scenarios. For example, the FORESIGHT analysis of different LUC scenarios demonstrates the difference in outcomes that are achieved when an LUC scenario is implemented up to 2020 versus 2050 [40]. Most of the outcomes that differed in terms of the areas and types of LUCs are due to the assumptions in the scenarios (IPCC, MEA, GEO, etc.) about future conditions. These scenarios are implemented with different temporally dynamic drivers (e.g. IMAGE, MminiCAM, etc.) that are subject to a variety of assumptions.

A more long-term bioenergy outlook, 2050 and beyond, would be primarily based on second-generation feedstocks, but the drivers of LUC will depend on advances in technology and non-technological changes in society that become harder to project farther into the future. Changes in diet, for example, can lead to changes in the amount of land that is used for livestock and pasture that competes with land available for fuel crops. While bioenergy-related LUC is a timely problem that needs to be addressed, bioenergy has not been the main driver of LUC in the past. Thus, policies that

incentivize integrated land management would discourage unintended LUC in the future.

The role of bioenergy in global LUC depends on the extent to which we favour options that do not need a lot of land, that extend on low-quality soils, or where feedstocks are co-produced with food, feed and fibre. Long-term changes in societal trends and production practices may thus have different effects on projections from LUC models that run at different timescales.

## 6. CONCLUSIONS

Regionally specific strategies are needed to optimize resource-use efficiency and reduce iLUC owing to bioenergy development. At the same time, there is a need for cooperation among regions to maintain fair accountability of land conversion at the global scale. This underscores the importance of common standards between regions with different needs and resources. The fundamental goal of policies should be to maximize the value of land services at the lowest social cost. If this can be accomplished on a smaller land footprint, then lands will be available for energy feedstocks. To minimize greenhouse gas emissions, all resources that are cultivated should be subject to the same emissions standards: management of any agricultural resource can be improved to use less land and lower carbon emissions. Efficient and sustainable land management should be rewarded equally (e.g. by way of incentives) in the case of food production, feed and livestock cultivation, and bioenergy feedstock plantations.

Recently, there has been an effort to develop models that can assess iLUC, but results are still so diverse that these models cannot usefully inform detailed management decisions. GLC datasets lack detailed information on actual land use (e.g. grassland being used as pasture, subsistence rangeland) and associated ecosystem services (e.g. carbon sequestration, biodiversity), which is necessary to assess net environmental impacts and services displaced by using that land for bioenergy. We conclude that global data are not yet sufficient for full assessment of the impacts of implementing bioenergy scenarios. It is however possible to determine impacts by aggregating different modelling tools and data that are available regionally. Options that guarantee low risk of iLUC, high potential for positive externalities and increased efficiency of resource production should be promoted in the short term, while maintaining a long-term view of societal demands and technology advancement.

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