Summer 7-8-2013

Reviewing models of land availability and dynamics for biofuel crops in the United States and the European Union

Ruopu Li
University of Nebraska–Lincoln, rli3@unl.edu

Nicola di Virgilio
CNR–IBIMET, Institute of Biometeorology, Bologna, Italy, n.divirgilio@ibimet.cnr.it

Qingfeng Guan
China University of Geosciences, Wuhan

Song Feng
University of Nebraska–Lincoln, sfeng2@unl.edu

Goetz M. Richter
Rothamsted Research, Harpenden, Hertfordshire, U.K., goetz.richter@rothamsted.ac.uk

Published in *Biofuels, Bioproducts & Biorefining* 7 (2013); doi: 10.1002/bbb.1419

Submitted March 8, 2013; revised and accepted May 22, 2013; published online July 8, 2013.

Reviewing models of land availability and dynamics for biofuel crops in the United States and the European Union

Ruopu Li, CALMIT, School of Natural Resources, University of Nebraska–Lincoln, NE, U.S.A.

Nicola di Virgilio, CNR–IBIMET, Institute of Biometeorology, Bologna, Italy

Qingfeng Guan, China University of Geosciences, Wuhan, Hubei Province, China and CALMIT, School of Natural Resources, University of Nebraska–Lincoln, NE, U.S.A.

Song Feng, School of Natural Resources, University of Nebraska–Lincoln, NE, U.S.A.

Goetz M. Richter, Rothamsted Research, Harpenden, Hertfordshire, U.K.

Corresponding author — Dr. Goetz M. Richter, Dept of Sustainable Soils and Grassland Systems; Rothamsted Research, Harpenden, Hertfordshire AL5 2JQ, UK; email goetz.richter@rothamsted.ac.uk

Abstract

The biofuel-related land use in the U.S.A. and the EU has significantly expanded during the last decade; models have been used to estimate land availability and demand in these regions. This paper provides an overview of different land-use modeling practices applicable to first- and second-generation biofuels. We review the importance of different land categories for biofuels, modeling approaches (top-down/bottom-up) and their integration, data availability for calibration and validation, model scale, and uncertainty. Possible future changes of biofuel land use and research gaps and limitations are synthesized. Key issues are the lack of data for independent validation and the need for better integration of dynamic bottom-up models into the top-down policy analysis. More research is needed to deal with the large-scale introduction of second-generation biofuel crops required. The paper culminates in describing how models can help to meet the challenge of supplying more fuel from lignocellulosic crops (LCC) in ways that reduce indirect land-use change (iLUC) and how such transition could be implemented in policy and practice.

Keywords: biofuel crops; first-generation biofuel; land-use change; cellulosic biofuel

Introduction

In the past decade, significant biofuel-related land-use changes have been observed in the United States and the EU. The northern Great Plains in the U.S.A. witnessed large-scale expansion of corn production for bioethanol.[1,2] In the EU27, the area dedicated to biofuel crops increased from 3.6 in 2008[3] to approximately 5.5 million ha of agricultural land, representing 3.2% of the total cropping area.[4] In between 2008 and 2012 bioethanol/biodiesel production increased by 93% and 14%, respectively, and reached 80% self-sufficiency for a consumption of 16.7 Mtoe[3].

The rapid increase of land dedicated to conventional

crop (CC) production for bioenergy reflects the legislative efforts to promote energy independence and renewable resources to reduce carbon emission. The U.S. Congress passed the Energy and Independence and Security Act (EISA) and expanded the Renewable Fuel Standards (RFS2), which mandates at least 136 billion liters (BL) of liquid biofuels to be blended into transport fuel by 2022. The total renewable fuel target limits corn-based ethanol to 56.8 BL and demands a minimum of 60.6 BL of cellulosic ethanol and other advanced biofuels.[5] In the EU, the Renewable Energy Directive (RED)[6] sets a mandate of 20% of its final energy consumption to come from renewable sources by 2020 to be implemented by EU member states in their National Renewable Energy Action Plans (NREAPs). For the transport sector, 10% of the consumed energy should come from renewables, and it is under discussion how much of the 10% target can come from CC and how much from lignocellulose crops (LCC) or other advanced technologies.

The significant increase in production to meet the biofuel targets in the U.S.A. (by 2022) and in the EU (by 2020) is anticipated to change land use[7] and to increase the negative impacts of land-use change (LUC) in terms of greenhouse gas (GHG) emissions, biodiversity loss, and increase food price.[8,9] In 2008, about 3 Mha of soybean production in the Americas were associated with European biodiesel demand,[3] most of which could be related to arable land expansion. The use of perennial energy crops on marginal land could be a way out of this dilemma,[10] but only a very small proportion of land has been converted to low-input LCC.[11,12] This inevitably raises a series of important questions: First, is there enough suitable land available for biofuel crops, where is it located, and is it productive enough? Second, how can we increase the fraction of LCC to contain the negative effects of expanding biofuel production? And eventually, how can we establish sustainable biofuel production?[13] Modeling the land availability and productivity for LCC-based biofuel may provide useful clues to answer these questions.

During the past few decades, considerable efforts have been made to model the bioenergy and biofuel supply and demand in the U.S.A. and in the EU. The models used vary substantially in their objectives, biomass and biofuel crops, spatial and temporal settings, model design and formulation, and calibration and validation processes. The purpose of this paper is to review the land-use modeling practices related to biofuels in the U.S.A. and in the EU, to compare and summarize the methodological similarities and differences, and to identify the knowledge gaps and research priorities. Specifically, our review has the following objectives:

1) To summarize and synthesize current modeling approaches, objectives, and limitations with regard to biofuel crops with specific reference to LUC.
2) To draw some conclusions to overcome the identified limitations and to set trends in modeling research.
3) To provide suggestions to policymakers for an improved model use and implementation in favor of LCC.

In addressing these objectives, the following aspects concerning the adequacy of modeling biofuels-related LUC and availability will be examined: (i) the implementation of energy, environment, and economic policy into modeling; (ii) the detail representing the effects of crop (arable, perennial) and biofuel type (ethanol, diesel, gas), and end use (fuel, heat, power); (iii) the implementation of the interactions between the domains of demand (local/ regional/global economies) and supply (natural productivity, agronomy) and other system components (climate, soil, and terrain); and (iv), in a more technical sense, the implications of variable spatial and temporal scale, like cross-scale, spatially implicit and explicit modeling, and the impacts of local/neighborhood/regional/global scale.

Biofuel cropland modeling

Crops of interest

In general, bioethanol and biodiesel are the primary alternatives to fossil transport fuels and many plant species can be used for their production (Table 1). Corn, switchgrass, and wood can be used for starch- and cellulose-based bioethanol, and rapeseed, soybeans, and sunflowers, for biodiesel production.[14] Biofuel crops modeled in the U.S.A. include grain crops and herbaceous and woody perennials. Corn and soybeans are the main arable crops for large-scale commercial production of biofuels and substantially subsidized in the U.S.A. [15,16] Corn and soybeans have been intensively studied as biofuel feedstocks in the U.S.A. [2,17–19] Sorghum, recently listed as a qualifying renewable fuel source in RSF2 by the U.S. EPA, has been increasingly recognized as a promising grain energy crop due to its high yields, low input costs, and drought tolerance. [20,21] Herbaceous perennials such as switchgrass (*Panicum virgatum*), Miscanthus (*Miscanthus* spp.) and Alfalfa (*Medicago sativa* L.), are gaining interest in the U.S.A. Switchgrass, a

Table 1. Main crops and bioenergy carriers in the U.S.A. and in the EU.

	Biofuel Crops	Current Major Use
U.S.A	corn	starch-based bioethanol
	soybeans	biodiesel
	sunflower	biodiesel
	canola	biodiesel
	sorghum	starch-based, sugar-based and cellulose-based bioethanol
	switch grass	cellulose-based bioethanol
	Alfalfa	cellulose-based bioethanol
	poplar	cellulose-based bioethanol
	willow	cellulose-based bioethanol
EU	corn	biogas
	sorghum	starch-based bioethanol
	rapeseed	biodiesel
	sugar beet	sugar-based bioethanol
	Miscanthus	cellulose-based bioethanol

perennial warm-season grass, native to North America, is generally considered as a model feedstock for cellulosic ethanol production because of its broad adaptation and high yield potential on marginal land.[16] Miscanthus is the major perennial feedstock in the EU but is seen as a promising biofuel crop for large-scale production in the U.S.A.[22,23] Poplar (*Populus* ssp.) and willow (*Salix* spp.) are important short-rotation woody crops for ethanol production,[24] predominantly suitable in the east and northeast of the U.S.A., also being a focus of funding under the U.S. Department of Energy (DOE) Bioenergy Feedstock Development Program.[16] Other emerging biofuel crops like Crambe and Camelina, native to Europe, deliver substantial yields under low agricultural inputs[16] and are suitable for marginal land.[25]

In Europe, biomass from forest is the main source for bioenergy, but for transport biofuel most renewable sources come from first-generation crops used for food and feed like rapeseed, sugar, and starch crops.[3] Productivity for such crops like sugarbeet has been assessed at the national[26] and European scale.[11,27] Second-generation biofuel feedstocks from herbaceous and woody crops currently focus on Miscanthus in the UK[28,29] and in Europe,[30] and short rotation coppice (SRC).[28,31,32] Fiorese and Guariso[33] considered sorghum and short rotation forestry (SRF) in Italy. Others[34] considered maize producing energy from biogas in Germany, which represents 86% of the European crop-based biogas market.[3] Comprehensive analyses for typical first- and second-generation bioenergy crops covered lignocellulosic, herbaceous lignocellulosic, oil, sugar, and starch crops.[35,36]

Modeling focus/objectives

Figure 1 sketches the interactions between policy-driven macro-economic land demand for biofuel crops and

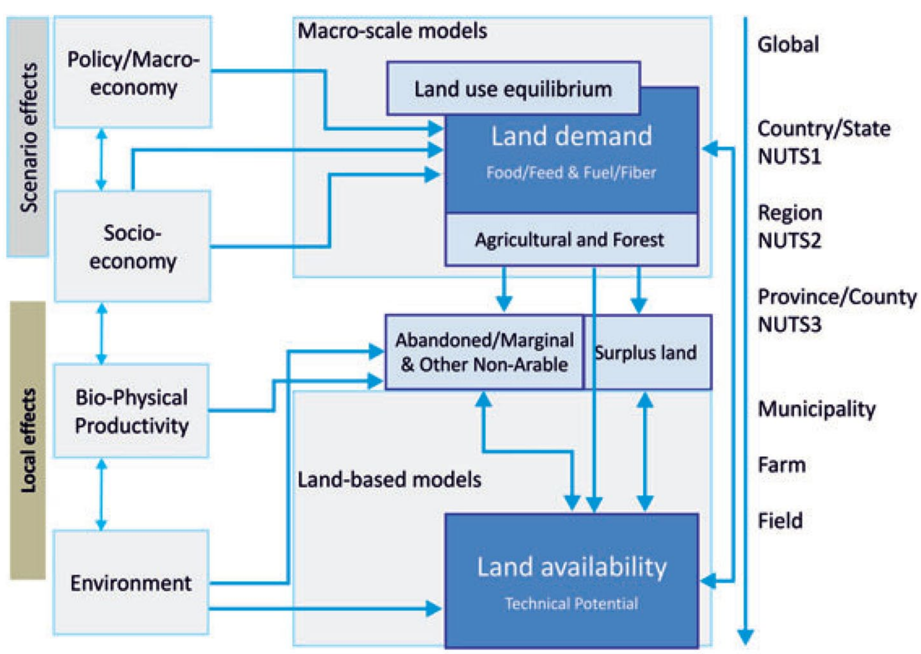


Figure 1. Interaction between drivers and constraints in land demand and availability for biofuel crops.

land availability, constrained by environmental and technical factors controlling the overall agricultural productivity and socio-/micro-economic management. Ideally, there is a bi-directional flow of information, iterating between top-level, global, and large-scale policy formulation and bottom-up decision-making in local production. Land availability addresses the issue of which and how much land is suitable for future biofuel production under the constraint of multiple land demands (Figure 1). Technically and environmentally constrained land allocation at the farm level will go through successive iterations to respond to market demands. Several pathways are being taken to meet the biofuel production mandates by the U.S. EISA,[5] RFS2,[37] and by the EU RED,[6] which to different degrees take account of direct land-use change (dLUC) and indirect land-use change (iLUC). dLUC refers to the conversion of a particular land area from some previous use to biofuel crop production; iLUC refers to other land conversion, not necessarily related to the biofuels, indirectly caused by expanding bioenergy crops using a different mix.[38]

Utilizing current agricultural land for biofuel production

This pathway feeds traditional agricultural crops into biofuel or converts rotational cropping to continuous corn.[17] This conversion has been widely observed in the U.S.A., especially in the northern Great Plains[2,39] but also in Europe.[34] For example, about 40 million acres (16%) of cropland in the U.S.A. were used for ethanol production in 2011,[40] which has been criticized for various reasons.[9] Of these, the socio-economic and environmental impacts may be aggravated during the years with extreme weather conditions[41] and degrade soil and crop productivity.[42] For Europe, the substitution of food crops considered solely issues arising from the diversion of crops on arable land to liquid biofuel[27] and biogas production.[34,43] Arable land for food has been converted to Miscanthus,[29] but usually not the high-yielding land.[27,29]

Converting non-arable land to dedicated biofuel crops

This path is often at the expense of losing pasture, forests, and wetlands, which is a loss of natural habitats and affects other commodities and ecosystem services. Large-scale draining of prairie wetlands for ethanol-corn production has been observed in the U.S.A.,[44] and biomass production from pasture can also affect livestock production.[42] In reality, both the first and second paths largely coexist, and they are the major paths for the current large-scale commercial biofuel production in the U.S.A.[15,16] In England, less than 10% of the Miscanthus was planted on former pastures.[45]

Using marginal land and abandoned land for the production of cellulosic biofuels

The third path is to make use of marginal agricultural lands for biomass production.[46] Both herbaceous and wood perennials are considered suitable bioenergy crops planted on marginal land.[46,47] The potentially available land area in the U.S.A. could range between 43 and 123 Mha.[47] This illustrates the difficulty of defining the different forms of "marginal" land. Land in the Conservation Reserve Program (CRP) is an important form of marginal land in the U.S.A. [48] In 2010, the Environmental Protection Agency (EPA) assigned pasture and CRP land as "fallow land" for the RFS2 mandate to meet the U.S. biofuel targets.[17]

For all of Europe, slightly less marginal land is found than in the U.S.A.,[47] most of which is in eastern Europe or in mountainous regions. It is anticipated that policy changes will cause land abandonment[49,50] in the EU27 due to market liberalization by 16 Mha (8% of arable and pasture), mostly in the hilly, mixed farms regions of Europe. A more detailed spatial analysis would be necessary to match emerging areas with plant requirements,[51] soil and terrain constraints.[29,31] Real examples for SRC willow in Austria show that these plants can grow at elevations greater (600 m a.s.l.) than assumed in the large scale UK study.[31] This may be further complicated by explicitly considering a dynamic transformation of agricultural land when abandoned.[52]

Intensification of crop management to increase productivity of currently cultivated land

When food production is intensified on established and highly productive land, then dedicated energy crops could grow on "surplus land."[53] There is no clear definition of surplus land, but it commonly comprises fallow, set-aside, abandoned, marginal, degraded, reclaimed, and waste land. There are constraints for the respective types of surplus land with respect to bioenergy[54] as shown by the conversion of marginal, abandoned land to SRF and set-aside to an annual herbaceous crop.[33] Surplus land is simply the difference between the amount of land needed for feed, food, and biomaterial production and the total available area.[55] Sustainable

intensification could generate surplus land depending on the assumptions on yield progression, which is assumed to range between 0.2 and 0.5%,[36] which is lower than observed in the past. Historically, crop yields have improved by more than 1% due to the advancement of breeding techniques,[56,57] though maximum yield potential of certain crops (e.g. corn) is still far from being reached.[58] Assumptions on the yield gap closure are associated with a rather large uncertainty as the gap may vary between 20 and 50% according to region[36] and agronomic practices[57] but they are crucial for implementing technological progress scenarios.[59] Thus increasing crop yields can free extra land required to meet biofuel demands. Modeled yield potentials can be improved using remote sensing techniques at field scale[60] and continental and national scales[39,61] thus avoiding overestimated feedstocks.[39,62] When intensive green maize production in Germany was considered unsustainable, the replacement of maize monoculture by a rotational mix of feedstocks actually increased the amount of area necessary to produce the same amount of energy.[63] Scenarios considering higher future yield increased the area available for energy crops in Europe.[36]

Some generic points of caution should be mentioned here, which are valid for all pathways. First, at the continental scale, different national land-use classifications are replaced by up-scaled sources, for example the CORINE Land Cover database (CLC2000 in Europe[64,65]) or the inventory of U.S. major land uses.[2,66] Using remote sensing and agro-statistics, the accuracy of the CLC2000 data varies between different land-use classes, and is lower for marginal, semi-natural (<80%) than arable land (> 90%).[67] Secondly, for some land-use scenarios, like organic farming and its impact on land demand,[36] the data availability is limited and scenarios remain speculative. This is also true for much of the impact assessment of new second-generation crops, which is based on either outdated[31,68] or limited experimental evidence[30] and differentiation.[65] Finally, the regionally and nationally variable implementation of biomass crop production for energy is difficult to model for different land-use classes.[17,42,69]

Most of current modeling studies have involved one or more of the aforementioned paths to meet the biofuel demands. The general purpose of most studies on land availability modeling is to understand the total amount of land available and the spatio-temporal dynamics of the land allocation for biofuel production. The focus of our review is the integrated modeling approaches that address both total quantity and spatial allocation of land change for biofuels.

Modeling approaches

Land-use models can be categorized as either resource-focused (bottom-up) or demand-driven (top-down). In a top-down approach energy crop production is estimated to meet exogenous targets on bioenergy; demand-driven studies typically focus on economic and implementation potentials.[70] They are usually scenarios applied to the "macro-scale." In a bottom-up approach, the theoretical or technical potential of bioenergy feedstock supply (productivity × land area) is estimated taking into account the land needed for food, feed, and biomaterials production and localized land conversion. Top-down and bottom-up approaches have often been combined in Europe[52,54,71,72] and the U.S.A.[17,73,74] to improve and test the validity of the scenarios. The effects on iLUC and dLUC will also be discussed.

Top-down approach

The top-down approach has become a widely used technique in studies of land-use planning, environmental impact, and ex-ante assessment of policy proposals,[75,76] which can vary in scale and resolution but are usually applied at the macro-scale. It typically includes quantity models, which determine and constrain the spatially aggregated area of change, and spatial allocation models, which allocate the aggregated change into individual spatial locations.[2,52] These model types merit the convenience of incorporating top-level scenarios such as national, regional, or global policies on decision-making.

Quantity models

The quantity models determine the spatially aggregated LUC associated with biofuel demands. The estimation of the impacts of biofuels on LUC can either be based on empirical statistical trend analysis[2] or on more complex economic multi-sectoral models.[27] It is becoming increasingly popular to use partial (PE) and computable general equilibrium (CGE) economic models to determine market supply and demand equilibrium.[72,77] The Global Trade Analysis Project (GTAP) model is a CGE model used in the U.S.A. and in the EU.[78] GTAP is used to assess the impact of biofuels from cellulosic materials in the U.S.A. including corn stover and dedicated energy crops on LUC.[76,79] Other economic models have been used to address the domestic biofuels-related land requirement. The Forestry and Agricultural Sector Optimization Model (FASOM), a PE model, was adopted by the U.S. EPA[37] to estimate the LUC in the U.S. agricultural sector. The Pol-

icy Analysis System (POLYSYS) model[81] was developed to evaluate potential shifts in U.S. crop areas resulting from changes in policy, economic, and resource conditions.[19,42] Britz and Hertel[75] present a multi-scale multi-model approach to estimate the impacts of EU biofuels on the global market and environmental quality by combining GTAP with a PE model CAPRI. The latter allows an assessment of the regional impact of the EU Common Agricultural Policy disaggregating space and commodities from previously parameterized and validated agricultural production models.

Spatial allocation models

The spatial allocation models establish causal spatial relationships between the locations of LUC and its driving factors. The relationships can be built either by statistical and empirical (e.g. CLUE model) or more complex models (e.g. neural networks, process-based models). These models typically involve generating land-suitability maps for biofuel production. The landscape suitability for corn and switchgrass in the U.S.A. was assessed using a two-species distribution model,[82] which showed a good correspondence with the current outline of the Midwestern Corn Belt and switchgrass for the eastern U.S.A. The expansion of corn and soybeans was simulated with success using a suitability map produced by an artificial neural network (ANN) model and biophysical factors.[2] Alternatively, the suitability can be represented based on simplified assumptions, for example, soil productivity potentials extracted from U.S. Soil Survey Geographic database.[17]

European modeling of land use and distribution of biofuels crops ranges from defining potentials based on temperature and water requirements[51] to using crop-specific empirical[68,83] and process-based models.[32,84,85] In GIS mapping, the focus is on agro-climatic suitability of bioenergy crops taking into account soil type and fertility, temperature, and water availability (rainfall) and constraints like terrain.[29] Sustainability and productivity assessment are carried out by matching climate characteristics with plant requirements,[86] and including consideration of soil and terrain characteristics.[65] These approaches are similar to work done for a series of crops in Europe, selecting "the best land for a given crop."[28,33] Aggregated spatial information from different data sets available in digitized maps is matched with agronomic cultivar needs listed in an Energy Crops Characteristics Catalogue such as the FAO (http://ecocrop.fao.org/ecocrop/srv/en/home). Usually, the pedo-climatic variables are used as constraints, defining an optimal range able to satisfy agronomic and phyto-climatic characteristics similar to the AEZ concept.[65]

Integration of quantity and spatial allocation models

Either a quantity model or spatial allocation model can solely address spatial allocation of aggregated areal change. The quantity models are typically integrated with the spatial allocation models in a top-down manner by combining quantity models to determine market supply-demand equilibrium and biophysical models for spatial allocation. For example, Li *et al.*[2] implemented a simple trend analysis to estimate the quantity change in corn and soybeans fields and then allocated the total change based on the agricultural suitability modeled by a neural network in a U.S. state. Mehaffey *et al*.[17] utilized the output from the Center for Agriculture and Rural Development (CARD) econometric model and soil production potentials indicated by the soil datasets to model the conversion of corn plantings. Delzeit *et al*.[34] combined an economic model with a regional GIS to allocate and size the processing plants for biogas from (green) maize producing energy. Hellmann and Verburg[27] used a spatially explicit model to forecast changes in biofuel crops in Europe.

Bottom-up approach

In a bottom-up approach, typically the theoretical or technical potential of bioenergy crops is estimated by taking into account the productivity and the production profile of the farm. This has the advantage to estimate the land needed for food and feed and to choose the options for land-use transition and integration determined by local conditions. Agent-based modeling is commonly used as a bottom-up approach to involve the local stakeholders (e.g. farmers) decision-making processes, and socio-economic factors. It allows agents (e.g. farmers) to interact with each other (e.g. grower groups, cooperatives) and natural resource constraints (terrain, field size, etc.), in which the local effects could be accumulated into higher hierarchical levels (trader). For example, Scheffran and BenDor[18] modeled the introduction of bioenergy crops in the landscape of Illinois, U.S.A., using an agent-based modeling approach, which incorporates the dynamics of farmers' planting decisions.

In the UK, decisions on land use can be based on field-scale, empirical, or process-based models to estimate the productivity of cellulosic feedstocks[32,68,83] under various land-use constraints which include land quality criteria.[29] Micro-economic decisions can then be based on gross margins[87] and total costs which include opportunity costs to grow other crops.[28] The distance to traders and end users will determine the spatial distribution and relative yields and costs will determine

which crop is best for each respective environment.[28] Recent work for the UK Energy Technologies Institute on an integrated Biomass Value Chain Model included the up-scaling of process-based models for three major first-generation/food staples to allow decisions based on multiple feedstocks, productivity and LCA-based GHG emission. As this example shows, in practice, bottom-up approaches were rarely applied independently because the bottom-up models often have problems of predicting aggregate land change correctly at an upper hierarchical level.

Integration of top-down and bottom-up approaches

The top-down modeling is better suited to dealing with the biofuels-related LUC from the higher hierarchical scales, whereas the bottom-up approach excels at the simulation of LUC phenomena at local scales. The combination of top-down and bottom-up approaches is needed to better account for multiple factors, processes, and interactions that occur at different scales[52]. Castella *et al*.[71] and Verburg and Overmars[52] demonstrated excellent examples on the integration of top-down and bottom-up approaches for LUC although not directly biofuels-related. The Intergovernmental Panel on Climate Change (IPCC) scenarios of land use and land cover (LULC) were analyzed by integrating macro-scale and local scale drivers for the USGS Biological Carbon Sequestration project.[74] However, there were very few cases that utilized the integrated approach for biofuels-related LUC modeling. Parish *et al.*[73] used the POLYSYS top-down model to generate scenarios of biofuel crop yields and price (profit targets), and adopted the Biomass Location for Optimal Sustainability Model (BLOSM) and SWAT hydrologic model to evaluate the bottom-up environmental consequences (water quality targets) in a watershed of Tennessee, U.S.A. The top-down profit targets and bottom-up environmental targets were then combined for assessing different LUC scenarios of switchgrass cultivation. European researchers developed approaches to explore agricultural LUC in Europe combining economic and geographic aspects of the land-use system and policy scenarios,[72] which can be extended to biofuel questions.[34,38]

Spatial and temporal scale of models

LUC is a spatio-temporal phenomenon and different factors may play different roles at different scales. The output of spatially explicit models can only be as valid as the input data that drive the process and subsequent decision-making and implementation depends on the accuracy of the underlying data. The assessment of land availability has to acknowledge that bioenergy systems can scale from farm-size up to landscape-size with processing in either decentralized processing plants or in industrial-sized central facilities.[54] Existing studies vary substantially regarding both spatial and temporal scales (Table 2). One must account for both, extent (i.e. the entire study area or modeling time period) and resolution (i.e. the smallest mapping unit or time interval represented in the dataset). [2] Land-use and cover data are usually at a scale that temporal setting (i.e. extent and resolution) is critical to the data presentation of the modeling process. Land-use observations made over short-time intervals are essential for intra-annual analysis and modeling, while data with coarser temporal resolution (e.g. annual or longer) are often acceptable for long-term studies.

Factors affecting modeling of LUC to biofuels

Biofuel-related LUC involves a multitude of macro- and socio-economic, environmental, biophysical, and agro-climatic factors. Originating from policy targets the environment and the economy act as constraints. The distinction between "drivers" and "constraints" (Table 2) is in practice fuzzy: initially, high feed-in tariffs act as a driver, but when reduced become a constraint to a single crop and a driver of further LUC.[63] The selection of factors also depends on the chosen system boundaries and modeling scale. Here, we summarize the commonly used variables for models operating at different scales and sets of driven/constraint factors. The land area of bioenergy crops and productivity are often overestimated because constraining factors such as water, productivity, pedo-climatic conditions, social aspects and nature conservation are not sufficiently taken into account.[69,88,89]

Driving factors

Economic models for analyzing biofuel supply-demand scenarios are associated with factors operating at macro levels, which often arise from policies,[49] market demands and supplies,[17,34,63] price for biomass,[19] and other commodities, like oil,[43] farming costs and revenues,[18] etc. Spatially explicit suitability models use localized biophysical factors derived from soil maps, e.g. fertility,[17] texture and water capacity,[29] and climate.[82] These variables are usually inputs to estimate productivity, which drives decision-making on second-generation biofuel crops[28] based on productivity maps.[68,83] Simi-

Table 2. Current major biofuel crops and their product destination in different cropping systems and landuse studies in the U.S.A. and the EU.

	Biofuel Crops (destination)	Study/Research	Focused Cropping Systems	Used Land or Pathways
U.S.A	corn (starch-based bioethanol);	Evans *et al.*, 2010[58]	corn, switchgrass	current agricultural land
		Li *et al.*, 2012[2]	corn, soybeans	current agricultural land
		Mehaffey *et al.*, 2012[17]	corn	current agricultural land
	soybeans, sunflower, canola (biodiesel);	Parish *et al.*, 2012[73]	switchgrass	current agricultural and nonagricultural land
	switchgrass, alfalfa, poplar, willow (cellulose-based bioethanol)	Scheffran and BenDor, 2009[18]	corn, soybeans, Miscanthus and switchgrass	current agricultural lands
		Smith *et al.*, 2012[39]	general bioenergy potential	surplus agricultural land; marginal and abandoned land
		Walsh *et al.*, 2003[19]	switchgrass, hybrid poplar and willow	current agricultural land
EU	corn (biogas);	Britz and Hertel, 2011[72]	rice, wheat, coarse grain, oilseeds, sugar, others (first-generation)	current agricultural lands
		De Wit and Faaij, 2010[35]	LCC, herbaceous LCC, oil, sugar and starch crops	surplus agricultural and pasture land
	sorghum (starch-based bioethanol);	Delzeit *et al.*, 2012a,b[34,38]	green maize for biogas	current agricultural land
	sugar beet (bioethanol)	Fischer *et al.*, 2010[36]	biofuels crops (first-generation) and LCC on permanent grasslands	surplus arable land; permanent grassland
	rapeseed (biodiesel);	Hellmann and Verburg, 2011[27]	cereals, s.bt., rapeseed (first-generation); willow/ Miscanthus (second-generation)	current agricultural land
	Miscanthus (cellulose-based bioethanol)	Dauber *et al.*, 2012[54]	crop mix based on climate and agronomy	surplus land
		Renwick *et al.*, 2013[49]	arable & grassland area	marginal and abandoned land
		Tuck *et al.*, 2006[51]	26 promising bioenergy crops	all potential suitable land

larly, environmental variables have been used as driving factors for modeling first-generation biofuel cropland changes, including terrain elevation and slope, soil organic matter, and long-term mean precipitation and temperature[2] and aridity index.[90] For both economic and environmental evaluation, yield assessment and dynamics are paramount, whether for a top-down analysis[12,43] or spatially detailed bottom-up analysis for non-food crops which have eluded to local yield density and transport in the cost-benefit analysis.[28]

Coupling a (static) economic model with a GIS-based regional allocation model of processing plants for biogas from maize, the effect of feed-in tariffs was shown to have reduced maize production overall but increased land requirement for biofuel production, due to change of feedstock composition.[38]

In another example, the multi-criteria analysis for Denmark's domestic energy demand supplied from a resource mixture[43] was modeled for economic (oil price), land-use (protected forest and grassland), and management scenarios (groundwater, food and feed, carbon sequestration). Although its production of bioenergy was clearly constrained by competition with food, feed, and fossil fuel, perennial biomass crops like SRC-willow are considered a cost-effective feedstock with environmental benefit, similar to other studies which show positive impact on the development of rural areas.[92]

Socio-economic factors which describe either added values for the suitability (energy crops in flatlands, set-aside area) or constraint (productive forest areas, woody fruit crops), farm size, mechanization, etc., have also been considered.[90] All studies accept the criterion that fertile lands should be first dedicated to food and feed production, and that dedicated energy crops are cultivated on surplus arable land and marginal land.

Considering environmental impacts of crops is another approach to refine suitability and land allocation maps on the basis of site-specific vulnerability, for example, eutrophication and toxicity.[93,94] Perennial grasses with recognized environmental benefits could be grown on fertile but environmentally vulnerable land to replace high intensity food crops (e.g. maize). Environ-

mental mitigation potential of low-input non-food crops can be added to the list of factors deciding the suitability of land for fuel. In general, the assessment of suitability is more reliable using a bottom-up approach, reducing the risk of misjudging the biofuel suitable areas.[80]

Constraint factors

Changing water availability and climate may impact the biofuel-crop productivity, directly and indirectly. The 2012 drought in the U.S. Great Plains resulted in significant stress for corn and soybean, reducing U.S. corn yields by 24%.[63] In a globalized food system, drought in a crop production region may impact the food prices and security globally, as observed in 2008 and 2011 prices after droughts in Russia and the United States.[95,96] Next to land area, water availability will be an increasingly critical constraint factor[97] in projections for a future warmer climate.[98,99] Many agricultural regions in the U.S.A. will experience declines in crop production.[100,101] Although biofuels have the potential to benefit the environment, the consumptive water use over the life cycle of corn-based ethanol is high, and as a knock-on effect, corn-based ethanol might affect water availability in marginal and abandoned land.

In Europe, the land area as a finite or declining resource and the demand for biomass for the production of bioenergy generates land-use conflicts[54] in the food versus fuel controversy,[102] and the debate on iLUC.[103] Land-use modeling is one way to satisfy various demands and ensure sustainability in the long term. Land-use models are used in order to project land utilization and availability for bioenergy crops after satisfying food demand.[36] Economic growth, international trade, and policies drive the demand of agricultural products and land-use requirements,[27] which depend on production technology, biophysical suitability, and special restrictions of land resources.[104]

For the UK the land availability for (lignocellulosic) bioenergy crops was analyzed by combining site-specific productivity with land-use constraints.[29,31] In comparison to earlier studies,[30] yield maps were based on down-scaled empirical models developed from multi-site/-annual observations,[68,83] for which soil hydrological data played a crucial role. Nine "hard" physical constraints (e.g. infrastructure, national parks, and topography) and two "soft" constraints (permanent grassland, landscape sensitivity) were distinguished to exclude land from energy crops, which reduced the available land by about 50%.[29] Similar constraints (nature conservation, protected natural areas) are practice elsewhere.[33] Applying (pseudo-economic) grades of the Agricultural Land Classification constrained dedicated (second-generation) energy crops to lower-grade land.

Avoiding negative consequences of biofuel production is achieved by a set of mandatory sustainability criteria, i.e. GHG reduction with respect to fossil fuel use (RED)[6] for all biofuels. No-go areas within the EU (e.g. areas with high biodiversity value and high carbon stock) have been implicitly included in studies mentioned; the most recent regulation related to emissions from iLUC give a multiple weighting for perennial LCC, which become mandatory above the first-generation biofuel threshold of 5%.

Model validation

Most of the current biofuels-related modeling studies face a lack of data for proper validation,[75] often due to a lack of reliable, spatially explicit data on cropland distribution. Verburg and Overmars[52] recognized the lack of suitable, independent data in Europe necessary as an input or as a baseline for the validation of models. Land-cover data (e.g. 2000 CORINE European land-cover maps[64]) are available only at spatially aggregated (1 km × 1 km) scales and cannot distinguish between abandoned farmland and grassland due to the spectral resemblance of the latter, which explains the relatively low accuracy for this land-cover category.[67] The same applies to new alternative uses of agricultural land as they cannot be distinguished from traditional land cover. Down-scaling land-use maps developed within the CORINE project to the sub-regional level (<NUTS3) using ground-truthed Landsat remote sensing data (30 m resolution) would be more appropriate for detecting local peculiarities. In comparison, the Cropland Data Layer (CDL) developed by U.S. National Agricultural Statistics Service (NASS) provides detailed crop types at high spatial resolution (30–56 meter). It started around 1998, is annually updated with increasing spatial coverage, and could be used for validation of land availability.

Spatial allocation models should be validated to test their ability to make realistic projections of the changes in land-use pattern.[105] Potential methods useful for validation purpose include allocation disagreement based on three-map comparison,[105] Relative Operating Characteristic (ROC),[106] and a simplified baseline (naïve) model.[107] These validation methods were used and successfully validated the spatial expansion of corn/soybeans in North Dakota, U.S.A. [2]

Modeling biogas production dependent on green maize availability was evaluated using state- (NUTS2) and county-specific ("Kreis"; NUTS3) distribution and size of power plants.[34] In the EU27, modeled biodiesel/

ethanol processing plants in German regions were visually compared to existing plants, showing that some model assumptions could be improved.[27] Similarly, feedstock allocation for biodiesel was simulated and validated against agro-statistical data aggregated at the NUTS2 level (r^2 range from 0.37 to 0.52). Data for second-generation energy crops do not exist yet.

Modeling uncertainties

There are many potential sources of the uncertainties of modeling biofuel-driven LUC at all levels including input data, calibration of process description or statistical relationships, scale transition, and interaction between different model domains which are often based on qualitative assumptions. Usually, productivity assessment of food/fuel crops is a crucial requirement for assessing their economic and environmental impact per unit product. Models, at best, are usually based on data derived from experimental plots and hardly ever reflect low fertility or marginal growth conditions. Further, their input requirements are often not met by the data availability and quality. Up-scaling process-based models (PBM) for first-generation biofuels (e.g. sugarbeet[26]) to the national scale involved a meta-model derived from aggregated model inputs (soil water availability, precipitation, radiation, temperature) and model outputs (yield, biomass) may explain between 65 and 70% of the PBM variability, whilst maintaining the effects of bio-physically relevant variables. The use of up-scaled mapped input data and cross-validating the model outputs, usually results in an increased model uncertainty due to the lower quality of the inputs (Richter and Qi in unpublished report to ETI[108]). A key issue is that the European Soil Data Base[109] does not provide the same resolution and detail as national soil survey and adjustments were necessary to compensate quality loss. In relative terms, the model predictions of biomass yield are more affected by data input uncertainty than reduced model complexity. Often, yields in top-down studies are crude estimates and not differentiated enough. Further, predictions into the future are even more dependent on assumptions taken for technology development[59] of which yield progress is one factor of uncertainty.[56] Assumptions on the yield gap[57] will be another factor of uncertainty.

Future projections

Modeling the future distribution of biofuel crops raises a series of challenges in terms of scenario assumptions, validation, and down-scaling.[110] Time-scales affect the relative importance of environmental, technical, and socio-economic drivers as scenario inputs and improvements of the modeling systems are needed to account for the scale of analysis and to describe the system components and dynamics adequately.

Climate change scenarios (e.g. rainfall and temperature) usually deal with projections to the end of the twenty-first century,[110] which affect future land suitability for regionally different biofuel crop cultivation[111,112] and surface vegetation.[113] In Europe, predictions are of a northward shift of biofuel crops[51] and of a possible increase in grain yields;[114] however, elsewhere yields may decrease.[115] In the U.S.A., land suitability for corn and soybeans in North Dakota also shifts northward[116] but by the end of the century grain yields are projected to decline.[100] Thus, future sustainable intensification of food and feed production might increase, or decrease, the availability of (surplus) land for energy crops.[54]

Projections of biofuel distribution for the near future (2020s) are very much dependent on established technology and socio-economic conditions. For projections to the 2050s, assumptions for technology progress and economic development become central to any scenario[59] but they are difficult to assess.[110]

Technological advancement of potential productivity and yield gaps are extrapolated from past experience[56,57] but more research is needed[117] to justify predictions for novel biomass crops as less data are available compared to food feedstocks.[118] Crucial to LCC feedstock market development is the advancement of conversion technology[119] but whether a market-driven economy will be innovative enough is questionable. Protected national and regional markets could be advantaged as investments in new technologies may prove less risky[110] and more encouraging for innovation.[120,121] Global socio-economic scenarios are proposed to be transferred into to a set of harmonized rules ("Shared Socio-Economic Pathways") within an iterative regional assessments/analyses[122] to reduce their "subjective nature of the qualitative interpretation."[110]

Economic policy scenarios have been explored by combining different models for the allocation of crops at various scales in different countries iterating the effects of macro-economic development and respective yield increase.[27,69] There are biofuel-related examples where the qualitative information of the IPCC-SRES scenarios was translated into numbers at the country or regional scale.[43,104,116] Other models use bioenergy crop allocation for natural resource planning purposes at the landscape scale driven by a set of (micro-) economic (farm profit) and environmental objectives.[73] To successfully down-scale regional or global scenarios and objectives to sub-regional level requires that feedback is modeled

between decisions at macro-scale level[70] and local stakeholders (e.g. uptake of subsidies).[27,104]

The regional implementation of global policies on iLUC[91] could be explored for future land-use modeling. Implementation into the EU RED, under the constraint to maximize carbon savings to at least 50%, would cause a shift away from oil to sugar/starch crops.[123] LCC feedstocks would gain much higher carbon savings (70–90%) under current technical constraints.[119] With regard to the regional comparison between the EU and the U.S.A., it will be interesting to compare the impacts of scenarios emphasizing energy or food security, economic or environmental targets, respectively.

Some important limitations in model parameters, process formulation, and scale[110] are needed to simulate the impact of these scenarios. Previously, the mechanism underlying LUC was not well understood, models were static, economic drivers came from data that were externally provided, and feedback from land-use models to economic models was not considered. These limitations have been partially addressed by coupling policy/economic and land-use models in the U.S.A.[18] and in Europe.[52,72]

Discussion

At the start, we set out to review the capability to quantitatively answer some crucial questions on how, and at what expense, the agricultural industry would be able to satisfy biofuel feedstock demands. First, can we quantify the available land of considered land categories? How much of it is needed to match the production demand? What is needed to make biofuel production sustainable in competition with other demands on land? We reviewed more than 100 papers which refer to data, mapping tools, and models that are relevant to the modeling of land availability for fuel and fiber mainly covering the last decade. We extended the review to land use in the context of land demand for different products for food and feed in competition with feedstocks for fuel and fiber. A selection of the most important studies is compiled in Table 3.

Supply paths to match future biofuel demands

Both the U.S.A. and the EU are facing the challenge of optimizing the use of available land to meet the biofuel mandates set by their governments for the 2020s through choice of crop types and sustainable LUC and intensification. For the transition period, first-generation biofuels remain the main source, deeply rooted in the existing agricultural and processing infrastructure. Compared to the fast delivery of first-generation ethanol from corn starch[124] the pace of introduction of LCC feedstock has been slow and the shift from first- to second-generation biofuels in the near future of the U.S. biofuel industry remains to be seen. To compensate for negative impacts of first-generation biofuels (i.e. iLUC), the implementation of second-generation biofuels was stimulated (EU 2009/28/EC) and most recently strengthened (EU 2012; IP/12/1112).[125] New market opportunities for low-input LCC and the exploitation of low-quality land arise but need underpinning scientific work to refine productivity constraints.[118] For widespread cultivation of second-generation LCC biomass several hurdles[124,126] like high capital costs, non-existing processing, and transport infrastructure need to be overcome. A policy is needed to establish a socio-economic framework with stable markets and contracting mechanisms.

Since first- and second-generation biofuel production compete with food for arable land, different pathways to alleviate negative effects were discussed. The use of marginal land[47] or low-grade land[29] may not be realistic for first-generation crops because of low agricultural productivity, suitability, and high production costs. However, second-generation biofuel crops, like switchgrass[73] and Camelina[16] can be cultivated on marginal land. But much research is still needed to determine the optimal configuration of existing arable and marginal land for second-generation biofuels, in particular down-scaling top-down estimates[47] to something more realistic[49] and familiar.[29]

Challenges and opportunities in modeling

Can we quantitatively predict the land that we need to match the demand? The large body of existing literature on modeling land availability and representative case studies during the last decade are summarized in Table 3. Both regions currently rely on first-generation biofuel crops to meet the biofuel mandates and increasing demands, have similar latitudinal distribution of AEZ suggested by FAO[127] but differ in the dominant crop types. The U.S. biofuel No. 1 crop is corn, and whilst rapeseed dominates in the EU there is also more regional diversity[3] for which spatially distributed productivity estimates exist.[11,26,65] Although 2nd-generation biofuel crops and technologies are still under development, plenty of evidence indicates that both regions are suitable for a wide range of second-generation biomass crops.[23,28–30,46]

Top-down modeling is the preferred approach when evaluating the consequences for policy scenarios for

Table 3. Spatial and temporal representation and resolution, driving factors and model mechanisms as well as validation criteria for various land-use modeling studies reflecting on biofuel feedstock distribution.

	Study/ Research	Spatial Extent, Resolution (km)	Temporal Extent, Resolution (year)	Driving Factors	Model Mechanism	Quantity Validation	Spatial Validation
U.S.	Evans *et al.*, 2010[58]	continental U.S.A., 9	n/a, 1	Climate, topology and major road density	SDMs: Maxent and SVM[1]	n/a	AUC, Kappa and rank correlation
	Li *et al.*, 2012[2]	state scale, 1.5	20, 2	Climate, topography, soil	ANN.[3] Land demands by regression, spatial suitability	n/a	Allocation disagreement[105], ROC[106], naïve model[107]
	Mehaffey *et al.*, 2012[17]	12 U.S. Midwest states, SSU	20, 1	Top-down biofuel regional demand, available acreage, soil productivity	CARD[4]	n/a	n/a
	Parish *et al.*, 2012[73]	watershed, 0.056	12, 1	National economy, hydrologic system, soil, climate, land management. Scenarios for farm profits and water quality	BLOSM; SWAT; POLYSIS[5]	n/a	n/a
	Scheffran, BenDor, 2009[18]	state scale, 9.66	50, 1	Available land, production & transport costs, revenue in agriculture, biofuel subsidies, farmers' decision making	Agent-based modeling	n/a	n/a
	Smith *et al.*, 2012[39]	continental U.S.A., 1	7, 8-day	Satellite-derived net primary productivity (NPP)	Remote sensing techniques	n/a	NPP derived from the network of Eddy fl ux
	Walsh *et al.*, 2003[19]	continental U.S.A., ASD	10, 1	U.S. national economy, policy, bioenergy farm gate price scenarios	POLYSIS[5]	n/a	n/a
EU	Britz, Hertel, 2011[72]	**EU27**, NUTS2	scenario until 2015	Global market, land use, iLUC, CAP	CAPRI[6] & modified GTAP[2]. PE and CGE model integration	methodology paper; database evolution	agricultural statistics
	De Wit, Faaij, 2010[35]	EU27 + Ukraine, NUTS2	25,10	Food/feed self-sufficiency, urban area, set aside, nature conservation, on-farm production cost and productivity, AEZ	MOSU.S.[7] project	n/a	n/a
	Delzeit *et al.*, 2012 a,b[34,38]	Germany, NUTS3 (350)	n/a	Policy (feed-in tariffs, environmental impact) economy (feedstock & manure availability & demand distribution, transport & operational cost)	ReSI-M; RAUMIS.[8] GIS with iterative algorithm	test against reality	CORINE land cover (CLC)
	Fischer *et al.*, 2010[36]	EU27 + Ukraine, NUTS1	scenarios until 2030	Food/feed demand & self-sufficiency Crop residue. FAOSTAT. Land use-baseline, ~ -Environment s, and ~ -Energy scenario	MOSUS project	comparison with literature	comparison with literature
	Hellmann, Verburg, 2011[27]	8 EU regions, NUTS2	25, 1	SRES policy scenarios: capacity and location of processing plants, infrastructure, NATURA2000-areas	GTAP-IMAGE[2] x Dyna-CLUE[9], biophysical control	compared to NUTS2 rapeseed (Germany)	location of processing plants

Table 3. Continued.

	Study/ Research	Spatial Extent, Resolution (km)	Temporal Extent, Resolution (year)	Driving Factors	Model Mechanism	Quantity Validation	Spatial Validation
EU	Dauber *et al.*, 2012[54]	EU27, NUTS2	30, 10	Food/feed demand & self-sufficiency, import/export balance. EUROSTAT & FAOSTAT. 13 bioclimatic areas for crop mix	Land allocation balance model (RENEW-4 modules).	comparison with literature	comparison with literature
	Renwick *et al.*, 2013[49]	**EU27**, NUTS2	scenarios until 2020	Policy; economy (marginal economic rent)	CAPRI[6]; Dyna-CLUE.[9] Dynamic simulation of landuse competition	compared to farming in marginal areas	empirical evidence for mountainous regions
	Tuck *et al.*, 2006[51]	EU, NUTS1	End of century, 30	Climatic conditions, elevation. IPCC emission scenarios	Simple rules for suitability, global climate models	comparison with literature	n/a

1. SDMs: species distribution models; Maxents: maximum entropy; (SVM): support vector machine.
2. GTAP: global macro-economic multi-sector and land-use modeling.
3. ANN: artificial neural network.
4. CARD: center for agricultural and rural development.
5. BLOSM: biomass location for optimal sustainability model-spatial allocation model; SWAT: water quality model; POLYSIS: modular economic simulation agricultural policy model.
6. CAPRI: EU regional agricultural production model, spatial.
7. MOSU.S.: agricultural and forestry products trade balance database.
8. ReSI-M: regionalized location model; RAUMIS: regional agricultural and environmental information system[4], static, equilibrium model.
9. Dyna-CLUE: conversion of land use and its effects, Dyna-CLUE version, spatial allocation rules.

bioenergy, environmental targets, or multiple-objectives at national, regional, or global scale. Bottom-up modeling better accounts for the drivers of land-use transition determined by local conditions, for example yield maps/forecasts and land-use constraints. Both methods have been widely used in the U.S.A. and in the EU to provide spatially discernible modeling results. However, the sole use of top-down or bottom-up approaches will not be enough to model complex interactions between scales and entities, for example, alternative biofuel policies changing bioenergy demands, or spatial heterogeneity and yield uncertainty affecting farmer's decision-making. An integrated approach combining top-down and bottom-up mechanisms is critical for dealing with the cross-scale modeling of land availability. Currently, there are more studies using an integrated approach simulating biofuel land availability in the EU compared to the U.S.A. This reflects the importance of a cross-discipline/-national structure of science-based European agricultural and environmental policy whereas the U.S. studies are predominantly top-down with the twist toward a policy of energy security. Europe also has a different socio-economic/environment structure to the U.S.A. with a generally higher population density. In the U.S.A., vast stretches of extensive rural economy have largely embraced the energy policy as a welcomed (and subsidized) diversification. From a modeling point of view,[12] significant and relevant improvements in model specification have been observed, which take into account the use of biofuel by-products for animal feed, and which try to allocate LUCs to differentiated AEZ. Limitations in modeling can be related to the absence of endogenous energy markets, restrictions to the current technological developments, and to the fact that crop yield increase is generally based on past trends.

For the accelerated introduction of second-generation biofuel crops, many of current models may not be sufficient to deal with the interaction/competition between second- and first-generation crops, and other land uses. Instead of assuming that first-generation suitability may hold for second-generation biofuel crops, new models and crop/environment relationships for second-generation biofuel crops need to be developed as in the UK.[28,29,32,83] These can then be comprehensively compared with productivity patterns of various first-generation to define purpose-driven interaction/competition between all crops for different land-use types. A tool based on modeling in a bottom-up manner was developed and is being evaluated for the UK to evaluate economic and environmental policy scenarios (ETI-BVCM). A multi-metric modeling framework linked with different policy objectives can be

very instructive for planning, management, and decision-making purposes as shown for switchgrass.[73]

Another critical problem identified in land availability modeling is a general lack of proper validation using explicit spatial statistics. Most studies did not validate or only qualitatively validated their modeling results, and very few used statistically defendable ways to validate the model (Table 3). Since biofuel and related environmental policies need to be explicitly linked with locations, the accuracy and uncertainty for the modeling results are crucial to policymakers. It is difficult to calibrate or validate space-related components of the model for second-generation biofuel crops due to their limited spatial extent. Emphases on the modeling validation are much needed in future research. Methods useful for validation purpose includes were already mentioned.

Policy recommendations

Policymakers in both the U.S.A. and the EU are inclined to use models as the main instrument to quantify the LUC effects due to the expansion of biofuels.[77] Four considerations are relevant to highlight here. First, from a modeling point of view, linking top-down and bottom-up models is crucial for shaping and assessing agricultural policy across different scales. Policymakers tend to think top-down while overlooking bottom-up decision-making processes of growers interacting with biofuel policies and the biophysical environment. Considering the paucity of modeling studies based on an integrated approach, much research is still needed to apply and test the approach. The lack of data to define the processes at the farm- and landscape-scale must be overcome. Integrating reliable data from small-scale case studies (which usually produce more conservative LUC) with large-scale analysis could be an effective way to support policy-making. Secondly, spatially explicit land availability models are more useful to evaluate spatially detailed targets for biofuels and GHG policies because the spatially detailed results can be easily linked with other models. Thirdly, policymakers should advocate those models that have been properly evaluated. Interactions with (sub-) regional governments/agencies as stakeholders could ensure that data for model calibration and validation are readily available. Finally, the LUC model needs to be embedded in a whole systems analysis including well-founded GHG balances.

Summary

Increasing energy use, climate change, and carbon dioxide emissions from fossil fuels make switching to low-carbon biofuels a high priority in recent decades. This review covers a wide range of issues related to the recent modeling practices on biofuel-related land use in the U.S.A. and in the EU, including frequently modeled crops, modeling approaches, modeling scales and factors, uncertainties and limitations, and future research priorities. Throughout the review, we identify those models integrating top-down with bottom-up approaches as ideal for biofuel policymaking purposes. However, there is still a research gap regarding modeling cases using the integrated approach. Future work is much needed in this area. Also, model validation of biofuel-related LUC modeling should receive more attention from LUC modelers. Toward the future, we are facing a pressing deadline to meet the biofuel mandates/targets set by the U.S.A. and the EU for second-generation biofuel crops. To achieve this, considerable modeling efforts are still needed to deal with the complex interactions among second-generation, first-generation, and other land-use types.

Acknowledgments — All authors are grateful for the opportunity to contribute. We are also indebted to two unknown referees for numerous valuable suggestions. The corresponding author Goetz Richter would like to thank the UK Biotechnological and Biological Sciences Research Council (BBSRC) for funding his work within the Institute Strategic Programme Grant "Cropping Carbon" at Rothamsted Research, an Institute supported by the BBSRC.

References

1. Wallander S, Roger C and Cynthia N, *The Ethanol Decade: An Expansion of U.S. Corn Production, 2000–09*. Online: http://purl.umn.edu/117982 [February 27, 2013].
2. L i RP, Guan QF and Merchant J, A geospatial modeling framework for assessing biofuels-related land-use and land-cover change. *Agr Ecosyst Environ* **161**:17–26 (2012).
3. Hamelinck C, Koper M, Berndes G, Englun O, Diaz-Chavez R, Kunen E *et al.*, *Biofuels Baseline 2008*. Study for the European Commission DG Energy under Tender No. TREN/D1/458/2009. Online: http://ec.europa.eu/energy/renewables/studies/doc/biofuels/2011_biofuels_baseline_2008.pdf [March 7, 2013].
4. Project team ME4, *An integrated framework to assess spatial and related implications of biomass delivery chains*. Online: http://edepot.wur.nl/176833 [March 7, 2013].
5. Congress of the United States of America, Energy security through increased production of biofuels, Part A — Renewable fuel standard. *Energy Independence and Security Act*. Government Printing Office, Washington, DC, U.S.A. (2007).
6. European Commission, Directive 2009/28/EC on the promotion of the use of energy from renewable sources and amending and subsequently repealing Directives 2001/77/EC and 2003/30/EC. *OJEU* L **140**:16–62 (2009).

7. Food And Agriculture Organization, *The State of Food and Agriculture. Biofuels: Prospects, Risks and Opportunities*. Online: ftp://ftp.fao.org/docrep/fao/011/i0100e/i0100e.pdf [February 27, 2013].

8. Landis DA, Gardiner MM, van der Werf W and Swinton SM, Increasing corn for biofuel production reduces biocontrol services in agricultural landscapes. *P Natl Acad Sci U.S.A.* **105**(51):20552–20557 (2008).

9. Searchinger T, Heimlich R, Houghton RA, Dong FX, Elobeid A, Fabiosa J *et al.*, Use of U.S. croplands for biofuels increases greenhouse gases through emissions from land-use change. *Science* **319**(5867):1238–1240 (2008).

10. Smith KA and Searchinger TD, Crop-based biofuels and associated environmental concerns. *GCBiol Bioenergy* **4**(5):479– 484 (2012).

11. Defra, *Area of Crops Grown For Bioenergy in England and the UK: 2008-2011: Experimental Statistics*. Online: https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/141626/defra-stats-foodfarm-landuselivestocknonfoodcrops-latestrelease-130125.pdf [June 14, 2013].

12. Fonseca MB, Burrelll A, Gay H, Henseler M, Kavallari A, M'Barek R *et al., Impacts of the EU biofuel target on agricultural markets and land use: A comparative modelling assessment*. Publications Office of the European Union, Luxembourg 978-92-79-16310-4 (2010).

13. Campbell JE, Lobell DB, Genova RC and Field CB, The global potential of bioenergy on abandoned agriculture lands. *Environ Sci Technol* **42**(15):5791–5794 (2008).

14. Pimentel D and Patzek TW, Ethanol production using corn, switchgrass, and wood; Biodiesel production using soybean and sunflower. *Nat Resources Res* **14**(1):65–76 (2005).

15. Hill J, Nelson E, Tilman D, Polasky S and Tiffany D, Environmental, economic, and energetic costs and benefits of biodiesel and ethanol biofuels. *P Natl Acad Sci U.S.A.* **103**(30):11206–11210 (2006).

16. Johnson JM-F, Coleman MD, Gesch R, Jaradat A, Mitchell R, Reicosky D *et al.*, Biomass-bioenergy crops in the United States: A changing paradigm. *Am J Plant Sci Biotechnol* **1**(1):1– 28 (2007).

17. Mehaffey M, Smith E and Van Remortel R, Midwest U.S. landscape change to 2020 driven by biofuel mandates. *Ecol Appl* **22**(1):8–19 (2012).

18. Scheffran J and BenDor T, Bioenergy and land use: A spatial-agent dynamic model of energy crop production in Illinois. *Int J Environ Pollut* **39**(1/2):4–27 (2009).

19. Walsh ME, Ugarte DGD, Shapouri H and Slinsky SP, Bioenergy crop production in the United States - Potential quantities, land use changes, and economic impacts on the agricultural sector. *Environ Resour Econ* **24**(4):313–333 (2003).

20. Bennett AS and Anex RP, Production, transportation and milling costs of sweet sorghum as a feedstock for centralized bioethanol production in the upper Midwest. *Bioresource Technol* **100**(4):1595–1607 (2009).

21. U.S. EPA, *Supplemental Determination for Renewable Fuels Produced Under the Final RFS2 Program From Grain Sorghum*. Online: http://www.gpo.gov/fdsys/pkg/FR-2012-12-17/pdf/2012-30100.pdf [June 14, 2013].

22. Heaton EA, Dohleman FG and Long SP, Meeting U.S. biofuel goals with less land: The potential of Miscanthus. *Glob Change Biol* **14**(9):2000–2014 (2008).

23. Khanna M, Dhungana B and Clifton-Brown J, Costs of producing miscanthus and switchgrass for bioenergy in Illinois. *Biomass Bioenerg* **32**(6):482–493 (2008).

24. Simmons BA, Loque D and Blanch HW, Next-generation biomass feedstocks for biofuel production. *Genome Biol* **9**(12):242.1–242.6 (2008).

25. Evans J, *Crambe is the new corn*. Online: http://www.biofpr.com/details/feature/162117/Crambe_is_the_new_ corn.html [February 18, 2013].

26. Richter GM, Qi A, Semenov MA and Jaggard KW, Modelling the variability of UK sugar beet yields under climate change and husbandry adaptations. *Soil Use Manage* **22**(1):39–47 (2006).

27. Hellmann F and Verburg PH, Spatially explicit modelling of biofuel crops in Europe. *Biomass Bioenerg* **35**(6):2411–2424 (2011).

28. Bauen AW, Dunnett AJ, Richter GM, Dailey AG, Aylott M, Casella E *et al.*, Modelling supply and demand of bioenergy from short rotation coppice and Miscanthus in the UK. *Bioresource Technol* **101**(21):8132–8143 (2010).

29. Lovett AA, Sünnenberg GM, Richter GM, Dailey AG, Riche AB and Karp A, Biomass production and land use trade-offs revealed by GIS constraint and yield mapping of Miscanthus in England. *Bioenerg Res* **2**(1):17–29 (2009).

30. Clifton-Brown JC, Stampfl PF and Jones MB, Miscanthus biomass production for energy in Europe and its potential contribution to decreasing fossil fuel carbon emissions. *Glob Change Biol* **10**(4):509–518 (2004).

31. Aylott MJ, Casella E, Farrall K and Taylor G, Estimating the supply of biomass from short-rotation coppice in England, given social, economic and environmental constraints to land availability. *Biofuel* **1**(5):719–727 (2010).

32. Tallis MJ, Casella E, Henshall PA, Aylott MJ, Randle TJ, Morison JIL *et al.*, Development and evaluation of ForestGrowth-SRC a process-based model for short rotation coppice yield and spatial supply reveals poplar uses water more efficiently than willow. *GCB Bioenergy* **5**(1):53–66 (2013).

33. Fiorese G and Guariso G, A GIS-based approach to evaluate biomass potential from energy crops at regional scale. *Environ Modell Softw* **25**(6):702–711 (2010).

34. Delzeit R, Britz W and Holm-Mueller K, Modelling regional input markets with numerous processing plants: The case of green maize for biogas production in Germany. *Environ Modell Softw* **32**:74–84 (2012).

35. de Wit M and Faaij A, European biomass resource potential and costs. *Biomass Bioenerg* **34**(2):188–202 (2010).

36. Fischer G, Prieler S, van Velthuizen H, Berndes G, Faaij A, Londo M *et al.*, Biofuel production potentials in Europe: Sustainable use of cultivated land and pastures, Part II: Land use scenarios. *Biomass Bioenergy* **34**(2):173–187 (2010).

37. U.S. EPA, *Renewable Fuel Standard Program (RFS2) Regulatory Impact Analysis*. EPA-420-R-10-006. U.S. Environmental Protection Agency, Washington, DC (2010).

38. Delzeit R, Britz W and Kreins P, *An economic assessment of biogas production and land use under the German Renewable Energy Source Act 2012*. Online: http://www.econstor.eu/bitstream/10419/58280/1/716922266.pdf [June 14, 2013].

39. Smith WK, Cleveland CC, Reed SC, Miller NL and Running SW, Bioenergy potential of the United States constrained by satellite observations of existing productivity. *Environ Sci Technol* **46**(6):3536–3544 (2012).

40. U.S. Department of Agriculure, *USDA Agricultural Projections to 2021*. Online: http://usda01.library.cornell.edu/usda/ers/94005/2012/OCE121.pdf [March 7, 2013].

41. Trostle R, Marti D, Rosen S and Westcott P, *Why Have Food Commodity Prices Risen Again?* Online: http://www.ers.usda.gov/publications/wrs-international-agricultureand-trade-outlook/wrs1103.aspx [March 7, 2013].

42. Larson JA, English BC, Ugarte DGD, Menard RJ, Hellwinckel CM and West TO, Economic and environmental impacts of the corn grain ethanol industry on the United States agricultural sector. *J Soil Water Conserv* **65**(5):267–279 (2010).

43. Callesen I, Grohnheit PE and Ostergard H, Optimization of bioenergy yield from cultivated land in Denmark. *Biomass Bioenerg* **34**(9):1348–1362 (2010).

44. Brooke R, Fogel G, Glaser A, Griffin E and Johnson K, *Corn Ethanol and Wildlife – How Increases in Corn Plantings are Affecting Habitat and Wildlife in the Prairie Pothole Region*. Online: http://www.nwf.org/News-and-Magazines/Media-Center/Reports/Archive/2010/~/media/PDFs/Wildlife/01-13-10-Corn-Ethanol-Wildlife.ashx [February 27, 2013].

45. Richter GM, Agostini F and Costomiris D, *Estimating the Yield Gap in Miscanthus from On-Farm Evaluation of Productivity in the Energy Crop Scheme*. Rothamsted Research, Harpenden, UK, May 2012. Report (2012). Online: http://www.rothamsted.ac.uk/ssgs/reports/ECS_Miscanthus_On-farm_Yield_(Report-to-NE)-1.pdf [June 17, 2013].

46. Holzmueller EJ and Jose S, Biomass production for biofuels using agroforestry: Potential for the North Central Region of the United States. *Agroforest Syst* **85**(2):305–314 (2012).

47. Cai X, Zhang X and Wang D, Land availability for biofuel production. *Environ Sci Technol* **45**(1):334–339 (2011).

48. Kang S, Post W, Wang D, Nichols J, Bandaru V and West T, Hierarchical marginal land assessment for land use planning. *Land Use Policy* **30**(1):106–113 (2013).

49. Renwick A, Jansson T, Verburg PH, Revoredo-Giha C, Britz W, Gocht A *et al.*, Policy reform and agricultural land abandonment in the EU. *Land Use Policy* **30**(1):446–457 (2013).

50. Ericsson K and Nilsson LJ, Assessment of the potential biomass supply in Europe using a resource-focused approach. *Biomass Bioenerg* **30**(1):1–15 (2006).

51. Tuck G, Glendining MJ, Smith P, House JI and Wattenbach M, The potential distribution of bioenergy crops in Europe under present and future climate. *Biomass Bioenerg* **30**(3):183–197 (2006).

52. Verburg PH and Overmars KP, Combining top-down and bottom- up dynamics in land use modeling: Exploring the future of abandoned farmlands in Europe with the Dyna-CLUE model. *Landscape Ecol* **24**(9):1167–1181 (2009).

53. Renewable Fuels Agency, *The Gallagher Review of the Indirect Effects of Biofuels Production*. Online: http://www.bioenergy.org.nz/documents/liquidbiofuels/Report_of_the_Gallagher_review.pdf [February 27, 2013].

54. Dauber J, Brown C, Fernando AL, Finnan J, Kraskuska E, Ponitka J *et al.*, Bioenergy from 'surplus' land: Environmental and socio-economic implications. *BioRisk* **7**:5–50 (2012).

55. Smeets EMW, Paappanen T and Bottcher H, Energy Crops, in *Biomass Resource Assessment Handbook: Harmonisation of Biomass Resource Assessments, Best Practices and Methods Handbook*, ed by Vis M and Dees M. VDM Verland Dr. Muller, Saarbrücken (2011).

56. Fischer RA and Edmeades GO, Breeding and cereal yield progress. *Crop Sci* **50**(2):S85–S98 (2010).

57. Jaggard KW, Qi AM and Ober ES, Possible changes to arable crop yields by 2050. *Philos T Roy Soc B* **365**(1554):2835–2851 (2010).

58. Evans LT and Fischer RA, Yield potential: Its definition, measurement, and significance. *Crop Sci* **39**(6):1544–1551 (1999).

59. Ewert F, Rounsevell MDA, Reginster I, Metzger MJ and Leemans R, Future scenarios of European agricultural land use I. Estimating changes in crop productivity. *Agr Ecosyst Environ* **107**(2/3):101–116 (2005).

60. Launay M and Guerif M, Assimilating remote sensing data into a crop model to improve predictive performance for spatial applications. *Agr Ecosyst Environ* **111**(1/4):321–339 (2005).

61. Tum M and Gunther KP, Validating modelled NPP using statistical yield data. *Biomass Bioenerg* **35**(11):4665–4674 (2011).

62. Haberl H, Beringer T, Bhattacharya SC, Erb KH and Hoogwijk M, The global technical potential of bio-energy in 2050 considering sustainability constraints. *Curr Opin Env Sust* **2**(5/6):394–403 (2010).

63. Al-Kaisi MM, Elmore RW, Guzman JG, Hanna HM, Hart CE, Helmers MJ *et al.*, Drought impact on crop production and the soil environment: 2012 experiences from Iowa. *J Soil Water Conserv* **68**(1):19A–24A (2013).

64. European Environment Agency, *Corine Land cover update, IMAGE2000 and CLC2000 project.* Technical guidelines. (2002). Online: http://www.eea.europa.eu/publications/COR0-landcover/at_download/file [June 14, 2013].

65. Fischer G, Prieler S, van Velthuizen H, Lensink SM, Londo M and de Wit M, Biofuel production potentials in Europe: Sustainable use of cultivated land and pastures. Part I: Land productivity potentials. *Biomass Bioenerg* **34**(2):159–172 (2010).

66. Lubowski RN, Vesterby M, Bucholtz AB and Roberts MJ, *Major Uses of Land un the United States, 2002*. Online: http://www.ers.usda.gov/data/majorlanduses/ [March 7, 2013].

67. European Environment Agency, *The thematic accuracy of Corine land cover 2000. Assessment using LUCAS (land use/cover area frame statistical survey)*. Online: http://www.eea.europa.eu/publications/technical_report_2006_7/at_download/file [March 7, 2013].

68. Aylott MJ, Casella E, Tubby I, Street NR, Smith P and Taylor G, Yield and spatial supply of bioenergy poplar and willow shortrotation coppice in the UK. *New Phytol* **178**(2):358–370 (2008).

69. van Vuuren DP, van Vliet J and Stehfest E, Future bio-energy potential under various natural constraints. *Energ Policy* **37**(11):4220–4230 (2009).

70. Vis MW, Smeets EMW and Rettenmaier N, General approach, in *Biomass Resource Assessment Handbook: Harmonisation of biomass resource assessments, best practices and methods handbook,* ed. Vis M and Dees M. VDM Verland Dr. Muller, Saarbrücken (2011).

71. Castella JC, Kam SP, Quang DD, Verburg PH and Hoanh CT, Combining top-down and, bottom-up modelling approaches of land use/cover change to support public policies: Application to sustainable management of natural resources in northern Vietnam. *Land Use Policy* **24**(3):531–545 (2007).

72. Britz W, Verburg PH and Leip A, Modelling of land cover and agricultural change in Europe: Combining the CLUE and CAPRISpat approaches. *Agr Ecosyst Environ* **142**(1/2):40–50 (2011).

73. Parish ES, Hilliard MR, Baskaran LM, Dale VH, Griffiths NA, Mulholland PJ *et al.*, Multimetric spatial optimization of switchgrass plantings across a watershed. *Biofuel Bioprod Bioref* **6**(1):58–72 (2012).

74. Sohl TL, Sleeter BM, Sayler KL, Bouchard MA, Reker RR, Bennett SL *et al.*, Spatially explicit land-use and land-cover scenarios for the Great Plains of the United States. *Agr Ecosyst Environ* **153**:1–15 (2012).

75. Britz W and Hertel TW, Impacts of EU biofuels directives on global markets and EU environmental quality: An integrated PE, global CGE analysis. *Agr Ecosyst Environ* **142**(1/2):102– 109 (2011).

76. Taheripour F, Tyner WE and Wang MQ, *Global Land Use Changes due to the U.S. Cellulosic Biofuel Program Simulated with the GTAP Model.* Purdue University/ Department of Agricultural Economics, West Lafayette, Indiana, U.S.A. (2011).

77. Nassar AM HL, Bachion LC and Moreira MR, Biofuels and land-use changes: Searching for the top model. *Interface Focus* **1**(2):224–232 (2011).

78. Hertel TW, *Global Trade Analysis, Modeling and Applications*. Cambridge University Press, Cambridge (1997).

79. Taheripour F, Hertel TW, Tyner WE, Beckman JF and Birur DK, Biofuels and their by-products: Global economic and environmental implications. *Biomass Bioenerg* **34**(3):278–289 (2010).

80. Caldiz DO, Gaspari FJ, Haverkort AJ and Struik PC, Agroecological zoning and potential yield of single or double cropping of potato in Argentina. *Agr Forest Meteorol* **109**(4):311–320 (2001).

81. de La Torre Ugarte DG and Ray DE, Biomass and bioenergy applications of the POLYSYS modeling framework1. *Biomass Bioenerg* **18**(4):291–308 (2000).

82. Evans JM, Fletcher RJ and Alavalapati J, Using species distribution models to identify suitable areas for biofuel feedstock production. *GCB Bioenergy* **2**(2):63–78 (2010).

83. Richter GM, Riche AB, Dailey AG, Gezan SA and Powlson DS, Is UK biofuel supply from miscanthus water-limited? *Soil Use Manage* **24**(3):235–245 (2008).

84. Hastings A, Clifton-Brown J, Wattenbach M, Stampfl P, Mitchell CP and Smith P, Potential of miscanthus grasses to provide energy and hence reduce greenhouse gas emissions. *Agron Sustain Dev* **28**(4):465–472 (2008).

85. Price L, Bullard M, Lyons H, Anthony S and Nixon P, Identifying the yield potential of miscanthus x giganteus: An assessment of the spatial and temporal variability of M-x giganteus biomass productivity across England and Wales. *Biomass Bioenerg* **26**(1):3–13 (2004).

86. Zegada-Lizarazu W, Elbersen HW, Cosentino SL, Zatta A, Alexopoulou E and Monti A, Agronomic aspects of future energy crops in Europe. *Biofuel Bioprod Bioref* **4**(6):674–691 (2010).

87. Godfray HCJ, Crute IR, Haddad L, Lawrence D, Muir JF, Nisbett N *et al.*, The future of the global food system. *Philos T R Soc B* **365**(1554):2769–2777 (2010).

88. Beringer T, Lucht W and SchaphoffS, Bioenergy production potential of global biomass plantations under environmental and agricultural constraints. *GCB Bioenergy* **3**(4):299–312 (2011).

89. Haber I H, Gaube V, Diaz-Delgado R, Krauze K, Neuner A, Peterseil J *et al.*, Towards an integrated model of socioeconomic biodiversity drivers, pressures and impacts. A feasibility study based on three European long-term socioecological research platforms. *Ecol Econ* **68**(6):1797–1812 (2009).

90. Villani R, Piccioni E, Ragaglini G, Sabbatini T and Bonari E, GIS-based land suitabililty evaluation for bioenergy chains: A multi-disciplinary approach applied to Mediterranean regions. *15th European Biomass Conference & Exhibition*, 7–11 May, 2007, Berlin, Germany, pp. 222–227 (2007).

91. Delzeit R, Klepper G and Lange M, *Review of IFPRI study: Assessing the land use change consequences of European biofuel polices and its uncertainties*. Online: http://www.ebb-eu.org/EBBpressreleases/Review_iLUC_ IfW_final.pdf [May 12, 2013].

92. Plieninger T, Bens O and Huttl RF, Perspectives of bioenergy for agriculture and rural areas. *Outlook Agr* **35**(2):123–127 (2006).

93. di Virgilio N, Fazio S, Battistel E and Monti A, *Advances in Bidirectional Method for Land Allocation of Energy Crops,* ed by EBCE, 19th European Biomass Conference and Exhibition, 6–10 June 2011, Berlin, Germany (2011).

94. di Virgilio N, Fazio S, Fernando AL and Monti A, *A New Methodolgical Study to Allocate Energy Crops at Different Scale Levels: A Multi-Directional Approach*. 18th European Biomass Conference and Exhibition, Lyon, France 2010.

95. FAO, *The State of Food Insecurity in the World — How Does International Price Volatility Affect Domestic Economies and Food Security*? United Nations, Rome (2011).

96. Trostle R, Marti D, Rosen S and Westcott P, Why have food commodity prices risen again? [Online]. (2012). Online: http://www.ers.usda.gov/publications/wrs-internationalagriculture-and-trade-outlook/wrs1103.aspx [March 7, 2013].

97. Healey NC, Irmak A, Hubbard KG and Lenters JD, Environmental variables controlling site suitability for cornbased ethanol production in Nebraska. *Biomass Bioenerg* **35**(7):2852–2860 (2011).

98. Dai A , Increasing drought under global warming in observations and models. *Nat Clim Change* **3**:52–58 (2013).

99. Peterson TC, Stott PA and Herring S, Explaining extreme events of 2011 from a climate perspective. *B Am Meteorol Soc* **93**(7):1041–1067 (2012).

100. Lee JH, Gryze Sd and Six J, Effect of climate change on field crop production in California's Central Valley. *Clim Change* **109**(1):S335–S353 (2011).

101. Lobell DB, Schlenker W and Costa-Roberts J, Climate trends and global crop production since 1980. *Science* **333**(6042):616–620 (2011).

102. Baffes J and Haniotis T, *Placing the 2006/08 Commodity Price Boom into Perspective* Online: http://www-wds.worldbank.org/external/default/WDSContentServer/IW3P/IB/2010/07/21/000158349_20100721110120/Rendered/PDF/WPS5371.pdf [February 27, 2013].

103. Wiegmann K, Hennenberg KJ and Fritsche UR, *Joint International Workshop on High Nature Valu e Criteria and Potential for Sustainable Use of Degraded Lands, Paris, June 30-July 1, 2008: Degraded Land and Sustainable Bioenergy Feedstock Production*. Online: http://gisthal.ornl.gov/sites/default/files/nagendra/KC_090916160517.pdf [February 27, 2013].

104. Busch G, Future European agricultural landscapes - What can we learn from existing quantitative lan d use scenario studies? *Agr Ecosyst Environ* **114**(1):121–140 (2006).

105. Pontius Jr RG, Huffaker D and Denman K, Useful techniques of validation for spatially explicit land -change models. *Ecol Model* **179**(4):445–461 (2004).

106. Pontius Jr. RG and Schneider LC, Land-cover change model validation by an ROC method for the Ipswic h watershed, Massachusetts, U.S.A. *Agr Ecosys Environ* **85**(1/3):239–248 (2001).

107. Pontius RG and Millones M, Death to Kappa: Birth of quantity disagreement and allocation disagreeme nt for accuracy assessment. *Int J Remote Sens* **32**(15):4407–4429 (2011).

108. Murshed SM, Sliz B, Montemurro F, Vad K, Bauen A, Richter G *et al., BVCM Report on tools and data — Section A: Resource Models and Yield Calculation*. The Energy Technologies Institute, Loughborough, UK (2011).

109. Joint Research Centre, European Soil Database v2.0, in *European Soil Bureau Network E.* (2006). Online: http://eusoils.jrc.ec.europa.eu/library/esdac/esdac_ access2.cfm [June 14, 2013].

110. Rounsevell MDA, Reginster I, Araujo MB, Carter TR, Dendoncker N, Ewert F *et al.*, A coherent set of future land use change scenarios for Europe. *Agr Ecosyst Environ* **114**(1):57–68 (2006).

111. Barney JN and DiTomaso JM, Bioclimatic predictions of habitat suitability for the biofuel switchgrass in North America under current and future climate scenarios. *Biomass and Bioenergy* **34**(1):124–133 (2010).

112. de Castro M, Gallardo C, Jylha K and Tuomenvirta H, The use of a climate-type classification for as sessing climate change effects in Europe from an ensemble of nine regional climate models. *Clim Change* **81**:329–341 (2007).

113. Bailey RG, *Ecosystem Geography: From Ecoregions to Sites, 2nd edition*. Springer, New York (2 009).

114. Richter GM and Semenov MA, Modelling impacts of climate change on wheat yields in England and Wales : Assessing drought risks. *Agr Syst* **84**(1):77–97 (2005).

115. Ferrara RM, Trevisiol P, Acutis M, Rana G, Richter GM and Baggaley N, Topographic impacts on wheat yields under climate change: Two contrasted case studies in Europe. *Theor Appl Climatol* **99**(1/2):53–65 (2010).

116. Li RP and Merchant JW, Modeling vulnerability of groundwater to pollution under future scenarios of climate change and biofuels-related land use change: A case study in North Dakota, U.S.A. *Sci Total Environ* **447**:32–45 (2013).

117. Karp A and Richter GM, Meeting the challenge of food and energy security. *J Exp Bot* **62**:3263–3271 (2011).

118. Karp A and Shield I, Bioenergy from plants and the sustainable yield challenge. *New Phytol* **179**(1):1 5–32 (2008).

119. Stephenson AL, Dupree P, Scott SA and Dennis JS, The environmental and economic sustainability of p otential bioethanol from willow in the UK. *Bioresource Technol* **101**(24):9612–9623 (2010).

120. De Smedt P, Borch K and Fuller T, Future scenarios to inspire innovation. *Technol Forecast Soc Chan ge* **80**(3):432–443 (2013).

121. Freeman C, The national system of innovation in historicalperspective. *Cambridge J Econ* **19**(1):5–24 (1995).

122. Kriegler E, O'Neill BC, Hallegatte S, Kram T, Lempert R, Moss RH *et al.*, *Socioeconomic Scen ario Development for Climate Change Analysis*. Online: http://www.centre-cired.fr/IMG/pdf/CIREDWP-201023.pdf [22 May 2013].

123. Malins C, A model-based quantitative assessment of the carbon benefits of introducing iLUC factors in the European Renewable Energy Directive. *GCB Bioenergy* (2013). Online: http://onlinelibrary.wiley.com/journal/10.1111/(ISSN)1757-1707/earlyview [May 22, 2013].

124. Dweikat I, Weil C, Moose S, Kochian L, Mosier N, Ileleji K *et al.*, Envisioning the transition to a next-generation biofuels industry in the U.S. Midwest. *Biofuel Bioprod Bioref* **6**(4):376– 386 (2012).

125. EU IP/12/1112, New Commission proposal to minimise the climate impacts of biofuel production. Online: http://europa.eu/rapid/press-release_IP-12-1112_en.htm.accessed [June 14, 2013].

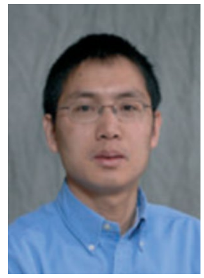
126. Richard TL, Challenges in Scaling Up Biofuels infrastructure. *Science* **329**(5993):793–796 (2010).

127. FAO, Global Agro-Ecological Zones. Online: http://www.fao.org/nr/gaez/en/ [June 14, 2013].

Ruopu Li
Dr. Ruopu Li is an Adjunct Assistant Professor in the School of Natural Resources at University of Nebraska– Lincoln (UNL) where he teaches Advanced Geographic Information Systems. He received his PhD degree in natural resource sciences with speciality in geographic information sciences (GIS) from UNL. His research interests include land-use change modeling, groundwater vulnerability assessment, LiDAR-based hydrologic analysis, water resource planning. Dr. Li is currently working as a researcher at the state Department of Natural Resources, Nebraska, U.S.A. He is member of the American Geophysical Union (AGU) and the Association of American Geographers (AAG).

Nicola Di Virgilio
Dr. Nicola Di Virgilio is a researcher at the Institute of Biometeorology of the National Research Council of Italy (CNR-IBIMET). He holds a PhD *Europaeus* at University of Bologna in sustainability of Agro-ecosystems, GIS for environmental studies and LCA of agricultural products and agro-energy chains for a sustainable land use. He graduated *cum laude* at the Agricultural Faculty of the University of Bologna. His research topics include use of GIS (Geographical Information Systems) for environmental studies and relation of crop yield with environmental factors; land suitability studies of crops, land vulnerability. Life Cycle Assessment (LCA) tools in agriculture. Dr. Di Virgilio is a member of the Preparation team of the Plaftorm 'Land and Water Management and Engineering' (Climate-KIC) and a member of the CCPB working group on the Evaluation of impacts and renewable energy during life time of agro-food products and agro-energies.

Qingfeng Guan
Dr. Qingfeng Guan is Professor at the Faculty of Information Engineering at China University of Geosciences, and also an Adjunct Assistant Professor at the School of Natural Resources at the University of Nebraska–Lincoln. He holds a PhD in Geography from the University of California, Santa Barbara. A member of the Association of American Geographers (AAG), Cartography and Geographic Information Science (CaGIS), his research topics include geographic information systems (GIS) and science (GIScience), land-use and land-cover change, human-environment relationships and interactions.



Song Feng
Dr. Song Feng is a climatologist/ research assistant professor at the School of Natural Resources at the University of Nebraska–Lincoln (UNL), U.S.A. He received his PhD in atmospheric sciences in China in July 1999 and has worked at UNL since December 1999. His research interests encompass past, present, and future climate changes and impacts using global and regional climate models and advanced statistical methods. More specifically, his research can be summarized in the following three areas: 1) climate changes and physical mechanisms on regional and continental scales; 2) climate change and its impacts on water sustainability and agriculture; 3) paleoclimate change and variability.

Goetz M Richter
Dr. Goetz Richter is a Senior Scientist in the Department of Sustainable Soils and Grassland Systems, at Rothamsted Research. Rooted in Agricultural and Environmental Science his key area is the soil-plant-atmosphere interaction. Within the Institute's Strategic Program "Carbon Cropping" he leads a group of natural scientists and mathematical modelers to optimize the plant-environment system. Key achievements are the implementation, evaluation and scaling of generic process-based models for arable and perennial crops within an agro biophysical modelling framework. His group works on understanding the phenotype-environment interaction (including exploiting the genomic information), optimizing crop carbon management and assessing productivity at the landscape-scale.