AGRICULTURAL ECONOMICS

Agricultural Economics 45 (2014) 103–116

Impacts of increased bioenergy demand on global food markets: an AgMIP economic model intercomparison

Hermann Lotze-Campen[a,*], Martin von Lampe[b], Page Kyle[c], Shinichiro Fujimori[d], Petr Havlik[e], Hans van Meijl[f], Tomoko Hasegawa[d], Alexander Popp[a], Christoph Schmitz[a], Andrzej Tabeau[f], Hugo Valin[e], Dirk Willenbockel[g], Marshall Wise[c]

[a]*Potsdam Institute for Climate Impact Research (PIK), Telegrafenberg A 31, 14473, Potsdam, Germany*
[b]*Trade and Agriculture Directorate (TAD), Organisation for Economic Co-operation and Development (OECD), 2 rue André Pascal, 75775, Paris Cedex 16, France*
[c]*Joint Global Change Research Institute, Pacific Northwest National Laboratory, 5825 University Research Court, Suite 3500, College Park, MD 20740, USA*
[d]*National Institute for Environmental Studies (NIES), Center for Social & Environmental Systems Research, 16-2 Onogawa, Tsukuba, Ibaraki, 305-8506, Japan*
[e]*Ecosystems Services and Management Program, International Institute for Applied Systems Analysis (IIASA), Schlossplatz 1, 2361, Laxenburg, Austria*
[f]*Agricultural Economics Research Institute (LEI) Wageningen University and Research Centre, 2585 DB, The Hague, The Netherlands*
[g]*Institute of Development Studies, University of Sussex, Brighton BN1 9RE, United Kingdom*

Received 3 March 2013; received in revised form 28 August 2013; accepted 20 September 2013

Abstract

Integrated Assessment studies have shown that meeting ambitious greenhouse gas mitigation targets will require substantial amounts of bioenergy as part of the future energy mix. In the course of the Agricultural Model Intercomparison and Improvement Project (AgMIP), five global agro-economic models were used to analyze a future scenario with global demand for ligno-cellulosic bioenergy rising to about 100 ExaJoule in 2050. From this exercise a tentative conclusion can be drawn that ambitious climate change mitigation need not drive up global food prices much, if the extra land required for bioenergy production is accessible or if the feedstock, for example, from forests, does not directly compete for agricultural land. Agricultural price effects across models by the year 2050 from high bioenergy demand in an ambitious mitigation scenario appear to be much smaller (+5% average across models) than from direct climate impacts on crop yields in a high-emission scenario (+25% average across models). However, potential future scarcities of water and nutrients, policy-induced restrictions on agricultural land expansion, as well as potential welfare losses have not been specifically looked at in this exercise.

JEL classifications: C61, C68, Q11, Q16, Q42

Keywords: Energy demand; Agricultural markets; General equilibrium modeling; Partial equilibrium modeling; Model comparison

1. Introduction

Future scenarios from Integrated Assessment and energy modeling studies (Calvin et al., 2012; Clarke et al., 2009; Popp et al., 2011; van Vuuren et al., 2010a) have shown that meeting ambitious mitigation targets with respect to global greenhouse gas (GHG) emissions requires substantial amounts of bioenergy as part of the future energy mix. Especially in the longer term, bioenergy from ligno-cellulosic feedstocks may become relevant for reducing carbon emissions in the transportation sector, as other technical low-emission options are relatively expensive. This has been shown in various studies on the future energy mix (Azar et al., 2010; Luckow et al., 2010; Luderer et al., 2012; van Vuuren et al., 2010b) and indicated by the International Energy Agency (IEA, 2004). But various forms of bioenergy are also attractive for other energy conversion pathways, as they are easily storable and can be transformed into various forms of secondary and final energy such as liquid fuel, electricity, and hydrogen (Luderer et al., 2012). Currently, bioenergy production worldwide is dominated by first-generation transport biofuels, like ethanol from sugar cane, grains and sugar beets, or bio-diesel from oil crops. These conversion technologies are readily available and national mandates for blending biofuels

*Corresponding author. Tel.: +49-331-288-2699; fax: +49-331-288-2600. *E-mail address*: lotze-campen@pik-potsdam.de (H. Lotze-Campen).

Data Appendix Available Online

A data appendix to replicate main results is available in the online version of this article.

 DOI: 10.1111/agec.12092

with fossil fuels have favored their strong rise in production in recent years (Chum et al., 2011).

While medium-term trends in first-generation biofuel demand are taken into account, the focus of this particular article is on the longer term development of bioenergy demand, based on ligno-cellulose as the primary input. Within the next few decades, energy sector studies suggest that new technologies will emerge for converting different types of ligno-cellulosic biomass into transportation fuel and other types of secondary energy carriers (Calvin et al., 2012; Luderer et al., 2012). If GHG emissions were priced at a certain level and if technologies like the Fischer–Tropsch process were to become competitive, this would open up a much larger potential for bioenergy feedstocks. According to several estimates, global demand for ligno-cellulosic bioenergy would need to rise to about 100 ExaJoule (EJ) in 2050 (Calvin et al., 2012; Popp et al., 2011) if global warming is to be held at about 2°C above pre-industrial levels (comparable with a representative concentration pathway RCP2.6 (Moss et al., 2010).

First-generation biofuel use has a direct impact on food markets, as fuel production competes with food and feed production for basically the same raw products and inputs. Various studies have pointed to these market effects as well as impacts on land-use change and the environment, as biofuel demand induces additional pressure on agricultural markets, which have often sustained long periods of strain during the past decade (Clarke et al., 2009; van Vuuren et al., 2010a). It has also been shown that for first-generation biofuels specific GHG savings are rather low and marginal abatement costs are rather high (OECD, 2008).

Possible feedstocks for ligno-cellulosic bioenergy would not only include crop and forest residues, wastes, but also purpose-grown grasses (e.g., miscanthus, switch grass) or fast-growing trees (e.g. poplar, willow, eucalyptus; Chum et al., 2011). Potential energy yields per ha for ligno-cellulosic bioenergy crops are much higher than for current agricultural crops, except for sugar cane (Havlik et al., 2011). For instance Woods et al. (2010) show switch grass yields of about 180 GJ/ha, while ethanol from winter wheat is accounted as about 90 GJ/ha. The global technical potential for ligno-cellulosic bioenergy is estimated at about 100–400 EJ (Chum et al., 2011). While uncertainty about these estimates is still high, it is clear that these amounts could provide a considerable share of total energy use by the middle of the 21st century and beyond. The economic potential has been estimated at around 100 EJ in 2050 (Popp et al., 2011).

In this article we show to what extent a strong increase in ligno-cellulosic bioenergy deployment may affect agricultural markets and land-use change. As part of the Agricultural Model Intercomparison and Improvement Project (AgMIP, www.agmip.org; von Lampe et al., 2014), five global economic models with a focus on agricultural production, trade, and land use have been applied to analyze a future scenario with strongly rising bioenergy demand until the year 2050. As part of the AgMIP economic model intercomparison, we also compare the specific impacts of bioenergy demand to the direct impacts of climate change on crop yields and productivity.

2. Methods: overview of participating models and scenarios

2.1. Model descriptions

Five very different models have participated in this model comparison. They include two computable general equilibrium (CGE) models and three partial-equilibrium (PE) models. The AIM model is primarily used for Integrated Assessment studies of climate change and climate policy issues. The MAGNET model has a focus on the links between agricultural markets and the general economy as well as detailed analyses of agricultural policy issues. In previous studies, it has also been linked to the IMAGE Integrated Assessment model. The GCAM model has a PE representation of agricultural and energy markets as part of a wider Integrated Assessment framework. GLOBIOM and MAgPIE are both PE mathematical programming models with a focus on spatially explicit land use and land-use change analyses. They explicitly link biophysical constraints on land and water availability as well as crop yields with the economics of agricultural production and trade. GLOBIOM is the only model with a detailed representation of the forestry sector. Both GLOBIOM and MAgPIE have also been used for Integrated Assessment studies, linked to energy–economy models. This diversity of models should make sure that the "model uncertainty" of the results, due to different processes and parameterizations, can be explored to some degree in the analysis. The specific implementation of agricultural land expansion into currently unused land across the models is described in Schmitz et al. (2014).

2.2. Asia-Pacific Integrated Model (AIM)

AIM (the Asia-Pacific Integrated Model) is a CGE model used for the analysis of global and national CO_2 emissions, mitigation costs, or carbon taxes. The base year data for 2005 are assembled and reconciled by the model development team, based on the GTAP database, national accounts, industrial statistics, and energy balance tables (Fujimori and Matsuoka, 2011). Production is captured by multinested structures, and CES (constant elasticity substitution) functions are mainly used. Demand is represented by LES (linear expenditure system) functions, income elasticities are derived from FAO projections. Land is classified into three types of AEZs (agro-ecological zones). The inputs for each production activity, the aggregated land, and three specific types of land are nested by a logit function. The land owner, that is, the aggregate household, decides on the share of land use allocated to cropland, pasture, and forest land. Natural forest and grassland are assumed to be available for agricultural use. The land share decision is also made by a logit function.

2.3. MAGNET

The MAGNET model is a multiregional, multisectoral, static, applied general equilibrium model based on neoclassical microeconomic theory. It is an extended version of the standard GTAP model (van Meijl et al., 2006), which is characterized by an input–output structure, based on regional and national input–output tables, that explicitly links industries in a value-added chain from primary goods, over continuously higher stages of intermediate processing, to the final assembling of goods and services for consumption. MAGNET uses a multilevel nested CES production function. In the primary value-added nest, the multilevel CES production function describes the substitution of different primary production factors (land, labor, capital, and natural resources) and intermediate production factors (e.g., energy and animal feed components). The CES nest is also introduced to allow for substitution between different energy sources including biofuels (Banse et al., 2008). The model uses fixed input–output coefficients for the remaining intermediate inputs. Land and natural resources are heterogeneous production factors, and this heterogeneity is introduced by using a CET transformation function, which allocates these factors among the agricultural sectors. Capital and labor markets are segmented between agriculture and nonagriculture. Labor and capital are assumed to be fully mobile within each of these two groups of sectors, but imperfectly mobile across them. This leads to differences in prices of capital and labor between agriculture and nonagriculture. This is implemented by using a linear dynamic agricultural employment equation in the model, which explains the agricultural employment growth by agricultural relative to nonagricultural wages and total factor supply (Tabeau and Woltjer, 2010). This relationship is consistent with the theoretical Harris and Todaro's (1970) model describing rural–urban migration, which asserts that rural to urban migration rate will be zero when the expected rural income equals the expected urban income.

2.4. Global Change Assessment Model (GCAM)

GCAM (Clarke et al., 2009; Edmonds and Reilly, 1985) is an Integrated Assessment model of energy, agriculture, and climate that has been used extensively by the IPCC, US government agencies, and the research community. GCAM is a dynamic-recursive partial equilibrium model that uses physical-based representations of the various technologies, crops, resources, and land being modeled. As implemented in the present study, GCAM includes 16 geopolitical regions, and 173 agriculture and land-use regions, defined by the intersection of the geopolitical regions with the 18 GTAP AEZ types (Monfreda et al., 2009). The agricultural and land-use component is documented in Wise and Calvin (2011) and Kyle et al. (2011). In summary, land use is calibrated to the base year 2005, and in future periods is allocated among different uses according to relative land profit rates, using a nested logit choice formulation. This approach assumes a distribution of profits for each land-use type (in contrast to constrained linear optimization, for example). In the future periods, land allocated to ligno-cellulosic bioenergy production within any agricultural region and time period depends on its profitability compared with other land uses (both commercial and noncommercial). The profitability of bioenergy production is influenced in turn by endogenous bioenergy demands, which include production of electricity, liquid fuels, and heat.

2.5. Global Biosphere Management Model (GLOBIOM)

GLOBIOM (Havlik et al., 2013) is a partial equilibrium model that covers the agricultural and forestry sectors, including the bioenergy sector. It is used for analyzing medium- to long-term land-use change scenarios. In GLOBIOM, the world is divided into 30 economic regions, in which a representative consumer is modeled through a set of isoelastic demand functions. The spatial resolution of the supply side relies on the concept of simulation units, which are aggregates of 5–30 arcmin pixels belonging to the same altitude, slope, and soil class within a single country. For crops, grass, and forest products, Leontief production functions covering alternative production systems are calibrated on the basis of biophysical models like EPIC (Williams, 1995). For the present study, the supply side spatial resolution was aggregated to 120 arcmin (about 200 $\times$ 200 km at the equator). GLOBIOM incorporates a particularly detailed representation of the global livestock sector distinguishing between several alternative production systems. Six land cover types are explicitly considered: cropland, grassland, short-rotation tree plantations, managed forest, unmanaged forest, and other natural vegetation. Depending on the relative profitability of the individual activities and on the inertia constraints, the model can switch from one land cover type to another. Economic optimization is based on the spatial equilibrium modeling approach (Takayama and Judge, 1971). The price–quantity equilibrium is computed as in McCarl and Spreen (1980) at the regional level. The model is calibrated to year 2000 FAOSTAT activity levels and is then recursively solved in 10-year time steps.

2.6. Model of Agricultural Production and its Impact on the Environment (MAgPIE)

MAgPIE is a nonlinear recursive-dynamic optimization model for global land and water use (Lotze-Campen et al., 2011; Popp et al., 2011; Schmitz et al., 2012). MAgPIE links regional economic information with grid-based biophysical constraints simulated by the dynamic vegetation and hydrology model LPJmL (Bondeau et al., 2007). The model considers spatially explicit patterns of production, land-use change, and water constraints in different world regions, consistently linking economic development with food and energy demand. Ten world regions represent the demand side of the model. Required calories for the demand categories (food and nonfood energy intake) are determined by a cross-sectional country regression based on population and income projections. The model has a cost-minimization objective function. In order to fulfill food, feed, and bioenergy demand, the model allocates 19 cropping and 5 livestock activities to the spatially explicit land and water resources, subject to resource, management, and cost constraints. MAgPIE has three options to increase total production in agriculture at additional costs: agricultural land expansion, spatial crop re-allocation, and an endogenous mode for agricultural intensification. The model takes four different cost types into account: production costs for crop and livestock production, investments in technological change, land conversion costs, and intraregional transport costs.

2.7. Regional aggregation

All five models use different aggregations from countries to economic world regions. For comparability of results, regional aggregations for reporting of model outputs have been harmonized as much as possible. The overall AgMIP economic model comparison distinguishes 13 world regions. For this bioenergy study, we focus on eight different regional aggregates that can be well compared across the five models: CHN—China, EUR—Europe, FSU—Former Soviet Union, MEN—Middle East and North Africa, NAM—North America, OAM—Other America, SEA—Southeast Asia, SSA—sub-Saharan Africa.

2.8. Technological change in agriculture

The treatment of future productivity changes in agriculture in the different models is important, as it determines the ability of the agricultural sector to adjust to increased bioenergy demand. All models, except MAgPIE, use a harmonized series of exogenous productivity shifters for all major crops, which has been provided by the IMPACT modeling group (Rosegrant and IMPACT Development Team, 2012; von Lampe et al., 2014). Next to these exogenous shifters, each model has different options for factor substitution in production, which may lead to varying trends in effective yield changes over time. The MAgPIE model, by contrast, uses an exogenously fixed trajectory of food demand, and derives an endogenous rate of agricultural productivity increase (Schmitz et al., 2012).

2.9. Scenario description and implementation of bioenergy demand

The focus of this study is on the effects of large-scale ligno-cellulosic bioenergy deployment in the energy sector. Hence, we compare a scenario with strong increase in ligno-cellulosic bioenergy demand (S8) to a reference scenario for the period 2005–2050 where ligno-cellulosic bioenergy does not enter the market beyond the level of the base year 2005 (S7). The scenario numbers are part of the nomenclature of the overall AgMIP economic model comparison, as described in von Lampe et al. (2014). Population and GDP growth in both scenarios are in line with the shared socioeconomic pathway SSP2 (Kriegler et al., 2012). In order to analyze the isolated effects of bioenergy use on agricultural markets, both scenarios in this study do not account for direct climate impacts on crop productivity. Other relevant scenarios in the overall model comparison include a reference scenario S1 as well as four climate impact scenarios (S3–6; see von Lampe et al., 2014 and Nelson et al., 2014 for more details).

The demand for first-generation biofuels used in the AgMIP exercise is the same in both scenario S7 and S8. Due to different model implementations, it has not been fully harmonized across models, but is generally based on the political commitments from different countries to incorporate a certain share or an absolute quantity of liquid biomass into their fossil fuel mix for transportation. Total demand for first-generation bioenergy, which is mainly determined by public policy measures, rises to about 6 EJ of final energy globally in 2030 (Table A1). The support programs taken into account are mainly the USA Renewable Fuel Standards (RFS2) and the EU Renewable Energy Directive. Precise analysis of the first-generation targets corresponding to these programs can be found in Mosnier et al. (2012) for the United States or in Laborde and Valin (2012) for the EU. For Brazil, we assume that the current incorporation share is maintained, and the biofuel policy development is driven by the growing demand for transportation fuel (Crago et al., 2010). Other developments that are taken into account include the recent expansion of biodiesel in Argentina, Canada, and China, based on information from the USDA Foreign Agricultural Service. All these programs provide information on current development and mid-term projections (up to 2020 for EU and 2022 for USA). We make the assumption that these programs follow their expansion trend until 2030. Due to political and scale economy considerations, first-generation biofuel demand after 2030 is kept constant rather than phased out (Babcock et al., 2011). Hence, all market, price and land-use effects in the scenario S7 already include the impacts of the projected development of first-generation biofuel mandates in major world regions.

The total global ligno-cellulosic bioenergy production in 2050, in terms of primary energy content, is intended to be consistent with a wide range of scenarios focused on emission mitigation, documented in the recent IPCC Special Report on Renewables (Fischedick et al., 2011). The total used here is approximately the mean of studies examining long-term stabilization of CO_2 concentrations between 440 and 600 parts per million by volume (ppmv). The demand for ligno-cellulosic bioenergy in scenario S8 is derived from an Integrated Assessment scenario exercise by the GCAM group (Calvin et al., 2012). Global demand is expected to rise to 108 EJ in 2050 (Table 1). These figures are in line with a very ambitious climate policy scenario to limit global warming at about 2°C above pre-industrial levels (comparable to RCP2.6; Calvin et al., 2012; van Vuuren et al., 2010b). This scenario can be considered

Table 1
Future trends in ligno-cellulosic bioenergy demand (Scenario S8) (ExaJoule primary energy)

Region	2005	2010	2020	2030	2040	2050
CHN	0.0	0.0	2.0	7.8	11.7	16.7
EUR	0.0	0.0	3.3	8.1	9.7	11.1
FSU	0.0	0.0	3.3	13.5	21.8	32.2
MEN	0.0	0.0	1.3	5.2	8.1	11.3
NAM	0.0	0.0	2.2	10.3	15.5	22.4
OAM	0.0	0.0	0.1	0.3	0.5	0.8
SEA	0.0	0.0	0.3	1.0	1.5	2.1
SSA	0.0	0.0	0.1	0.5	0.8	1.0
Other	0.0	0.0	1.2	5.0	7.5	10.4
WLD	0.0	0.0	13.7	51.8	76.9	107.8

Source: See text for explanation.

as a high-level scenario with respect to the impacts of energy emission mitigation on the agricultural sector. The regional allocation of demand is predefined by the GCAM model and used as a harmonized input by the other models.

The demand trajectory for bioenergy has been implemented in different ways in the five models. In the AIM model, the level of bioenergy demand is endogenously adjusted by the choice of an appropriate carbon price. All other models take the bioenergy demand trajectory as an exogenous driver for the agricultural sector. GLOBIOM and MAgPIE implement bioenergy as an additional demand component. As this is not an option in the CGE model MAGNET, here the amount of ligno-cellulosic bioenergy, as provided by the GCAM model, is translated into an additional demand for land for production, which is subtracted from the total agricultural land endowment.

Ligno-cellulosic bioenergy can be produced from specific grass or tree crops or from forest or other residues, but not all of these production modes are available in all models. In the present GLOBIOM version, ligno-cellulosic bioenergy can be produced from woody biomass, which comes either from dedicated short-rotation tree plantations, from traditional forests as a by-product of saw-log harvesting or as a single-purpose harvest, or from sawmill residues. In MAgPIE, ligno-cellulosic bioenergy can only be produced with short-rotation tree plantations or different types of energy grasses (e.g., miscanthus). In GCAM, the following ligno-cellulosic bioenergy sources are included: short-rotation woody species (eucalyptus, willow), several perennial grass species (switchgrass, miscanthus), and a drought-tolerant oil crop (Jatropha) for some arid regions. In this study, the GCAM output for land area and production does not include the use of residues from crops, forestry, or milling. The AIM model implements two types of ligno-cellulosic bioenergy. One is produced from crop or wood wastes and the other from energy grasses. In all models, except AIM, ligno-cellulosic biomass can be traded internationally.

3. Results

The key results we report are changes in world market prices, regional market prices, land-use change, as well as food and feed consumption by the year 2050. In terms of agricultural commodities, the focus is on five major agricultural crop groups, that is, wheat (WHT), coarse grains (CGR), rice (RIC), sugar crops (SUG), and oilseeds (OSD), as well as the aggregate of these (CR5). In terms of land use, we distinguish between total cropland (CRP), pasture land (PAS), and ligno-cellulosic bioenergy land.

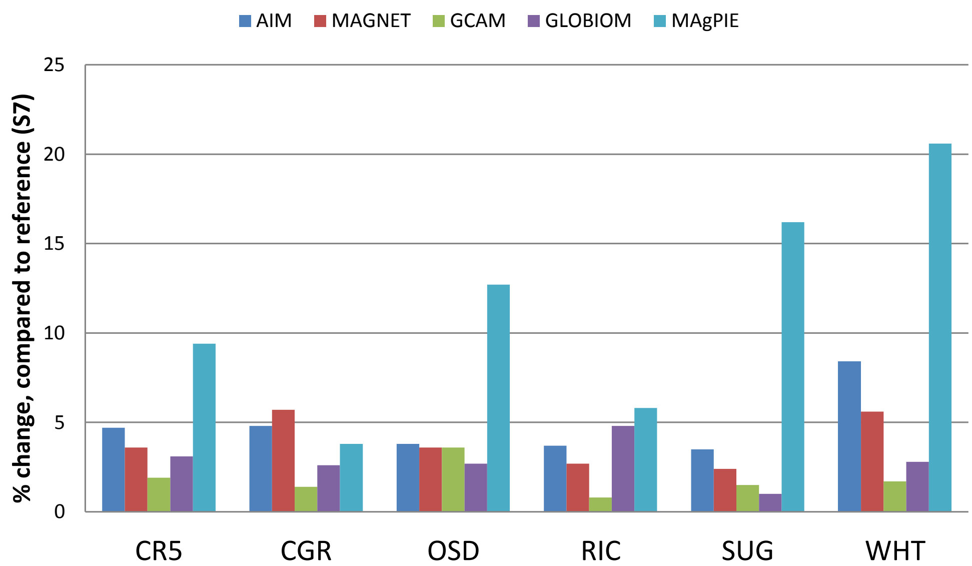
The five models react differently to reference scenario drivers, like population and income growth, due to different implementations of demand, productivity changes, factor substitution in production, and international trade in food, feed, and bioenergy. For the reference scenario S1 and the no-bioenergy scenario S7, MAGNET, GCAM, and GLOBIOM show either flat or slightly falling world market prices by 2050, compared to 2005 (for more details see Robinson et al., 2014). By contrast, the MAgPIE model shows price increases of 54% for CR5, while AIM shows lower price increases at about 20%.

Increased bioenergy demand in scenario S8 causes world market prices for the aggregate CR5 to increase by 2–9%, compared to S7 (Fig. 1). MAgPIE shows the highest average price effect, and GCAM the lowest. The average price increase across models is about 5%, compared to scenario S7. MAgPIE also shows the strongest price increase for most single crops, going as high as 21% for WHT. Price spreads are especially large for OSD, SUG, and WHT.

While average world market price effects for CR5 are rather small, there is more variation across the models at the regional level (Fig. 2). The highest price effects are shown for Europe by MAgPIE (+39%) and AIM (+22%), and for FSU and NAM (+25%) by MAgPIE. AIM even projects falling prices in CHN (−2%), FSU (−9%), and SSA. The variance across models is largest for EUR, FSU, and NAM. The related changes in net trade are provided in Fig. A1.

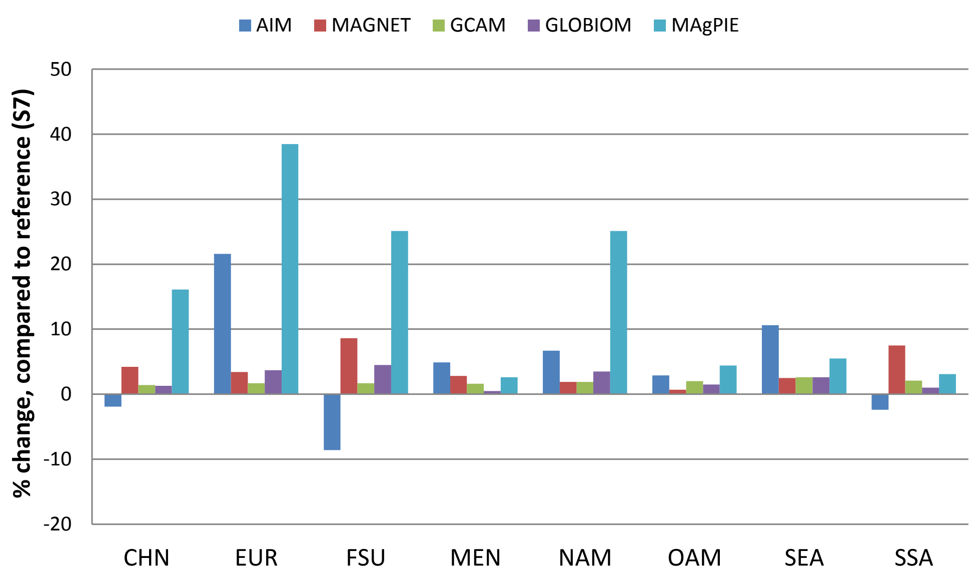
In Fig. 3, the overall modest price effects for CR5 in the ligno-cellulosic bioenergy scenario S8 are compared with the overall price effects from the climate change scenarios (S3–6) in the model comparison (von Lampe et al., 2014). The average price effect of direct climate impacts on crop yields (across four different crop model inputs) for a strong climate signal (see Nelson et al., 2014) is much stronger. With the exception of the GCAM model (+5%), all models show a climate-induced price effect by 2050 of between +22% (AIM) and +47% (MAgPIE). The average effect across models is about +25% for the climate change scenarios S3–6, compared to about +5% in the bioenergy scenario S8.

The five models adjust very differently to provide the resources for producing 108 EJ of primary energy from ligno-cellulosic biomass. Figure 4 shows for the year 2050 the global area changes for cropland (CRP), pasture land (PAS), ligno-cellulosic bioenergy, and other land use and cover types. It must be remembered that CRP only includes land for food,



Source: AgMIP model calculations.

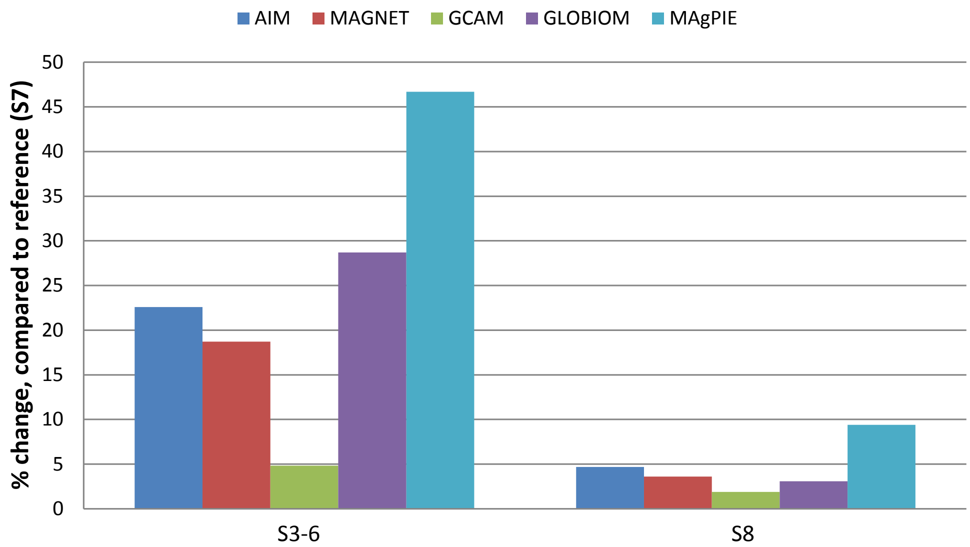
Fig. 1. Bioenergy-induced change in world market prices in 2050 (S8 compared to S7, %).



Source: AgMIP model calculations.

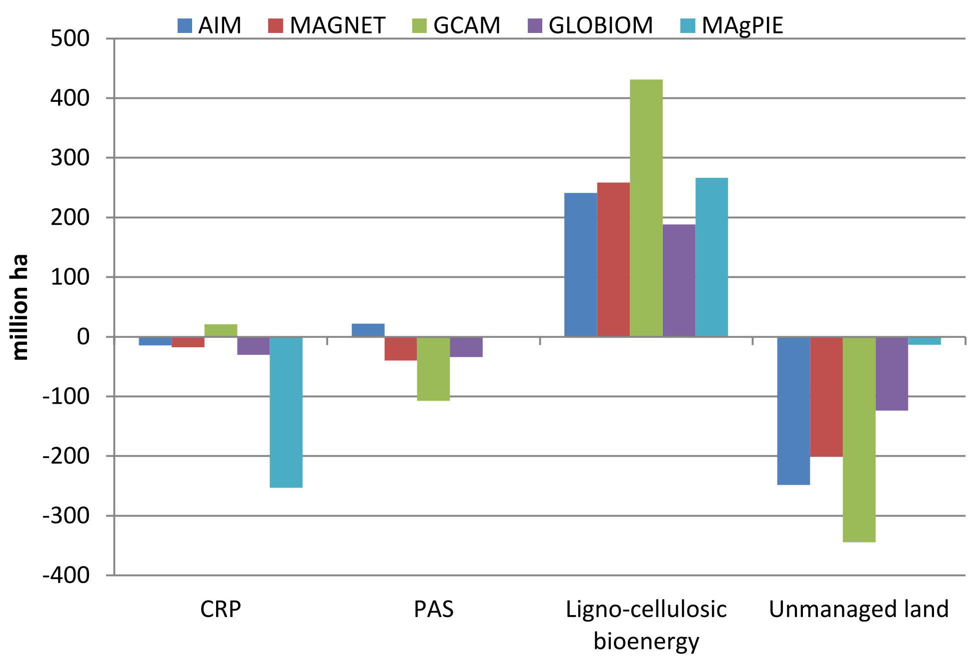
Fig. 2. Bioenergy-induced change in regional market prices in 2050 (CR5, S8 compared to S7, %).

feedstuffs, and first-generation bioenergy production, and thus is strictly separated from ligno-cellulosic bioenergy land. The models allocate between 188 million ha (GLOBIOM) and 431 million ha (GCAM) to ligno-cellulosic bioenergy production. In GLOBIOM, only about 70% of the primary energy is satisfied from dedicated cellulosic bioenergy crops. The other 30% come from forests and forest industry residues (the related area is not reported here). In GLOBIOM, the additional land for bioenergy is partly provided by reducing cropland by 27 million ha and pasture land by 30 million ha. The remaining 131 million ha come from previously unmanaged land. Pasture land is also reduced by 40 million ha in MAGNET and 110 million ha in GCAM. While in MAgPIE pasture land is fixed in the standard implementation, cropland is reduced by 238 million ha by increasing crop productivity (see later). This accounts for almost all the required bioenergy area, so only about 30 million ha is taken from previously unmanaged land in this model. MAGNET, AIM, and GCAM require between 200 and 340 million ha of additional land. The apparently counterintuitive small global increases in CRP by GCAM and PAS by AIM can be explained by the specific regional composition of land-use change effects (see Figs. 6 and 7).



Source: AgMIP model calculations.

Fig. 3. Changes in world market prices in 2050: Climate shock (S3–6 compared to S1) versus bioenergy shock (S8 compared to S7; CR5, %).



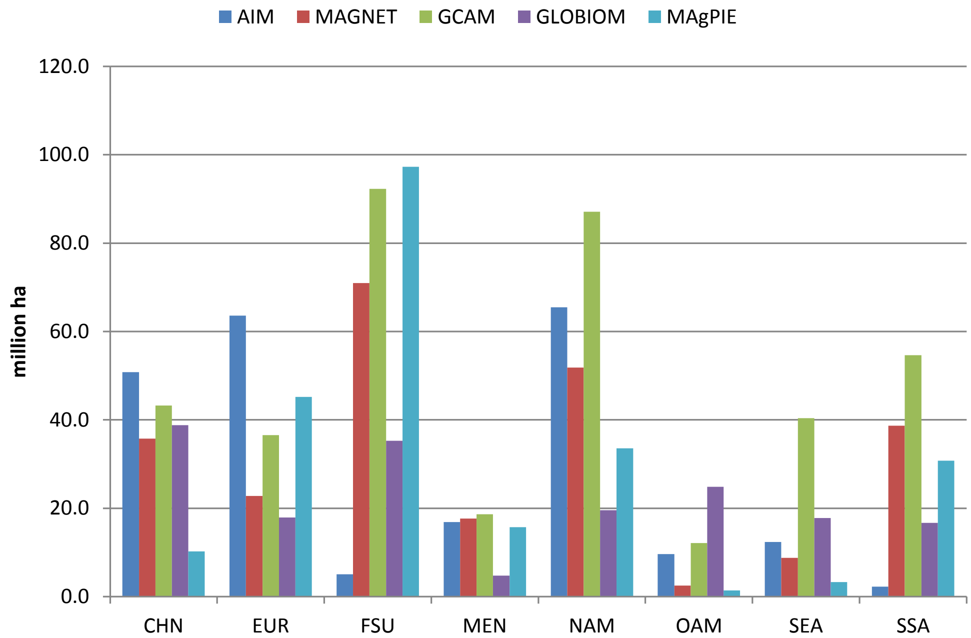
Source: AgMIP model calculations.

Note: Changes in unmanaged land are calculated residually from changes in crop, pasture, and ligno-cellulosic bioenergy land.

Fig. 4. Changes in global land use in 2050 (S8 compared to S7, million ha).

Regional allocation of ligno-cellulosic bioenergy production is also very different across models (Fig. 5). The largest variance across models can be observed in CHN and FSU, while in OAM and especially in MEN the variance is much lower. MAgPIE shows the largest area in FSU, while GCAM allocates large shares of bioenergy area to FSU, NAM, and SSA. AIM shows high shares in CHN, EUR, and NAM.

Figures 6 and 7 show relative changes in cropland and pasture land across regions. MAgPIE shows reduction of cropland by more than 20% in EUR, FSU, and MEN. GCAM projects increases in cropland of between 9% and 16% in SSA, SEA, and OAM. AIM shows cropland increases of about 12% in FSU. The highest variance across models is revealed in FSU and MEN.



Source: AgMIP model calculations.

Fig. 5. Regional area of ligno-cellulosic bioenergy in 2050 (million ha).

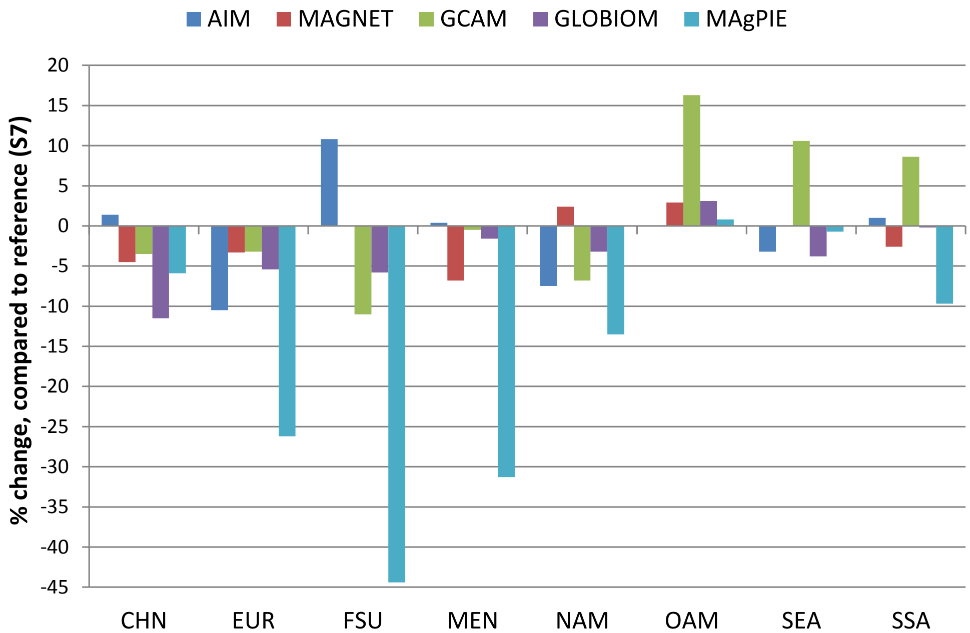
In AIM, GCAM, MAGNET, and GLOBIOM, pasture land is reduced in almost all regions, to allow for bioenergy production. The strongest reductions occur in GCAM in NAM, SEA, and EUR at minus 8–11%, and in GLOBIOM in EUR and FSU at minus 6–9%. Pasture land is increased by MAGNET in OAM, and by AIM in CHN. In MAgPIE, pasture is constant in the current implementation. Variance across models is highest in SEA, EUR, and FSU.

Another option for adjustment in the agricultural sector to allow for additional bioenergy production is through reduction in food and feed demand. While total food demand is determined by an exogenous trend in MAgPIE, GCAM has inelastic demand for crops, but allows for some flexibility in demand for livestock products. All other models react with a reduction in food demand to the additional bioenergy pressure in scenario S8. Figure 8 illustrates this for CR5 demand for food, which is reduced between 0% and 1.1% across models. Demand for CR5 as livestock feed is reduced between 0.1% and 1.6%. Here, also MAgPIE shows small internal adjustments in the composition of livestock feed.

4. Discussion

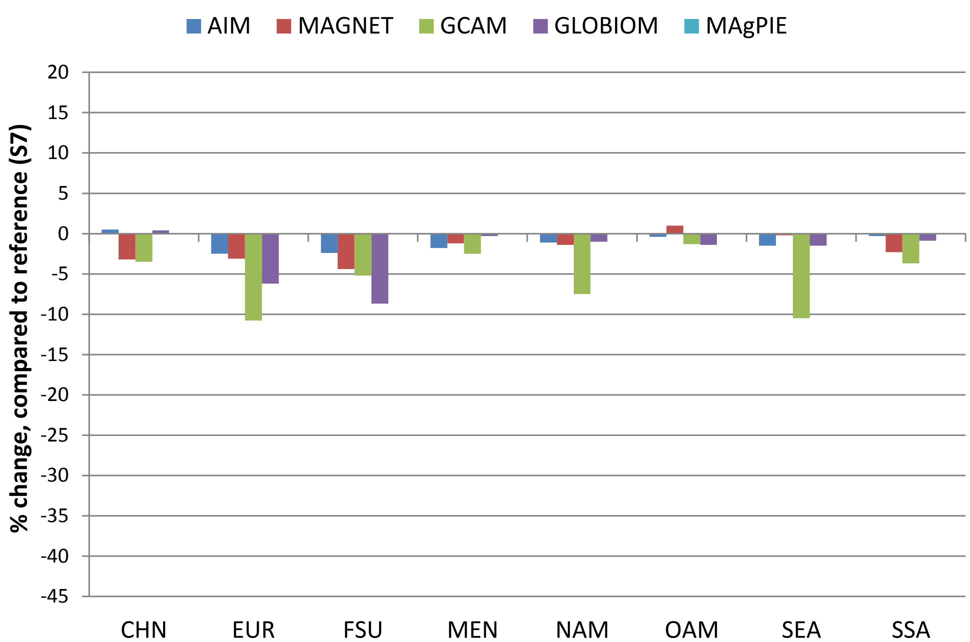
Meeting ambitious climate change mitigation targets may require substantial amounts of bioenergy as part of the future energy mix. The potential for reducing GHG emissions can even be increased, if bioenergy use is combined with carbon capture and storage (CCS) technologies, which are expected to develop over the coming decades as well (Luderer et al., 2012). Bioenergy with CCS (BECCS) plays a key role in the overall energy technology mix to limit global warming to about 2°C above pre-industrial temperature levels, especially later in the 21st century. BECCS, according to some studies, is a plausible technology that enables what have been called "negative carbon emissions" (Azar et al., 2010; Luckow et al., 2010). Several Integrated Assessment studies have shown that, without this option, GHG abatement costs and related welfare losses either become very high, or the models do not find a feasible solution (Knopf et al., 2010; Masui et al., 2011). In these energy sector studies, beyond the year 2030 ligno-cellulosic bioenergy typically becomes competitive against other forms of renewable energy (e.g., solar, wind, hydropower) and remains so later in the century (Luderer et al., 2012). van Vuuren et al. (2011) showed that the land area expected to be used for biomass crops in an RCP2.6 scenario could be about 250 million ha in 2050. While high-yielding ligno-cellulosic bioenergy crops and use of residues will reduce the pressure on traditional agricultural production and markets, the sheer size of the energy market could still have strong implications for agricultural resource use by the middle of the century.

Given the challenge of climate change mitigation in general and particularly the complexity of agricultural market interactions and the land-use system, we applied and compared five structurally different models to explore the impacts of large-scale ligno-cellulosic bioenergy production on agricultural prices, land-use change, and food and feed demand by the year 2050. Two general-equilibrium models (AIM, MAGNET) and three PE models (GCAM, GLOBIOM, MAgPIE) participated in this study. As this economic model intercomparison has shown, there are significant differences in how the models implement allocation of ligno-cellulosic bioenergy



Source: AgMIP model calculations.

Fig. 6. Changes in regional cropland in 2050 (CRP, S8 compared to S7, %).

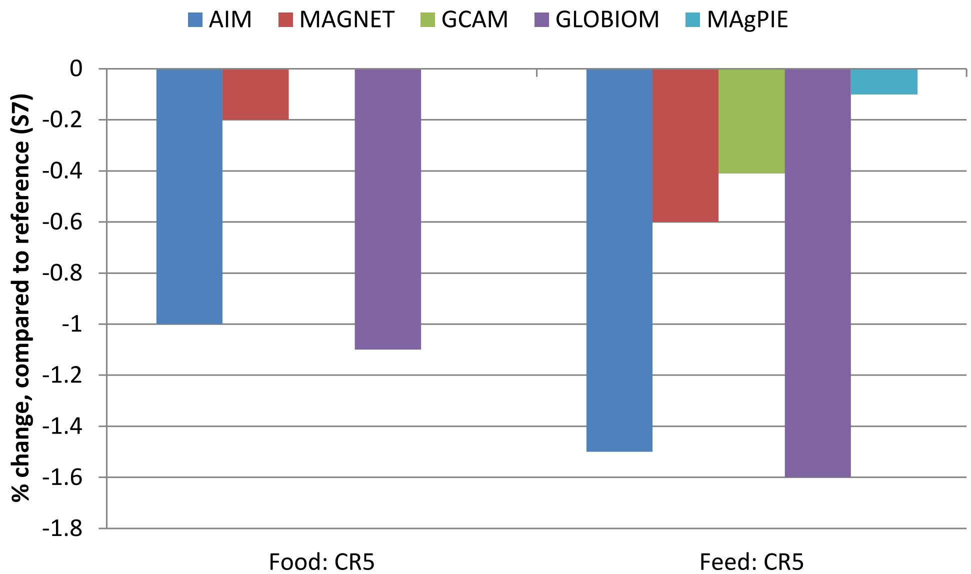


Source: AgMIP model calculations.

Fig. 7. Changes in regional pasture land in 2050 (PAS, S8 compared to S7, %).

production, land-use change, productivity change, demand, and international trade.

First, there are some specific model characteristics on the demand side. The MAgPIE model uses an exogenous demand trajectory for food and, as a consequence, shows the highest price responses across the models also in the reference scenario S1 (for more details see von Lampe et al., 2014). In the AIM model, the change in bioenergy demand is implemented via CO_2 emission constraints and a carbon price. Generally, the emission constraints cause welfare and GDP losses. As is discussed in the Introduction, the bioenergy scenario S8 is consistent with an RCP2.6 stabilization scenario and GDP



Source: AgMIP model calculations.

Fig. 8. Changes in global food and feed consumption (S8 compared to S7, %).

losses are significantly high. As a result, the household demand itself is pushed down, including the demand for agricultural commodities.

Second, the five models have very different coverage of international trade in agricultural commodities and bioenergy. GCAM and GLOBIOM have relatively flexible trade implementations and show rather small and proportional price increases across regions. This implies that ligno-cellulosic bioenergy production is shifted to the most competitive regions and that trade in agricultural commodities and bioenergy adjust rather flexibly to account for increased regional bioenergy demand (see Fig. A1). AIM and MAGNET reveal more limited price transmission through trade and slightly higher average price responses. Surprisingly, AIM even shows decreasing prices for some regions, which may be due to strong reallocation of agricultural production and the GDP loss associated with carbon emission constraints. MAgPIE has a rather static trade implementation, based on historical regional self-sufficiency ratios, and reports the highest average price increases and the largest spread across regions. AIM and GLOBIOM are also more responsive in terms of food and feed demand, which is in line with small price effects for GLOBIOM, but seems counterintuitive for AIM.

Third, differences in land availability for agricultural expansion across models also contribute to different price responses (for more details see also Schmitz et al., 2014). All models need additional land, at additional costs, from currently unmanaged resources to accommodate ligno-cellulosic bioenergy production in scenario S8. With respect to the GHG emission reduction potential of bioenergy, these changes in land use could trigger significant additional emissions, which are not accounted for in this analysis. However, the specific reactions of the models are quite different and can be partly explained by the models' behavior in the reference scenario. GCAM, MAGNET, and AIM show the highest flexibility in expanding ligno-cellulosic bioenergy production into currently unmanaged land. In GLOBIOM, a significant part of bioenergy production is contributed from forestry, including residues. In the version of GCAM used here, only purpose-grown crops are used to supply ligno-cellulosic bioenergy. Some counterintuitive results (increases in CRP in GCAM and increases in PAS in AIM) can be explained by the allocation of bioenergy to areas of high productivity and a shift of crop and livestock production to less productive areas. Within the CGE modeling framework of AIM, a strong climate mitigation policy with related GDP losses is inevitable and may contribute to such results. In the case of GCAM, the demand for crop-based agricultural goods is price-inelastic, and as such the amount of land required for CRP is largely a function of the yields. Having an additional bioenergy demand on the land resources will, all else equal, tend to put downward pressure on average yields and may increase cropland requirements in some regions. MAgPIE shows the smallest reduction in unmanaged land, despite comparable overall bioenergy areas. The model assumes a smaller area potential for agricultural land expansion than the other models, and most of this potential is already used in the reference scenario. With limited additional land available in the bioenergy case, the model relies almost completely on endogenous increases in crop yields. This also drives up the total costs of production and contributes to the comparatively stronger price increases in this model. The MAGNET model uses GCAM inputs on ligno-cellulosic bioenergy land to adjust land availability for agriculture. The decrease in pasture land in most regions, due to a reduction of agricultural land for bioenergy production, is partly compensated by an increase in pasture land in SEA and OAM. Land availability is affected least in these two regions and agricultural land area expands by

30–40%. These regions have comparative advantage in agricultural production.

The range of results with respect to land requirements arising from large-scale ligno-cellulosic bioenergy deployment are in line with previous studies (e.g., van Vuuren et al., 2011). However, the compared models show large differences with respect to the availability of land for agricultural expansion and the elasticity of land supply, which are even more pronounced at the regional level. The uncertainty and lack of data with respect to land availability and land quality remains a serious constraint on improving the robustness of this kind of scenario study (Lotze-Campen, 2011).

Finally, the price effects of the bioenergy scenario S8 have been compared with the impacts of climate change on crop yields and prices (scenarios S3–6). This was meant to contrast a very ambitious climate mitigation scenario with a "worst-case" climate impact scenario by 2050. Therefore, the climate impact scenarios assume no autonomous adaptation in crop growth, a high-level emission scenario (in line with RCP8.5), and no CO_2 fertilization effect (see Nelson et al., 2014). On the other hand, in the bioenergy scenario S8 no specific policy-based land-use restrictions were imposed for forest protection, and no other resource constraints, for example, related to water availability, were taken into account. Hence, this could lead to an overestimation of the difference in average price effects between the climate mitigation scenario S8 and the climate-impact scenarios S3–6. Furthermore, if the conversion of previously unmanaged land for agricultural or bioenergy production induces significant GHG emissions, the positive effects of increased bioenergy production for climate change mitigation may be overestimated.

5. Conclusions

Results from the detailed model comparison suggest that the overall impacts of high demand for second-generation bioenergy on global food prices are rather modest. Most models show either relatively elastic land supply beyond current agricultural areas, or they provide for some flexibility in adjusting livestock and feed production. Regional allocation of bioenergy production differs across models. This type of model comparison can also show to what extent specific implementations of food and feed demand, trade and land supply, and ligno-cellulosic bioenergy feedstocks matter. From this exercise a tentative conclusion can be drawn that ambitious climate change mitigation need not drive up global food prices much, if the extra land required for bioenergy production is accessible or if the feedstock, for example, from forests, does not directly compete for agricultural land. Agricultural price effects across models by the year 2050 from high bioenergy demand in an RCP2.6-type scenario appear to be much smaller (+5% average across models) than from direct climate impacts on crop yields in an RCP8.5-type scenario (+25% average across models).

However, the potential scarcity of water and nutrients, strong policy-based restrictions on agricultural land expansion, for example, for tropical forest protection, and overall welfare losses have not been specifically looked at in this exercise. Price effects might be considerably stronger if agricultural land expansion were restricted and the supply of residues for energy use limited. A harmonized analysis of these additional constraints, which could increase the pressure on agricultural markets, remains a challenge for further research. Improved and harmonized coverage of residues from crop and forestry production as well as explicit implementation of a variety of purpose-grown bioenergy crops in various models could also enhance the analysis. These challenges related to bioenergy coverage in the models, together with the uncertainties about the direct effects of climate change on crop yields, have to be overcome to better understand the relative pressures from climate change adaptation and mitigation on the agricultural sector.

Acknowledgments

This article is a contribution to the global economic model intercomparison activity undertaken as part of the AgMIP Project (www.agmip.org). The roots of this effort began in a scenario comparison project organized by the OECD in late 2010 with three models. We would like to thank the CGIAR Research Program on Climate Change, Agriculture and Food Security (CCAFS), and the British government (through its support for AgMIP) for providing financial support. The socioeconomic drivers were developed for the Shared Socio-economic Pathways (SSP) as part of a new set of IPCC scenarios for analyses of climate impacts, adaptation, and mitigation and are available at the SSP data portal https://secure.iiasa.ac.at/web-apps/ene/SspDb. Contributions by PIK researchers have been supported by the EU FP7 projects VOLANTE, LIMITS, and ERMITAGE. Researchers from PNNL were funded by the Integrated Assessment Research Program of the Office of Science of the U.S. Department of Energy. Our individual institutions, listed below, have also made substantial resources available for this effort. None of results reported in this article are the official positions of the organizations named here. Any errors or omissions remain the responsibility of the authors.

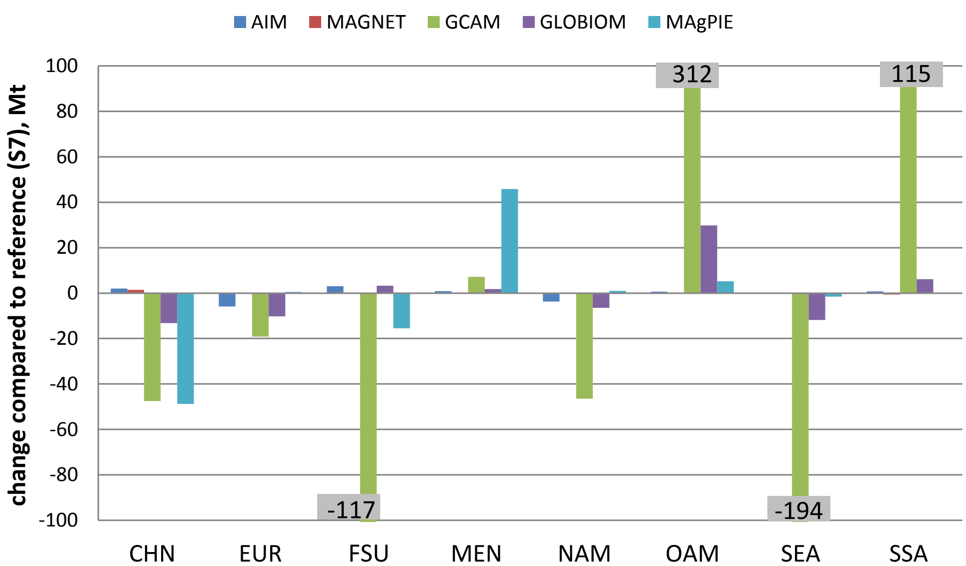
(1) Potsdam Institute for Climate Impact Research (PIK), www.pik-potsdam.de
(2) Organisation for Economic Cooperation and Development, www.oecd.org
(3) Pacific Northwest National Laboratory, www.pnnl.gov
(4) National Institute for Environmental Studies, www.nies.go.jp
(5) International Institute for Applied Systems Analysis, www.iiasa.org
(6) LEI Agricultural Economics Research Institute, Wageningen UR, www.lei.wur.nl
(7) Institute for Development Studies, www.ids.org

A1 Appendix

Table A1
Future trends in first-generation bioenergy demand in ExaJoule (EJ) final energy (Scenarios S7, S8).

Region	Country		2000	2005	2010	2020	2030
CHN	China	Ethanol	0.00	0.02	0.04	0.10	0.15
EUR	EU27	Ethanol	0.01	0.03	0.11	0.30	0.49
EUR	EU27	Biodiesel	0.03	0.12	0.42	0.89	1.36
NAM	USA	Ethanol	0.13	0.32	1.05	1.40	1.74
NAM	USA	Biodiesel	0.00	0.01	0.08	0.20	0.32
NAM	Canada	Ethanol	0.00	0.01	0.03	0.04	0.05
OAM	Brazil	Ethanol	0.20	0.22	0.47	1.09	1.71
OAM	Brazil	Biodiesel	0.00	0.00	0.08	0.18	0.28
OAM	Argentina	Biodiesel	0.00	0.00	0.02	0.06	0.11
WLD	World total		0.37	0.74	2.31	4.26	6.20

Sources: Mosnier et al. (2012), Laborde and Valin (2012), and Crago et al. (2010).



Source: AgMIP model calculations.

Fig. A1. Bioenergy-induced changes in regional net-trade in 2050 (CR5, S8 compared to S7, Mt).

References

Azar, C., Lindgren, K., Obersteiner, M., Riahi, K., van Vuuren, D.P., den Elzen, K.M.G.J., Möllersten, K., Larson, E.D., 2010. The feasibility of low CO_2 concentration targets and the role of bio-energy with carbon capture and storage (BECCS). Clim. Change 100(1), 195–202.

Babcock, B.A., Marette, S., Tréguer, D., 2011. Opportunity for profitable investments in cellulosic biofuels. Energy Pol. 39(2), 714–719.

Banse, M., van Meijl, H., Tabeau, A., Woltjer, G., 2008. Will EU biofuel policies affect global agricultural markets? Eur. Rev. Agric. Econ. 35(2), 117–141.

Bondeau, A., Smith, P.C., Zaehle, S., Schaphoff, S., Lucht, W., Cramer, W., Gerten, D., Lotze-Campen, H., Müller, C., Reichstein, M., Smith, B., 2007. Modelling the role of agriculture for the 20th century global terrestrial carbon balance. Global Change Biol. 13(3), 679–706.

Calvin, K., Clarke, L., Krey, V., Blanford, G., Jiang, K., Kainuma, M., Kriegler, E., Luderer, G., Shukla, P.R., 2012. The role of Asia in mitigating climate change: Results from the Asia modeling exercise. Energy Econ. 34(Supplement 3), S251–S260.

Chum, H., Faaij, A., Moreira, J., Berndes, G., Dhamija, P., Dong, H., Gabrielle, B. et al. (15 more), 2011. Bioenergy. In Ottmar, E., Pichs-Madruga, R., Sokona, Y., Seyboth, K., Matschoss, P., Kadner, S., Zwickel, T. et al. (Eds.), IPCC Special Report on Renewable Energy Sources and Climate Change Mitigation. Cambridge University Press, Cambridge, United Kingdom and New York, NY, pp. 865–952.

Clarke, L., Edmonds, J., Krey, V., Richels, R., Rose, S., Tavoni, M., 2009. International climate policy architectures: Overview of the EMF 22 International Scenarios. Energy Econ. 31(Supplement 2), S64–S81.

Crago, C.L., Khanna, M., Barton, J., Giuliani, E., Amaral, W., 2010. Competitiveness of Brazilian sugarcane ethanol compared to US corn ethanol. Energy Pol. 38(11), 7404–7415.

Edmonds, J.A., Reilly, J.M., 1985. Global Energy: Assessing the Future, Oxford University Press, Oxford, UK.

Fischedick, M., Schaeffer, R., Adedoyin, A., Akai, M., Bruckner, T., Clarke, L., Krey, V. et al., 2011. Mitigation potential and costs. In Ottmar E., Pichs-Madruga, R., Sokona, Y., Seyboth, K., Matschoss, P., Kadner, S., Zwickel, T. et al. (Eds.), IPCC Special Report on Renewable Energy Sources and Climate change Mitigation. Cambridge University Press, Cambridge, United Kingdom and New York, NY, pp. 791–864.

Fujimori, S., Matsuoka, Y., 2011. Development of method for estimation of world industrial energy consumption and its application. Energy Econ. 33(3), 461–473.

Harris, J.R., Todaro, M.P., 1970. Migration, unemployment and development: A two-sector analysis. Am. Econ. Rev. 60(1), 126–142.

Havlik, P., Schneider, U.A., Schmid, E., Böttcher, H., Fritz, S., Skalský, R., Aoki, K. et al. 2011. Global land-use implications of first and second generation biofuel targets. Energy Pol. 39(10), 5690–5702.

Havlik, P., Valin, H., Mosnier, A., Obersteiner, M., Baker, J.S., Herrero, M., Rufino, M.C., Schmid, E., 2013. Crop productivity and the global livestock sector: Implications for land use change and greenhouse gas emissions. Am. J. Agric. Econ. 95(2), 442–448.

International Energy Agency (IEA), 2004. Biofuels for transport: An international perspective. Accessed August 2013, available at http://cleanairinitiative.org/portal/node/2254.

Knopf, B., Edenhofer, O., Flachsland, C., Kok, M. T. J., Lotze-Campen, H., Luderer, G., Popp, A., van Vuuren, D.P., 2010. Managing the low-carbon transition: From model results to policies. Energy J. 31, 223–245.

Kriegler, E., O'Neill, B.C., Hallegatte, S., Kram, T., Lempert, R.J., Moss, R.H., Wilbanks, T., 2012. The need for and use of socio-economic scenarios for climate change analysis: A new approach based on shared socio-economic pathways. Global Environ. Change 22(4), 807–822.

Kyle, P., Luckow, P., Calvin, K., Emanuel, W., Nathan, M., Zhou, Y., 2011. GCAM 3.0 Agriculture and Land Use: Data Sources and Methods. Accessed March 2013, available at http://wiki.umd.edu/gcam/images/2/25/GCAM_AgLU_Data_Documentation.pdf.

Laborde, D., Valin, H., 2012. Modeling land-use changes in a global CGE: Assessing the EU biofuel mandates with the MIRAGE-Biof Model. Climate Change Econ. 03(03), 1250017, 39 pp.

Lotze-Campen, H., 2011. Improved data for integrated modeling of global environmental change. Environ. Res. Lett. 6(4), 041002, 2 pp.

Lotze-Campen, H., Müller, C., Bondeau, A., Rost, S., Popp, A., Lucht, W., 2008. Global food demand, productivity growth, and the scarcity of land and water resources: A spatially explicit mathematical programming approach. Agric. Econ. 39(3), 325–338.

Luckow, P., Wise, M.A., Dooley, J.J., Kim, S.H., 2010. Large-scale utilization of biomass energy and carbon dioxide capture and storage in the transport and electricity sectors under stringent CO_2 concentration limit scenarios. Int. J. Greenhouse Gas Contr. 4(5), 865–877.

Luderer, G., Bosetti, V., Jakob, M., Leimbach, M., Steckel, J.C., Waisman, H., Edenhofer, O., 2012. The economics of decarbonizing the energy system: Results and insights from the RECIPE model intercomparison. Clim. Change 114(1), 9–37.

Masui, T., Matsumoto, K., Hijioka, Y., Kinoshita, T., Nozawa, T., Ishiwatari, S., Kato, E., Shukla, P.R., Yamagata, Y., Kainuma, M., 2011. An emission pathway for stabilization at 6 Wm^{-2} radiative forcing. Clim. Change 109(1–2), 59–76.

McCarl, B., Spreen, T.H., 1980. Price endogenous mathematical programming as a tool for sector analysis. Am. J. Agric. Econ. 62(1), 87–102.

Monfreda, C., Ramankutty, N., Hertel, T.W., 2009. Global agricultural land use data for climate change analysis. Hertel, T.W., Rose, S.K., Tol, R.S.J. (Eds.), Economic Analysis of Land Use in Global Climate Change Policy. Routledge Press, Milton Park, UK, Chapter 2, pp. 33–48.

Mosnier, A., Havlik, P., Valin, H., Baker, J.S., Murray, B.C., Feng, S., Obersteiner, M., McCarl, B.A., Rose, S.K., Schneider, U.A., 2012. The Net Global Effects of Alternative U.S. Biofuel Mandates: Fossil Fuel Displacement, Indirect Land Use Change, and the Role of Agricultural Productivity Growth (NI-R 12-01). Nicholas Institute for Environmental Policy Solutions, Duke University, Durham, NC, USA.

Moss, R.H., Edmonds, J.A., Hibbard, K.A., Manning, M., Rose, S.K., van Vuuren, D.P., Carter, T.R. et al., 2010. The next generation of scenarios for climate change research and assessment. Nature 463(7282), 747–756.

Nelson, G.C., van der Mensbrugghe, D., Ahammad, H., Blanc, E., Calvin, K., Hasegawa, T., Havlik, P., Heyhoe, E., Kyle, P., Lotze-Campen, H., von Lampe, M., Mason d'Croz, D., van Meijl, H., Muller, C., Reilly, J., Robertson, R., Sands, R.D., Schmitz, C., Tabeau, A., Takahashi, K., Valin, H., Willenbockel, D., 2014. Agriculture and climate change in global scenarios: Why don't the models agree. Agric. Econ., 45(1), 85–101.

OECD, 2008. Biofuel Support Policies: An Economic Assessment. Organisation for Economic Co-operation and Development, Paris.

Popp, A., Dietrich, J.P., Lotze-Campen, H., Klein, D., Bauer, N., Krause, M., Beringer, T., Gerten, D., Edenhofer, O., 2011. The economic potential of bioenergy for climate change mitigation with special attention given to implications for the land system. Environ. Res. Lett. 6(3), 034017, 9 pp.

Robinson, S., van Meijl, H., Willenbockel, D., Valin, H., Fujimori, S., Masui, T., Sands, R., Wise, M., Calvin, K., Havlik, P., Mason d'Croz, D., Tabeau, A., Kavallari, A., Schmitz, C., Dietrich, J., von Lampe, M., 2014. Comparing supply-side specifications in models of global agriculture and the food system. Agric. Econ. 45(1), 21–35.

Rosegrant, M.W., IMPACT Development Team, 2012. International Model for Policy Analysis of Agricultural Commodities and Trade (IMPACT) Model Description. International Food Policy Research Institute (IFPRI), Washington DC.

Schmitz, C., Biewald, A., Lotze-Campen, H., Popp, A., Dietrich, J.P., Bodirsky, B., Krause, M., Weindl, I., 2012. Trading more food: Implications for land use, greenhouse gas emissions, and the food system. Global Environ. Change 22(1), 189–209.

Schmitz, C., van Meijl, H., Kyle, P., Nelson, G.C., Fujimori, S., Gurgel, A. Havlik, P., Heyhoe, E., Mason d'Croz, D., Popp, A., Sands, R., Tabeau, A., van der Mensbrugghe, D., von Lampe, M., Wise, M., Blanc, E., Hasegawa, T., Kavellari, A., Valin, H., 2014. Land-use change trajectories up to 2050—insights from a global agro-economic model comparison. Agric. Econ. 45(1), 69–84.

Tabeau, A., Woltjer, G., 2010. Modeling the agricultural employment development within the CGE framework: the consequences for policy responses. Conference Paper, Thirteenth Annual Conference on Global Economic Analysis, Trade for Sustainable and Inclusive Growth and Development. 9–11 June 2010, Penang, Malaysia.

Takayama, T., Judge, G., 1971. Spatial and Temporal Price and Allocation Models. North-Holland, Amsterdam.

van Meijl, H., van Rheenen, T., Tabeau, A., Eickhout, B., 2006. The impact of different policy environments on agricultural land use in Europe. Agric. Ecosyst. Environ. 114(1), 21–38.

van Vuuren, D.P., Bellevrat, E., Kitous, A., Isaac, M., 2010a. Bio-energy use and low stabilization scenarios. Energy J. 31, 192–222.

van Vuuren, D.P., Stehfest, E., den Elzen, M.G.J., van Vliet, J., Isaac, M., 2010b. Exploring IMAGE model scenarios that keep greenhouse gas radiative forcing below 3 W/m^2 in 2100. Energy Econ. 32(5), 1105–1120.

van Vuuren, D.P., Stehfest, E., den Elzen, M.G.J., Kram, T., van Vliet, J., Deetman, S., Isaac, M. et al. 2011. RCP2.6: Exploring the possibility to keep global mean temperature increase below 2 degrees C. Clim. Change 109(1–2, SI), 95–116.

von Lampe, M., Willenbockel, D., Ahammad, H., Blanc, E., Cai, Y., Calvin, K., Fujimori, S., Hasegawa, T., Havlik, P., Heyhoe, E., Kyle, P., Lotze-Campen, H., Mason d'Croz, D., Nelson, G.C., Sands, R.D., Schmitz, C., Tabeau, A., Valin, H., van der Mensbrugghe, D., van Meijl, H., 2014. Why do global long-term scenarios for agriculture differ? An overview of the AgMIP global economic model intercomparison. Agric. Econ. 45(1), 3–20.

Williams, J.R., 1995. The EPIC model. In: Singh, V.P. (Ed.), Computer Models of Watershed Hydrology. Water Resources Publications, Highlands Ranch, CO, pp. 909–1000.

Wise, M.A., Calvin, K.V., 2011. GCAM 3.0 agriculture and land use modeling: Technical description of modeling approach. Accessed March 2013, available https://wiki.umd.edu/gcam/images/8/87/GCAM3AGTechDescript12_5_11.pdf.

Woods, J., Williams, A., Hughes, J.K., Black, M., Murphy, R., 2010. Energy and the food system. Phil. Trans. R. Soc. B: Biol. Sci. 365(1554), 2991–3006.