Land-use transition for bioenergy and climate stabilization: model comparison of drivers, impacts and interactions with other land use based mitigation options

**Alexander Popp · Steven K. Rose · Katherine Calvin ·
Detlef P. Van Vuuren · Jan Phillip Dietrich ·
Marshall Wise · Elke Stehfest · Florian Humpenöder ·
Page Kyle · Jasper Van Vliet · Nico Bauer ·
Hermann Lotze-Campen · David Klein · Elmar Kriegler**

Abstract In this article, we evaluate and compare results from three integrated assessment models (GCAM, IMAGE, and ReMIND/MAgPIE) regarding the drivers and impacts of bioenergy production on the global land system. The considered model frameworks employ linked energy, economy, climate and land use modules. By the help of these linkages the direct competition of bioenergy with other energy technology options for greenhouse gas (GHG) mitigation, based on economic costs and GHG emissions from bioenergy production, has been taken into account. Our results indicate that dedicated bioenergy crops and biomass residues form a potentially important and cost-effective input into the energy system. At the same time, however, the results differ strongly in terms of deployment rates, feedstock composition and

A. Popp (✉) · J. P. Dietrich · F. Humpenöder · N. Bauer · H. Lotze-Campen · D. Klein · E. Kriegler
Potsdam Institute for Climate Impact Research (PIK), PO Box 60 12 03, 14412 Potsdam, Germany
e-mail: popp@pik-potsdam.de

S. K. Rose
Energy and Environmental Analysis Research Group, Electric Power Research Institute (EPRI),
2000 L Street NW, Suite 805, Washington, DC 20036, USA

K. Calvin · M. Wise · P. Kyle
Pacific Northwest National Laboratory, Joint Global Change Research Institute at the University of
Maryland–College Park, 5825 University Research Court, Suite 3500, College Park, MD 20740, USA

D. P. Van Vuuren · E. Stehfest · J. Van Vliet
PBL Netherlands Environmental Assessment Agency, Bilthoven, The Netherlands

D. P. Van Vuuren
Department of Geosciences, Utrecht University, Utrecht, The Netherlands

land-use and greenhouse gas implications. The current paper adds to earlier work by specific looking into model differences with respect to the land-use component that could contribute to the noted differences in results, including land cover allocation, land use constraints, energy crop yields, and non-bioenergy land mitigation options modeled. In scenarios without climate change mitigation, bioenergy cropland represents 10–18 % of total cropland by 2100 across the different models, and boosts cropland expansion at the expense of carbon richer ecosystems. Therefore, associated emissions from land-use change and agricultural intensification as a result of bio-energy use range from 14 and 113 Gt CO2-eq cumulatively through 2100. Under climate policy, bioenergy cropland increases to 24–36 % of total cropland by 2100.

1 Introduction

Fossil fuel combustion, deforestation and other human activities have released large amounts of greenhouse gases into the atmosphere. IPCC's Fourth Assessment has shown that the associated changes in climate may potentially lead to considerable impacts on ecosystems and human societies (Parry et al. 2007). Climate change can be reduced through the mitigation of greenhouse gas emissions (Metz et al. 2007). Land-based mitigation strategies, especially the use of bioenergy, could have a potentially large role as part of an overall mitigation strategy (Rose et al. 2012). Biomass can be used to provide energy in many forms including heat, electricity, gaseous, solid and liquid fuels. Recently, bioenergy has received even more attention in combination with carbon dioxide capture and geologic storage (BECCS), which can lead to a net removal of CO_2 from the atmosphere (Rose et al. 2013; Azar et al. 2010). However, large uncertainties exist on deployment levels of bioenergy and the impacts of large scale bioenergy on the land system, including resulting greenhouse gas emissions (e.g. Chum et al. 2011, Searchinger et al. 2008).

The explicit modeling and analysis of integrated energy and land use systems is relatively new . Most analyses so far have been single-model studies (e.g.Popp et al. 2011a, van Vuuren et al. 2009, Wise et al. 2009) that do not accommodate a comparison of the various models' land use drivers, assumptions and impacts of large scale bioenergy deployment in a consistent way (Creutzig et al. 2012). In this paper, we use a multi-model approach, allowing comparison of drivers and results across different models, to assess the impacts of large scale bioenergy crop deployment on land use dynamics, carbon fluxes within the land use system and N2O emissions from fertilizer application in scenarios with and without climate change mitigation. In addition, the interaction of bioenergy with other land use based mitigation options is investigated. The model comparison framework of the Energy Modeling Forum's 27th Study (EMF 27; Kriegler et al. 2013) provides an opportunity to do this consistently, and do so in conjunction with the Rose et al. (2013) study that analyzes the production, use, dependence, and value of bioenergy to climate change mitigation for these and the other EMF-27 models.

2 Methods

Here, we use a set of comparable scenarios developed using the GCAM (Clarke et al. 2007), IMAGE (Bouwman et al. 2006) and REMIND/MAgPIE (Popp et al. 2011a, Klein et al. 2013) integrated assessment models (IAMs). All of these models have in common that they contain both a dedicated energy system and land use module that interact with each other. There are clear differences between these models however with respect to the modeling of biogeochemical processes and conditions and socio-economic processes and conditions; and the explicit

coverage and detail of links and interactions between these two spheres, and the interaction with other land use based mitigation options.

The remainder of this section introduces the model frameworks with a special focus on their land-use modules and reflects on their advantages and limitations. More detailed descriptions of the landuse modules and models can be found in the Supporting Online Material (SOM).

2.1 Overview on integrated modeling frameworks

Here, we give an overview on the three integrated assessment frameworks and describe how the respective land-use modules interact with the energy and economy modules (see also Table 1).

The **GCAM** integrated assessment model links modules of the economy, the energy system, the agriculture and land-use system, and the climate. The agriculture and land-use component (Wise and Calvin 2011; Kyle et al. 2011) determines supply, demand, and prices for crop, animal and forestry production and bioenergy based on expected profitability. In doing so, the model determines land allocation across these categories, as well as pasture-land, grassland, shrubland, and non-commercial forestland. The agriculture and land-use component of GCAM is fully-coupled with the energy, economic, and climate modules within GCAM; that is, all four components are solved simultaneously. In the version of GCAM used in the EMF27 study, bioenergy provides the linkage between the agriculture and land-use component and the energy component, with bioenergy produced by the land system and consumed by the energy system. The agriculture and land component is coupled to the economy through bioenergy and carbon prices. Carbon prices are imposed iteratively until the prescribed climate target is reached. The carbon prices influence the cost of fossil fuel energy technologies, and the profitability of land cover options. In particular, GCAM assumes the carbon price is applied to carbon stocks held in the terrestrial system, incentiv-izing land owners to increase these stocks. As a result, strong incentives exist to expand carbon stocks under a climate policy, resulting in significant afforestation. The agriculture and land-use component is connected to the climate through emissions (CO_2 and non-CO_2), which are produced by the land system and passed into the climate system to calculate concentrations, radiative forcings, and other climate indicators.

The **IMAGE** framework (Bouwman et al. 2006) describes various global environmental change issues using a set of linked submodels describing the energy system, the agricultural economy and land use, natural vegetation and the climate system. The use of bioenergy plays a role in several components of the IMAGE system. First, the potential for bioenergy is determined using the land use model, which takes into account several sustainability criteria: the exclusion of forests areas, agricultural areas and nature reserves (see van Vuuren et al. 2009). To model the potential production of bioenergy (and food crops), an adapted version of the Agricultural Ecological Zones (AEZ) model is used that determines yields as a function of land and climate conditions and assumed changes in technology on a grid cell basis (0.5 degree). Based on these spatially explicit attainable yields, and other suitability considerations, land use is allocated. The information on potential yields, associated costs and potential greenhouse gas emissions is translated into bioenergy supply curves for the energy submodel of IMAGE. In the energy submodel, the demand for bioenergy is assessed by describing the cost-based competition of bioenergy versus other energy carriers (mostly in the transport, electricity production, industry and the residential sectors). Climate policy can be represented by introducing a carbon price that taxes fossil fuels, but also the greenhouse gas emissions associated with the production of biomass and its conversion into bioenergy. The resulting demand for bioenergy crops as output from the energy system is subsequently combined with the demand for other agricultural products as input for the land-

Table 1 Overview and description of land modeling approaches in GCAM, IMAGE and ReMIND/MAgPIE

	GCAM	IMAGE	ReMIND/MAgPIE
Interactions of the LU module			
Energy module	Bioenergy demand	Bioenergy potential and bioenergy demand	Bioenergy demand
Economy module	Bioenergy prices and Carbon prices	Arable land	Bioenergy prices and Carbon prices
Climate module	GHG emissions	GHG emissions	GHG emissions
Land use dynamics			
Between economic units	Profit maximization	Cost minimization	Cost minimization
Between biophysical units	Profit maximization	Rule based approach	Cost minimization
Land types modeled			
Cropland	Dynamic	Dynamic	Dynamic
Bioenergy Cropland	Dynamic	Dynamic	Dynamic
Pasture	Dynamic	Dynamic	Constant
Forest	Dynamic	Dynamic	Dynamic
Managed Forest	Dynamic	Dynamic	Constant
Urban	Constant	Dynamic	Constant
Other Land	Dynamic	Dynamic	Dynamic
Spatial resolution (biophysical)	151 world regions	0.5×0.5 degree grids	0.5×0.5 degree grids
Spatial resolution (economic)	14 world regions	24 world regions	10 world regions
GHG emissions			
Land Use Change [CO2]	Yes	Yes (including regrowth of natural vegetation)	Yes
Livestock [CH4, N2O]	Yes	Yes	Yes
Cropland [CH4, N2O]	Yes	Yes	Yes
LU mitigation options			
Afforestation	Yes	No	No
Reforestation	Yes	No	No
Forest management	No	No	No
Avoided deforestation	Yes	No	Yes
Bioenergy	Waste, residues, 1st and 2nd generation bioenergy crops	Residues, 1st and 2nd generation bioenergy crops (only fast growing trees)	Residues, 2nd generation bioenergy crops
Agricultural Management [CH4, N2O]	Yes	Yes	Yes
Agricultural soil carbon management [CO2]	No	No	No
Crop yields			
Climate change impacts	No	Yes	No
Technological change	Exogenous	Exogenous	Endogenous
Irrigation	Yes	Yes (no irrigation for bioenergy crops)	Yes
Irrigation dynamics (efficiency increase, irrigation expansion)	No	Yes	Yes

use system to determine future land use. Finally, the emissions associated with land use and land-use change (including N_2O emissions associated with fertilizer use and CO_2 emissions from deforestation) and the energy system are used in the climate model (MAGICC-6) to determine climate change, which then affects all biophysical submodels, including future crop yields and bioenergy potential.

The **ReMIND/MAgPIE** integrated assessment framework (Popp et al. 2011a, Klein et al. 2013) provides a consistent system for the evaluation of bioenergy potentials and conflicts between economic development, food and bioenergy demand in different world regions. It consists of two components: ReMIND (Leimbach et al. 2010) and MAgPIE (Lotze-Campen et al. 2008, Popp et al. 2010). The multi-regional integrated assessment model, ReMIND, represents the energy-economy-climate system and covers a wide range of bioenergy and competing conversion technologies. The MAgPIE model consists of a global dynamic vegetation, land use and water balance model. To ensure a consistent application of these models, the land-use sector in ReMIND is represented by an emulation of MAgPIE. To create the emulation, MAgPIE was run to derive region specific response curves for bioenergy production costs, GHG emissions from land use and land use change and marginal abatement cost curves (MACs) for mitigation from avoided deforestation. Spatially explicit (0.5 degree resolution) agricultural yields, carbon contents and water fluxes in MAgPIE come from the vegetation and hydrology model LPJmL (Bondeau et al. 2007). The underlying dynamics of and implications for the land use sector due to bioenergy deployment can be evaluated in MAgPIE using the bioenergy demand and GHG prices for mitigation in the land use sector from ReMIND to MAgPIE for each scenario. ReMIND assumes an upper annual limit of 300 EJ per year for second-generation biomass use (Klein et al. 2013). This assumption is consistent with the upper end of potential 2050 deployment levels identified in the Intergovernmental Panel on Climate Change's Special Report on Renewable Energy Sources and Climate Change Mitigation (Chum et al. 2011).

2.2 Comparison of land use modules

Important details of the land use modules differ (see Table 1 for an overview). A brief comparison is given here. More detailed descriptions of each model's land modeling can be found in the SOM.

First, the models describe economic decisions associated with bioenergy supply in different ways. In MAgPIE, land use decisions at the 0.5×0.5 degree grid are based on minimizing production costs. In GCAM, land is allocated to 151 biophysical regions based on profit-maximization. Finally, in IMAGE, food production is determined first by a macro-economic description, and subsequent decisions on regional bioenergy production are based on cost minimization. The final allocation of land-use at the 0.5×0.5 degree grid within a region follows a rule-based land mechanism that accounts for crop productivity and other suitability factors, such as proximity to existing agricultural land and water bodies.

The models have fairly similar land type categories, but treat land pools differently. In GCAM and MAgPIE, urban land is considered to be static, while in IMAGE, a relationship with population density is used. In GCAM and IMAGE, pasture area is driven by demand for animal products, but it is constant in MAgPIE.

The models differ in terms of geographic resolution at which differences in land quality and climatic conditions are taken into account for biophysical data inputs such as agricultural production, water availability for irrigation or carbon content of natural vegetation and agricultural crops. IMAGE considers this information at the level of 0.5 degree grid cells. In this application of MAgPIE, 0.5 degree data is aggregated to 200 clusters, whereas GCAM functions on the level of 151 regions.

Agricultural yields in all models are assumed to change over time. Yield increases due to technological change are either considered mostly exogenously (GCAM and IMAGE) or treated endogenously (MAgPIE). In addition, in IMAGE, agricultural yields as well as carbon content of crops and natural vegetation are affected by climatic change. All models consider carbon fluxes of vegetation and soils and greenhouse gas emissions from agricultural management. In all models, carbon emissions from land use change occur if the carbon content of the previous land use activity exceeds the carbon content of the new land-use activity. Carbon uptake occurs if a more carbon-rich ecosystem replaces a less carbon-rich one. IMAGE assumes regrowth of natural vegetation and associated CO2 uptake on abandoned land. Land use based mitigation in the models is driven by GHG prices in the mitigation scenarios. However, the models produce different GHG price trajectories for a given policy (see Rose et al. 2013) for discussion of GHG prices and other cost metrics).

There are differences in the land use based mitigation options available in the models. All models include production of dedicated bioenergy crops for deployment in the energy sector and mitigation of non-CO2 GHGs from agricultural production. However, the current IMAGE scenarios do not consider avoided deforestation, and afforestation/reforestation is only taken into account by GCAM. Importantly, the models differ in their assumptions on availability of land and water resources for dedicated bioenergy crops. In GCAM and MAgPIE, bioenergy crops will be allocated based on suitability of soil and climatic conditions and the competition with land needed for the production of other agricultural goods. In GCAM, all land is available. In MAgPIE, however, managed forests and pasture land are static and cannot be used for bioenergy production. Also, nature conservation areas are not available for cropland expansion. In contrast, IMAGE allows bioenergy crops only to be grown on land other than that required for food production, forests, nature conservation and urban areas (representing successful implementation of sustainability criteria). While all models consider irrigation for food crops, IMAGE, unlike GCAM and ReMIND/MAgPIE, assumes irrigation is unavailable for bioenergy crops, again due to sustainability considerations. GCAM includes both irrigated and rainfed croplands but only implicitly, that is, they are not distinct technology choices. The greatest flexibility for irrigation is in ReMIND/MAgPIE, which can shift production from irrigated to rainfed in response to economic or climatic drivers for all types of crop production.
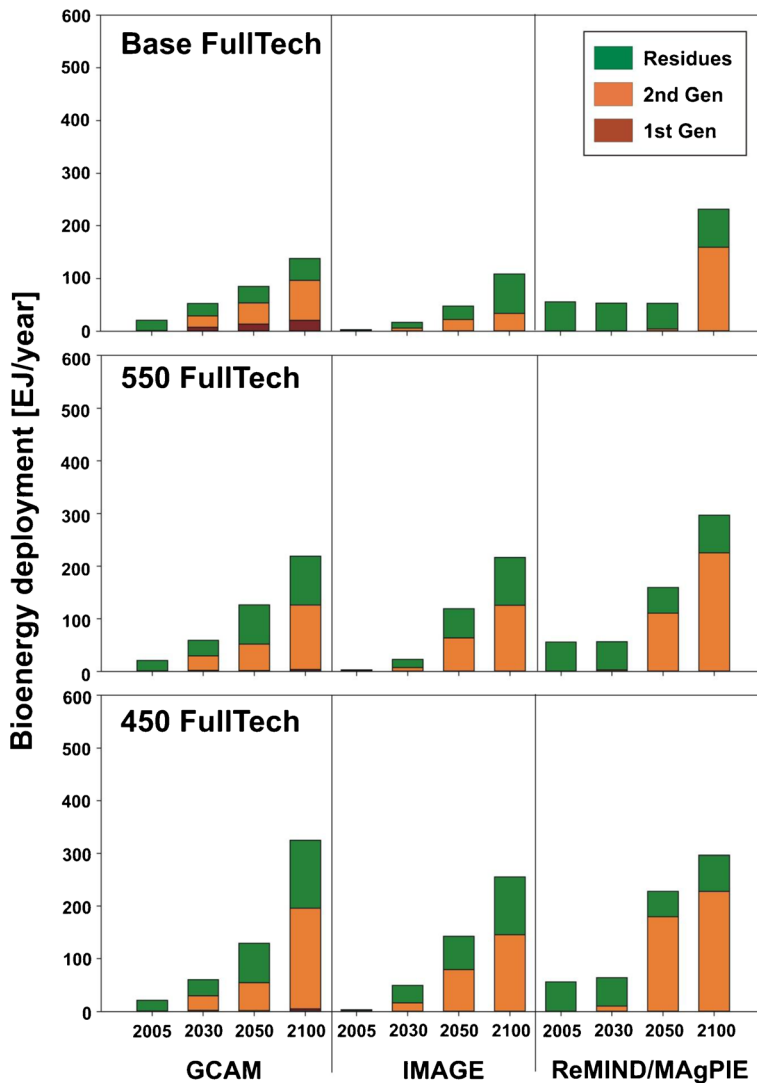
2.3 Scenarios

In this paper we utilize five scenarios—one baseline and two stabilization scenarios from the EMF27 exercise (Kriegler et al. 2013), and two no bioenergy diagnostic reference scenarios (without and with climate policy). All three of the EMF27 scenarios include a full portfolio of mitigation technologies. The first scenario does not include climate change mitigation (*Base FullTech*), the second scenario limits the GHG (CO$_2$ equivalent) concentration in the atmosphere to 550 ppm in 2100 (*550 FullTech*), and the third scenario limits the GHG concentration to 450 ppm in 2100 (*450 FullTech*). The 'reference scenarios' are no bioenergy variants of *Base FullTech* and *450 FullTech*. The reference scenarios represent a hypothetical future without bioenergy production but their input assumptions are identical to the corresponding scenarios otherwise. They serve as a point of reference for the assessment of land use, vegetation and soil carbon fluxes, and nitrous oxide emissions implications from bioenergy crops and other land use based mitigation measures. The models have not been harmonized in their socio-economic conditions that drive emissions, food, feed and energy demand (see Figure SI1 and SI1 in the SOM for projected global food demands).

3 Results

3.1 Bioenergy deployment

All models indicate that bioenergy deployment in the energy system increases over time in the baseline (*Base FullTech*) and climate policy scenarios (Fig. 1). By 2050, regional biofuel consumption is as much as 10 %, 45 %, and 70 % of liquid fuel consumption across regions in GCAM, IMAGE, and REMIND respectively, while regional bioelectricity consumption is as much as 10 %, 25 %, and 20 % of electricity consumption across regions in the three models

Fig. 1 Global deployment of bioenergy feedstocks. Brown bars represent 1st generation bioenergy crops (such as maize, rapeseed or oilpalm), orange bars 2nd generation cellulosic bioenergy crops (such as poplar or Miscanthus) and green bars feedstock coming from residues. Traditional biomass is not included in this figure

respectively (Rose et al. 2013). Deployment grows with the stringency of the climate target. However, the levels and make-up of bioenergy deployment varies substantially across models. There is no single reason for the differences. The results derive from each models combination of plausible assumptions regarding, for instance, economic growth, available technologies, intensities (relationships between variables) and model structure. In GCAM and IMAGE, deployment increases steadily over time. In ReMIND/MAgPIE deployment levels remain constant in the first half of the century and then increase rapidly in the second half. In 2050, in the *Base FullTech* scenario, total global deployment levels range from 48–85 EJ/year (48 EJ in IMAGE, 53 EJ in ReMIND/MAgPIE and 85 EJ in GCAM) and increase to 109–231 EJ/year in 2100 (109, 231, and 138 EJ respectively). In the *450 FullTech* scenario, 2050 global deployment levels increase to 129–228 EJ/year (142, 228, and 129 EJ respectively), with 2100 deployment of 255–324 EJ/year (255, 296, and 324 EJ respectively). Except of slightly higher deployment levels in 2100 in ReMIND/MAgPIE in the *Base FullTech* and in GCAM in the *450 FullTech* scenario, deployment levels reported by the IAM models considered in this paper are in the range of the other 12 models applied in EMF27 that report 9–130 EJ/year in 2050 and 68–168 EJ/year in 2100 for the *Base FullTech* scenario and 94–207 EJ/year in 2050 and 205–300 EJ/year in 2100 for the *450 FullTech* scenario (see Rose et al. 2013). Not only the time path and level of bioenergy deployment differs across the 3 models but also the share of different biomass resources deployed. In IMAGE and ReMIND/MAgPIE, cellulosic bioenergy crops and residues are used as primary energy carriers. In GCAM 1st generation bioenergy crops are also used. In the *Base FullTech* scenario, GCAM deploys a considerable share of 1st generation bioenergy crops, but in the *450 FullTech* scenario, this decreases. BECCS energy technologies play an important role in the three models. By mid-century, BECCS energy technologies dominate global bioenergy—67 %, 50 %, and 99 % of primary energy in GCAM, IMAGE, and REMIND. By end-of-century, BECCS represents almost all bioenergy—97 %, 86 %, and 100 % respectively (Rose et al. 2013). See Rose et al. (2013) for additional analysis of global bioenergy deployment for these and other models. Dedicated energy crops are of particular importance to land use dynamics, which is discussed next.

3.2 Land use dynamics
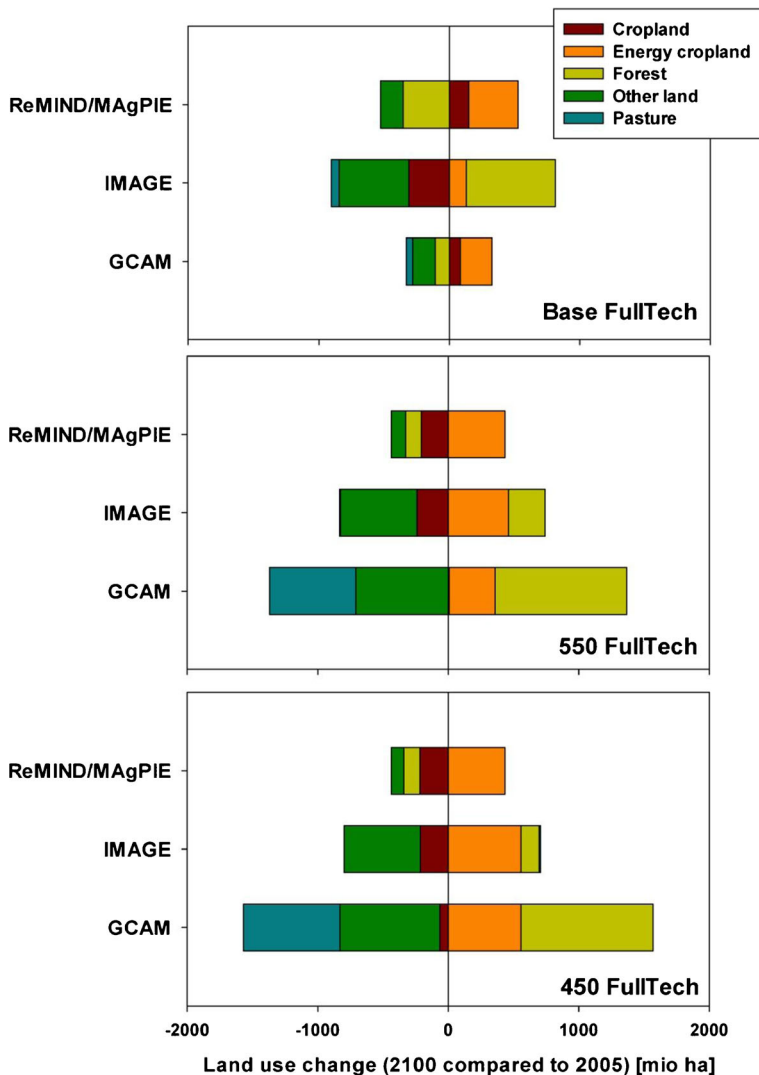
In the main text we present global land cover change results; however, in the SOM, we also provide results for five aggregate regions: OECD90 countries (OECD), reforming economies of Eastern Europe and the Former Soviet Union (REF), countries of the Middle East and Africa (MAF), countries of Latin America and the Caribbean (LAM), and Asian countries (ASIA) excluding countries already represented (Middle East, Japan and Former Soviet Union states). The discussion below considers both the global and regional results.

We begin by discussing the base year. The initial allocation of land defines production and conversion opportunities for a model. Table SI1 indicates that the models have similar total land cover, but notably differ in their allocation in 2005. In GCAM and IMAGE, for instance, forest and other land dominate. Yet GCAM has 500 million more hectares (ha) of forests and 500 million less ha of cropland than IMAGE. Global pasture area in both models is similar. In contrast, global pasture area is most prominent in ReMIND/MAgPIE at the expense of 'other land' primarily, but also forest. ReMIND/MAgPIE has approximately 1.5 billion more hectares of pasture than the other models. Regionally, all models indicate that most pasture area but also other land can be found in MAF, forest area dominates in LAM, OECD and REF, and most cropland appears in ASIA and OECD (See Fig SI1). In general, dissimilarities in the base year across the models is caused by implementation of different land use data sources and categorizations, and use of different methodologies and definitions

(e.g., pasture) in deriving the land use data sets (e.g. Ramankutty et al. 2008). For example, in contrast to IMAGE and ReMIND/MAgPIE where fallow cropland is accounted in the category of cropland, fallow cropland in GCAM is reported as other land, wherefore cropland in GCAM shows much lower numbers. The land cover allocation differences, along with differences in model structure, likely affect results. For instance, smaller cropland or forest area can imply higher productivity, larger land rents, as well as GHG intensity per hectare, while conversion constraints will have a greater impact the larger the land cover allocation (e.g., IMAGE's use of abandoned agricultural land and natural grass land, ReMIND/MAgPIE's fixing of pasture land).

Figure 2 shows that the models project very different global land cover conversion futures. In the baseline (*Base FullTech*), total cropland increases by 330 million ha by 2100 in GCAM

Fig. 2 Change in global land pools [million ha] from 2005 to 2100 in GCAM, IMAGE and ReMIND/MAgPIE

(approximately the country area of India), compared to 530 million ha in ReMIND/MAgPIE, and a decrease of 180 million ha in IMAGE. IMAGE's result is driven by ongoing yield increases and a stabilizing global population in the second half of the century. Regionally, ReMIND/MAgPIE and GCAM project increases in cropland in all regions until 2100 with the highest increases in ReMIND/MAgPIE in LAM and in GCAM in ASIA (Fig SI1). Land use changes to 2030 and 2050 are also provided in the SOM. Globally, by 2100, energy crops represent 18 % of total cropland (non-energy and energy crop) in GCAM and ReMIND/ MAgPIE and 10 % in IMAGE. In GCAM and ReMIND/MAgPIE bioenergy cropland is most prominent in ASIA and OECD in 2100. In addition, ReMIND/MAgPIE reports also high bioenergy cropland in LAM. In IMAGE bioenergy cropland is most prominent in REF. Total Cropland expansion happens mainly at the expense of 'other land' and pasture in GCAM, and forest and other land in ReMIND/MAgPIE. In IMAGE, forest area increases substantial as cropland and other land contract and natural vegetation regrowth occurs. The baseline contraction of cropland in IMAGE frees up land for energy crops.

In the mitigation scenarios, bioenergy cropland expands significantly. Forests do as well, though for ReMIND/MAgPIE it appears as reduced forest loss (relative to the baseline). Non-energy cropland, other land and pasture are all affected, but to substantially different degrees across models. In IMAGE, total cropland (non-energy and energy) is 23 % (*550 FullTech*) and 28 % (*450 FullTech*) higher than in the *Base FullTech* scenario in 2100. The main driver is bioenergy cropland that covers 26 % (*550 FullTech*) and 30 % (*450 FullTech*) of total cropland. In ReMIND/MAgPIE, non-energy cropland switches from expansion in the baseline to contraction in the mitigation scenarios, however there is very little difference in conversion levels and patterns between the mitigation scenarios. Here, the share of bioenergy cropland in total cropland increases to 24 % in *550 FullTech* and *450 FullTech*. In GCAM, total cropland expands at the cost of pasture and other land in both mitigation scenarios. Again, the main driver is bioenergy cropland, which uses 36 % of total cropland. In all models, bioenergy cropland increases strongly in ASIA, OECD, and REF by 2100 in the *450 FullTech* scenario (Fig SI1).

Global forest dynamics differ strongly across the different models in the *550 FullTech & 450 FullTech* scenarios. In IMAGE, forest cover is globally 12 % lower compared to the *Base FullTech* scenario in 2100 as abandoned land is used for bioenergy crops, instead of regrown forests (*450 FullTech* scenario). Due to avoided deforestation, forest cover remains almost constant in ReMIND/MAgPIE in *550 FullTech & 450 FullTech.* In GCAM, global forest cover even increases by 20 % until 2100 in the *550 FullTech & 450 FullTech* scenarios due to afforestation and avoided deforestation, especially in MAF, REF and LAM.

Overall, the land conversions reflect structural features of the models. Bioenergy land expansion is primarily cropland and other land in ReMIND/MAgPIE due to pasture constraints and avoided deforestation, while it is reduced cropland contraction and natural forest regrowth in IMAGE. In GCAM, it is reductions in other and pasture land.
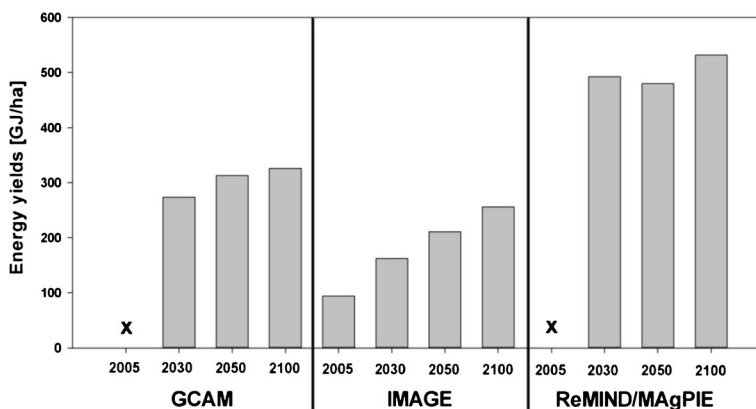
3.3 Bioenergy yields

Current and projected future yields of bioenergy crops are important determinants for bioenergy potentials. The models consider different types of bioenergy crops, different types of management, different rates of future technological change and impacts of climatic change, as such a detailed analysis of agricultural yields is complicated. Instead, we focus on the overall simulated global energy yield (global bioenergy crop production divided by global bioenergy crop area) and its development over time for the scenario with most ambitious climate change mitigation (*450 FullTech*).

Figure 3 shows that energy crop yields differ strongly across the models. In 2030, the highest yields of 491 GJ ha^{-1} year^{-1} are reported from ReMIND/MAgPIE. This is consistent with the fact that the model only considers cellulosic bioenergy crops and a large share is irrigated as the model shifts production from rainfed to irrigated for all types of crop production to minimize agricultural production costs. In GCAM, in 2030, lower yields of 273 GJ ha^{-1} year^{-1} result due to different assumptions about future management practices (e.g. irrigation). The lowest yields in 2030 are found in IMAGE (162 GJ ha^{-1} year^{-1}). IMAGE only considers rain-fed woody crops and constrains bioenergy crops to marginal and abandoned land. Acreage required for food production, forests, and nature conservation is off limits. In all models, yields increase over time—by a factor of 1.6 from 2030 to 2100 in IMAGE, 1.2 in GCAM, and 1.1 in ReMIND/ MAgPIE. These yield results are comparable with the wide range reported in the literature (see Lewandowski et al. 2000, Fischer et al. 2005, Beringer et al. 2011, Hong et al. 2011) where energy yield values range from 564 GJ ha^{-1} year^{-1} with irrigation and nitrogen supply to 291 GJ ha^{-1} year^{-1} without N supply and irrigation (e.g. Ercoli et al. 1999).
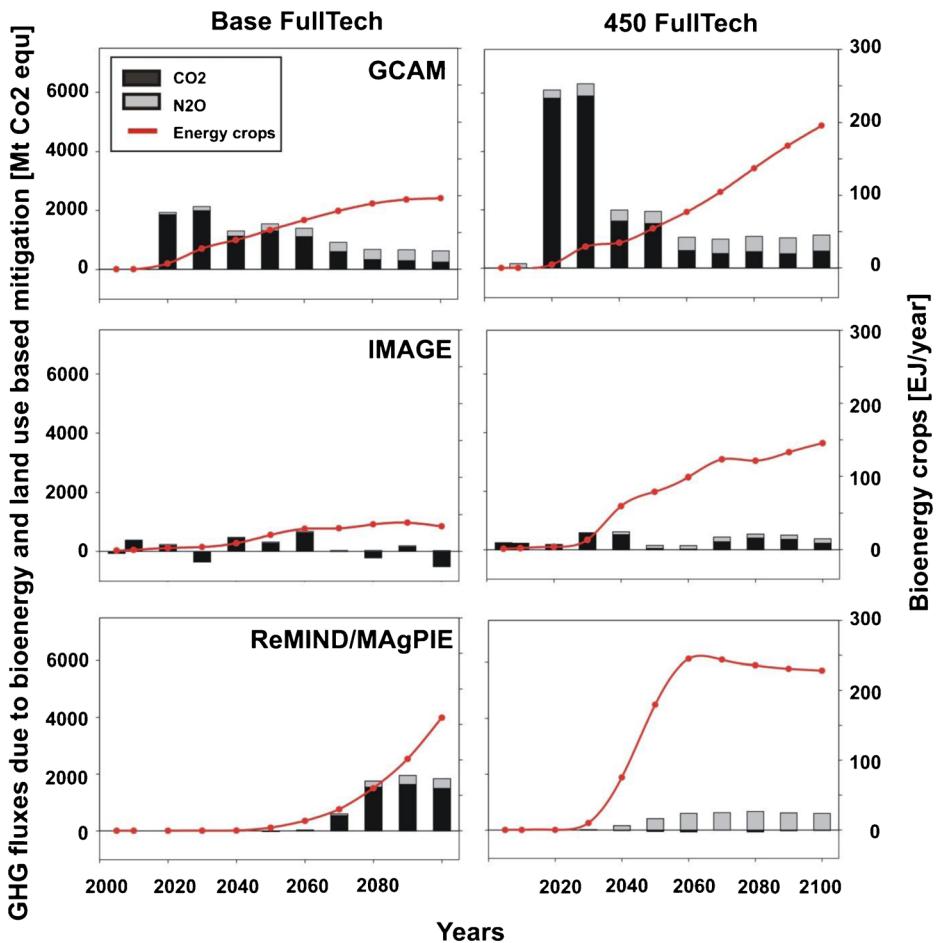
3.4 Greenhouse gas fluxes

Figure 4 presents the net land related greenhouse gas implications of bioenergy and other land use based mitigation measures—without and with climate policy. Shown are differences between the bioenergy scenarios (*Base FullTech* and *450 FullTech*) and their respective no bioenergy reference scenarios (see Figure SI1 and SI1 for GHG emissions in the no bioenergy reference scenarios for *Base FullTech* and *450 FullTec* respectively). Comparing to a scenario without bioenergy provides a diagnostic that isolates the emissions implications of bioenergy. In Fig. 4 we see very different emissions responses to bioenergy crops.

In the *Base FullTech* comparison to reference, emissions of CO2 from land-use change and N2O are revealed for all models, with CO2 emissions dominating. However, the differences in the pattern of fluxes are stark. GCAM shows large initial CO2 emissions of 63 Gt CO2-equ cumulatively in the period 2005–2050 associated with early land conversion that declines with time as land conversion slows down (only 89 Gt CO2-equ cumulatively from 2005 to 2100). In contrast, dedicated bioenergy feedstocks aren't deployed in the ReMIND/MAgPIE baseline until the second half of the century, at which point increasing deployment produces increasing land-

Fig. 3 Global energy yields (global bioenergy crop production divided by global bioenergy crop area) for the *450 FullTech* scenario in GCAM, IMAGE and ReMIND/MAgPIE for the years 2005, 2030, 2050 and 2100. For GCAM and ReMIND/MAgPIE yields could not be calculated for 2005 as there are no bioenergy crops produced

Fig. 4 Bioenergy crop production (*red line*) and greenhouse gas (GHG) fluxes due to bioenergy production and other land use based mitigation options (improved agricultural management, avoided deforestation and afforestation) as a difference between the default scenarios with bioenergy (*Base FullTech* and *450 FullTech*) and the respective reference scenarios without bioenergy. GHG fluxes are shown for land use change (CO2 – *black bars*) and N2O emissions from nitrogen application (*grey bars*) from 2005 until 2100

use emissions (52 Gt CO2-equ in the time period 2050–2100 alone). IMAGE has more modest bioenergy crop levels and also more modest CO2 emissions (10 Gt CO2-equ from 2005 to 2100) that occur as bioenergy crops prevent regrowth of natural vegetation on abandoned land and associated carbon uptake. N2O emissions, from the application of fertilizers for non-energy and energy crop production, increase over time with bioenergy deployment and are highest cumulatively for GCAM (24 Gt CO2-equ), followed by ReMIND/MAgPIE (9 Gt CO2-equ) and IMAGE (3 Gt CO2-e) from 2005 to 2100.

In the *450 FullTech* comparison to reference, dedicated bioenergy deployment levels are much higher than in the baseline comparison. In IMAGE, the higher production of bioenergy crops reduces terrestrial carbon uptake by displacing regrowth of natural vegetation on abandoned land. On the other hand, ReMIND/MAgPIE reaches up to 250 EJ per year from energy crops; however, avoided deforestation prevents CO2 emissions from land-use change

by restricting cropland expansion. In GCAM, a completely different dynamic plays out. It appears GCAM is releasing huge quantities of terrestrial carbon. However, the actual story is quite different. More afforestation is used for carbon sequestration in the land use sector when the energy system does not have the option to use bioenergy. Therefore, more carbon is stored in forests in the *450 FullTech* reference scenario compared to the *450 FullTech* scenario with bioenergy. Figure 4 shows the afforestation carbon opportunity cost of bioenergy. When bioenergy is available, GCAM chooses bioenergy, BECCS in particular, over additional afforestation for mitigation (176 GtCO2-equ from 2005–2100 of additional afforestation). While the land-use CO2 emissions stories vary widely, the models all project increases in land-use N2O emissions with bioenergy. However, it is important to note, as shown in Rose et al. (2013), that the integrated perspective of these models finds that, despite increased land use CO_2 and N_2O emissions, bioenergy can still be a cost-effective climate stabilization strategy over the long-run.

4 Conclusion

The land use sector could contribute significantly to climate change mitigation, for instance in the form of producing bioenergy (Rose et al. 2013, van Vuuren et al. 2009 Popp et al. 2011a) but also by afforestation/reforestation and avoiding deforestation (Wise et al. 2009, Rose et al. 2012). However, especially large-scale bioenergy crop production is seen to increase the competition for land, water, and other inputs, affecting land use dynamics and leading to deforestation, emissions from land use change and agricultural intensification. (e.g. Searchinger et al. 2008, Popp et al. 2012, 2011a, Wise et al. 2009).

We apply and compare three structurally different integrated assessment models (GCAM, IMAGE and ReMIND/MAgPIE) to explore drivers and impacts of bioenergy production on the global land system as well as the interaction with other land use based mitigation options.

The three models differ strongly in their assumptions and definitions of land cover distribution in 2005 and the availability of biomass resources for deployment in the energy system. They also include different sets of other land use based mitigation options (such as avoided deforestation and afforestation) that interact with bioenergy.

We find that different choices of bioenergy feedstocks (1st vs. 2nd generation but also woody vs. herbaceous cellulosic), land use restrictions and current as well as future management (such as irrigation vs. rainfed) for bioenergy production significantly affect simulated bioenergy crop energy yields, with results ranging from 162–491 GJ ha^{-1} year^{-1} in 2030. Despite the dissimilarities, a number of robust findings emerge. In baseline scenarios without climate change mitigation, bioenergy cropland represents 10–18 % of total cropland by 2100 and leads to cropland expansion, mainly at the expense of carbon richer ecosystems. Global CO2 emissions from land-use change range from 11 and 89 Gt CO2-equ cumulatively through 2100. The lowest emissions occur in IMAGE as bioenergy crops can only be grown on marginal and abandoned land, excluding carbon rich ecosystems such as forests. If also agricultural N2O emissions are considered, global co-emissions from baseline bioenergy production range from 14 to 113 Gt CO2-equ cumulatively through 2100. Disparities in these results derive from each models combination of plausible assumptions regarding, for instance, agricultural yields, economic growth, available technologies, intensities (relationships between variables) and model structure.

In all models, dedicated bioenergy crops are seen as an important and cost-effective component of the energy system, especially in the scenario with the most ambitious climate stabilization targets (150–230 EJ/year in 2100). However, bioenergy interacts and competes

with other land use based mitigation options. In general, bioenergy production leads to N2O emissions from fertilization but improved agricultural management (such as precision farming) increases the efficiency of nitrogen application and therefore reduces agricultural N2O emissions from both crop and bioenergy crop production (see also Popp et al. 2011b). The models also indicate that other land-demanding climate change mitigation measures (afforestation and avoiding deforestation) are cost-effective and prominent in scenarios with climate change mitigation. Simulations with ReMIND/MAgPIE show that avoiding deforestation, by pricing carbon emissions from land-use change, reduces forest loss in Latin America, Asia and Africa and hence co-emissions from bioenergy production. In addition to avoided deforestation and large scale bioenergy production, strong incentives exist under a climate policy to expand carbon stocks on land by afforestation in the GCAM simulations at the cost of pasture and other land. Overall, land demanding mitigation measures dominate land-use dynamics and enhance the competition for land and water by either restricting land availability for agricultural expansion (avoided deforestation) or spreading directly into agricultural land dedicated for food and feed production (bioenergy and afforestation). This analysis focused on potential bioenergy land use and GHG implications within climate management scenarios. However, other social dimensions will also be important and affect bioenergy's appeal and social acceptance, e.g., food prices, biodiversity and nature conservation and water security.

Basic biophysical (such as agricultural yields), techno-economic (such as conversion efficiencies in the energy system) and socio-economic conditions (such as food demand or trade of agricultural goods) strongly influence land-use outcomes and resulting bioenergy production as well as impacts. Therefore, it will be of key importance to reduce uncertainty in the outcomes and to improve our understanding of how bioenergy and other land use based mitigation perform and interact under different sets of techno-economic and socio-economic settings. Further research to address the issue of land use based climate change mitigation in general and specifically the issue of bioenergy will be crucial to inform decision-makers about robust strategies towards a more environmental-friendly future.

References

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

Beringer T, Lucht W, Schaphoff S (2011) Bioenergy production potential of global biomass plantations under environmental and agricultural constraints. Gcb Bioenergy 3:299–312

Bondeau A, Smith PC, Zaehle S, Schaphoff S, Lucht W, Cramer W, Gerten D, Lotze-Campen H, Müller C, Reichstein M et al (2007) Modelling the role of agriculture for the 20th century global terrestrial carbon balance. Glob Chang Biol 13:679–706

Bouwman AF, Kram T, Klein Goldewijk K (eds.) (2006) Integrated Modelling of Global Environmental Change: An Overview of IMAGE 2.4. Netherlands Environmental Assessment Agency (MNP), Bilthoven

Chum H et al. (2011) in IPCC Special Report on Renewable Energy Sources and Climate Change Mitigation (eds Edenhofer O, Pichs-Madruga R, Sokona Y & Seyboth K) 209–332 (Cambridge Univ. Press, 2011)

Creutzig F, Popp A, Plevin R, Luderer G, Minx J, Edenhofer O (2012) Reconciling top-down and bottom-up modelling on future bioenergy deployment. Nat Clim Chang 2:320–327

Clarke L et al. (2007) Scenarios of Greenhouse Gas Emissions and Atmospheric Concentrations. Sub-report 2.1 A of Synthesis and Assessment Product 2.1 by the U.S. Climate Change Science Program and the

Subcommittee on Global Change Research. Department of Energy, Office of Biological & Environmental Research, Washington, D.C., USA

Ercoli L, Mariotti M, Masoni A, Bonari E (1999) Effect of irrigation and nitrogen fertilization on biomass yield and efficiency of energy use in crop production of Miscanthus. Field Crop Res 63:3–11

Fischer G, Prieler S, van Velthuizen H (2005) Biomass potentials of miscanthus, willow and poplar: results and policy implications for Eastern Europe, Northern and Central Asia. Biomass Bioenergy 28:119–132

Hong C, Fang J, Jin A, Cai J, Guo H, Ren J, Shao Q, Zheng B (2011) Comparative growth, biomass production and fuel properties among different perennial plants, bamboo and miscanthus. Bot Rev 77:197–207

Klein D, Luderer G, Kreigler E, Strefler J, Bauer N, Popp A, Dietrich JP, Humpenöder F, Lotze-Campen H, Edenhofer O (2013) The value of bioenergy in long-term low- stabilization scenarios: an assessment with ReMIND-MAgPIE. Clim Chang. This volume

Kriegler E, Weyant J, Blanford G, Krey V, Clarke L, Edmonds J, Fawcett A, Luderer G, Riahi K, Richels R, Rose S, Tavoni M, van Vuuren D (2013) The role of technology for achieving climate policy objectives: overview of EMF27 study on technology and climate policy strategies. Clim Chang. This issue

Kyle P G et al. (2011) GCAM 3.0 Agriculture and Land Use: Data Sources and Methods. Pacific Northwest National Laboratory. PNNL-21025. http://wiki.umd.edu/gcam/images/2/25/GCAM_AgLU_Data_Documentation.pdf

Leimbach M, Bauer N, Baumstark L, Edenhofer O (2010) Mitigation costs in a globalized world: climate policy analysis with ReMIND-R. Environ Model Assess 15:155–173

Lewandowski I, Clifton-Brown JC, Scurlock JMO, Huisman W (2000) Miscanthus: European experience with a novel energy crop. Biomass Bioenergy 19:209–227

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 39:325–338

Metz B, Davidson OR, Bosch PR, Dave R, Meyer LA (eds) (2007) Climate Change 2007: Mitigation of Climate Change. Contribution of Working Group III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge, UK: Cambridge Univ. Press

Parry ML, Canziani OF, Palutikof JP, van der Linden PJ, Hanson CE, eds. (2007) Climate Change 2007: Impacts Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge, UK: Cambridge Univ. Press

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

Popp A, Lotze-Campen H, Leimbach M, Knopf B, Beringer T, Bauer N, Bodirsky B (2011b) On sustainability of bio-energy production: integrating co-emissions from agricultural intensification. Biomass Bioenergy 35:4770–4780

Popp A, Krause M, Dietrich JP, Lotze-Campen H, Leimbach M, Beringer T, Bauer N (2012) Additional CO2 emissions from land use change — Forest conservation as a precondition for sustainable production of second generation bioenergy. Ecol Econ 74:64–70

Popp A, Lotze-Campen H, Bodirsky B (2010) Food consumption, diet shifts and associated non-CO2 greenhouse gases from agricultural production. Glob Environ Chang 20:451–462

Ramankutty N, Evan AT, Monfreda C, and Foley JA (2008) Farming the planet: 1. Geographic distribution of global agricultural lands in the year 2000. Glob Biogeochem Cycles 22

Rose SK, Ahammad H, Eickhout B, Fisher B, Kurosawa A, Rao S, Riahi K, van Vuuren DP (2012) Land-based mitigation in climate stabilization. Energy Econ 34:365–380

Rose S, Kriegler E, Bibas R, Calvin K, Popp A, van Vuuren D, Weyant J (2013) Bioenergy in energy transformation and climate management. Clim Chang. This issue

Searchinger T, Heimlich R, Houghton RA, Dong F, Elobeid A, Fabiosa J, Tokgoz S, Hayes D, Yu T-H (2008) Use of U.S. Croplands for biofuels increases greenhouse gases through emissions from land-use change. Science 319:1238–1240

van Vuuren DP, van Vliet J, Stehfest E (2009) Future bioenergy potential under various natural constraints. Energy Policy 37:4220–4230

Wise M, Calvin K, Thomson A, Clarke L, Bond-Lamberty B, Sands R, Smith SJ, Janetos A, Edmonds J (2009) Implications of limiting CO2 concentrations for land use and energy. Science 324:1183–1186

Wise M and Calvin K (2011) GCAM 3.0 Agriculture and Land Use: Technical Description of Modeling Approach. Pacific Northwest National Laboratory. PNNL-20971. Available at http://wiki.umd.edu/gcam/images/2/25/GCAM_AgLU_Documentation.pdf