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An agro-economic model comparison of cropland change until 2050

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Abstract

The future development of land under agricultural production has important implications for environment and climate. Different methods to project future agricultural land use have been published indicating large uncertainty due to different model assumptions and methodologies. In this paper we present a first comparison of global agro-economic models, which have been harmonized on drivers like future population, GDP growth and biophysical yields.

The comparison includes four partial and six general equilibrium models, which differ largely according to their modelled land supply and amount of available land. We analyse results of four scenarios: The reference scenario assumes no climate change and a medium pathway of economic growth and population development. The second scenario assumes higher economic growth and population, whereas scenario three and four assume the impacts of climate change on crop yields (HadGEM2, RCP 8.5) and differ according to the used crop model to project the yield changes (DSSAT and LPJmL).

Most models (7 out of 10) project an increase of cropland of around 10 to 25% by 2050 compared to 2005, whereas one model projects a decrease. Across all models most of the cropland expansion takes place in South America and Sub-Saharan Africa but also in North America (especially Canada), if the impacts of climate change are considered. In general, the strongest differences in model results are related to differences in the costs or substitution elasticities of land expansion, the endogenous productivity responses and the assumed development of bioenergy demand.

1. Introduction

Land use and surface cover is determined to a large extent by human intervention, primarily through land conversion for crop cultivation (Vitousek et al., 1997). In fact, cropland expansion was the main source of growth of agricultural production throughout preindustrial history. However, since the industrial revolution and related inventions in the agricultural sector, intensification with land-saving technologies as its primary goal has been the main engine of growth in production (van Meijl and van Tongeren, 1999; Wik et al., 2008). Hence, in the past 50 years, arable land increased depending on the source between only 7% (FAO, 2013) and 15% (HYDE; Klein Goldewijk et al., 2011), whereas agricultural production rose by more than 200% (FAO, 2013). In the future, it is unclear how total cropland will respond to the anticipated increases in demand for agricultural products. The question has implications not only for food security, but also for natural ecosystems, and as such, biodiversity, terrestrial carbon stocks, and other ecosystem services (Houghton, 2003; Gorenflo and Brandon, 2005).

In contrast to its current political and societal relevance, land use was traditionally not a focal area for research in global economic modeling. In the last couple of decades, however, economic land-use modeling has evolved as a new research field. New spatially explicit models of land use have been developed, with a focus on the agricultural and forestry sectors as the main users of land. As well, modeling teams have explicitly introduced global land use into existing computable general equilibrium (CGE) models. These efforts – land use modeling in CGE models and in general – are still in their infancy, and important studies in recent years have indicated large heterogeneity and uncertainty in terms of future land use. Most prominently, models used in the IPCC report AR4 project cropland changes from -18 to +69% by 2050 relative to 2000 (-123 to +1158 million hectares) and forest land changes range from -18 to +3% (-680 to +94 million hectares) by 2050 (Metz et al., 2007). FAO projects an increase of cropland between 2005 and 2050 of 71 million ha (Bruinsma, 2009) and the International Assessment of Agricultural Knowledge, Science and Technology for Development (IAASTD) around 180 million ha in average (van Vuuren et al., 2008). Within the UK Foresight Project, Smith et al. (2010) provided a review of studies on land use projections of the past two decades, indicating a range between 90 and 470 million ha. They concluded that the spectrum of uncertainty in terms of future land use is large and mainly associated to the use of different input data and assumptions about future pathways. Popp et al. (2013) show that the land use modules of 3 Integrated Assessment Models project very different global land cover conversion futures due to strong differences in their assumptions and definitions of land cover distribution in 2005 and structural features of the models.

Hence, in this paper we want to go a step further by harmonizing key input data and assumptions across different models. For this purpose we use a unique model inter-comparison that includes four partial and six general equilibrium models, all of which differ in their modeled land supply, and the amount of available land. In this paper we use the model scenarios to answer two research questions:

1) How much cropland will be used in 2050 under different socio-economic and climate change scenarios?

2) How do methods to model land supply and land expansion differ across models and explain differences in results?

We approach the first part of the second question by reviewing methodological insights and advances for partial equilibrium (PE) and computable general equilibrium (CGE) modeling of land use under five key aspects: 1) Spatial dimension and data source; 2) Accessing new lands; 3) Mobility of land across uses; 4) Forest and bioenergy sector; 5) Technological change. The first research question is answered by comparing the results of four different scenarios, which have been harmonized on future population, income, crop yields and exogenous productivity rates. The reference scenario assumes no climate change and a medium pathway of economic growth and population development (SSP2)[2]. The second scenario includes higher economic growth and population (SSP3), whereas scenario three and four include the impacts of climate change on crop yields (HadGEM2, RCP 8.5) and differ according to the used crop model to project the yield changes (DSSAT and LPJmL). We examine the projected cropland use in the

[2] for an overview on the SSP (Shared socio-economic pathways) scenarios, please see Kriegler et al. (2012).

year 2050 in different world regions and discuss the differences against the methodological differences. Finally, we draw some conclusions regarding policy implications and future research.

2. Models and Scenarios

2.1 Model descriptions (with a special focus on land implementation)

The comparison includes four partial (PE) and six general equilibrium models (GE). Among the PE models, the spatial explicit land use models, MAgPIE (Lotze-Campen et al., 2008; Popp et al. 2010; Schmitz et al., 2012) and GLOBIOM (Havlik et al., 2011; 2013) can be differentiated from GCAM (Thompson et al., 2011; Wise and Calvin, 2011) and IMPACT (Nelson et al., 2010), which model on a higher resolution with linkages to grid-based inputs. The six CGE models are all based on the GTAP database. Whereas AIM (Fujimori et al., 2012), FARM (Sands et al., 2013a; 2013b) and GTEM (Pant, 2007) are model on basis of agro-ecological zones (AEZ's), ENVISAGE (van der Mensbrugghe, 2013) and MAGNET (van Meijl et al., 2006) model on national level with inputs from the grid-specific IMAGE model (Bouwman et al., 2006). EPPA (Melillo et al., 2009) is coupled with TEM (Felzer et al., 2004) to model future land use. The models differ largely according to their modeled land supply and amount of available land. Table 1 gives an overview of key parameters for the modeling of land use and especially cropland expansion and how they are implemented in the different models. Table 2 provides information on the land types and how they are implemented. More details on the models can be found in the appendix and in von Lampe et al. (2013).

Model	Model Type	Land types[+]	Spatial dimension	Data		Method		Bioenergy assumptions in S1
				Land use	Potential cropland expansion	Crop allocation	Cropland expansion	
AIM	GE	3	AEZ	GTAP, FAO, RCP	GTAP AEZ	nested logit	Within nested logit	1st + 2nd gen
ENVISAGE	GE	1	National	GTAP	FAO	CET function	Land supply curve **	No
EPPA	GE	5	National	GTAP / TEM [+++]	TEM	-	Conversion costs	1st gen
FARM	GE	3	AEZ	GTAP	GTAP AEZ	CET function	Within CET	No
GCAM	PE	18	AEZ	GTAP, FAO, HYDE	GTAP AEZ	nested logit	Within nested logit	1st + 2nd gen
GLOBIOM	PE	7	SimU [++]	GLC2000, FAO, SPAM	EPIC	land rent /profitability	Conversion costs + land rent	1st + 2nd gen
GTEM	GE	1	National	GTAP	based on historic expansion	CET function	Within CET	No
IMPACT	PE	2	FPU's *	FAO	Expert opinion ***	price elast.	Exogenously given	1st gen
MAGNET	GE	1	National	GTAP, FAO	IMAGE	CET function	Land supply curve **	1st gen
MAgPIE	PE	3	Grid	own data base	own data base	land rent	Conversion costs	1st gen

[+] only land types, which are able to change over time (please see also Table 2)
[++] Clusters of 5 arcmin pixels belonging to the same slope, soil, and altitude class, to the same country and to the same 30 arcmin pixel.
[+++] Terrestrial Ecosystem Model (Felzer et al., 2004)
* FPU (food production unit) is a river basin with the political boundary of a region. Globally, 251 FPU's are differentiated.
** total agricultural land (crop and pasture land)
*** through Delphi methods

Table 1: Key parameters for modeling land use

Model	Cropland	Pasture	Managed forest	Un-managed Forest	Other natural vegetation	Urban
AIM	dyn	dyn	dyn	-	-	-
ENVISAGE	dyn	dyn	-	-	-	-
EPPA	dyn	dyn	static	dyn	dyn	-
FARM	dyn	dyn	dyn	static	-	-
GCAM	dyn	dyn	dyn	static	dyn	static
GLOBIOM *	dyn	dyn	dyn	dyn	dyn	static
GTEM	dyn	dyn	-	-	-	-
IMPACT	dyn	-	-	-	-	-
MAGNET	dyn	dyn	static**	static**	static**	static**
MAgPIE	dyn	static	static	dyn	dyn	static

* short rotation plantations as a separate land category

** These land use types can be defined within or outside the land supply curve dependent on whether they can be transformed into agricultural land. Shifts are determined within IMAGE model.

Table 2: Land Types represented in the different models

Although the models are classified into two broad types (general or partial equilibrium), there is still considerable heterogeneity within the two groups (more so within PE than within GE models). In the following, those differences are presented along with several key features (see, also Hertel, Rose and Tol, 2008). Those include:

- Spatial dimension and data source
- Mobility of land across uses
- Accessing new lands
- Forest and bioenergy sector
- Technological change

Spatial Dimension and Data Source

The spatial dimension is crucial in land use modeling. Since recent years global land data bases are available on high resolution in various forms. For instance, Klein Goldewijk (2001) provides data on land use over the past centuries, Ramankutty et al., (2008) does so for the year 2000 on a 5arc minute resolution. Monfreda et al. (2008) provides harvested area and yields on the same resolution. The same is done with a different approach by SPAM (Spatial Production Allocation Model), which additionally accounts for physical area (You and Wood, 2006). Some newer models, like GLOBIOM and MAgPIE, are constructed as grid-specific optimization models and can make use of those disaggregated data. The data for MAgPIE are taken from a consistent land use database developed by Krause et al. (2009), which is based on Erb et al. (2007) and integrates crop suitability indicators (van Velthuizen et al., 2007), intact and frontier forest types (Bryant et al., 1997; Potapov et al., 2008), and protected areas (UNEP-WCMC, 2006). GLOBIOM spatial infrastructure is based on the concept of Homogeneous Response Units (HRU) delineated by geographically clustering 5 arc min pixels according to only those parameters of the landscape, which are generally not changing over time and are thus invariant with respect to land use and management or climate change. At the global scale, GLOBIOM includes five altitude classes, seven slope classes, and five soil classes. In a second step, the HRU layer is intersected with a 0.5° × 0.5° grid and country boundaries to delineate Simulation Units (SimU) (Skalský et al., 2008). For each SimU a number of cropland management options are simulated using the bio-physical process model EPIC (Environmental Policy Integrated Climate Model; Izaurralde et al., 2006). And the SimUs are the basis for estimation of land use/management parameters in all other supporting models as well. Initial land cover and land use distribution is based mainly on GLC2000 harmonized when necessary to match with FAO and the crop distribution map of SPAM (You and Wood, 2006).

In contrast, other PE models and the CGE models adopted a somewhat aggregated level of resolution, which is more in line with the spatial resolution of economic statistics. IMPACT runs on around 270 Food Production Units (FPU's), but its climate induced shock originating from crop models are based on the

5arc minute resolution of the SPAM data. MAGNET, GTEM and ENVISAGE use the country level for global results of land allocation across crops. EPPA does so as well but runs in connection with the Terrestrial Ecosystem Model - TEM (Felzer et al., 2004), which distributes EPPA´s land use predictions by 0.5 degree grid cell level based on climate, soil and economic information. FARM, GCAM and AIM use the GTAP AEZ data and land use is aggregated to the level of Agro-Ecological Zones within countries (Monfreda et al. 2009). As most economic data are also available at the country level, FARM and AIM assume a single, national production function in which land types from different AEZs substitute for one another. In contrast, in GCAM, each AEZ within a region has its own land allocation tree.

Mobility of Land across Uses and Diversification of Production

Farms and the area units of observation (e.g., grid cells or AEZs) show a diversified pattern of production. In case of homogenous land, land rents will be equalized and in absence of risk and uncertainty would specialize in one crop. Therefore, some CGE models (ENVISAGE, FARM, GTEM and MAGNET) used in this paper assume land heterogeneity and employ a simple Constant Elasticity of Transformation (CET) function by which an aggregate endowment of land is transformed across alternative uses, subject to some transformation parameter that governs the responsiveness of land supply to changes in relative yields. Some other models like AIM and GCAM use logit functions rather than constant elasticities to model the competition between different land types. Exponents of these functions, which determine the degree of substitutability, are usually derived from literature-based estimates of elasticities, or assumed, and in the base year they are used for calibration (in GCAM they are constant over time; Wise and Calvin 2011). Although the CET and logit approaches are suited quite well for the representation of land use change, they have one important limitation: The CET and logit exponents are the same for both directions. For instance, the conversion from agricultural land to forest land is the same as the other way around.

CGE models typically “nest” the supply functions (EPPA is an exception here), such that producers first determine the allocation of land amongst crops, then, based on the average return to crop land, an allocation is made between crops and livestock or crops and forestland. All models use a different nesting structure and there is little evidence that favors one structure over another. An example for a basic nested logit structure of land used is presented for the AIM model in the supplementary material (Figure S1).

In a first step agricultural, forest and other land types are differentiated. The agricultural land is then further distinguished between cropland and grassland, which then is divided among primary grassland and pasture which is actively used for livestock production. Under the cropland node the different crops are classified. The individual design within each model is usually more detailed and differs from this example, but the basic structure is similar across the CGE models and GCAM. The source of the nested coefficients or transformation elasticities is remains a challenge in CGE modeling as good conclusive empirical evidence does not exist. They are based on econometric studies and expert knowledge. In MAGNET, for instance, transformation elasticities are based on the more detailed OECD's Policy Evaluation Model (PEM) structure (OECD, 2003, Huang *et al*. 2004)

A similar approach to CET is used by the IMPACT model, which specifies harvested area for each crop based on given own and cross price elasticities of supply. The problem with both approaches is that the "transformation" of land from one use to another destroys the ability to track the allocation of hectares across agricultural activities. This behavior is avoided through the spatially explicit land rent methodology of the other PE models. Here, the allocation of land to the different crops is based on the relative profitability of the crops and the location of the crop area can be clearly determined. Due to its cost minimizing goal function, MAgPIE differs slightly from GLOBIOM and GCAM, by favoring crops with lowest production costs instead of those with highest profitability.

EPPA adopts an alternative approach to land use changes compared to other models. It assumes that farmers can transform one land category to other if they are able to cover explicitly the costs of conversion (similar to MAgPIE and GLOBIOM but in a general equilibrium framework). This approach allows tracking land area in a consistent way and implies that intensively managed land can be "produced" from less intensively or unmanaged land, as also that farmland can be abandoned. Compared with the CET, the land transformation approach allows for longer term analysis where demand for some uses could expand substantially (as the case of biofuels in some countries), since the share preserving nature of the CET functions may limits radical land use change.

Accessing New Lands

A critical issue in modeling the long run supply of land to different activities in agriculture and forestry is the availability of new lands that might be brought into production. The simplest way to handle this problem is to construct a land supply schedule in which rising land rents cause additional land to be brought under cultivation. This is the approach adopted by Meijl et al. (2006) and Eickhout et al. (2009) in their specification of the MAGNET model, which is also used in the ENVISAGE model. The appeal of their approach lies in the way they build up this supply schedule. In particular, they capitalize on the detailed productivity information available from the crop growth model of IMAGE (Leemans and Van den Born, 1994). For each region, they first remove all the lands which are: (a) non-productive, or (b) unavailable for conversion to agriculture (i.e., protected or built-up). The remaining lands are subsequently arranged in order of diminishing productivity. The authors then invoke the assumption that land rents are inversely related to yields, which gives them a land supply schedule where the total amount of land in production is an increasing function of land rents. As equilibrium land rents rise, the model brings in additional lands up to the point where the benefit of the last hectare of land, as measured by its marginal value product, equals the "marginal cost" of this land, i.e. the land rent that must be paid in the market place. This approach brings detailed biophysical information in the integrated assessment model to bear on the issue of land supply, with special areas, such as forest reserves and national parks omitted from the commercial supply schedule. The problem is that there is no spatial component to the supply decision – as might be the case if there were AEZs distinguished in the model. This is exactly done by the models AIM and GCAM which use the 18 different AEZs specified in the GTAP database (Monfreda et al, 2009). FARM does the same but aggregates the 18 AEZs into six land classes of each world region. The expansion from crop or agricultural land into forest and other land types is done within the CET or logit structure (see, example of AIM model in Figure S1). The conversion of natural vegetation in EPPA is limited by the observed land supply response in the last two decades. It mimics the increasing costs associated to larger deforestation in a single period, in terms of building additional infrastructure, transport the timber to markets and so on. Also it represents additional institutional costs in the economies in terms of environmental legislation and consumer pressures to conservationism, contributing to slow down intense transformation of natural ecosystems.

The PE models GLOBIOM and MAgPIE model explicitly the expansion of cropland into other land types, like rainforest, savannah area or pasture land (not for MAgPIE in this version). GLOBIOM uses non-linear conversion costs in each region to convert non-agricultural land (forest, other natural vegetation) to agricultural land or to short rotation plantations, as well as to switch between cropland and grassland. The conversion costs are exogenously determined and used for calibration. MAgPIE has a similar approach as GLOBIOM. The conversion of non-agricultural land into cropland consists of costs for preparation of new land and investments into basic infrastructure. The values are determined by different case studies and range between 600 and 7500 US$/ha depending on topography, forest type, soil conditions, applied technology, and the governmental system (Schmitz et al., 2013). In the version of MAgPIE used in this study, it is only possible to expand cropland into intact and frontier forest and natural vegetation not defined as grazing land or forest (in total around 734 million ha). Pasture and other land categories are kept constant over time. In GCAM land allocation between different land types is modelled at the level of each AEZ within each geopolitical region, and is responsive to changes in land profit rates. While the specific characteristics of any technology (e.g., yield, cost) within any sub-regional AEZ are exogenous, endogenous yield increases may nevertheless occur at the larger spatial scales due to inter-regional shifting in production. In contrast to all other approaches, IMPACT focuses only on cropland changes. It bases its expansion potential on exogenous area growth rates, which have been determined by a combination of historical changes in land use and expert judgment on potential future regional dynamics (Delphi method).

Incorporation of forestry and bioenergy sector

Most models assume that forest area trends are driven almost exclusively by agricultural land expansion or contraction, and only deal superficially with driving forces such as global production, consumption and trade in agricultural and forest products and conservation demands. A key problem is that it takes decades to grow a new forest and that the forest stock, as well as sequestration potential, depends critically on the type of forest and its vintage. There are very few global forestry models that handle all these aspects reasonable well in partial equilibrium (e.g. GLOBIOM in this comparison). The models AIM, FARM and GCAM treat forestry within the CET or logit structure. In ENVISAGE and MAGNET forest land is not modeled explicitly but it is part of the potential agricultural land within the land supply curve. In EPPA natural vegetation is incorporated explicitly considering their "non-use" value in the utility function.

The forestry sector is of particular importance in the study in the context of second generation bioenergy as an additional demand of land in the future. Second generation bioenergy feedstocks typically include crop and forest products grown in short-rotation plantations, and also residues from crop production or forestry. In this exercise, GLOBIOM, GCAM, and AIM account for second generation bioenergy and account for an additional threat on cropland[3]. Additionally, all models (except ENVISAGE, FARM and GTEM) treat various first generation biofuels such as ethanol and biodiesel which are made from sugar, wheat, coarse grains and oilseeds, the demand figures differ quite substantially between models. The future demand of this category in all models in this study is based on policy mandates. For simplicity they are kept constant after 2030. Concerning the incorporation in CGE models (and also in most PE models), there appear to be two main obstacles. The first is simply the issue of data. In the case of biofuels, many of the potentially important technologies (e.g., ethanol from cellulose) are not currently commercially viable – so they do not appear in most data bases. Introducing them into the model requires the generation of an appropriate profile of costs, sales, and trade shares, to invoke when they would come into production. Secondly, there is the question of profitability – how high does competing energy prices have to rise

[3] The land for second generation bioenergy is not reported under cropland in contrast to first generation bioenergy, which usually comes from cropped feedstocks.

before these technologies enter commercial production? Taking this to a level of detail that bears directly on land use will be more challenging; and, it is in the competition for land that the global impact of biofuels production may be most significant. This fact is highlighted by the work of van Vuuren *et al.* (2007), who project a massive increase in land devoted to biofuels and hence continued rapid rates of deforestation in developing countries.

Production Technology and Technological Change

Technological change (TC) is a critical driver of land use, and a critical assumption in the projection of land use. For example, Sands and Leimbach (2003) suggest that globally 800 million hectares of cropland expansion could be avoided with a 1.0% annual growth in crop yields. Popp et al. (2011) show that protecting natural forests does not decrease biomass availability for energy production as reducing the land available for agricultural use can be compensated by higher rates of TC. The Millennium Ecosystem Assessment (MEA, 2005) scenarios project positive but declining crop productivity growth over time due primarily to diminishing marginal technical productivity gains and environmental degradation. For this study, most models have harmonized their exogenous TC rates to the assumed rates from the IMPACT model. The only exception is MAgPIE, which generates endogenous technological change rates. However, in addition to the exogenous given TC rates, the models have individual endogenous adjustments related to an improved allocation of crops or substituting capital and labour for land (please see more details on the different implementations in Robinson et al. (2013)).

Robinson et al. (2013) describe the specifications of the various production technologies used in the various models. They conclude that the elasticity of substitution between land and other production factors is crucial with regard to land use. Within the production Substitutability of land with other factors of production is key for the demand for land in CGE models. The greater the substitutability, the easier it is to replace land by labour and capital if land prices increase as land gets scarcer. In this way the same production can be produced with less land inducing an endogenous yield effect. A concern is that in theory a commodity like crops could be produced without an adequate amount of land, as the substitution between the various inputs (land, capital, and labor) is not bounded by physical constraints. In practice AIM assumes low substitutability between land and other factors and most yield changes are from the exogenous yield assumptions. In MAGNET the elasticity of substitution is also low (0.05 for crops and 0.1 for livestock, based on Salhofer (2000)). ENVISAGE and GTEM assume a much higher elasticity of substitution between land and other factors of 0.5, while this elasticity in FARM is 0.3.

2.2 Scenario Description

For this paper we selected four out of eight scenarios, which have been run for the AgMIP model comparison. The detailed description of the scenarios is provided in Von Lampe et al. (this issue). Table 3 gives an overview about the four scenarios.

Scenario	Socio-Economic Pathway	Climate Change
Reference (S1)	SSP2	constant climate
Fragmentation (S2)	SSP3	constant climate
CC-LPJmL (S4)	SSP2	HadGEM 8.5 with LPJmL
CC-DSSAT (S6)	SSP2	HadGEM 8.5 with DSSAT

Table 3: Scenario Overview

We differentiate between two influencing factors: First, the socio-economic developments and second, climate change affecting agricultural yields. The socio-economics are reflected by different population and income projections reflected within the shared socio-economic pathways (SSP) scenarios, developed for the IPCC 5th Assessment Report (Kriegler et al., 2012). Climate change is considered by using the HadGEM2-ES global circulation model using the strongest representative concentration pathway (RCP) with a radiative forcing of 8.5 W/m² (Meinshausen et al., 2011). The reference scenario (S1) assumes no climate change and a medium pathway of economic growth and population development (SSP2). The fragmentation scenario (S2) considers in average lower economic growth and higher population growth (SSP3), whereas S4 and S6 include the impacts of climate change on crop yields. They differ according to the used crop model to project the yield changes. We use the vegetation and hydrology model LPJmL (Bondeau et al., 2007) and the crop growth model DSSAT (Jones et al., 2003)[4]. In all scenarios future trade is not further liberalized and forest protection is kept to current levels. However, as Table 3 shows the models differ according to the implemented bioenergy demand.

The main intention of the scenarios presented here is to shed light on the behavior of the different models in terms of land use change and to support the learning process of this comparison exercise. Hence, the chosen scenarios are rather extreme than plausible. On the one hand, S1 and S2 are kind of optimistic in terms of climate change, since perfect mitigation is assumed with no climate shocks on crop yields. On the other hand, S4 and S6 represent pessimistic scenarios with the strongest possible climate change effect on yield (RCP 8.5), assumed ineffectiveness of CO_2 fertilization (see Müller and Robertson (2013) for a discussion) and no adaptation measures in agricultural management to climate change.

The results of this comparison exercise are either illustrated on global level or on seven regional aggregations:

AME = Africa and Middle East; ANZ = Australia and New Zealand; EUR = Europe; FSU = Former Soviet Union; NAM = North America; OAM = Latin America; SAS = South Asia

3. Projected development of cropland

In the following, we show the development of global and regional cropland area in the different models compared to historic development based on the HYDE dataset (Klein Goldewijk et al., 2011). The projected growth rates of cropped area of the different models are multiplied with the HYDE data of the year 2005[5]. The boxplots indicate the cropland expansion in the year 2050 compared to 2005 (HYDE

[4] For a detailed presentation and discussion on the results of the crop model runs, please see Müller and Robertson (2013).
[5] It has to be noted that all models have different base year quantities of cropland due to different definitions and crops covered in the models. We use the HYDE data base to harmonize the base year values and make the model results comparable, thereby assuming that the growth rates are independent of the base year values.

data) in the four different scenarios. This is done in order to account for the different land use modeling in the two model types. Whereas the CGE models plus IMPACT model harvested area, GCAM, GLOBIOM and MAgPIE model in physical area units. The key results and numbers of the graphical illustrations are summarized in Table 4.

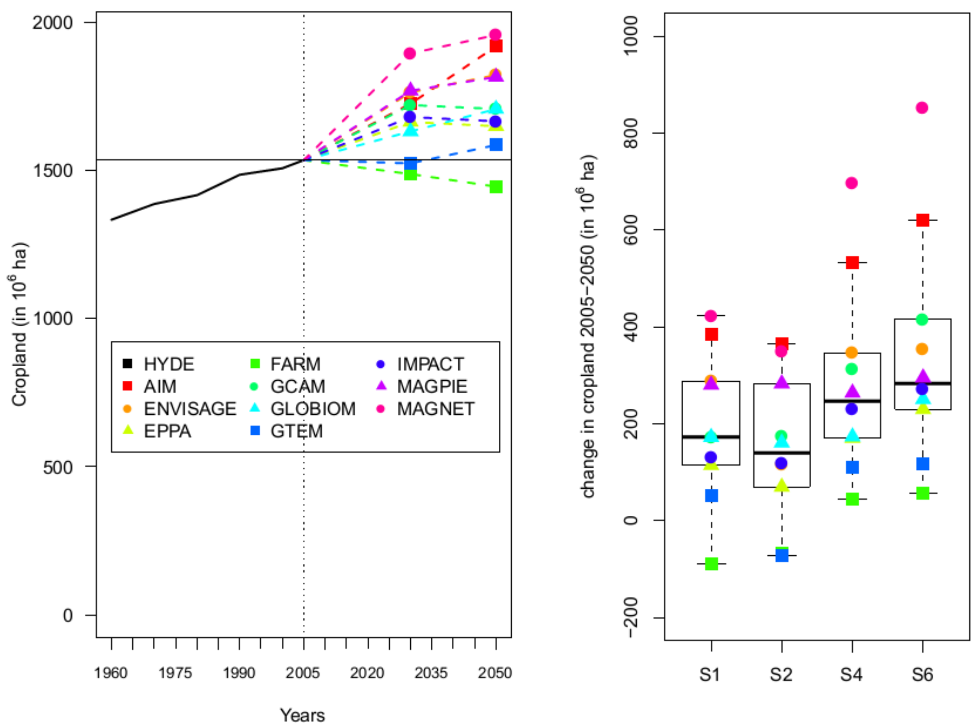


Figure 1: Development of global cropland in S1 (compared to HYDE) (left graph) and change in cropland between 2005 and 2050 in S1, S2, S4 and S6 (right graph)

In Figure 1, showing the development of global cropland area, most models indicate that the growth in global crop land continues to increase. FARM is the exception by a decreasing crop land use at global level. GTEM, IMPACT, EPPA, GLOBIOM and GCAM indicate that the rate of change will be lower than in the past 50 years projected by HYDE[6]. MAgPIE and ENVISAGE indicate a continuous trend while AIM and MAGNET projects a slightly increasing trend in global land use. The fragmentation (S2) instead

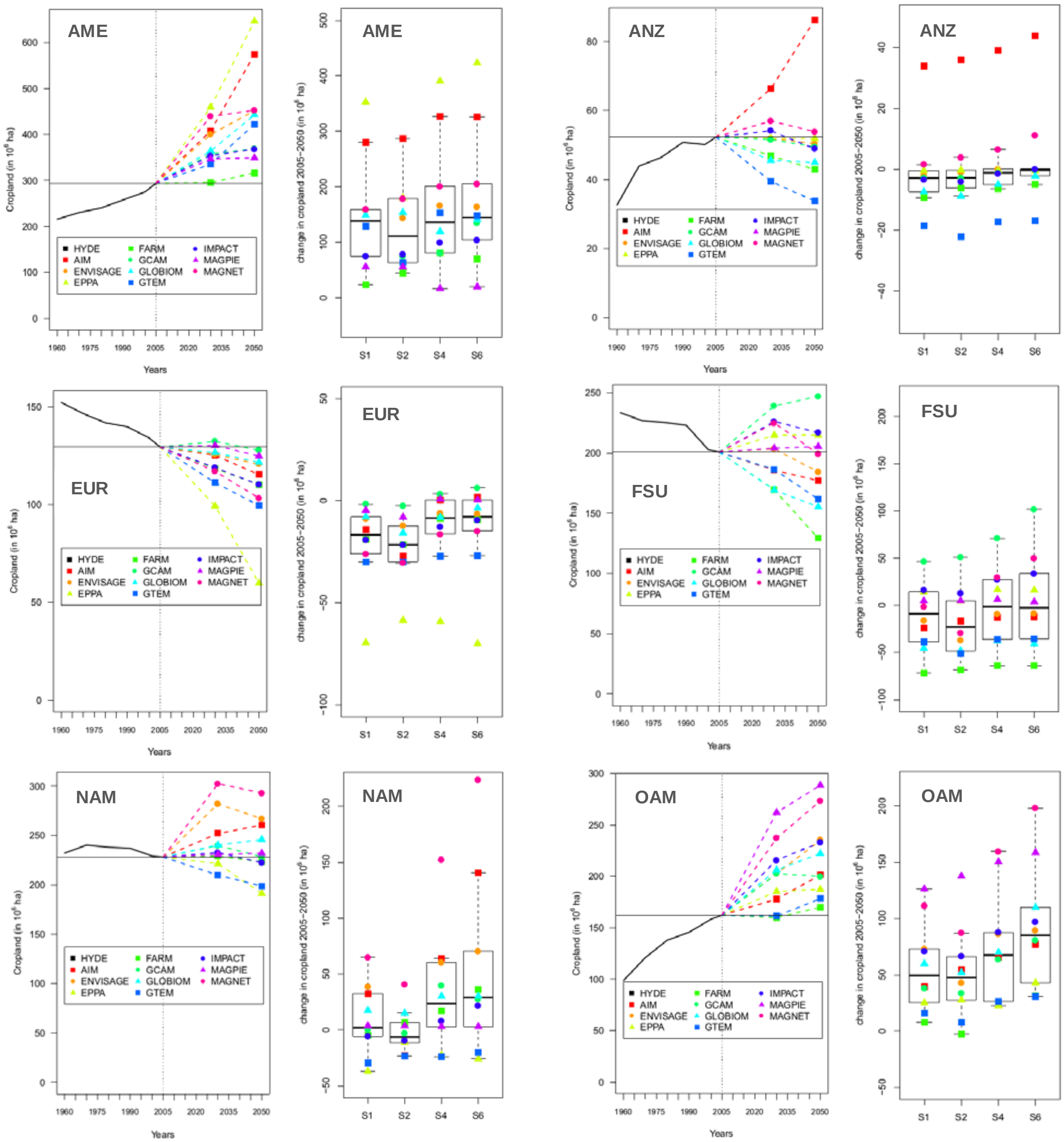
[6] FAO projects a much lower rate of cropland increase in the past (around 7% compared to 15% by HYDE). Hence, comparing the results to FAO, would lead to the result that GCAM, GLOBIOM and IMPACT are closest to the historical trend. In general, the projected range of possible future developments of cropland is very much in line with the uncertainty range of the estimation of historical rates.

of the middle-of-the road (S1) scenario leads to lower global crop land use in most models. Decreasing global cropland can be seen in AIM, GTEM and MAGNET, whereas FARM has lower cropland reduction rates than in S1. The climate change scenarios (S4 and S6) show increasing cropland in all cases, however the differences between the models are large. AIM, GCAM and MAGNET expect a relatively large increase in area. Other models indicate no huge cropland changes due to climate change.

Figure 2 highlights the results for the seven different regions considered in this analysis. Starting with the region Africa and Middle East (AME), cropland in EPPA increases by 120% and in AIM by almost 100%. In contrast, the area in FARM increases only marginally. AIM, ENVISAGE, GLOBIOM and GTEM show an increased growth rate in the second half of the projected period (2030-2050), whereas the growth rates in GCAM, IMPACT, MAgPIE and MAGNET are reduced. The fragmentation scenario influences EPPA and GTEM results, where cropland decreases by 27% and 16%, respectively (Table 4). The influence of climate change is consistently low. In GLOBIOM, cropland area decreases slightly and in FARM in average around 17% more land is used for agriculture under climate change.

The range of future cropland use in Australia and New Zealand (ANZ) is comparably large. AIM projects an increase by almost 60% and GTEM and GLOBIOM see a decrease of around 35% and 14%, respectively. The difference between AIM and GTEM in 2050 amounts to more than 40 million ha (based on 53 million ha in 2005). The influence of fragmentation (decrease by 11% in GTEM) and climate change (average increase by 14% in MAGNET) is rather low.

For Europe, the models indicate that the declining crop land will continue in the future, although MAgPIE and GCAM show some slight increases up to 2030. Strongest reductions are projected by EPPA with cropland area more than halved by 2050. GTEM, MAGNET and IMPACT follow largely the trend of the past decades. Climate change puts additional pressure on cropland since all models project an increase, with AIM (+13%) and MAGNET (+10%) at highest.



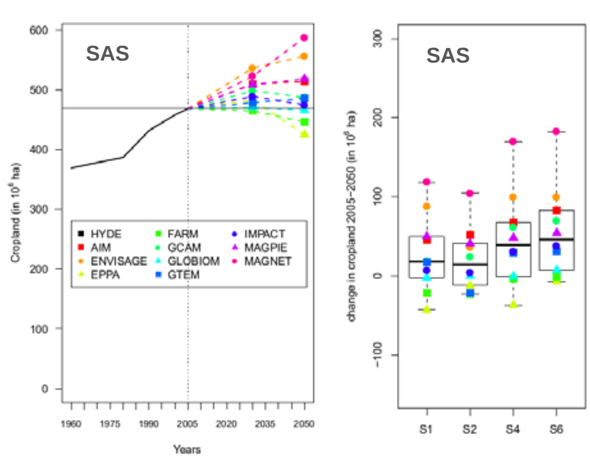


Figure 2: Development of cropland in in the each of the 7 regions in S1 (compared to HYDE) (left graph) and change in cropland between 2005 and 2050 in S1, S2, S4 and S6 (right graph)

The Former Soviet Union (FSU) saw dramatic declines in cropland after the collapse of the USSR in the 1990s. This trend has generally stabilized in the last decade, and in the future, the models show especially divergent trends for cropland in this region. The changes in cropland vary between -36% (FARM) and +23% (GCAM). GCAM sees an increase to almost 250 million hectares, whereas FARM a decrease to almost 125 million hectares. Still, 6 out of 10 models project a decrease of cropland in this region. ENVISAGE, MAGNET and IMPACT see an increasing trend up to 2030 but a decreasing up to 2050. The influence of increasing population and decreasing income (S2) generally has a negative impact on cropland use, with AIM, FARM and MAgPIE as exceptions. Climate change, in contrast, puts new pressures on cropland. Highest increases (as average of S4 and S6) compared to S1 are obtained for GCAM (+16%) and MAGNET (+21%).

While cropland was fairly stable in North America in the last 50 years with around 230 million hectares, MAGNET, ENVISAGE and AIM see an increase in 2050 to about 270 to 300 million hectares. Only GTEM, EPPA and IMPACT project lower cropping area in 2050 compared to 2005. Fragmentation and climate change seem to have huge impacts on cropland in North America. Under SSP3, cropland is mostly reduced with highest reductions from AIM (-21%) and ENVISAGE (-18%). An exception is EPPA with a 13% increase in cropland. With climate change the opposite is projected with highest expansion rates from MAGNET (+43%) and AIM (27%). In MAGNET cropland expansion exceeds 200 million ha in 2050, mostly in Canada.

In the past fifty years, Latin America (OAM) was the region with the greatest expansion of cropland. According to HYDE, it increased from around 100 to 160 million hectares between 1960 and 2005. ENVISAGE, IMPACT and GLOBIOM continue this trend, to around 220 million hectares in 2050. FARM, GTEM and to a lesser extent GCAM and AIM observe a slowing down of expansion, whereas MAgPIE projects an accelerating trend to 280 million hectares. Climate change increases cropland area with rates ranging from 5% to 25%. SSP3 has a low, but largely negative impact with highest reduction in ENVISAGE (-13%).

The projections in South Asia (SAS) are similar to OAM by having overall increasing rates of cropland use, except for FARM and EPPA. However, the rates are much lower with the maximum of 40% (AIM).

Region	Scenario	AIM	ENVISAGE	EPPA	FARM	GCAM	GLOBIOM	GTEM	IMPACT	MAgPIE	MAGNET
AME	2050	+95	+54	+120	+	+26	+51	+44	+25	+19	+51
	SSP3	+	–	–27	+	o^-	+	-16	+	o^+	+
	CC	+	+	+	+17	+	–	+	+	o^+	+
ANZ	2050	+65	–	–	-18	–	–14	–35	–	n.a.	+
	SSP3	+	+	o^+	+	o^+	–	–11	–	n.a.	+
	CC	+	+	o^-	+	+	+	+	+	n.a.	+14
EUR	2050	–11	–	-54	–15	–	–	–23	–15	–	–20
	SSP3	–12	–	+19	o^+	–	–	o^+	–	–	–
	CC	+13	+	+	+	+	+	+	+	+	+10
FSU	2050	–12	–	+	–36	+23	–23	–19	+	+	–
	SSP3	+	–11	–	+	–	–	–	–	o^+	–14
	CC	+	+	+	+	+16	+	+	+	o^+	+21
NAM	2050	+14	+17	–16	–	o^+	+	–13	–	+	+30
	SSP3	–21	–18	+13	+	–	–	+	–	o^+	–
	CC	+27	+	+	+14	+15	+	+	+10	–	+43
OAM	2050	+24	+45	+15	+	+23	+37	+	+44	+78	+65
	SSP3	+	–13	+	–	–	–	–	–	+	–
	CC	+16	+	+	+12	+17	+14	+	+10	+	+25
SAS	2050	+40	+19	–	–	+	o^-	+	+	+11	+24
	SSP3	–	–	+	o^-	+	o^+	–	o^-	–	–
	CC	+	+	+	+	+	+	+	+	+	+
WLD	2050	+25	+19	+	–	+11	+11	+	+	+18	+26
	SSP3	–	–	–	+	o^+	o^-	–	o^-	o^+	–
	CC	+10	+	+	+	+11	+	+	+	+	+18

2050 cropland change in S1 between 2005 and 2050
SSP3 cropland change in S2 compared to S1 in 2050
CC cropland change in S4+S6 (average) compared to S1 in 2050
\+ cropland change between +1 and +9% o^- cropland change between -1 and 0%
o^+ cropland change between 0% and +1% – cropland change between -9 and -1%

Table 4: Change in cropland cropland in over time (in S1) and across scenarios (compared to S1) (in %)

Table 5 summarizes the regional and global results for the reference scenario (S1) and the climate change scenarios (S4/S6) in physical units, as well as the absolute difference and the percental difference compared to 2005. By far the largest cropland expansion is projected in Africa (+121 million ha). Latin America and South Asia are other sources for converted land. However, the difference due to climate change is largest in North America (+34 million ha) followed by Latin America (+27 million ha), which accounts for around 15% of the initial cropland area in 2005. Globally, almost 200 million ha are converted in the constant climate scenario and additionally, 120 million ha with climate change.

Region	**Cropland expansion by 2050**		**Difference due to climate change**	
	in S1 (10^6 ha)	**in S4/S6** (10^6 ha)	**absolute** (10^6 ha)	**as share of total cropland**
AME	145.6	168.5	22.9	7.7 %
ANZ	-0.4	3.1	3.5	6.7 %
EUR	-20.1	-13.3	6.8	5.3 %
FSU	-11.6	1.8	13.4	6.7 %
NAM	8.1	41.8	33.7	14.8 %
OAM	56.7	83.7	27.0	16.6 %
SAS	27.6	51.0	23.4	5.0 %
World	**192.7**	**317.2**	**124.5**	**8.1%**

Table 5: Impacts of Climate Change on cropland expansion (mean of all models)

4. Discussion of differences in model results

The interpretation of model results is quite challenging due to the huge amount of data and methodological differences in the models.

From the point of results, ENVISAGE and MAGNET are the closest group due to their similar implementation. MAGNET is usually a bit higher caused by the different available land pools. In addition, the elasticity of substitution between land and other factors is five times higher in ENVISAGE and equal to 0.5. This induces more substitution effects when the land price gets higher and subsequently the land expansion is less. In many cases the group of FARM and GTEM estimate future land use more conservative compared to other models. This can be partly explained by relatively low elasticities of transformation for allocating land. Furthermore, FARM is the only model that indicates a decrease in global cropland, and FARM is with AIM the only CGE model that includes forestry within a CET structure. In FARM, simulations of future land use are sensitive to two types of parameters: relative rates of land-augmenting technical change, and income elasticities of demand for forest products. Exogenous rates of yield improvement for managed forests are much lower than rates of yield improvement for crops.

In contrast, the other CGE models are usually at the upper end, especially MAGNET and AIM and to a lower extent EPPA and ENVISAGE. The increasing trends in AIM and MAGNET are caused by the assumption that still a lot of additional land can be made available for agriculture. In MAGNET these potentials are based on the IMAGE model which indicates that still a lot of land can be taken into production in Africa, South America and North America (especially Canada). In other words these countries are on the flat part of the supply curve where more land can be taken into production without much additional costs. Furthermore, their production trees imply that land has a low degree of substitutability with other factors such as capital and labour. In AIM there are especially limited substitution possibilities of land with other factors, as compared with the other models in this study (see, also Robinson, et al., 2013).

Except for Latin America, MAgPIE project only modest expansion of cropland area in the different regions. One reason is available land for conversion. In the version of MAgPIE used here, only natural vegetation and intact and frontier forest can be converted to cropland. Especially in Sub-Sahara Africa this makes a huge difference as compared to other models, since MAgPIE already uses the entire land potential in the S1 scenario. Another reason for conservative estimations of future land use is the physical land use data base, which is used in MAgPIE. This data base distinguished non-cropland into suitability classes. Hence, a lot of potential land is not suitable for cropland and falls out of the available land pool. Furthermore, MAgPIE considers land conversion costs (as explained in Chapter 2). The same holds for GLOBIOM, which mostly increases cropland in AME and OAM. For FSU, GLOBIOM sees considerable decreases due to low profitability of agriculture.

Another source of uncertainty is the assumed bioenergy demand. Except ENVISAGE, FARM and GTEM, all models assume first generation bioenergy demand in the future. Whereas, GLOBIOM, MAgPIE and GCAM have harmonized their demand for future first generation bioenergy according to current policy mandates (constant after 2030), MAGNET, for instance, has relatively high first generation biofuel targets in countries, like the United States and Brazil. This puts additional pressure on cropland in contrast to models with lower bioenergy demand. Land devoted to second generation bioenergy is not reported here, but still reduces the potential cropland pool for expansion.

The fragmentation scenario (S2, SSP3) differs from the middle-of-the-road scenario (S1, SSP2) by a much higher population growth and a much lower GDP growth. The differences between the scenarios are especially large in developing countries. Significant decreasing global cropland is obtained for AIM, ENVISAGE, EPPA, GTEM and MAGNET (all CGE models). Hence, it seems that in the CGE models (except FARM) lower cropland demand due to lower GDP effects dominate the increase in demand for cropland due to a higher population. In S2, GDP is 32% lower than in S1 but population only 11% higher by 2050. Since most of crops are consumed via processed products with relatively high income per capita demand elasticities in those models, the demand in S2 is lower than in S1 (see Valin et al., (2013) for the differences in demand between SSP2 and SSP3). For FARM the results are opposite and there are largely positive effects of SSP3 indicating that population effects dominate GDP effects due primarily to low income elasticities of demand for crops. The PE models are hardly affected by the different SSP assumptions.

Climate change induces a relatively large increase in area in AIM, GCAM and MAGNET. The mechanism is similar to the baseline: large potential land availability and in case of MAGNET and AIM low endogenous yield effects. Other models indicate no or very little cropland change and assume that (almost) all negative effects in yield can be compensated by endogenous yield effects in their model. This is because land expansion is largely exogenous (IMPACT), adaptation through switches across production systems and also reallocation across the SimUs (GLOBIOM) or substitution possibilities (ENVISAGE, GTEM) are easy. Moreover, except for MAgPIE, the demand side adjusts due to the climate change pressure (see Valin et al., 2013) and international trade is rather flexible (especially for IMPACT and GLOBIOM with homogenous goods assumption, to a lesser extent for the CGE models with Armington assumptions). In MAgPIE crop land even decreases due to climate change as it adjusts for climate change effect by investing in technological change. A second reason is the different implementation of climate change induced yield shocks. In contrast to the other models, climate change impacts are not considered on FPU level, but on grid cell level (see Nelson et al. (2013) for more details). This allows MAgPIE to consider the large heterogeneity of climate change within FPU's and leads to more specialization and lower effects of climate change.

Turning now to the analysis of the regional specific results, we obtain the largest cropland expansion in Africa and the Middle East (AME). EPPA and AIM increase cropland by around 100-120% due to the combination of a 2.5 fold population increase, economic growth and only 50% yield increase of other agriculture products which dominate in AME. Another reason for EPPA are the low land conversion and institutional costs in Africa, resulting in a large land supply response. ENVISAGE, GLOBIOM, MAGNET and GTEM get an increase in crop land use around 50%. The PE models MAgPIE and

IMPACT observe a relatively moderate increase of about 15%. Key to this result is the land availability, or how easy it is to get new land into production. As explained, the potential cropland in MAgPIE in Africa is limited. In the fragmentation scenario (S2) we see for most models an increase in cropland and that differs from the global situation discussed above. Population effects dominate GDP impacts in AME. EPPA and GTEM, however, show the opposite with cropland decreases a lot in S2 relatively to S1. While cropland productivities are identical in S1 and S2, GTEM enables differential land productivity shocks across scenarios for livestock. Since a general negative productivity shock implied under S2 relative to S1 is distributed across inputs and sectors, including land used in the livestock sector, and since the demand for livestock products is relatively price insensitive (a feature of GTAP based CDE parameters) livestock sector uses more land per unit of output under S2 relative to S1. Consequently, land moves out of crops into pastoral activities displaying a relative decline in the cropping land. In the case of EPPA, GDP shocks are applied through labour productivity changes, nulling the effect of the population shock. The decrease in productivity to reach the prescribed GDP in EPPA is the largest in AME and the lowest in EUR, changing agriculture comparative advantage in favor of EUR.

GLOBIOM and especially GTEM assume a strong reduction in cropland in ANZ which is in contrast to the historical trend. In GTEM, this has two reasons: First, total agricultural land drops by 27% significantly over the projection period (the change is exogenously imposed and based on a 20-year historical trend as described in Chapter 2); Second, export driven growth in livestock sector raises land rental in livestock sector relative to crops sector such that land moves out of crops into pasture. In addition, one has to consider the distribution of agricultural land in ANZ. 90% of agricultural land is used by the livestock sector, while only 10% is used by cropping sectors in total. Because of this relativity, a small increase in the pastoral activity would mean a big drop in land used by the cropping sectors in a relative sense. AIM on the other hand shows a strong increase till about 80 million hectares as it assumes that a lot of potential cropland is available. GTEM expects also a decrease in cropland in the fragmentation scenario (S2) mainly due to the lower GDP growth rate and related demand. Climate change impacts are slightly positive for this region. In Europe, models agree on the downwards trend for Europe in S1. EPPA even projects a bisection of European cropland since in S1 EUR is losing competitiveness in crop production to regions with low costs of cropland conversion. In contrast, in S2 EUR is gaining comparative advantage due to the lowest shock in labour productivity compared to other regions, leading to almost 20% more cropland use than in S1. Except EPPA, almost all other models indicate that the fragmentation scenario will release more crop land to other uses as the lower GDP effects dominate the small population effects in Europe. Climate change impacts increase cropland use in all models in Europe. The impacts are highest for AIM and MAGNET as land is more abundant than in other models and expands due to lower yields under climate change.

In FSU, the CGE models plus GLOBIOM[7] see a decrease in area. Among the other models, especially GCAM allows for especially considerable cropland expansion. This expansion in GCAM occurs in part due to low base-year (2005) land profit rates for the dominant agricultural crops, which become substantially more profitable in the future due to the assumed baseline improvements in yields. This expansion also occurs because of a large amount of land that is potentially available for agricultural conversion - approximately 1,700 million ha, with about 200 in relatively productive AEZs.

In North America, the key between the models is the potential land that can be taken into production (MAGNET, AIM). IMAGE-based models show large potential, especially in Canada, where most other regions of the world are relatively limited. Therefore, land increase is highest in MAGNET and AIM. The increase in ENVISAGE is much less as these models assume much higher substitution elasticities between land and other production factors. Almost all models show decreasing land in the Fragmentation scenario (S2) as the lower demand effect to a lower GDP in NAM dominates the slightly lower population effects in NAM. Climate change impacts are very high in MAGNET and AIM as the lower yields lead directly to land use expansion as possibilities are there and incentives for higher yields therefore are low. The

[7] Likely due to the non-linear trade cost in GLOBIOM, which tend to maintain some inertia in the trade patterns. Hence, a fast crop yield growth, decreasing population and medium strong GDP growth may lead to further land abandonment.

assumptions on land availability in Brazil and other countries containing a lot of natural vegetation determine the results in OAM. The Fragmentation scenario lowers crop land use in OAM quite substantially in almost all models as the exporter of the world suffers more than average with an economic downturn. In FARM, cropland expansion is slightly negative as forestry is more competitive and counterbalances the demand from agriculture.

5. Key Messages and Conclusions

The future of human influence on land is critical from environmental and climate perspectives. Especially, the use of land for cropping activities threatens biodiversity, carbon stocks and ecosystem services. At the same time attempts to project future land use have been largely uncertain. We analyze methodological differences among different land use models on the basis of the results of the first land use model intercomparison exercise. Besides providing a future outlook on land use, the second goal of the exercise is to gain insights into modeling land use and cropland expansion and thirdly, to identify future research tasks.

In terms of the first task we project future cropland area up to the year 2050. Global cropland without the impact of climate change increases on average across all models by almost 200 million hectares until 2050. Climate change further increases the pressure on land resources by increasing cropland expansion to more than 300 million hectares. Those average values of this land use model intercomparison exercise correspond with the previous assessment study conducted by van Vuuren et al. (2008), who came up with an average increase of 180 million hectares of cropland expansion globally under no climate change. Smith et al. (2010) provided a review of the existing studies giving 10-80th percentile range of 90 to 470 million hectares. Most of the cropland expansion in this exercise takes place in Africa, followed by Latin America and South Asia. This is not surprising, since especially in Sub-Saharan Africa and Latin America the largest potential of suitable cropland is located. According to Fischer et al. (2000) in both regions between 800 and 900 million hectares of additional land would be suitable for cropland. The potential in South Asia is much lower and estimated to be around 120 million hectares. Another important result of this study is the largely agreed decrease of cropland in Europe and increase in North America. Whereas Europe loses a lot of cropland to other uses (which is not captured by all models), it also lowers its cropland area due to lower domestic demand (decreasing population) and diminishing international competitiveness. The result for North America is more striking, as population growth projections are higher than in Europe but lower compared to the world average. Some models see large potential for area expansion, especially in Canada. For instance, the IMAGE model, which serves as a basis for MAGNET assumes potential cropland area of 347 million hectares in the United States and 464 million hectares in Canada in 2001. The sensitivity to climate change in North America is equally surprising and related to the huge land potential there. Together with Latin America most of the cropland is expanded due to climate change in those two regions. In contrast, in Sub-Saharan Africa climate change induced cropland expansion is moderate.

A critical need for modeling economic land use change is the availability of data. Although the data basis on global land use has improved considerable (see Chapter 2), especially data on potential cropland and its suitability on a global level and data about the ease of converting this land into cropland is lacking. With the latter, we refer to land conversion costs and substitution elasticities. A lot of qualitative assumptions are taken in those fields, leading to biased results and a low replicability. In terms of potential cropland, especially Africa and the northern countries, like Canada and Russia (due to climate change) leave us with high uncertainty. In Latin America, data availability is much better but high uncertainty exists concerning forest protection. In recent years, land clearing has slowed down (Soares-Filho et al, 2010), indicating a way towards a forest transition, as observed in countries like Thailand or Vietnam (Meyfroidt et al., 2010; Meyfroidt and Lambin (2011).

In terms of the methods used, all of the models approach land use change from an economic perspective. However, land conversion can not only be explained by economic behavior. Social, political and cultural factors have to be considered as well. Here land use modeling is still at the beginning of this trajectory. Modelling of future technological change is decisive due to its direct link with land expansion. Endogenous approaches are emerging but still in its infancy. Data and empirical studies are the main challenges. A further big field of future research should be devoted to the interaction of cropland and pasture. Not all models are able to represent this relationship and some only in a crude way. The same holds for managed forest area, which seems to gain competitiveness as energy prices continue to rise. Here the different time scales of agriculture and forestry is a major challenge for modelers.

In this first land use model intercomparison, analyzing the sensitivity of input data and parameters as well as the range of uncertainty was not possible. As this exercise was hopefully only the starting point, the aim for future studies should be to explore the uncertainty space by applying sensitivity analyses on key parameters like substitution elasticities, land conversion costs and assumed technological change pathways. Finally, the need for validating land use models is apparent. How well are the approaches suited to describe past and current developments? Hind casting (model starts in the past) or back casting (model forecasts into history) would be options to validate the model outcome with observed data. It is only through such systematic research that it will be possible to eliminate the least promising approaches and focus on those that are worthy of further attention.

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