chapter 6

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chapter 6

Global climate change, food supply and livestock production systems: A bioeconomic analysis

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main chapter messages

- Climate change impacts on crop and grass yields are projected to have only small effect on global milk and meat production by 2050, which remains under any climate scenario within +/-2 percent of the projected production without climate change.

- Depending on the scenario, the climate change effects can be more pronounced at the regional scale. In sub-Saharan Africa, the effects are both the most uncertain and potentially the most severe; e.g. ruminant meat production could increase by 20 percent but it could also decrease by 17 percent.

- The effects on regional consumption are less pronounced because the impacts of climate change are mostly buffered through international trade. Virtually all the negative effects are smaller than 10 percent.

- Adjustment in the production systems structure will be an important adaptation measure. Grass yields benefit more (or are hurt less) from climate change than crop yields. Climate change would hence favour the grazing systems, leading potentially to a change in the current trend towards more intensive systems.

- Depending on the impact scenario, optimal adaptation strategies can go in opposite directions. Efforts to decrease this uncertainty must go hand in hand with search for robust strategies effective under many different climate futures.

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1. Introduction

Livestock are the source of 33 percent of the protein in human diets, and continued population and economic growth could double the total demand for livestock products by 2050 (Alexandratos and Bruinsma, 2012). Currently, 30 percent of global land area is already being used for livestock rearing (Steinfeld *et al*., 2006), which means that substantial efficiency gains will be required to satisfy the rising demand within the physical constraints related to land, and, to some extent, water (Doreau *et al.*, 2012). At the same time, global mean surface temperature is projected to rise by 0.4-2.6 °C by 2050, and the contrast in precipitation between wet and dry regions and between wet and dry seasons will also increase according to the Intergovernmental Panel on Climate Change (IPCC) 5th Assessment Report (2013). Climate change will have multiple impacts on livestock, from heat stress to livestock diseases to feed quality and availability (Thornton *et al.*, 2009). The objective of this chapter is to assess how the impacts of climate change on crop and grass yields will influence the global livestock sector from now to 2050, and to explore the potential for adaptation through transitions in livestock production systems, which have been identified as an efficient adaptation mechanism to address future challenges, even in the absence of climate change (Havlík *et al.*, 2014).

Global economic assessments of climate change impacts on agriculture over the last couple of years have experienced an unprecedented boom. In 2007, Schmidhuber and Tubiello (2007) could state that most global assessments relied on a single modelling framework, represented by the International Institute of Applied Systems Analysis (IIASA)'s Agro-ecological zones (AEZ)/ Basic Linked System (BLS) (Fischer *et al.*, 2005). During the past year, however, a coordinated climate change impact and adaptation model intercomparison exercise has been implemented within the Agricultural Model Intercomparison and Improvement Project (AgMIP)/ Inter-Sectoral Impact Model Intercomparison Project (ISI-MIP), which combines nine global economic models with five global gridded crop models (Nelson *et al.*, 2014a). However, the effects of climate change on fodder availability remain under-researched (Wheeler and Reynolds, 2013). Most of the studies, including the recent model intercomparison, have considered climate change impacts only on crop yields. In the past, climate change effects on grassland productivity were taken into account in only two models, Future Agricultural Resources Model (FARM) (Darwin, 2004) and Emissions Predictions and Policy Analysis (EPPA) (Reilly *et al.*, 2007). Both models represented the whole livestock sector as an aggregate single activity and the potentially important effects of changes in grass yields on ruminant sectors were blurred by climate change impacts on crops as the main feedstuff for pigs and poultry. For this chapter, we implement the Global Biosphere Management Model (GLOBIOM), a global partial equilibrium agricultural and forestry sector model with detailed livestock sector representation, to provide a new view on this topic (Havlík *et al.*, 2013; Havlík *et al.*, 2014).

GLOBIOM (Havlík *et al.*, 2011) represents agricultural production at a spatial resolution going down to 5x5 minutes of arc[2]. Crop and grassland productivities for current and future climate scenarios are estimated at this resolution by means of biophysical process-based models, such as Environmental Policy Integrated Climate (EPIC) (Williams, 1995). Livestock representation follows a simplified version of the Seré and Steinfeld (1996) production system classification. This approach recognizes differences in feed base and productivity between grazing and mixed crop-livestock production systems across different agro-ecological zones (arid, humid, temperate/ highlands). Parameters for the model were obtained from a recently published global livestock production systems dataset (Herrero *et al.*, 2013). GLOBIOM allows for endogenous shifts

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[2] 60 arcminutes correspond to 1 degree

of livestock between the different production systems based on their relative profitability. The model has been implemented for climate change impact assessments in the past, both individually (Mosnier *et al.*, 2014) and as part of the AgMIP/ISI-MIP model intercomparison, but it is in this chapter that climate change impacts on grasslands are included for the first time.

Future climate development is highly uncertain and the large differences in impact assessments provided by crop or vegetation models add to this uncertainty (Asseng *et al.*, 2013; Ramirez-Villegas *et al.*, 2013; Challinor *et al.*, 2014; Rosenzweig *et al.*, 2014). The ISI-MIP project results (www.isi-mip.org) that were made available to impact modellers downscaled and bias-corrected climate change scenarios, based on the results of the Coupled Model Intercomparison Project (CMIP). Subsequently, a database of global, spatially explicit, modelled climate change impacts across different sectors has been created (Warszawski *et al.*, 2013). These datasets make it possible, in principle, to account for the uncertainties inherent in climate change impact assessments. We have identified the most important sources of uncertainty to be: use of a particular crop/grass growth model; and assumptions about the strength of the carbon dioxide (CO$_{2)}$ fertilization effect. These two aspects will be systematically treated throughout our study.

2. Methodology

The assessment provided in this chapter follows a sequential approach. First, climate change scenarios quantified by general circulation models (GCMs) are selected, then results of these scenarios are used as input to biophysical process-based models to assess the impacts on crop and grass yields, and finally these models are used as input for the economic model to project the effects of climate change on the agricultural sector as a whole. In the next sections, we will present these three steps in detail.

2.1 Climate scenarios[3]

The most recent generation of climate change scenarios available at the time of this study corresponds to the fifth phase of the Coupled Model Intercomparison Project (CMIP5) (Taylor *et al.*, 2011). In this project, more than 50 climate models were used to simulate four emission scenarios (Representative Concentration Pathways, or RCPs). The four RCPs cover a range of “radiative forcing”[4] in the year 2100, going from 2.6 to 8.5 W/m^2 (Vuuren *et al.*, 2011). Depending on the climate model, these levels of radiative forcing would spread the global temperature increase above pre-industrial levels, from below 1 °C for RCP2.6 to about 7 °C for RCP8.5, the median across the models for the latter RCP being just below 5 °C (Rogelj *et al.*, 2012). For this analysis, we will focus on RCP8.5 for three reasons: first, because this scenario shows best what the future challenges of climate change could be; second, because together with the “present climate” scenario, it allows for judgment about the intermediate emission pathways; and finally, because the recent emission developments exceed even the RCP8.5 emission levels for the relevant years (Peters *et al.*, 2013).

The ISI-MIP provided impact modellers with spatially interpolated and bias-corrected climate datasets for all four RCPs and for five GCMs (GFDL-ESM2M, HadGEM2-ES, IPSL-CM5A-LR, MIROC-ESM-CHEM, NorESM1-M) selected to span the CMIP5 range of global mean temperature changes and relative precipitation changes (Warszawski *et al.*, 2013). Of the five GCMs, ISI-MIP retained HadGEM2-ES as the

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[3] The scenarios reported in this study were developed as part of a European Union-funded FP7 project called “An integration of mitigation and adaptation options for sustainable livestock production under climate change” (ANIMALCHANGE) (Grant 266018)

[4] “radiative forcing” is linked to the CO$_2$ concentration measured in part per million value or ppmv. The higher the CO$_2$ concentration, the higher the radiative forcing which in turn raises the radiative energy reaching the earth’s surface and causes the average earth temperature to increase

reference model, and we do the same in this chapter. Under RCP8.5, HadGEM2-ES projects a global temperature increase for 2050 of about 2.5 °C and an average increase in precipitation of about 3 percent. This ranks HadGEM2-ES as the hottest and driest of the five models, with potentially the most negative effects on agricultural production. The spatial distribution of the change in temperature and precipitation is presented in Figure 1. The temperature increases follow the typical spatial pattern, with higher increases in the north. Reductions in precipitation are projected to affect large parts of Australia, Brazil and Europe, the southwest part of the United States of America, and parts of Africa and the Near East.

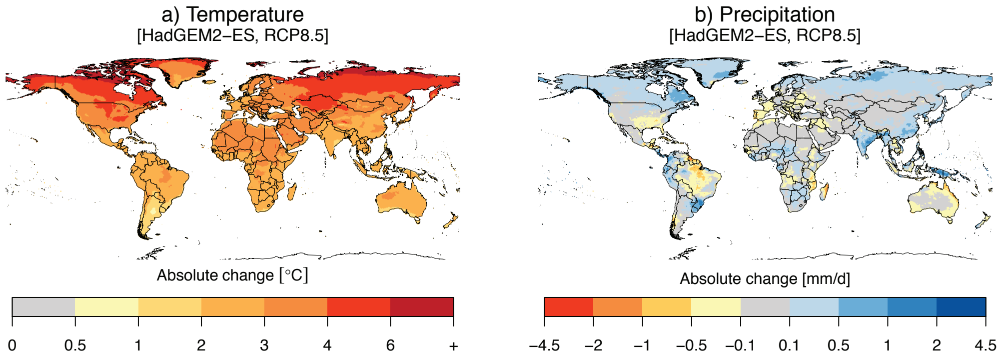
2.2 Biophysical impact modelling

Climate scenarios need to be translated into impacts on crop and grass yields. In general, two approaches are available: biophysical process-based (mechanistic) models; or statistical models (Porter *et al*., 2014). However, as described by these authors, it is difficult for the statistical models to represent the direct effect of elevated CO_2, which makes them less suitable for long-term assessments. These models have also never been applied to assess climate change impacts on grass productivity at the global scale, and therefore can be ruled out as an option for our study. Two different approaches exist for implementation of crop growth models at global scale: the models can be run for a limited number of specific sites, and the results extrapolated to the areas not directly covered; or the crop models can be run on a more or less detailed spatial grid for each relevant pixel. For purposes of this chapter we adopt the second option.

Our preferred crop growth model is EPIC (Williams, 1995), which is a standard component of the model cluster around the economic model GLOBIOM. EPIC is a long-established crop growth model and, in addition to crop simulations, it has been applied to forage yield projections (Izaurralde *et al.*, 2011). However, EPIC has been designed to model managed grasslands. Globally, large areas of pasture are managed very extensively and their composition is close to natural biomes. The climate change impacts on potentially species-rich and highly heterogeneous natural rangelands can then be very different from those on intensively managed grasslands consisting of a few selected species at most. Therefore, we considered using the output of one of the global vegetation models developed to

figure 1

Absolute changes in annual mean temperature (◦C, left) and annual mean precipitation (mm/day, right), from 1980–2010 to 2035–2065 for the HadGEM2-ES model under RCP8.5



a) Temperature
[HadGEM2–ES, RCP8.5]

b) Precipitation
[HadGEM2–ES, RCP8.5]

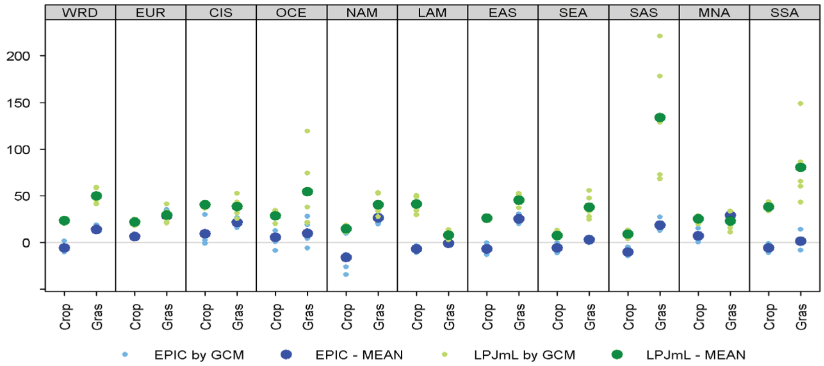
simulate natural terrestrial vegetation, as discussed in Friend *et al*. (2013) within the ISI-MIP framework. These models simulate climate change impacts on vegetation in terms of change in the net primary productivity (NPP). Their limitation is that the results reported by these models at 0.5°x0.5° resolution do not distinguish between different vegetation types, and hence the change in NPP cannot be directly associated with grasslands unless they cover a large majority of the pixel. Our analysis showed that such usable pixels do not provide sufficient coverage over the globe, so the results of the global vegetation models as provided in the fast track phase of ISI-MIP were not suitable for our purposes. However, we found that the climate change impacts on managed grasslands reported by Lund-Post-Jena Dynamic Global Vegetation Model with managed Land (LPJmL) (Müller and Robertson, 2014) showed similar patterns to the climate change impacts on natural vegetation simulated with the global vegetation module of LPJmL, for areas where sufficient cover by grasslands allowed for comparison between the two modules. Because the managed grassland simulations by LPJmL provide sufficient coverage at the global scale, we decided to use them as the model most closely representing natural grasslands. LPJmL also provides simulation results for major agricultural crops. For reasons of consistency, we decided to use the LPJmL grassland simulations together with the LPJmL crop yield simulations. Thus, two alternative model set-ups are used for representing the climate change impacts on crop and grass productivity – one entirely based on EPIC and the other on LPJmL. In addition to exploiting the complementarities between the two models, this approach also makes it possible to deal with the uncertainties inherent in the use of crop models, given that, at global scale, LPJmL is a rather optimistic model and EPIC a rather pessimistic one – in particular, when the direct effects of elevated CO_2 concentrations are considered (Rosenzweig *et al.*, 2014).

The pure climate change impacts on crop and grass yields as simulated by the two models for RCP8.5 and the five ISI-MIP GCMs for 2050 relative to 2000 are shown in Figure 2. These results include the direct effect of elevated CO_2. The regional aggregates are calculated as averages from the spatially explicit results based on crop and management system distribution as of 2000, using either the Spatial Production Allocation Model (SPAM) dataset from the International Food Policy Research Institute (IFPRI) (You and Wood, 2006) or the current grassland distribution calculated from Global Land Cover 2000 (GLC2000) and feed requirements as described in Havlík *et al*. (2014). The definitions of the ten large regions that, for presentation purposes, aggregate the 30 GLOBIOM regions are provided in the Annex, Table A1. The EPIC simulations indicate that crop yields would fall by 6 percent globally, while grass yields would increase by 14 percent. The LPJmL model projects much more positive effects of climate change, increasing overall crop yields by 23 percent on average, and grass yields by 50 percent. The pattern of systematically more positive (or less negative) effects of climate change on grass yields as compared to crop yields applies for EPIC in all the aggregate world regions. The prediction is similar for the LPJmL model, with the notable exception of Latin America, where the crop yields would increase by 41 percent on average, while grass yields would only increase by 8 percent. The climate change impacts on yields calculated by LPJmL provide a more optimistic picture compared with EPIC across all the regions except in the case of grass yields in Europe, where the average values from both crop models are similar, and for the Near East & North Africa, where EPIC shows a slightly more significant grass yield increase than LPJmL. Although there is a wide variation in the results of each individual crop model across the GCMs, the domain of results of one crop model rarely overlaps with the domain of results of the other model.

The extent to which the full CO_2 fertilization effect will materialize in the real world remains highly uncertain (Tubiello *et al.*, 2007). Therefore, for the selected GCM – HadGEM2-ES – we have also considered the climate change impacts with

figure 2

Relative climate change impacts on crop and grass yields as projected by EPIC and LPJmL for five GCMs retained for the fast track phase of ISI-MIP, with full direct effects of elevated CO_2 concentration for 2050 compared with 2000 in %

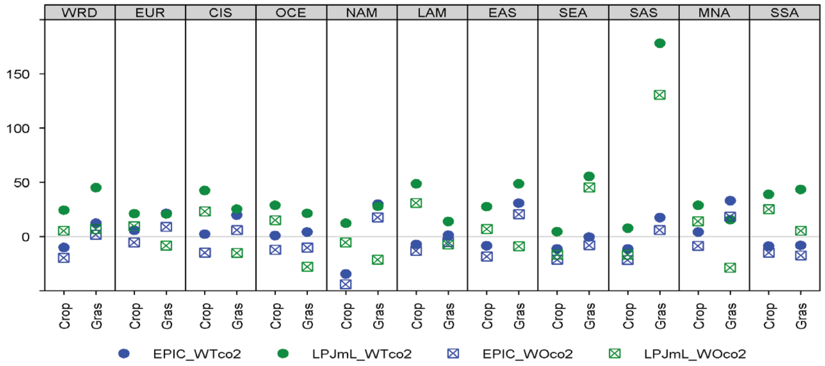


constant CO_2 concentrations corresponding to 2000 levels of 370 ppm in LPJmL (or 2005 levels of 380 ppm in EPIC). The effect of the assumption about CO_2 fertilization on the crop model results is presented in Figure 3. With CO_2 fertilization activated, EPIC and LPJmL simulate for crop yields a global decrease of 10 percent and an increase of 24 percent, respectively. The predicted grass yields for EPIC and LPJmL call for increases of 12 percent and 45 percent, respectively. However, ignoring the CO_2 fertilization effect leads to substantially different results. In this case, crop yields in LPJmL would increase by only 5 percent, and according to EPIC, they would fall by 20 percent. The contrast at global scale is the most pronounced for grass yields projected by LPJmL; whereas they would increase by 45 percent with CO_2 fertilization activated, they are nearly stagnant (+7 percent) without the CO_2 fertilization effect. Looking at the regional results, crop yields projected by LPJmL are higher than those projected by EPIC, even without the effect of CO_2 fertilization. However, the CO_2 fertilization effect seems to play a very important role in grass yield projections by LPJmL. In some regions, such as North America or Eastern Asia, removing the CO_2 fertilization effect turns LPJmL from a rather optimistic model, projecting substantial yield improvements, into a more pessimistic model, projecting decreases in yields. In general, LPJmL is more responsive to the CO_2 fertilization assumption than EPIC.

The differences between EPIC and LPJmL models in terms of the simulated effects of climate change and atmospheric CO_2 concentration are the result of significant differences in the type and parameterization of biophysical processes accounted for by the two models, as well as differences in their input data regarding soil and management assumptions. The EPIC model accounts for more factors co-limiting biomass accumulation (such as stresses from heat or from soil state with respect to oxygen, aluminum, and bulk density), while LPJmL considers only water and sub-optimal temperature stresses. LPJmL is thus expected to be more optimistic with respect to impacts of changes in climate and CO_2. However, the models also differ in their representation of fundamental processes such as light utilization (i.e. spatially homogeneous radiation-use efficiency for EPIC vs. detailed and spatially heterogeneous photosynthesis and respiration for LPJmL), evapotranspiration (Penman-Montheith vs. Priestley-Taylor

figure 3

Relative climate change impacts on crop and grass yields as projected by EPIC and LPJmL for HadGEM2-ES with full direct effects of elevated CO_2 concentration ($WTco_2$) and without any direct effects of CO_2 ($WOco_2$) for 2050 compared with 2000 in %



approaches for EPIC and LPJmL, respectively) and crop phenology, as well as soil, water and nutrient dynamics and yield formation. These differences significantly blur expectations with respect to model output differences, even without accounting for changes in CO_2. Differences in accounting for CO_2 effects add further complexities; in the EPIC model, CO_2 increases light utilization and water transpiration efficiencies homogenously across space, whereas in LPJmL these factors can have highly contrasted spatial responses. Management assumptions further differentiate the two models. LPJmL does not account for nutrient stress as a factor limiting biomass accumulation, but only parameterizes management intensity to mimic current management systems (Fader *et al.*, 2010). EPIC accounts for the stress related to nutrient availability and takes into account spatially heterogeneous levels of nitrogen application rates for crops (representing current management systems). For grassland this effect should not be large, as we assumed low nitrogen stress in EPIC simulations, but assumptions regarding grassland harvest and grazing efficiencies differ significantly. In EPIC, a high and homogeneous harvest efficiency (70 percent) was considered for grassland, without specific effects of mowing regimes. However, in LPJmL, an intensive mowing system is assumed, in which mowing is triggered by phenology and biomass thresholds. While such assumptions may not be representative for both models in many parts of the world, the LPJmL model suggests that accelerated phenology under global warming and higher biomass production could lead to amplified effects on harvested biomass, as additional harvest events could become possible.

Given these results and the number of analysed scenarios, and considering the trade-off between exhaustiveness and ease of presentation, we decided to focus this chapter on results for the two different crop models and the two assumptions on CO_2 fertilization for just a single GCM. This approach makes it possible to capture the most important uncertainties among the five climate change scenarios, including the current climate as a benchmark. The scenarios are summarized in Table 1.

2.3 Economic impact modelling

The first economic assessments of climate change impacts on the global agricultural sector appeared

table 1
Climate change impact scenarios

	Radiative forcing	GCM	Crop model	CO_2 concentration
Present climate	Current	HadGEM2-ES	EPIC	current
EPIC_WTco$_2$	RCP8p5	HadGEM2-ES	EPIC	RCP8p5
LPJmL_WTco$_2$	RCP8p5	HadGEM2-ES	LPJmL	RCP8p5
EPIC_WOco$_2$	RCP8p5	HadGEM2-ES	EPIC	current
LPJmL_WOco$_2$	RCP8p5	HadGEM2-ES	LPJmL	current

over twenty years ago. At that time, three modelling efforts in this area were launched, more or less simultaneously. The first global assessment used Static World Policy Simulation (SWOPSIM) (Kane *et al.*, 1992; Reilly *et al.*, 1994), a partial equilibrium model developed by the Economic Research Service at the United States Department of Agriculture (USDA). By that time, GCMs had already provided projections of future climate to models for crop growth, which in turn calculated the estimated changes in crop yields. These changes were finally implemented in economic models as exogenous crop yield shifters. However, the Economic Research Service at the USDA then switched to a second approach for climate change impact modelling, based on the FARM model (Darwin and Kennedy, 2000; Darwin, 2004). FARM was a computable general equilibrium model based on a geographic information system. FARM adopted a completely different approach to representing impacts of climate change on production activities. The FARM model divided land endowments into six land classes, characterized by soil temperature and length of growing season. As a result of climate change, distribution of land across the different classes was changing. This approach made it possible to account for effects on crop yields and also on pasture and forest productivity; in addition to FARM, it was used in World Trade Model with Climate-Sensitive Land (WTMCL) (Juliá and Duchin, 2007). This approach also accounted for changes in runoff and the resulting changes in water supply for irrigation. However, the model was highly aggregated in terms of regions and sectors. While SWOPSIM divided the world into 13 regions and differentiated between 20 agricultural commodities, FARM, as implemented in 1995, represented the world in 8 regional aggregates, and agriculture was split into only two sectors – crops and livestock. The third modelling approach among the early attempts relied on the general equilibrium model BLS, developed at IIASA. Initially, the climate change impacts on crop production were based on crop model simulations using the International Benchmark Sites Network for Agrotechnology Transfer (IBSNAT) of the International Consortium for Agricultural Systems Applications (ICASA). The simulations covered 124 sites in 18 countries and then extrapolated to other parts of the world through derived yield transfer functions (Fischer *et al.*, 1994; Rosenzweig and Parry, 1994; Parry *et al.*, 1999; Parry *et al.*, 2004). Later on, the climate change impact module has been replaced by the AEZ framework of the Food and Agriculture Organization of the United Nations (FAO)-ILASA (Fischer *et al.*, 2005; Tubiello and Fischer, 2007). The BLS model divides the world into 34 countries/regions and aggregates global agricultural production into nine sectors, with the rest of the economy aggregated in a single sector. The model has been extensively used for climate change impact analysis for more than a decade.

Since 2007, global climate change impact assessments focusing on the agricultural sector have inspired an increasing number of economic models. The EPPA model developed at Massachusetts Institute of Technology (MIT) used the Terrestrial Ecosystem Model (TEM) to derive changes in crop, pasture and forest productivity (Reilly *et al.*, 2007; Reilly *et al.*, 2013). The Global Trade Analysis Project (GTAP) and its variants were implemented later; these usually relied on literature reviews or existing datasets for the climate change impact parameters (Lee, 2009; Hertel *et al.*, 2010; Calzadilla *et al.*, 2013). Recently, several influential studies on climate change impacts and the costs of adaptation were carried out at IFPRI with the International Model for Policy Analysis of Agricultural Commodities and Trade (IMPACT) model, which derived the climate change impact parameters from detailed Decision Support System for Agrotechnology Transfer (DSSAT) simulations (Nelson *et al*., 2009, 2010; Rosegrant *et al*., 2014). The widespread interest in this topic among the global economic modelling teams was expressed in the coordinated model intercomparison project, co-organized by AgMIP and ISI-MIP, in which nine global economic models jointly analysed climate change impacts on the agricultural sector based on the most recent climate change impact projections by five global gridded crop models (Nelson *et al.*, 2014a; Nelson *et al.*, 2014b).

In this study we use GLOBIOM (Havlík *et al.*, 2011). This model had been implemented for climate change impact assessments in the past, both individually (Mosnier *et al.*, 2014 Leclère *et al*., (in press) Climate change induced transformations of agricultural systems: insights from a global model Environ. Res. Lett.) and as part of AgMIP/ISI-MIP. GLOBIOM is a partial equilibrium model covering the agricultural and forestry sectors – including the bioenergy sector – which is used for analysing medium to long-term exploratory and policy oriented scenarios. The model divides the world into 30 economic regions, in which a representative consumer by region is modeled through a set of isoelastic demand functions. The spatial resolution of the supply side relies on the concept of Simulation Units, which are aggregates of 5 to 30 arc minutes pixels (or from 1/12 to ½ degree) that belong to the same altitude, slope, and soil class, and to the same country. For crops, grass and forest products, Leontief production functions covering alternative production systems are calibrated based on biophysical models, such as EPIC (Williams, 1995). For this study, the supply side spatial resolution is aggregated to 2° x 2° (about 200 x 200 km at the equator). Economic optimization is based on the spatial equilibrium modelling approach (Takayama and Judge 1971). The price-quantity equilibrium is computed using the method of McCarl and Spreen (1980) at the regional level. The model is calibrated to FAOSTAT activity levels as of the year 2000, and is then recursively calculated in 10 year intervals of time.

GLOBIOM includes a particularly detailed representation of the global livestock sector (Havlík *et al.*, 2013; Havlík *et al.*, 2014). The model distinguishes between dairy and other bovines, dairy and other sheep and goats, pigs and poultry, with further distinctions between laying hens and broilers. Livestock production activities are defined in several alternative production systems adapted from Seré and Steinfeld (1996) as follows: grass-based (arid - LGA, humid - LGH, temperate/highlands - LGT), mixed crop-livestock (arid - MRA, humid - MRH, temperate/highlands - MRT), urban (URB) and other (OTH), for ruminants; smallholder and industrial production for monogastrics. For each species, production system and region, a set of input-output parameters is calculated, based on the approach by Herrero *et al*. (2013). Feed rations are defined as consisting of grass, stover, feed crops aggregates and other feedstuff. Outputs include four meat types, milk and eggs, as well as environmental factors (manure production, nitrogen excretion, and greenhouse gas emissions). The initial distribution of livestock across the systems is based on Robinson *et al.* (2011). Switching among the production systems allows for feedstuff substitution and for intensification or extensification of livestock production.

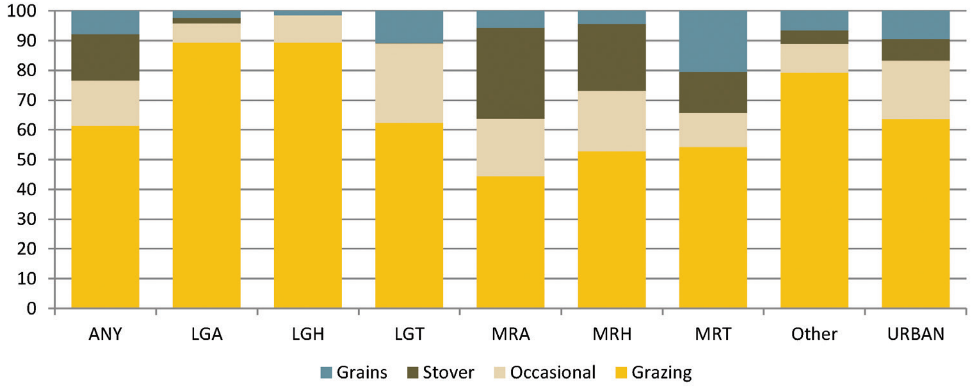
Furthermore, six land cover types are distinguished: cropland, grassland, short-rotation tree plantations, managed forest, unmanaged forest and other natural vegetation. Depending on the relative profitability of the individual activities and the constraints on recursivity, the model can switch from one land cover type to another. Comprehensive accounting of greenhouse gas for agriculture and land use change is also implemented in the model. Detailed descriptions of these accounts and additional background information are provided in Valin *et al*. (2013).

Climate change impacts on crop and grass yields are implemented in GLOBIOM as changes relative to the year 2000 values at the Simulation Unit level. Eighteen globally important crops, which cover about 75 percent of total harvested area as reported by FAOSTAT, are represented explicitly in the model (Barley, Dry beans, Cassava, Chick pea, Corn, Cotton, Groundnut, Millet, Oil palm, Potatoes, Rapeseed, Rice, Sorghum, Soybeans, Sugar cane, Sunflower, Sweet potatoes, and Wheat). All of them, except for Oil palm, are individually parameterized with EPIC for four management systems – subsistence, low-input commercial, high-input and irrigated. The initial distribution of crops and systems for the year 2000 is based on IFPRI's SPAM (You and Wood, 2006). The EPIC model provides not only information about yields but also the corresponding nitrogen and irrigation water requirements. Climate change impact simulations are conducted for three management systems – subsistence (used also for the low-input commercial system), high-input and irrigated. In the high-input management system, nitrogen fertilization is automatically adjusted to the changes in requirements by crops in response to climate change. In the irrigated systems, the levels of both nitrogen and water for irrigation are adjusted in response to climate change. Furthermore, the dates of operations such as sowing are adapted to the climate. For Oil palm, an average value is used – calculated from the climate change impacts on groundnuts, rice, soybeans and wheat – following the protocol of Müller and Robertson (2014). LPJmL provides climate change impact simulations individually for 11 major crops and for two management systems – rainfed and irrigated. The yields for the remaining seven crops are derived analogically from those 11 crops. The relative changes in yields from the single LPJmL rainfed system are used for all three GLOBIOM rainfed systems. Nitrogen and irrigation water requirements are adjusted proportionally to the yields, as are phosphorus requirements and production costs, for both EPIC and LPJmL climate change simulations. In GLOBIOM, the extent and distribution of grasslands are determined based on GLC2000 and livestock feed requirements. Grass productivity levels in the year 2000 are taken from EPIC for regions with intensive or semi-intensive grassland management and from CENTURY (Parton *et al.*, 1987; Parton *et al.*, 1993) for regions with extensive rangelands. Climate change impact on grasslands is captured through shifts in relative productivity calculated for managed grasslands by both EPIC and LPJmL, as discussed above.

Marginal adaptation to climate change, in terms of input level or adjustments of operation dates is implicit in the crop model results as mentioned above. GLOBIOM models additional mechanisms which can mitigate the effects of climate change on the agricultural sector. In addition to relocating production activities within or across the various regions to exploit new comparative advantages between locations and individual production activities, a major adaptation mechanism represented in GLOBIOM is switching between different production systems. In the crop sector, this can take the form of shifting some of the production from the rainfed system to the irrigated system in response to increased droughts. In the livestock sector, it generally involves shifting ruminants from grazing systems to mixed crop-livestock systems or vice versa, changes which can play an important role in the future livestock sector development (Havlík *et al.*, 2013; Havlík *et al.*, 2014). The ruminant diets differ widely in their composition across the production systems (Figure 4). For instance, in arid zones, an average of 90 percent of the ruminant diet in grazing systems (LGA) is composed of grass, but grass does not even constitute 50 percent of the diet for ruminants in mixed systems (MRA). It follows that climate change impacts on grass yields may substantially alter the relative competitiveness

figure 4

Average composition of global ruminant diets in terms of four feedstuff aggregates, in %
(calculations based on Herrero *et al*. (2013)



of the different systems and hence the overall outcome for the livestock sector.

Only one set of socio-economic drivers is used for all the climate scenarios in this study. Gross domestic product (GDP) and population projections correspond to the SSP2 – the Middle of the Road scenario out of the five Shared Socio-economic Pathways (SSPs) (O'Neill *et al.*, 2014). The impact of future technological change on crop yields and feed conversion efficiencies has been calculated from past relationships observed between crop yields and GDP, and has been transposed for the livestock sector based on past rates of feed conversion efficiency gains at global level (Herrero, M., Havlík, P., McIntire, J., Palazzo, A. and Valin, H. 2014. African Livestock Futures: Realizing the Potential of Livestock for Food Security, Poverty Reduction and the Environment in Sub-Saharan Africa. Office of the Special Representative of the UN Secretary General for Food Security and Nutrition and the United Nations System Influenza Coordination (UNSIC), Geneva, Switzerland, 118 p.). Global future consumer preferences are captured in the income elasticities of the demand functions used in this chapter, which have been calibrated to the FAO projections by Alexandratos and Bruinsma (2012) (Valin *et al.*, 2014).

3. Results

Climate change impacts on crop and grass yields will trigger a series of adjustments in the global agricultural system, which is trying to buffer the negative effects and exploit the new opportunities. Here we first briefly present our projections of livestock sector development up to 2050 without climate change, and then discuss how these developments could be altered through climate-induced crop and grass yield changes. In a final step, we analyse the adaptation mechanisms at play in the area of land management and in the livestock sector.

3.1 Livestock sector developments without climate change

Demand for milk is projected to almost double globally (+91 percent) between 2000 and 2050 (Figure A1 in the Annex). The fastest growth is expected to occur in South Asia, sub-Saharan Africa and Southeast Asia (+230-250 percent). In absolute terms, half of the new demand is projected to come from South Asia (+255 million tonnes), followed by Latin America

(+67 million tonnes). Regional production is mostly projected to follow the increases in local demand, leaving a minor role for international trade. The noticeable exception is South Asia, which is projected to increase production by "only" 183 percent, leading to a gap of 50 million tonnes, which will need to be covered through imports. Europe and Oceania would remain the only major exporters. At the global scale, the price of raw milk would increase by only 4 percent by 2050. Even at the regional level, the price increase would remain below 10 percent, except for the Near East & North Africa and sub-Saharan Africa, where the prices are projected to rise by about 20 percent.

Demand for ruminant meat is projected to increase globally at almost the same rate as milk demand (+90 percent). The fastest increases are projected to occur in sub-Saharan Africa (+269 percent) and Southeast Asia (+255 percent). In absolute terms, however, the largest increase is projected to occur in East Asia (+14 million tonnes), followed closely by Latin America and sub-Saharan Africa. On the opposite end of the scale, total demand is projected to increase by only about 10 percent in Europe and North America. Ruminant meat production is projected to increase the most noticeably in Latin America and East Asia – by 18 and 14 million tonnes, respectively. Latin America is also projected to become the most important ruminant meat exporter, at 5.7 million tonnes per year by 2050, whereas the second largest exporter, Oceania – whose export rate is rather stagnant – would supply the global market with about half that volume, at 2.8 million tonnes. Imports are projected to rise most dramatically in the Near East & North Africa and in sub-Saharan Africa, reaching 2.9 and 2.7 million tonnes, respectively. China's rising demand is projected to be satisfied by local production, leaving imports close to the historical level of 1.4 million tonnes per year. Ruminant meat prices are projected to rise globally by 15 percent between 2000 and 2050, although they are actually projected to decrease slightly for all regions except South Asia, the Near East & North Africa and sub-Saharan Africa, where they would rise by 145 percent, 46 percent, and 40 percent, respectively.

Finally, demand for meat from monogastrics is projected to increase by 104 percent between 2000 and 2050. The fastest increases are projected for South Asia (+1300 percent), sub-Saharan Africa (+547 percent) and the Near East & North Africa (+289 percent). In terms of volume, the largest increase would still occur in East Asia, up to 37 million tonnes between 2000 and 2050, followed by Latin America, at 29 million tonnes, and South Asia, at 28 million tonnes. Most of the demand would be satisfied through local production, except in sub-Saharan Africa and South Asia, which are projected to be importing about 30 percent of their total demand by 2050. China is still projected to be importing about one million tonnes, but this would represent just 1 percent of its total demand. Meat prices for monogastrics are projected to increase only marginally at the global scale, with the exception of South Asia, where they are projected to rise more than 120 percent.

As mentioned earlier, the income elasticities of our demand functions have been calibrated to the FAO projections by Alexandratos and Bruinsma (2012). Hence, it comes as no surprise that the commodity demand projections presented above are similar to the FAO projections; our projection for total milk demand is only 6 percent higher, for ruminant meat demand it is 4 percent higher, and for monogastric meat demand it is just 2 percent higher than FAO projections for 2050. At the regional level, the discrepancies in projections are larger, for both demand and supply. This has an effect on the level of agreement between our projected net trade and the FAO projections. However, given the difference in approaches for producing the two sets of projections, even the net trade values are often reasonably comparable. The major exception to this is South Asia; our projections indicate that this region will have to satisfy an increasingly large amount of its livestock product demand from imports, in particular for dairy products, while the FAO projects net trade to remain close to the current levels.

By the year 2000, the largest share (22 percent) of ruminants, measured in tropical livestock units (TLU – equivalent of 250 kg body weight), had

figure 5

Livestock numbers distributed by livestock production systems for 2000, 2030 and 2050 in million (mio) TLUs. (RUMI – ruminants, BOVI – bovines, SHGT – small ruminants, BOVDh – bovines dairy herd, BOVOh – bovines other herd, SGTDh – small ruminants dairy herd, SGTOh – small ruminants other herd)

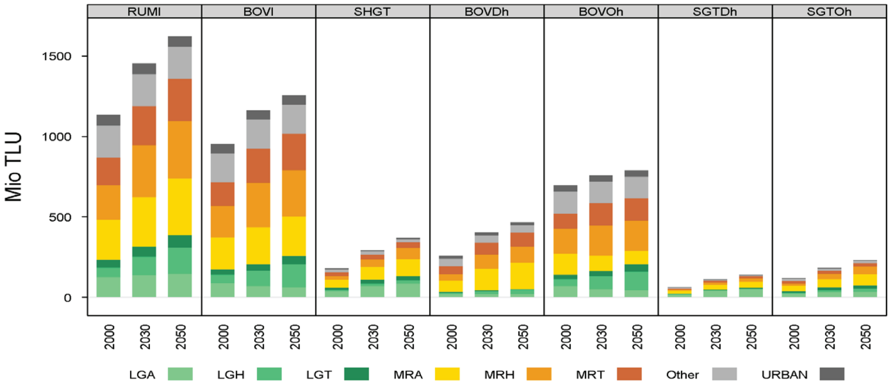
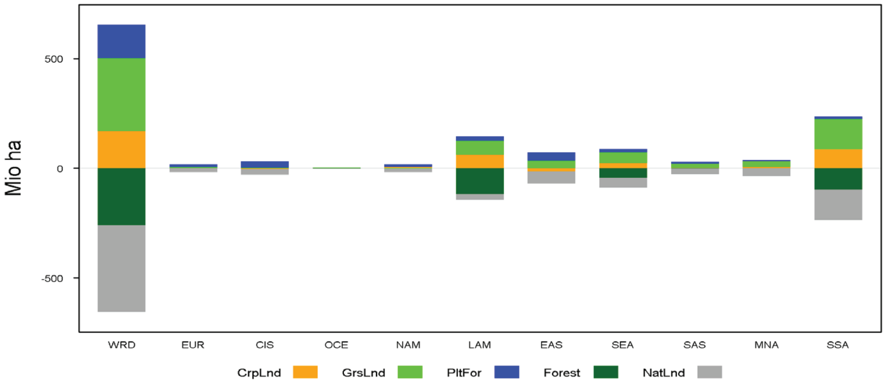


figure 6

Land cover change between 2000 and 2050 in million (mio) hectares.
(CrpLnd – cropland, GrsLnd – grassland, PltFor – energy plantations, Forest – managed and unmanaged forest, NatLnd – other natural land)

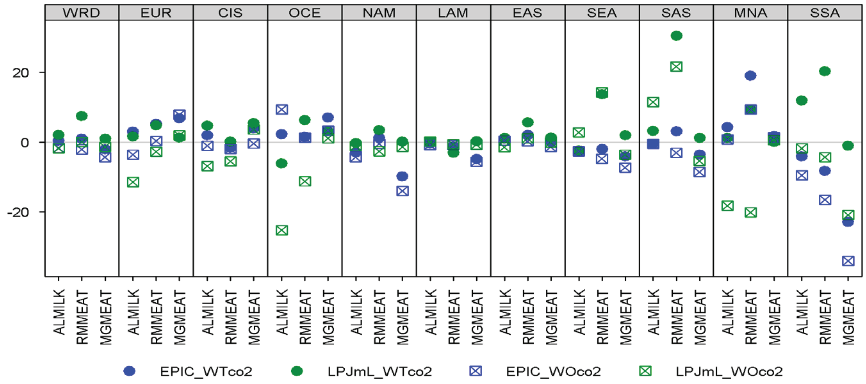


been reared in mixed arid systems, followed by mixed humid systems (19 percent) and other systems (18 percent). Only 20 percent of all ruminants were in the grazing systems (Figure 5). The number of ruminants is projected to increase by 43 percent between 2000 and 2050. This is approximately half of the projected increase in milk and ruminant meat production, indicating substantial productivity gains over this period. The largest increases in the numbers of animals are expected in humid systems, driven by the continued boom in Latin America; 144 million TLUs in the mixed humid system and 105 million TLUs in the grazing humid system.

The additional agricultural production will also come partly from cultivated land expansion. Global

figure 7

Relative climate change impacts on livestock production compared with the present climate scenario (presclim) by 2050 in %. (ALMILK – bovine and small ruminant milk, RMMEAT – bovine and small ruminant meat, MGMEAT – pig and poultry meat)



croplands are projected to expand by 170 million hectares, and grasslands by 331 million hectares (Figure 6). The largest expansion of both cropland and grassland is projected for sub-Saharan Africa, Latin America, and Southeast Asia. Significant grassland expansion is also projected for Eastern Asia and for the Near East & North Africa.

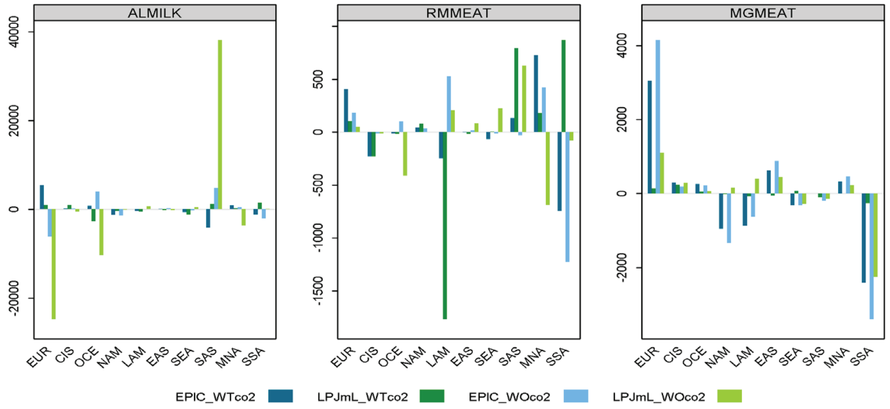
3.2 Climate change impact on livestock markets

Climate change impacts on crop and grass yields are projected to have only minimal effect on global milk and meat production by 2050, which remains within +/-2 percent of the projected production without climate change (Figure 7). The only two exceptions are as follows: ruminant meat production increases by 7.5 percent under the yields projected with LPJmL, taking into account the CO_2 fertilization effect; and monogastric meat production decreases by 4.3 percent under the yields projected with EPIC without the CO_2 fertilization effect. These results reflect the climate change impacts presented in Figure 3: grass yields projected globally by LPJmL with CO_2 fertilization benefit most from climate change – grass being the most important feedstuff for ruminant meat production; and crop yields projected by EPIC without CO_2 fertilization experience the most severe negative impacts of climate change – crops being the major feedstuff for monogastrics in commercial systems.

Depending on the scenario, the climate change effects can be more pronounced at the regional level. In three regions – the former Union of Soviet Socialist Republics (USSR), Eastern Asia and Oceania – the climate change effect on livestock production remains within +/-10 percent under all the different yield impact projections. Two regions may experience strong increases in production in response to climate change – South Asia and Southeast Asia. Both regions could react to the large positive grass yield effects projected by LPJmL by increasing ruminant production; e.g. with the yields projected by LPJmL with CO_2 fertilization, ruminant meat production in South Asia in 2050 would be higher by 30 percent with climate change than without climate change. Other regions – Europe, Northern America, and Oceania – are expected to experience significant negative effects on livestock production in at least one of the yield scenarios. In Oceania, in particular, the pessimistic grass yield projections resulting from

figure 8

Climate change impacts on net trade by 2050 in *'000 tonnes.* (ALMILK – bovine and small ruminant milk, RMMEAT – bovine and small ruminant meat, MGMEAT – pig and poultry meat)



reduced precipitation could lead to a 25 percent decrease in milk production under the LPJmL yields without CO_2 fertilization, compared with the current climate scenario. The climate effects seem to be the most uncertain in the Near East & North Africa and in sub-Saharan Africa. For instance, in the Near East & North Africa, the change in ruminant meat production attributable to climate change varies by +/-20 percent, depending on the yield scenario. In sub-Saharan Africa, the effects are the most uncertain and potentially the most severe; ruminant production could increase by 20 percent but it could also decrease by 17 percent, and all yield scenarios except for LPJmL with CO_2 fertilization would lead to monogastric meat production falling by more than 30 percent.

The model scenario analysis confirms this approach confirms that there is a generally positive relationship between changes in crop yields and monogastric production, and between changes in grass yields and ruminant production. This link is the strongest with respect to changes in grass yields and ruminant meat production. This can be explained by the fact that grass represents a substantial share of the meat ruminant diet, and that adaptation options in grassland management are limited.

The relationship between grass yields and changes in milk production provides a good illustration of the complex interactions present in the global livestock sector. For instance, Oceania shows two cases of counterintuitive behavior with this respect. On the one hand, grass (and crop) yields decrease in projections by EPIC without CO_2 fertilization and milk production increases, and on the other hand, grass (and crop) yields increase in projections by LPJmL with CO_2 fertilization, and milk production decreases. Oceania is projected to be the second largest milk exporter by 2050; therefore, its local production depends on the supply in other regions. Under the EPIC scenario without CO_2 fertilization, supply of milk from Europe – which is projected to be the largest exporter by 2050 – decreases, as does milk production in sub-Saharan Africa and North America, and this gap is filled by the increased production in Oceania (Figure 8). Similarly, under yields projected by LPJmL with CO_2 fertilization, milk production increases in some of the importing regions – such as South Asia and sub-Saharan Africa – which reduces the demand for milk exports from Oceania, and leads to reduced production. However, another reason why change in grass yields is not a good predictor for change in milk production is the level of importance of crops in dairy ruminant diets; e.g. the decrease in milk production in North America, despite grass yield increases under the EPIC yield scenarios, can be attributed to substantial crop yield decreases under the same scenarios.

Rates of regional pig and poultry meat production do not show a strong connection to climate change impacts on crop yields but some regular patterns can be identified with respect to the different crop models. EPIC projects an overall deterioration in crop yields as a consequence of climate change. Under the EPIC scenarios, most regions behave as expected – i.e. they decrease meat production if crop yields decrease, and increase production if the climate change effect on yields is positive. Some regions also increase production when their crop yields decrease, particularly under the scenario without CO_2 fertilization. Under that scenario, many regions – including North America – are very negatively affected, which creates a comparative advantage for regions that are less affected, such as Europe and Oceania. LPJmL projects mostly positive effects of climate change on crops and, under these scenarios, monogastric meat production is less reactive to the crop yield change, because of low responsiveness of demand to price reduction of these commodities. Sub-Saharan Africa is an outlier under all but the most favourable yield scenario – LPJmL with CO_2 fertilization. Absolute crop yields in the reference case without climate change are very low, so even if climate change impacts are positive, such as under the LPJmL scenario without CO_2 fertilization, production in the pig and poultry sector decreases, as the impact on absolute yield is much smaller than in other parts of the world.

The effects on regional consumption are less pronounced than the effects on production because the impacts of climate change are partly buffered through international trade, as discussed above. The strongest negative effects correspond to a reduction of consumption by 12 percent (Figure 9). This occurs in the area of North America monogastric meat consumption under the worst crop yield scenario coming from the EPIC projections without CO_2 fertilization. The other region that experiences a similar consumption decrease in one of the livestock commodities is the Near East & North Africa, where the strong grass yield reduction in the projections by LPJmL

figure 9

Relative climate change impacts on livestock product consumption compared with the present climate scenario (presclim) by 2050 in %. (ALMILK – bovine and small ruminant milk, RMMEAT – bovine and small ruminant meat, MGMEAT – pig and poultry meat)

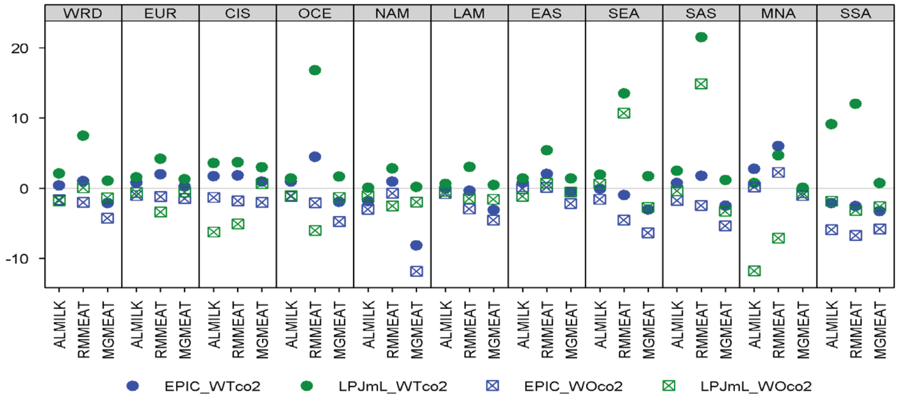
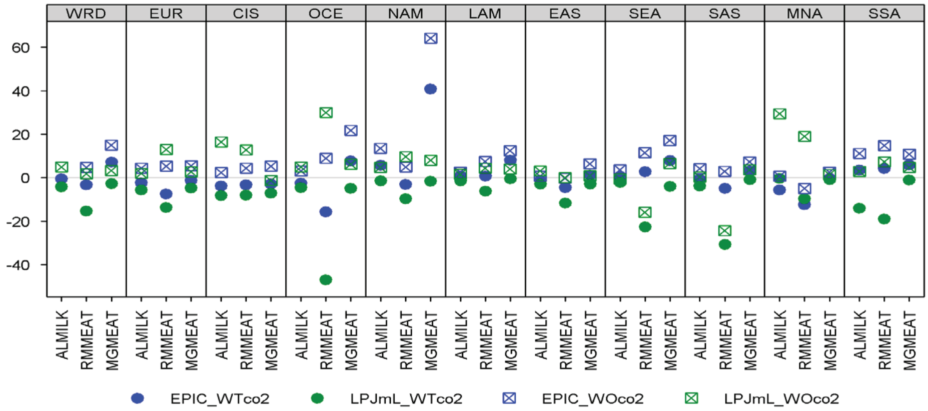


figure 10

Relative climate change impacts on livestock product prices compared with the present climate scenario (presclim) by 2050 in %. (ALMILK – bovine and small ruminant milk, RMMEAT – bovine and small ruminant meat, MGMEAT – pig and poultry meat)



without CO_2 fertilization leads to a substantial drop in milk consumption. Any other negative effects are smaller than 10 percent. Even sub-Saharan Africa, which is projected to experience a fall in production by up to 34 percent, depending on the scenario and the commodity, would see its consumption decreasing by at most 7 percent compared with the scenario without climate change. As can be expected, these mostly small changes in consumption go hand in hand with modest changes in commodity prices (Figure 10). The only case where the prices are projected to exceed 30 percent compared with the no climate change yield scenario is that of monogastric meat in North America, where the strong negative effect on crop yields meets up with the price inelastic demand.

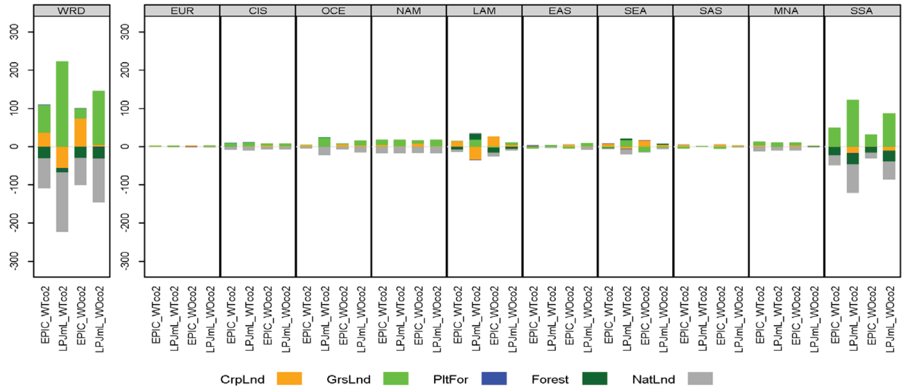
From the perspective of food availability, it will be more important to control developments in the crop sector, because crops are the source of about 80 percent of all food energy consumption. However, the loss of energy availability barely exceeds 50 kcal/cap/day, except under the yield scenario projected by EPIC without CO_2 fertilization. The climate change effect on overall food availability is systematically positive under the yield scenario projected by LPJmL with CO_2 fertilization.

3.3 Land management adaptation

In response to climate change impacts on yields, GLOBIOM allows for adaptation through changes in the management system and relocation of production to more or less productive land within and across countries, which will result in changes in aggregate regional or global yields (YILD). GLOBIOM also allows for adaptation through adjustments in the total area devoted to a given activity. The results, summarized in Figure A2 in the Annex, show that GLOBIOM tends to compensate for yield decreases caused by negative climate change effects, while positive climate change effects lead to extensification (crop area expansion in previously marginal lands or substitution with other activities) and to final yields lower than projections based on pure climate shock. An example of effective adaptation is in North America, where the EPIC crop yield projections without CO_2 fertilization lead to the most severe negative impact – a 44 percent decrease – but autonomous adaptation buffers a third of this impact, leading to a final yield decrease of only 30 percent. At the other extreme, one of the most positive effects is projected for the former USSR by LPJmL with CO_2 fertilization – a

figure 11

Land cover change due to climate change by 2050 in million hectares.
(CrpLnd – cropland, GrsLnd – grassland, PltFor – energy plantations, Forest – managed and unmanaged forest, NatLnd – other natural land)

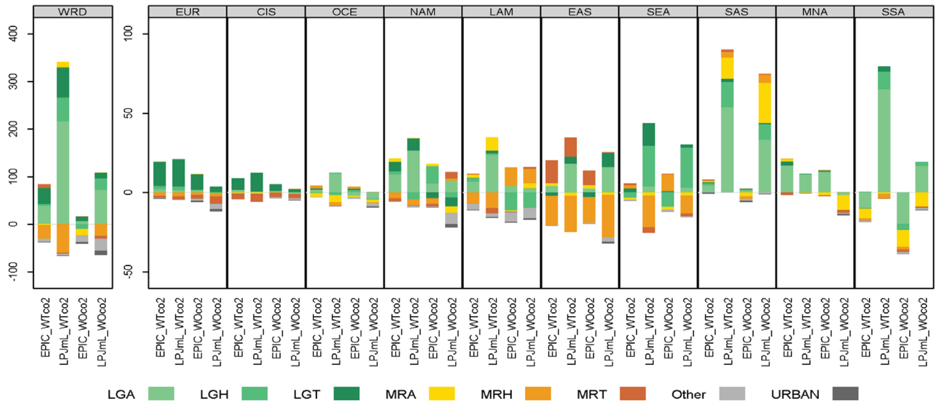


42 percent increase – but the final aggregate crop yield is only 15 percent higher compared with the present climate scenario. We can see also cases where overall positive effects may lead to slightly negative yields after adaptation. This is due to changes in the composition of the crop aggregate as some crops are favoured or disadvantaged by the climate change more than others. Relocation of production to lower-yielding crops may also lead to aggregate crop yield decrease through a composition effect. The autonomous yield adjustment can buffer about 50 percent of the pure climate change effect, on average, as indicated by the slope of the trend line, which is 0.48. The aggregate area response has a negative slope, meaning that the model tends to expand the crop area in regions and scenarios where crop yields are affected negatively, and decrease the crop area when crop yields are affected positively. This outcome complements the results presented in Nelson *et al.*, (2014a), which considered individual crops or just small crop aggregates. In these cases, GLOBIOM, unlike the other models, tends to expand the areas of particular crops that are affected positively by climate change, at the expense of crops affected negatively. The overall effect on crop production does not have a strong indicator. The negative effects are, in general, buffered through management change or area expansion, while the positive effects tend to be evened out, through extensification or crop area reduction.

The adapted regional grass yields are the direct result of livestock relocation to more or less productive land because, in the current version of GLOBIOM, no adaptation through grassland management is considered, and because reported yields are calculated as weighted averages, with the area of utilized grasslands in each pixel used as the weight. It is clear that livestock relocation within a given region has very little potential to buffer negative climate change impacts. Positive climate change impacts most often lead to expansion of grasslands into less productive areas, which then leads to a less than proportional increase in grass productivity compared with climate shock. The strength and direction of this effect is similar to the changes in crop yield. There is no significant relationship between the grass yield shock and the grassland area expansion which in turn leads to lack of relationships between the yield shock and grass production as between the yield shock and total yield change.

figure 12

Climate change impact on ruminant numbers across the different livestock productions systems by 2050 in million TLUs



These adjustments lead, overall, to minor land cover changes (Figure 11). The most significant land cover changes occur in sub-Saharan Africa in response to the new opportunities created by increases in grass productivity in yield scenarios by LPJmL. In this region the grassland increases by up to 122 million hectares, mostly at the expense of other natural land. This counter-intuitive result comes mostly from the fact that sub-Saharan Africa – which, under other yield scenarios, is a net importer of bovine meat – improves its competitiveness through the positive climate change impacts on grass yields and even becomes a small net exporter. However, since the beef production in Africa is very land-intensive, the area expansion is not accompanied by crop area reduction in other regions. Hence, the LPJmL impact scenarios lead to the globally largest losses of natural land.

3.4 Livestock sector adaptation

The major mechanism for adaptation to yield changes due to climate change in the livestock sector is a change in the composition of animal diets. In our modelling framework, this occurs through changes in allocation of the animals between grazing systems and systems relying on supplementation of the diets by crop-based feeds (mixed systems). Figure 12 shows that the relatively more positive impacts of climate change on grass yields compared with crop yields would translate to expansion of ruminants reared in the grazing systems, partly at the expense of ruminants in the mixed systems. For instance, under grass yields projected by LPJmL with CO_2 fertilization, 38 percent of ruminants globally would be reared in grazing systems by 2050, although it was only 20 percent in 2000, and would be just 24 percent in 2050 without climate change. This development would be the most significant for the dairy bovines. Without climate change, the share of dairy bovines reared in grazing systems is projected to further decrease, from the already low 13 percent in 2000 to 11 percent in 2050, but under the grass yield change projected by LPJmL with CO_2 fertilization, 30 percent of all dairy bovines would be reared in grazing systems. Such developments would present a substantial alteration of the current trends.

Except for Europe, the former USSR and Oceania, all regions are very sensitive to the grass yield projections. The region most affected by this uncertainty is South Asia, where LPJmL projects grass yield increases by 178 percent and 130 percent, with and without CO_2 fertilization, respectively. This leads to a large increase in bovine numbers in the mostly arid grazing systems. These developments contrast with the climate change impact scenarios in EPIC, under which the numbers of ruminants are not substantially different from the scenario without climate change. Ruminant production in sub-Saharan Africa is also highly sensitive to the yield projections. As in South Asia, a large expansion of ruminant numbers is projected to occur in the arid grazing systems under the yield scenario by LPJmL. Disagreement with the results from the EPIC scenarios is particularly large for sheep.

The differences in total livestock numbers and in the distribution of livestock across production systems are more pronounced than the differences in total production and its distribution across the systems. While the total number of ruminants under the yield scenario projected by LPJmL with CO_2 fertilization would be 17 percent higher than without climate change, the total ruminant protein production would be only 4 percent higher. This is due to the fact that most of this expansion would occur in relatively low-yielding regions, and in very unproductive, arid grazing systems (LGA).

Overall ruminant meat production is very closely related to climate impacts on grass yields. This is also true for distribution of production across the systems (Figure A1 in the Annex). The difference in the percentage of animals in the grazing systems with and without climate change is most directly related to the change in grass yields for the bovine meat herd. Overall, climate change is likely to increase the share of ruminants in grazing systems, as it is projected to occur in 30 out of 40 combinations of ten regions and four yield scenarios.

4. Conclusions

This study provides the most detailed global assessment of climate change impacts on the livestock sector available so far, accounting not only for changes in crop yields but also for changes in grass productivity. This type of analysis is generally subject to large uncertainties along the entire chain, from climate and crop models, through assumptions about the strength of some mechanisms that are still not well understood, such as the effects of CO_2 fertilization, up to the uncertainties inherent in the economic models (Nelson *et al.*, 2014a). Uncertainties within the chain of biophysical modelling of climate change impacts on crops have been well documented in Rosenzweig *et al.* (2014) and the issue of uncertainty is even more relevant to grass yield projections, where reference data are less available for model development and evaluation. In this report, we have considered two different crop models and two different assumptions about the effects of CO_2 fertilization – not attempting to cover the whole spread of uncertainty but rather to illustrate the challenge.

We have obtained several important results that appear fairly robust across the scenarios. First, our results coincide with the vast body of literature showing that, regardless of the scenario chosen, the effects of climate change on the agricultural sector in general, and on the livestock sector in particular, would remain fairly small on the global scale by 2050, as illustrated by projected price changes mostly being contained within a range of +/-10 percent. Second, international trade could buffer the majority of negative production shocks so that the impacts on consumption remain limited. Finally, because grass yields tend to benefit more (or to be hurt less) from climate change than crop yields, climate change would favour increasing the number of ruminants in the grazing systems, representing a rebalancing in the general trend towards more intensive systems projected without climate change (Havlík *et al.*, 2014). This last finding is also in agreement with previous studies (Jones and Thornton, 2009; Thornton *et al.*, 2011).

However, some regions remain more vulnerable than the others. South Asia and sub-Saharan Africa are the regions with potentially the most severe – but also the most uncertain – effects. For instance, the generally robust shift towards grazing systems is valid for South Asia and sub-Saharan Africa under only two of the four climate impact scenarios. This level of uncertainty makes it difficult to engage in investments that would steer the sector in a particular direction, and substantial reductions in uncertainty are not expected in the near future (Ramirez-Villegas *et al.*, 2013). Therefore, adaptation strategies that would be appropriate under a large set of future climate and climate impact scenarios need to be elaborated.

Although this study takes an important step forward in analysing climate change impacts on livestock production, it does not cover effects other than quantitative impacts on feed supply. Altered climate will cause changes in not only the quantity but also the quality of the forage. Heat stress may limit the capacity of the animals to fully benefit from the increased grass availability. In addition, the spread of disease may represent an unprecedented challenge. All these factors may make the impact of climate change on the livestock sector worse than what is projected here. On the other hand, although our modelling approach includes a high level of flexibility through the autonomous adjustments in the livestock production structure, it does not consider other potential adaptation options, such as changes in grassland management or development of new livestock production systems, and hence may overestimate the negative effects. Besides the long-term "trend" impacts of climate change discussed so far, a major challenge may come from increased climate volatility (Wheeler and von Braun, 2013). The effects may be particularly severe in the livestock sector, where, for instance, forage failure in one year can have long lasting effects because of the constraints it imposes on herd dynamics (Mosnier *et al.*, 2009).

In conclusion, this study shows that, contrary to the findings by Reilly *et al*. (2007, 2013), there is strong relationship between grass yield changes and livestock production, and that climate change impacts on grasslands will substantially shape the future of the livestock sector and will be a factor in determining the optimal adaptation strategies. Further research in this area is of the utmost importance for the whole food system.

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Annex

figure A1

Relationship between the pure climate change impact on crop and grass yields (YEXO) and livestock production (Supply) relative to the scenario with present climate (presclim) by 2050 in % (ALMILK – bovine and small ruminant milk, RMMEAT - bovine and small ruminant meat, MGMEAT – pig and poultry meat)

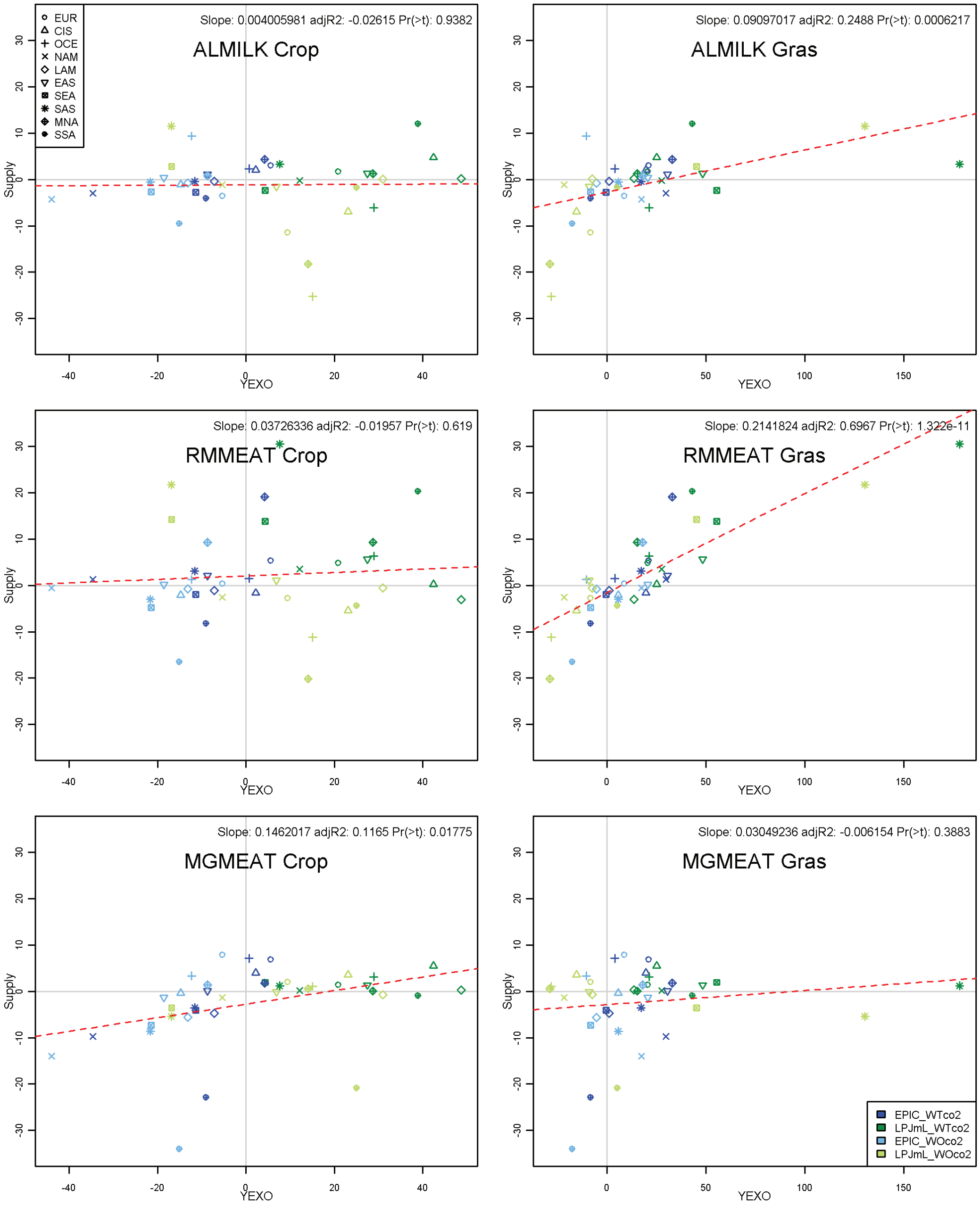

figure A2

Transmission of the pure climate change impact on crop (Crop) and grass (Gras) yields (YEXO) through autonomously adapted yields (YILD) and areas (Area) on total production relative to the scenario with present climate (presclim) by 2050 in %

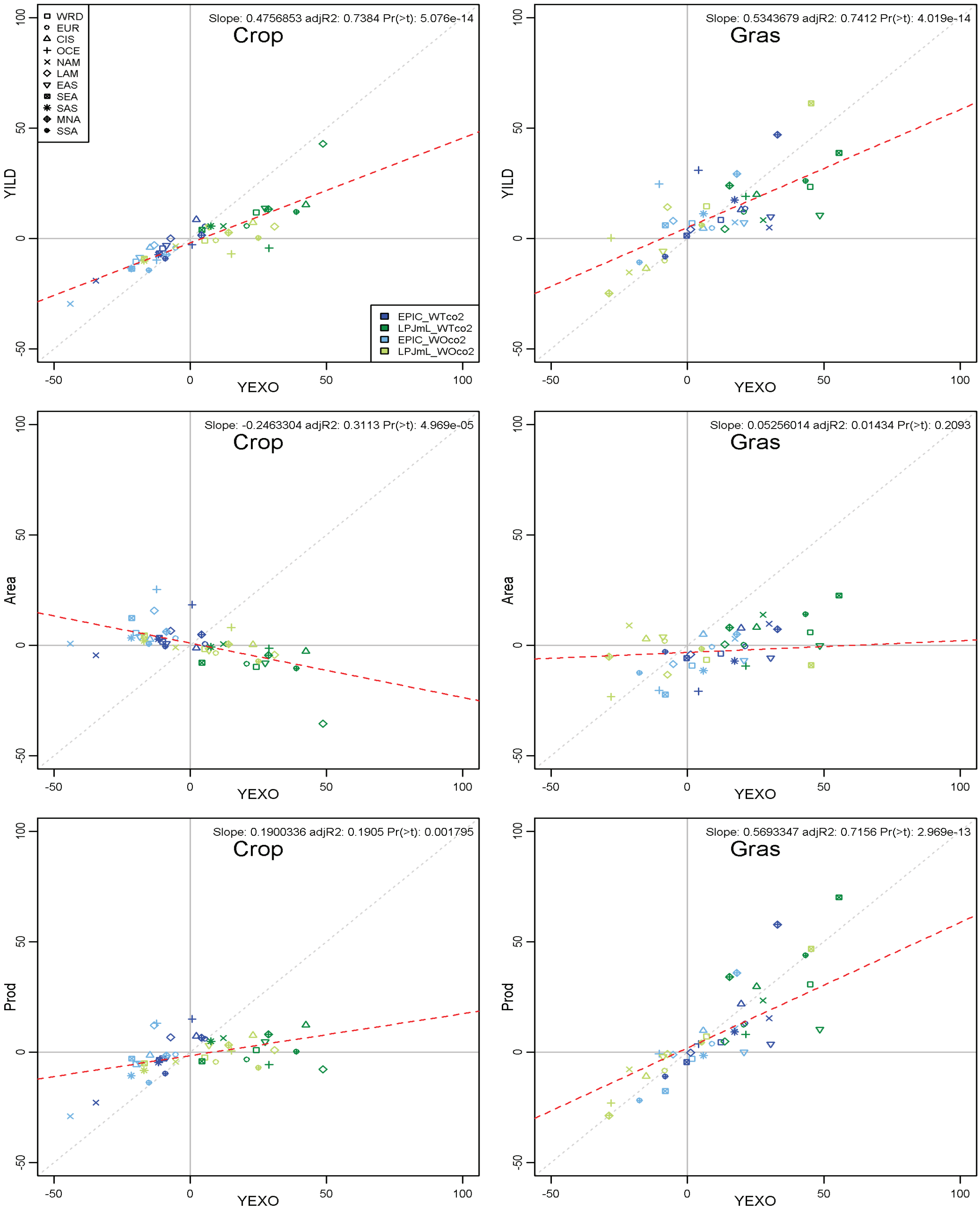

figure A3

Change in distribution of ruminant numbers across the livestock productions systems as compared with the present climate scenario (presclim) by 2050 in million TLUs. (BOVI – bovines, SHGT – small ruminants, BOVDh – bovines dairy herd, BOVOh – bovines other herd)

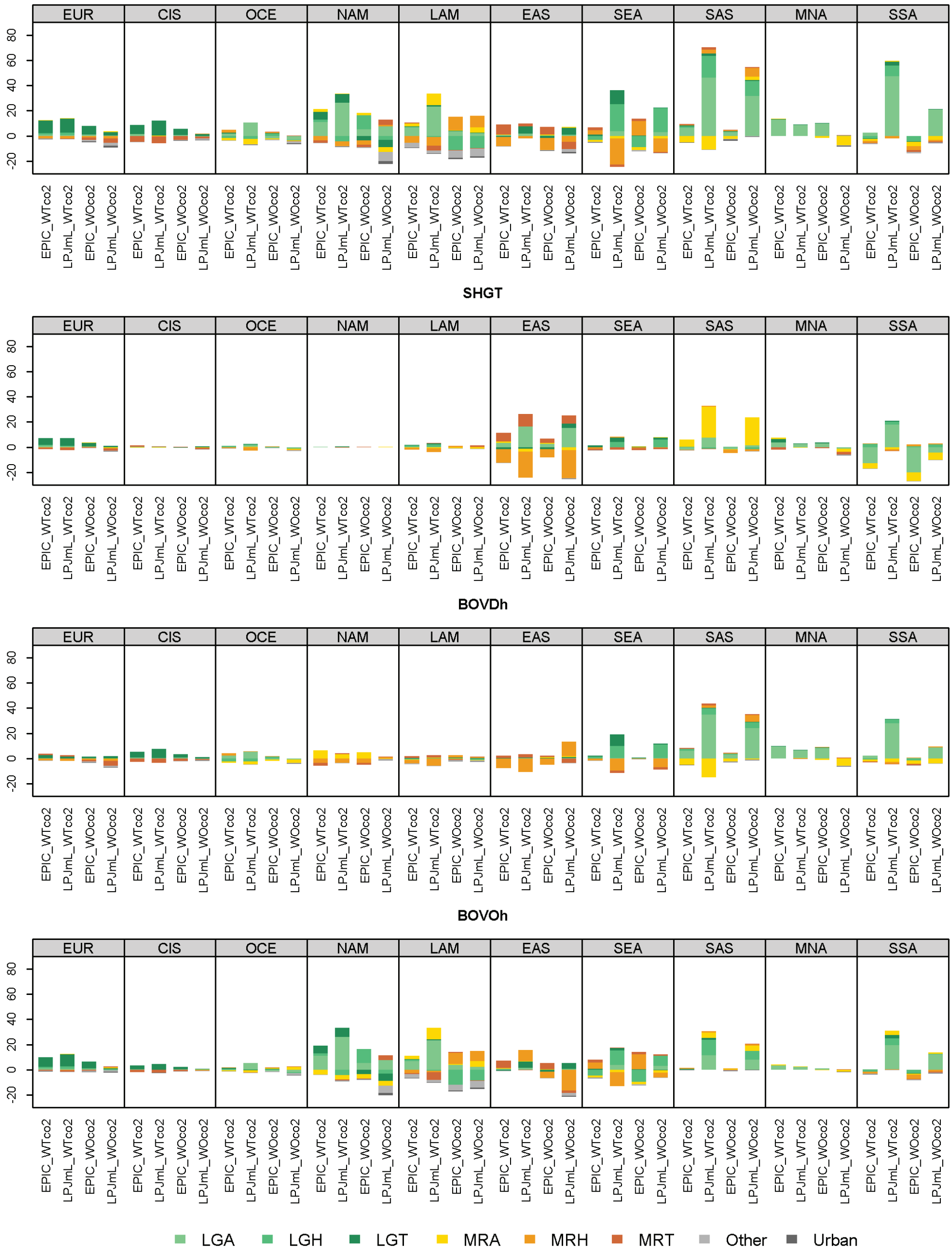

figure A4

Relationship between the pure climate change impact on grass yields (YEXO) and the share of ruminants reared in grazing systems (LG_SHR) relative to the scenario with present climate (presclim) by 2050 in %. (RUMI – bovines and small ruminants, BOVI – bovines, BOVDh – bovine dairy herd, BOVOh – bovines other herd)

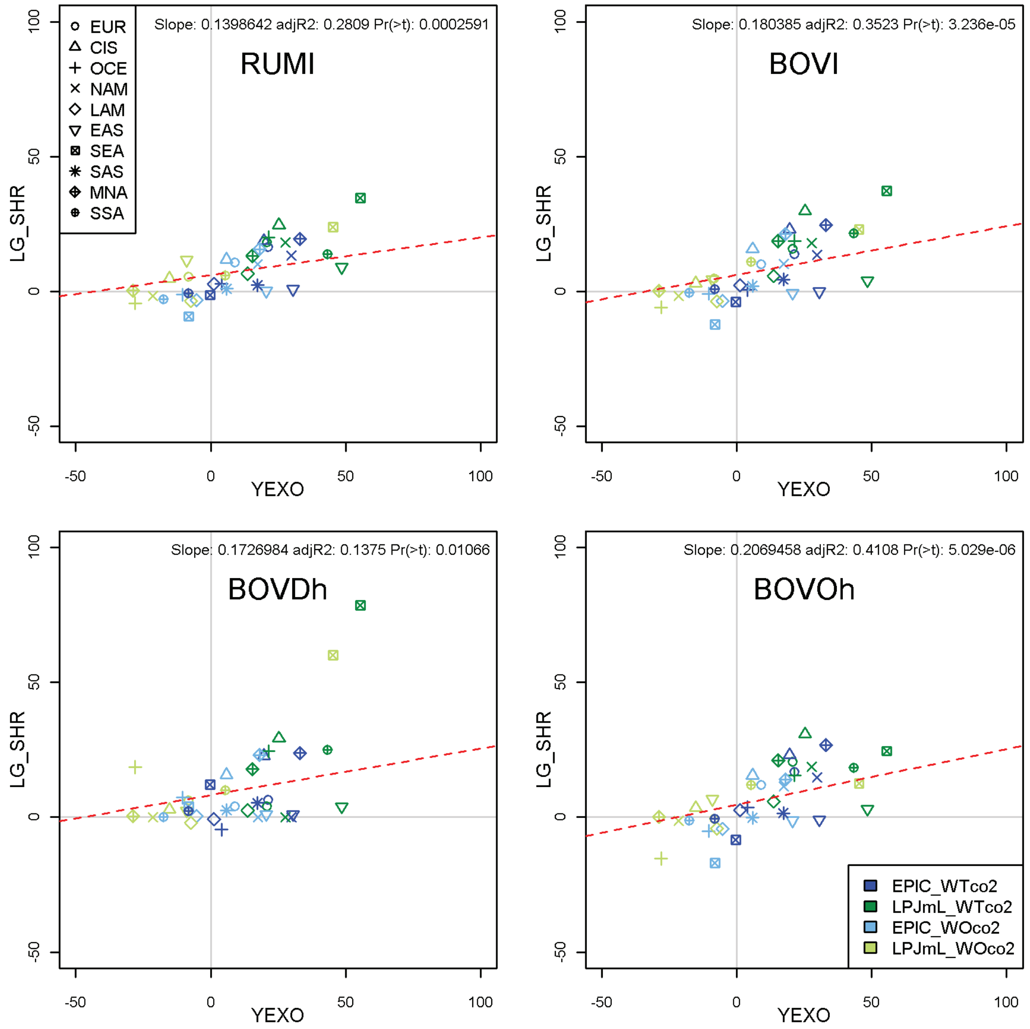

table A1
List of GLOBIOM regions

Macro region	Model regions	Countries
Europe (EUR)	EU Baltic	Estonia, Latvia, Lithuania
	EU Central East	Bulgaria, Czech Republic, Hungary, Poland, Romania, Slovakia, Slovenia
	EU Mid West	Austria, Belgium, Germany, France, Luxembourg, Netherlands
	EU North	Denmark, Finland, Ireland, Sweden, United Kingdom
	EU South	Cyprus, Greece, Italy, Malta, Portugal, Spain
	RCEU	Albania, Bosnia and Herzegovina, Croatia, Macedonia, Serbia-Montenegro
	ROWE	Gibraltar, Iceland, Norway, Switzerland
Former USSR (CIS)	Former USSR	Armenia, Azerbaijan, Belarus, Georgia, Kazakhstan, Kyrgyzstan, Moldova, Russian Federation, Tajikistan, Turkmenistan, Ukraine, Uzbekistan
Oceania (OCE)	ANZ	Australia, New Zealand
	Pacific Islands	Fiji Islands, Kiribati, Papua New Guinea, Samoa, Solomon Islands, Tonga, Vanuatu
North America (NAM)	Canada	Canada
	United States of America	United States of America
Latin America (LAM)	Brazil	Brazil
	Mexico	Mexico
	RCAM	Bahamas, Barbados, Belize, Bermuda, Costa Rica, Cuba, Dominica, Dominican Republic, El Salvador, Grenada, Guatemala, Haiti, Honduras, Jamaica, Nicaragua, Netherland Antilles, Panama, St Lucia, St Vincent, Trinidad and Tobago
	RSAM	Argentina, Bolivia, Chile, Colombia, Ecuador, Guyana, Paraguay, Peru, Suriname, Uruguay, Venezuela
Eastern Asia (EAS)	China	China
	Japan	Japan
	South Korea	South Korea
Southeast Asia (SEA)	RSEA OPA	Brunei Daressalaam, Indonesia, Singapore, Malaysia, Myanmar, Philippines, Thailand
	RSEA PAC	Cambodia, Democratic People’s Republic of Korea, Lao People’s Democratic Republic, Mongolia, Viet Nam

table A1 (cont'd.)

List of GLOBIOM regions

Macro region	Model regions	**Countries**
South Asia (SAS)	India	India
	RSAS	Afghanistan, Bangladesh, Bhutan, Maldives, Nepal, Pakistan, Sri Lanka
Middle East & North Africa (MNA)	Middle East and North Africa	Algeria, Bahrain, Egypt, Iran, Iraq, Israel, Jordan, Kuwait, Lebanon, Libya, Morocco, Oman, Qatar, Saudi Arabia, Syria, Tunisia, United Arab Emirates, Yemen
	Turkey	Turkey
Sub-Saharan Africa (SSA)	Congo Basin	Cameroon, Central African Republic, Democratic Republic of Congo, Equatorial Guinea, Gabon
	Eastern Africa	Burundi, Ethiopia, Kenya, Rwanda, Tanzania, Uganda
	South Africa	South Africa
	Southern Africa (Rest of)	Angola, Botswana, Comoros, Lesotho, Madagascar, Malawi, Mauritius, Mozambique, Namibia, Swaziland, Zambia, Zimbabwe
	West and Central Africa	Benin, Burkina Faso, Cape Verde, Chad, Cote d'Ivoire, Djibouti, Eritrea, Gambia, Ghana, Guinea, Guinea Bissau, Liberia, Mali, Mauritania, Niger, Nigeria, Senegal, Sierra Leone, Somalia, Sudan, Togo