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

DOI: 10.1016/j.gloenvcha.2011.09.013

Trading more Food - Implications for Land Use, Greenhouse Gas Emissions, and the Food System

Christoph Schmitz[1,a,b], Anne Biewald[a], Hermann Lotze-Campen[a],
Alexander Popp[a], Jan Philipp Dietrich[a,c], Benjamin Bodirsky[a,d],
Michael Krause[a,b], Isabelle Weindl[a]

[a] *Potsdam Institute for Climate Impact Research (PIK)*
Telegraphenberg A31, 14473 Potsdam, Germany

[b] *Department of Agricultural Economics and Social Sciences, Humboldt University,*
10115 Berlin, Germany

[c] *Department of Physics, Humboldt University, 12489 Berlin, Germany*

[d] *Economics of Climate Change, Technical University Berlin, 10623 Berlin, Germany*

---

[1] corresponding author: schmitz@pik-potsdam.de

Abstract

The volume of agricultural trade increased by more than ten times throughout the past six decades and is likely to continue with high rates in the future. Thereby, it largely affects environment and climate. We analyse future trade scenarios covering the period of 2005-2045 by evaluating economic and environmental effects using the global land-use model MAgPIE ("Model of Agricultural Production and its Impact on the Environment"). This is the first trade study using spatially explicit mapping of land use patterns and greenhouse gas emissions. We focus on three scenarios: the reference scenario fixes current trade patterns, the policy scenario follows a historically derived liberalisation pathway, and the liberalisation scenario assumes a path, which ends with full trade liberalisation in 2045.

Further trade liberalisation leads to lower global costs of food. Regions with comparative advantages like Latin America for cereals and oil crops and China for livestock products will export more. In contrast, regions like the Middle East, North Africa, and South Asia face the highest increases of imports. Deforestation, mainly in Latin America, leads to significant amounts of additional carbon emissions due to trade liberalisation. Non-CO_2 Emissions will mostly shift to China due to comparative advantages in livestock production and rising livestock demand in the region. Overall, further trade liberalisation leads to higher economic benefits at the expense of environment and climate, if no other regulations are put in place.

Keywords: international trade, GHG emissions, land use model, land use change

1. Introduction

During the last decades, the trade volume of agricultural goods has increased in an unprecedented way. Whereas between 1950 and 1955 every year an agricultural value of around 80 billion US$ was exported, it increased to an annual average of 827 billion US$ in the period from 2005 to 2008 (FAOSTAT, 2010). Two developments are responsible for this trend. First, technological change reduced transport and transaction costs for trading, and second, agricultural trade was liberalised after the huge domestic support following the Second World War (Hummels, 2007; Josling et al., 2010; Anderson, 2010).

Evaluating the consequences of increased trade, most studies focus on economic indicators, like distributional effects, poverty impacts, and welfare (e.g. Anderson and Tyers, 1993; Martin and Winters, 1996; Corden, 1997; Bouët et al., 2005; Hertel et al., 2009). Only since the mid-1990s trade economists started to consider the relationship between agricultural trade and the environment in their analyses, often not differentiating between agricultural and non-agricultural trade (Tamiotti et al., 2009). Some early studies state a positive impact of more liberalised trade on the environment (Anderson, 1992; Antweiler et al., 2001) or draw a mixed picture (Cole, 2000; Baek et al., 2009). Copeland and Taylor (1994) show with a simple theoretical model how world trade liberalisation leads to less environmental pollution in the North but to an increased level in the South. Lopez (1994) concludes that trade increases resource degradation if producing countries are not including production externalities in product prices. More sophisticated econometric studies indicate a clear positive relationship between trade liberalisation and CO_2 emissions (Cole and Elliot, 2003; Managi, 2004; Frankel and Rose, 2005).

Whereas all these studies focus on the past, some more recent studies include environmental effects in trade models or coupled versions of biophysical and economic models to predict the future impact of trade liberalisation. Verburg et al. (2009) use the coupled LEITAP-IMAGE model to analyse the impacts of trade liberalisation on greenhouse gas (GHG) emissions. They conclude that overall GHG emissions increase by about 6% in 2015, when full trade liberalisation by 2015 is compared with the “no-new policy scenario” from OECD. Similar studies by van Meijl et al. (2006) and Eickhout et al. (2009) show that trade liberalisation leads only to small land-use shifts in Europe but dramatic shifts in Africa and other developing regions resulting in negative implications for the environment.

In contrast to these studies, our analysis combines the results of several environmental and economic indicators in order to get a more comprehensive picture. We use the spatially explicit economic land use model MAgPIE ("Model of Agricultural Production and its Impact on the Environment") (Lotze-Campen et al., 2008; Lotze-Campen et al., 2010; Popp et al., 2010) to run different trade liberalisation scenarios. As an advantage to other models, MAgPIE takes biophysical information directly into account from the grid-based Lund-Potsdam-Jena dynamic global vegetation model with managed land (LPJmL) (Bondeau et al., 2007). In addition to the detailed representation of economic and environmental aspects, our modelling framework differs from comparable models by considering the interplay of land expansion and yield increasing technological change in an endogenous way (Dietrich et al., 2010b).

In this study we investigate the implications of different trade liberalisation scenarios on global production costs, technological change rates, land use dynamics, deforestation rates, and greenhouse gas emissions over the coming four decades. To do so, we first explain the model framework (section 2.1), outline the method of trade simulation (section 2.2), illustrate the calculation of GHG emissions (section 2.4), as well as present the applied scenarios (section 2.3). Chapter three illustrates the results of the analysis. In chapter four and five, we discuss the results and possible policy implications and draw the conclusions.

2. Model and Scenarios

2.1 Model framework

The global land-use model MAgPIE is a recursive dynamic optimization model with a cost minimization objective function (Lotze-Campen et al., 2008; Lotze-Campen et al., 2010; Popp et al., 2010). The biophysical supply side of the model is simulated spatially explicit using 0.5 degree data aggregated to 1000 clusters.

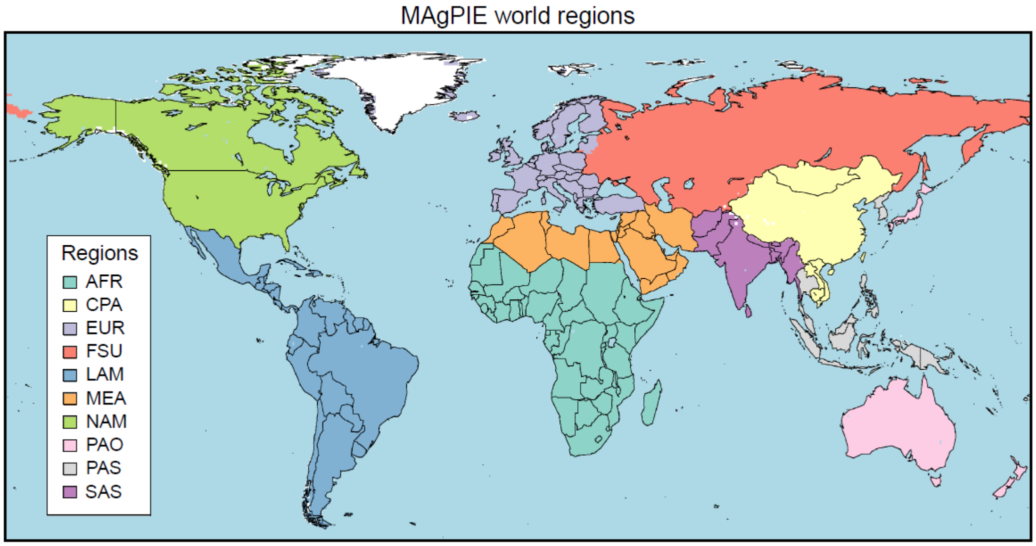

Figure 1: The ten world regions in MAgPIE [2]

The demand side is represented by ten world regions (see Figure 1). The required calories in the demand categories are initially derived from population data (CIESIN et al., 2000) and income growth (Gross Domestic Product per capita) (World Bank, 2001) for the year 1995. These data are regressed on a cross-sectional basis with country data on food and non-food energy intake. Future demand is then based on a medium population projection and a medium economic growth scenario (however, with optimistic assumptions for China and India), both defined in the ADAM project[3] and explained in van Vuuren et al. (2009). The resulting demand calories are produced by 16 cropping[4] and 5 livestock activities[5] (see Appendix A). MAgPIE simulates time steps of 10 years (starting in 1995) and uses in each period the optimal land-use pattern from the previous period as a starting point.

---

[2] AFR = Sub-Sahara Africa, CPA = Centrally Planned Asia (incl. China), EUR = Europe (incl. Turkey), FSU = Former Soviet Union, LAM = Latin America, MEA = Middle East and North Africa, NAM = North America, PAO = Pacific OECD (Australia, Japan and New Zealand), PAS = Pacific Asia, SAS = South Asia (incl. India)

[3] Adaptation and Mitigation Project, URL: http://www.adamproject.eu/

[4] Crops: temperate cereals (tece), maize, tropical cereals (trce), rice, soybean, rapeseed, groundnut, sunflower, oil palm, pulses, potato, cassava, sugar beet, sugar cane, cotton, others

[5] Livestock: ruminant meat, pig meat, poultry meat, egg, milk

The five livestock activities related to specific feed energy requirements per animal product and per region. These requirements are met by a certain mixture of pasture, fodder, and food crops again depending on the region and animal type. The data are derived from Wirsenius (2000) and contain minimum requirements for maintenance, growth, lactation, reproduction and other basic biological needs. Moreover, we differentiate between a general allowance for basic activity and temperature effects as well as by using extra energy expenditures for grazing. For more details we refer to Weindl et al. (2010). These differences in the livestock systems cause different emission levels from livestock which are explained in more detail in section 2.3. From these data Africa has the lowest efficiency whereas Europe has the most efficient systems in 1995.

The biophysical inputs (e.g. yields) for MAgPIE are derived from the grid-based Lund-Potsdam-Jena dynamic global vegetation model with managed land (LPJmL) (Bondeau et al., 2007). LPJmL is a process-based model which considers soil, water, and climatic conditions, like CO_2, temperature and radiation in an endogenous way. The model runs are based on climate projections from HadCM3 (Hadley Centre Coupled Model, version 3) (Cox et al., 1999) and SRES A2 (Special Report on Emissions Scenarios) (Nakicenovic and Swart, 2000). The inclusion of the hydrological cycle and a global map of irrigated areas (Döll and Siebert, 2000) allow LPJmL to differentiate between rainfed and irrigated yields. Irrigated areas receive their additional water from the natural runoff and its downstream movement according to the river routing in LPJmL (Rost et al., 2008; Gerten et al., 2004). Besides crop yields, LPJmL delivers this water discharge value for each grid cell as a possible constraint for irrigation in MAgPIE. The information about irrigation and rainfed land use fractions is derived from a modification of the MIRCA2000 land use dataset (Portmann et al., 2010). More information on the methodology can be found in Fader et al. (2010).

2.2 Cost Types

Four categories of costs arise in the model: production costs for livestock and crop production, yield increasing technological change costs, land conversion costs and intraregional transport costs. The model solution is derived by minimizing these four cost components on a global scale for the current time step.

In order to increase total agricultural production, MAgPIE can either invest in yield-increasing technological change or in land expansion (Popp et al, 2011b). The endogenous implementation of technological change (TC) is based on a surrogate measure for agricultural land use intensity (Dietrich et al., 2010). Investing in TC leads not only to yield increases but also to increases in agricultural land-use intensity, which in turn raises costs for further yield increases. Schmitz et al. (2010) related agricultural land-use intensity to empirical data on investments in TC based on a regression analysis. The data for agricultural Research & Development investments are from IFPRI (Pardey et al., 2006) and for infrastructure investments from GTAP (Narayanan and Walmsley, 2008). From the results they calculated a yield elasticity with respect to TC investments (ε_{Inv}^{Yld}) of 0.27. Appendix C shows the validation of the resulting TC rates in MAgPIE compared with observed data from FAO.

Production costs in MAgPIE reflect factor costs for labour, capital, and intermediate inputs. To determine the influence of TC on production costs, a regional correlation analysis between yield and costs per area and yield and costs per production unit was conducted (Schmitz et al., 2010). Results of the correlation analysis indicated the existence of a positive correlation between yields and area-related production costs, but no correlation between yield and output-related production costs. Based on this result production costs per ton had been implemented as a constant input, which led to the linear relationship between production costs per area and yield.

The other alternative for MAgPIE to increase production is to expand cropland into non-agricultural land (Krause et al, 2009; Popp et al., 2011b). In this model version no policy restrictions are in place regarding the expansion of cropland. However, the expansion involves land-conversion costs for every unit of cropland, which account for the preparation of new land and basic infrastructure investments. Land conversion costs are based on country-level marginal access costs generated by the Global Timber Model (GTM) (Sohngen et al., 2009). Moreover, land expansion in MAgPIE is restricted by intraregional transport costs which accrue for every commodity unit as a function of the distance to intraregional markets. The value is dependent on the quality and accessibility of the infrastructure. Hence, the less accessible the land is, the higher are intra-regional transport costs, which leads to higher overall costs of cropland expansion. The data are based on GTAP transport costs (Narayanan and Walmsley, 2008) and a 30 arc-second resolution data set on travel time to the nearest large city released by the European Commission Joint Research Centre (Nelson, 2008).

More information on the model framework is presented in a mathematical description of MAgPIE in Appendix H.

2.3 International Trade

We implemented international trade in MAgPIE by using flexible minimum self-sufficiency ratios at the regional level. Self-sufficiency ratios describe how much of the regional agricultural demand quantity has to be produced within a region. For instance, a ratio for cereals of 0.80 means that 80% of cereals are produced domestically, whereas 20% are imported. To represent the trade situation of 1995 we calculated the self-sufficiency ratios ($p^{sf}_{i,k}$) for each region *i* and production activity *k* from the food balance sheets of FAO for the year 1995 (FAOSTAT, 2010) (see Appendix B).

We implemented two virtual trading pools which allocate the global demand to the different supply regions (Figure 2). The demand which enters the first pool is allocated according to fixed criteria. Self-sufficiency ratios determine how much is produced domestically, and export shares determine the share of each region in global exports. The export shares are generated for every crop for the year 1995 and are taken from FAO (FAOSTAT, 2010) (see Appendix C). However, although the initial self-sufficiencies for this pool stay constant over time, the final self-sufficiencies do change since domestic demand and population change over time. The demand which enters the second pool is allocated according to comparative advantage criteria to the supply regions. The criteria, under given constraints like crop rotation or water availability, are biophysical yield, production costs and technological change leading to yield increase. This implies that the model optimizes supply with the goal of minimizing global production costs and produces in those cells where it is most economical compared to other cells.

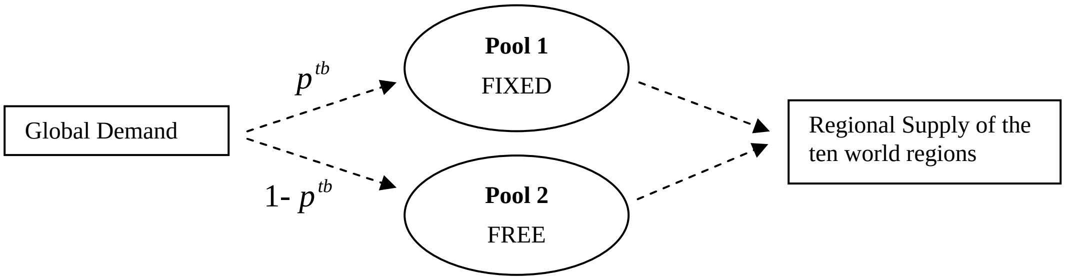

Figure 2: Trading pools in MAgPIE. The fixed pool allocates demand according to fixed criteria (self-sufficiency ratios and export shares). The free pool allocates it according to comparative advantage criteria.

The parameter p^{tb} defines the share of trade volume which flows into both pools.[6] If p^{tb} is equal to 1, the total demand will be distributed to the supply regions according to fixed self-sufficiencies and export shares. If p^{tb} is equal to 0, the whole trade volume will end up in the second pool and is distributed according to comparative advantage criteria to the supply regions.

---

[6] We call p^{tb} the "trade barrier reduction factor" (see below)

The following equations demonstrate the same procedure in mathematical terms. Equation (1) shows the global food balance, where the aggregated regional supply f^{prod} adjusted by the seed share p^{seed}[7] has to be equal or bigger than the aggregated regional demand f^{dem}.

Global trade balance:

$$\sum_i \frac{f_{t,i,k}^{prod}(x_t)}{1+p_{i,k}^{seed}} \geq \sum_i f_{t,i,k}^{dem}(x_t) \qquad (1)$$

with x as the variable for production, i as region, t as time and k as production activity. Subsequently, we introduced excess demand and supply equations. The global quantity of excess demand p^{xd} for each production activity k is calculated by subtracting domestic demand (f^{dem}) from domestic production for the importing countries (self-sufficiency ratio $p^{sf} < 1$) (equation 2). Domestic production is calculated by multiplying domestic demand with the self-sufficiency ratio ($f^{dem} \cdot p^{sf}$). The calculated excess demand is distributed to the exporting regions according to their export shares p^{exshr} (equation 3).

Excess Demand:

$$p_{t,k}^{xd} = \sum_i f_{t,i,k}^{dem}(x_t) \cdot (1 - p_{i,k}^{sf}) \qquad : p_{i,k}^{sf} < 1 \qquad (2)$$

Excess Supply:

$$p_{t,i,k}^{xs} = p_{t,k}^{xd} \cdot p_{t,i,k}^{exshr} \qquad (3)$$

The trade balance equation (4) assures that demand and supply are balanced at the regional scale. In the case of an exporting region, the regional supply has to be greater or equal than the domestic demand plus the exported quantity. In the case of an importing region, the regional supply has to be greater or equal than the domestic demand times the self-sufficiency. This holds true, if the trade barrier reduction factor p^{tb} is equal to one. If p^{tb} is equal to zero, the equation becomes zero and everything is solved via the global trade balance (equation 1).

Trade Balance Equation:

$$\frac{f_{t,i,k}^{prod}(x_t)}{1+p_{i,k}^{seed}} \geq p^{tb} \begin{cases} f_{t,i,k}^{dem}(x_t) + p_{t,i,k}^{xs} & : p_{i,k}^{sf} \geq 1 \\ f_{t,i,k}^{dem}(x_t) \cdot p_{i,k}^{sf} & : p_{i,k}^{sf} < 1 \end{cases} \qquad (4)$$

---

[7] The seed share accounts for the produced quantity which is used as seeds for the next farming season.

2.4 Greenhouse Gas Emissions

MAgPIE calculates greenhouse gas emissions of CO_2, CH_4 and N_2O resulting from land-use changes and agricultural activities.

CO_2 emissions are calculated as the difference in carbon content between natural vegetation and managed crop production. CO_2 emissions from land-use change occur whenever natural vegetation is converted into cropland. The difference in the carbon stocks between both land-use types is released in the form of CO_2 emissions. Carbon emissions from soils are not captured. Carbon stocks are projected using the LPJmL model.

CH_4 emissions in MAgPIE have three possible sources. First, animal waste management systems (AWMS) are responsible for CH_4 emissions by the anaerobic decomposition of manure. In MAgPIE, this effect is influenced by temperature, the kind of livestock, and the development level of the region. Second, ruminant livestock, like cattle, sheep, or goats, produce methane by fermenting feed in stomach and intestine. Third, rice cultivation is responsible for CH_4 emissions from flooded fields. Besides the amount of rice cultivation, this emission type depends on water management practices and a specific regional factor. CH_4 emissions are estimated using the emission factors of the Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories (IPCC, 1996).

N_2O emissions in MAgPIE have two possible sources. Like in the case of CH_4, one source is the AWMS which produces N_2O by denitrification and nitrification of animal excrements. In MAgPIE this is dependent on the amount of livestock products and the type of livestock system. The second source is N_2O emissions from cultivated soils. These are directly affected by the kind of nitrogen fertilizer used (synthetic fertilizer, manure, crop residues and N-fixing crops). In addition, indirect effects occur through atmospheric deposition of NO_x and NH_3 and through leaching of nitrogen fertilizer. N_2O emissions are estimated using the emission factors of the 2006 IPCC Guidelines for National Greenhouse Gas Inventories (IPCC, 2006).

The values are given in CO_2-equivalent using their “global warming potential” (GWP). According to IPCC (2007), CH_4 contributes 25 times as much to global warming compared to CO_2. The factor for N_2O is 298. Further information on the detailed calculation of these emissions within MAgPIE is provided in Popp et al. (2010) and Popp et al. (2011a).

2.5 Scenarios

We consider three scenarios: (1) The reference scenario (*reference*) keeps current trade patterns constant over time until 2045. (2) The policy scenario (*policy*) follows a historically derived pathway of trade liberalisation. Taking into account various literature sources we decided that a 10% trade barrier reduction each decade until 2045 reflects a realistic policy scenario for the future (Healy et al, 1998; Conforti and Salvatici, 2004)[8]. This is also supported by the general trade study of Dollar and Kraay (2004), who found a 22% tariff cut for non-globalising countries, 11% for globalising countries, and 0% for rich countries[9] between the 1980s and 1990s. (3) The liberalisation scenario (*liberal*) allows for full trade liberalisation in 2045 by reducing the trade barrier reduction factor to zero over time. The assumption here is that the world will be fully liberalised in 2045 and everything is traded according to comparative advantage criteria. In MAgPIE liberalising trade implies the reduction of boarder measures, like tariffs, quotas, export restraints and any other non-tariff barrier. Internal measures, like producer subsidies, are not explicitly captured in MAgPIE. Hence, in the case of trade liberalisation all trade distorting measures are removed and goods can be traded freely.

The scenarios differ by changing the trade barrier reduction factor p^{tb}, a parameter that describes the share of demand which is traded according to fixed self-sufficiencies. Table 1 gives the values for p^{tb} in each period and scenario. As mentioned, in the reference scenario demand is traded according to fixed rules. Therefore, the value for p^{tb} is 1 in all time steps. In the policy scenario it changes and the factor is reduced by 10% in each decade. In the liberalisation scenario p^{tb} is reduced continuously towards 0 in 2045, when demand is fully traded according to comparative advantage criteria.

Year	**1995**	**2005**	**2015**	**2025**	**2035**	**2045**
reference scenario	1	1	1	1	1	1
liberalisation scenario	1	0.8	0.6	0.4	0.2	0
policy scenario	1	0.9	0.81	0.73	0.66	0.59

Table 1: Trade barrier reduction factor in different trade scenarios over time

---

[8] In the course of the Uruguay Round, tariff lines have been reduced at least by 15 % for developed countries, 10% for developing countries, and 0% for least-developed countries (Healy et al, 1998).

[9] „Rich countries refer to the 24 OECD economies before recent expansion plus Chile, Hong Kong, Korea, Taiwan, and Singapore. Globalisers refer to the top one-third in terms of their growth in trade relative to GDP between 1975–9 and 1995–7 of a group of 72 developing countries for which we have data on trade as a share of GDP in constant local currency units since the mid-1970s. Non-globalisers refer to the remaining developing countries in this group." (Dollar and Kraay, 2004, p. 23)

2.6 Sensitivity Analysis

Due to space limitations and scope of the paper, we focus the sensitivity analysis on the two most important drivers, namely the rate of technological change (TC) and the rate of land expansion. We chose the estimated parameter for yield elasticity and intra-regional transport costs for the sensitivity test. Firstly, for TC, we base our assumption on the endogenous implementation presented by Schmitz et al. (2010). From their regression between investments in TC and the associated yield change, they derived a yield elasticity with respect to TC investments (ε_{Inv}^{Yld}) of 0.27. In the literature a value of 0.296 is given (Nelson et al. 2009). For the sensitivity analysis we chose two extreme scenarios, in which we set the elasticity to 0.32 (*cheapTC*) and 0.22 (*expensiveTC*). We conducted numerous tests on possible alternative regression results and in no case the elasticities were higher than 0.31 or lower than 0.24. Therefore, we choose a range of +0.05 and -0.05 around 0.27 as extreme values. In the first case, investments in TC are less profitable and in the second case it is more expensive to reach a certain yield level.

Secondly, we test the intra-regional transport cost level, which is crucial for land expansion and determines how costly it is for MAgPIE to subdue new cropland. As explained in chapter 2.2, the data are based on transport costs and the transport time to the next non-cropland cell, which includes distance and the quality of infrastructure. For the sensitivity analysis we halved the costs (*lowtrans*) and doubled them (*hightrans*), which are extreme scenarios on both ends.

3. Results

3.1 Trade Balances

Trade balances (in million tons) are calculated by taking the difference between exports and imports of a region. We decided to focus on the most important crop groups for international trade (cereals, oilcrops, sugar, vegetables/fruits, and meat).

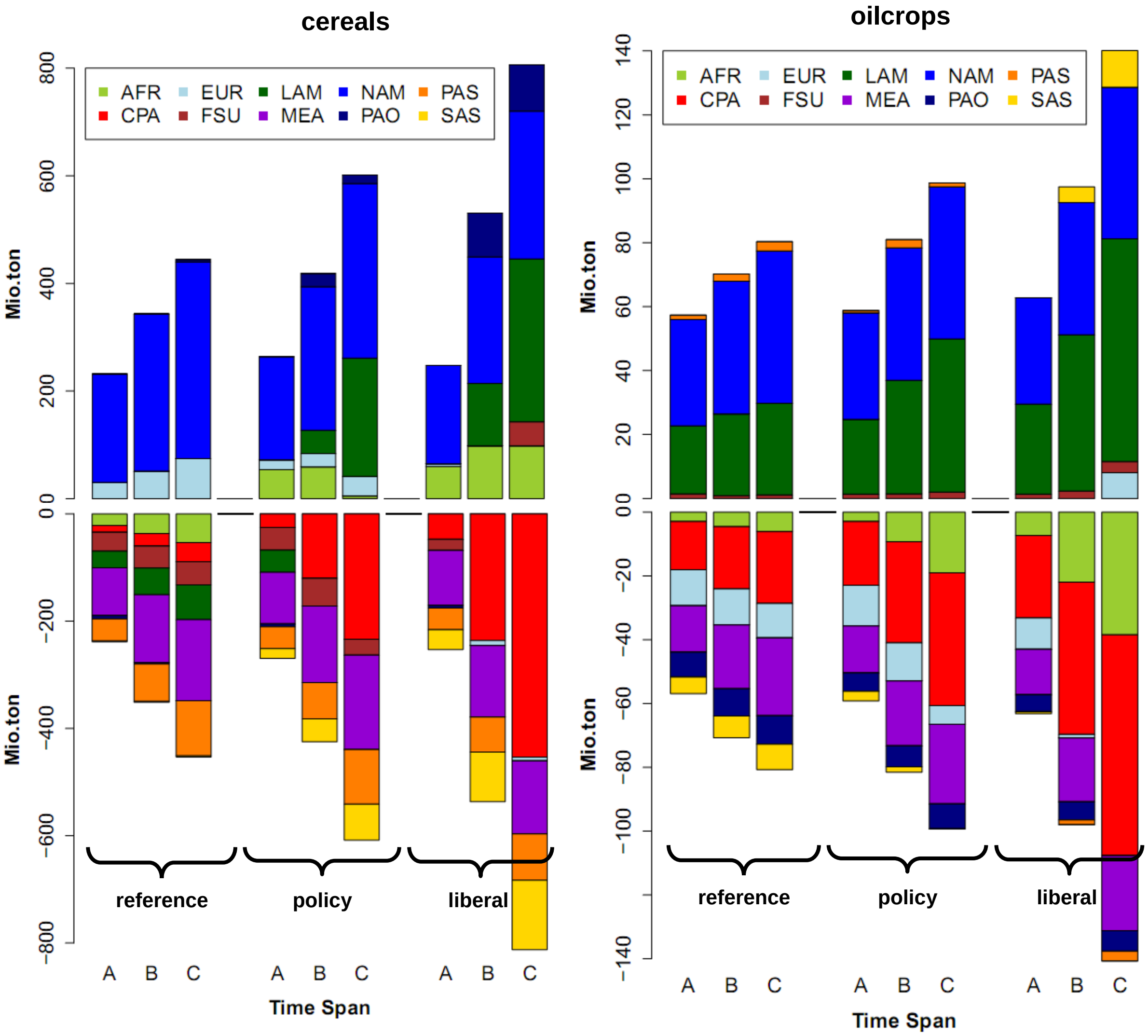

Figure 3: Net export quantities of cereals (incl. rice) and oilcrops for ten world regions in three trade scenarios and for three time spans (A = 2005-2020; B= 2020-2035; C= 2035-2050)

Figure 3 shows trade balances for cereals (incl. rice) and oilcrops. The ten world regions are distinguished by different colours. The three scenarios are compared in each graph (reference scenario on the left, policy scenario in the middle and liberalisation scenario on the right). The three bars in each scenario cover the three time spans: 2005-2020 (A), 2020-2035 (B) and 2035-2050 (C).

In the reference scenario, EUR and NAM dominate the market for cereal exports. The imports are shared among the other regions, led by MEA. This situation changes in the other two scenarios when PAO, AFR, LAM, and FSU join the export group at the expenses of EUR, which becomes partly a net importer. On the import side CPA and SAS increase their quantities most. The average global trade volume in cereals in the years 2035 to 2050 increases to over 800 mio. tons in the liberalisation scenario (compared to around 450 mio. tons in the reference scenario). The export market for oilcrops is mostly dominated by NAM and LAM. With more trade, LAM strongly increases its export volume. In the last time step, LAM increases its export from 30 mio. tons to around 80 mio. tons. In the liberalisation scenario, SAS and EUR join the export group with small shares. On the import side CPA and AFR face the highest increases over time and with more trade.

Appendix E shows the trade balances for sugar, vegetable/fruits, and meat. Concerning the sugar market, LAM dominates the market with an export share of around 75%. This increases under trade liberalisation to more than 90% in the last time step (2035-2050). Imports increases continuously across the importing regions, especially in CPA and AFR. Vegetables and fruits will mostly be exported by CPA and to a lower extent by SAS under increased trade. Europe will continue to be the leading importer. For meat, CPA will dominate the export market with shares of over 95% under trade liberalisation.

3.2 Global Costs and Food Scarcity

MAgPIE is a mathematical programming model which minimizes global agricultural production costs. These costs reflect the factor costs of labour, capital, and intermediate inputs. Figure 4 shows the global annual production costs for the reference scenario in 2005 and 2045 and the two increased trade scenarios in 2045.

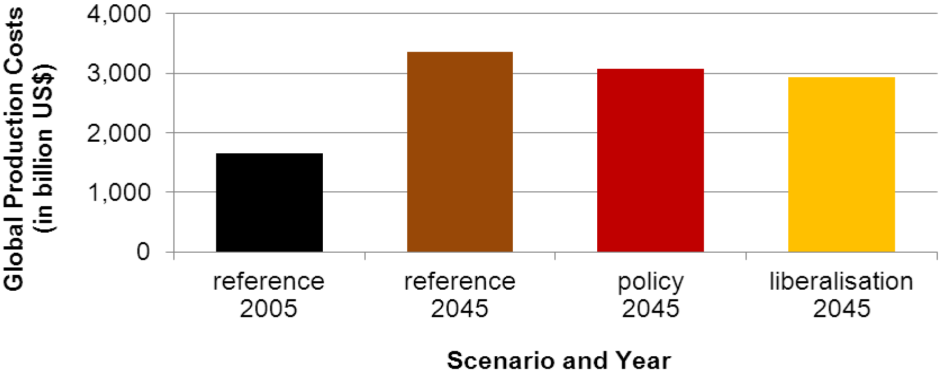

Figure 4: Global annual production costs in the reference scenario in 2005 and in each scenario in 2045

In 2005, MAgPIE starts with a value of 1.65 trillion US$. As a validation of this output we took the agricultural value-added output from the World Development Indicators[10]. The measured value amounts to 1.54 trillion US$ (average of 2004-2006) (World Bank, 2011). Although both figures are very close, we have to account for some differences. In contrast to the measured data, the model data include intermediate inputs (global share of 22%) but no land data (global share of 17%). In addition, MAgPIE production does not account for forestry, hunting and fishing which would also lead to higher total production costs. Hence, although the data are not fully comparable, they should be quite similar. The production costs increase over time in all three scenarios. In the reference scenario, costs amount to 3.35 trillion US$ in 2045. More liberalisation leads to lower global production costs. The costs in the policy scenario decrease to 3.07 trillion US$ and in the liberalisation scenario to 2.93 trillion US$ in 2045.

In Figure 5 we present a scarcity index for agricultural products. The index shows marginal costs of food production which indicate the costs of one additional unit of food. A rising index expresses that food production is becoming more expensive. In this analysis we obtain a sharp increase of the index by 80% until 2045 in the reference scenario. In the policy scenario marginal costs increase continuously by about 5 to 10% per decade and end up at 140 index points in 2045. For the liberalisation scenario we obtain a slow and uneven increase to an index value of 120 in 2045.

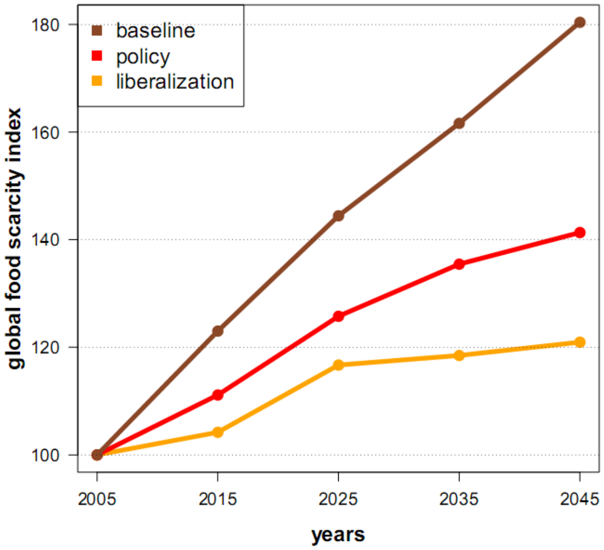

Figure 5: Scarcity Index for agricultural products over time in each scenario

---

[10] The agricultural value-added output measures the output of the agricultural sector less the value of intermediate inputs. The agricultural sector corresponds to ISIC (International Standard Industrial Classification) division 1-5 (Revision 3) and comprises value added from cultivation of crops and livestock production as well as forestry, hunting, and fishing.

3.3 Technological Change Rates

Figure 6 shows average annual technological change (TC) rates of the ten world regions, which are required to fulfil food demand over the period of 2005-2045. In all cases, except LAM, PAO and PAS the TC rates decrease with increasing trade. MEA and SAS face the strongest decreases. In MEA the required TC rate drops from 2.1% in the reference to 0.5% in the liberalisation scenario. In SAS it reduces from 2.0% to 1.1%. AFR and CPA show slight decreases in the policy scenario and the liberalisation scenario. The opposite holds true for LAM where the demand for TC slightly increases. In PAS and PAO, TC rates do not change between the different scenarios. In addition, the global values show a decline of TC rates from 1.2% (*reference*) to 1.0% (*policy*) and 0.9% (*liberalisation*). Appendix D shows the validation of TC rates of the reference scenario with FAO observations.

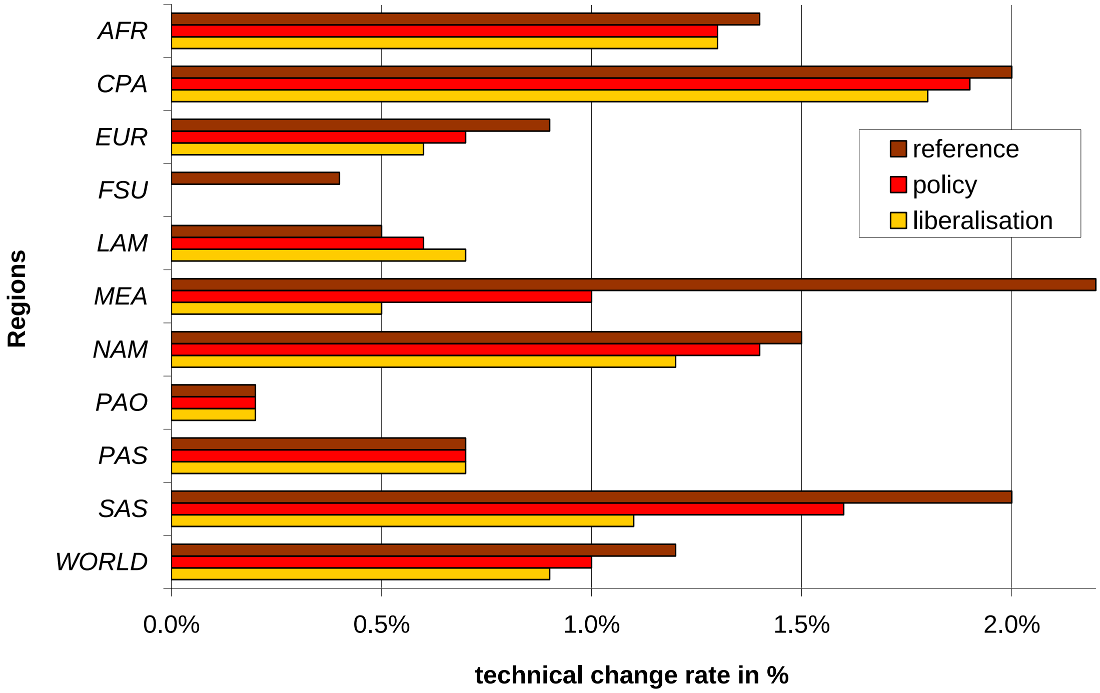

Figure 6: Average annual technical change from 2005 to 2045 for the 10 MAgPIE regions and globally aggregated (*WORLD*). The brown bars represent the rates under the constant trade scenario (*reference*), the orange bars the moderate trade liberalisation scenario (*policy*), and the yellow bars the full liberalisation scenario (*liberal*).

3.4 Land use Change and related Carbon Emissions

Besides technological change MAgPIE has also the option of expanding cropland in order to increase production. Figure 7 illustrates expansion of cropland into forest from 2005 to 2045. The map shows how much of each cell (in land use shares) is converted from forest to cropland in this period. The most affected area will be the Central African rainforest, followed by the Amazonian Rainforest and the rainforest in Indonesia and North Australia. Some land expansion takes place in the Savannah Region of West Africa and in Mexico.

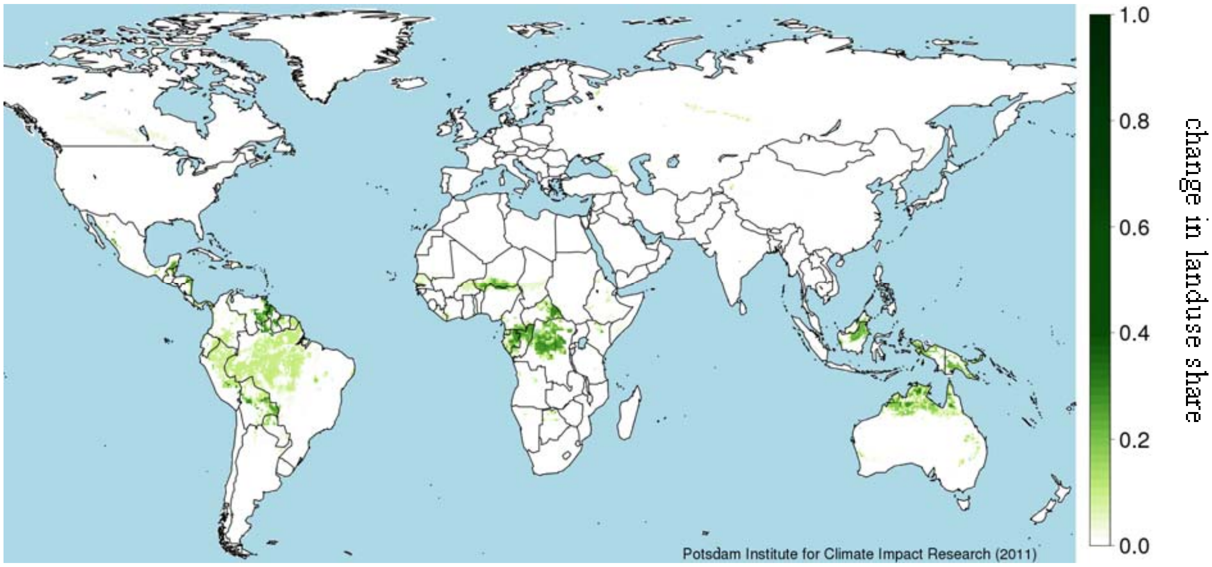

Figure 7: Relative rate of cropland expansion (change in land use share of all crops) per grid cell (0.5°) in the reference scenario between 2005 and 2045

Figure 8 illustrates the difference in cropland expansion between the reference and policy scenario (top) and the reference and liberalisation scenario (bottom). Positive values (green colour) indicate that MAgPIE uses more cropland in the featured scenario compared to the reference scenario. If the value is negative (orange/red colour), MAgPIE uses less cropland. In both maps total cropland expansion increases and the expansion in Africa is almost constant. In the policy scenario between 2005 and 2045 more area in the Amazonian Rainforest is converted into cropland (around 170 mio. ha). In the liberalisation scenario this amount increases further by 20 mio. ha. Some small increases in cropland are found in Indonesia, whereas in both trade scenarios less area is converted in the North of Australia.

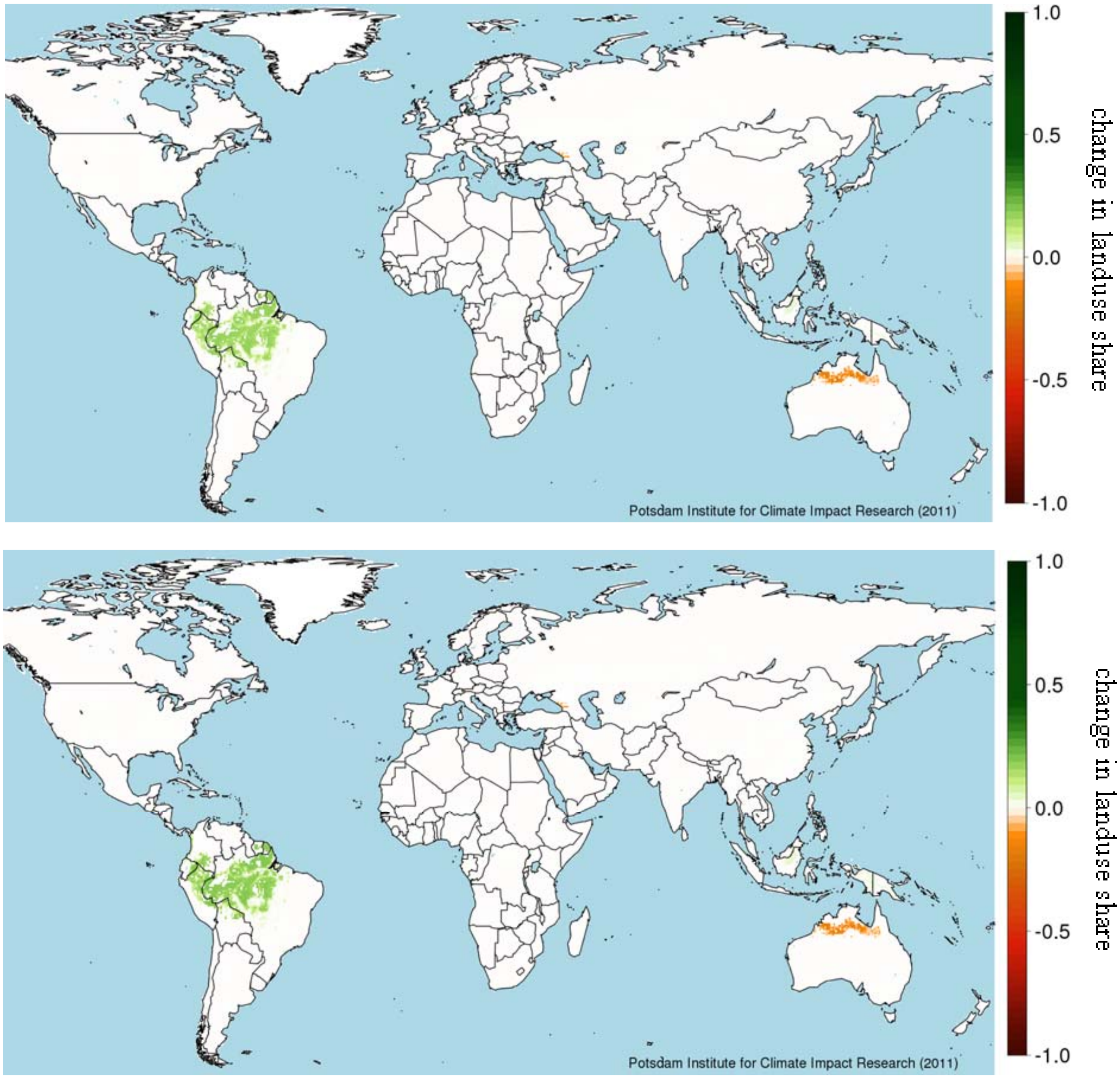

Figure 8: Relative change in land use share of all crops per grid cell (0.5°) between reference and policy scenario (top) and between reference and liberalisation scenario (down) in the period of 2005 to 2045

Expansion of cropland into forest results in significant amounts of CO_2 emissions (Figure 9). The rainforest regions LAM, AFR, and PAS emit most CO_2 until 2045. The emissions in AFR stay almost on a constant level throughout all scenarios. In LAM around 25% more carbon emissions are produced under the policy scenario and almost 60% under the liberalisation scenario. In PAS the amount of CO_2 emissions decreases with more trade; from 30 Gt in the reference scenario, to 28 Gt in the policy scenario and to 24 Gt in the liberalisation scenario. In total, cumulated CO_2 emissions between 2005 and 2045 increase from 192 Gt in the reference scenario to 217 Gt in the policy scenario. In the liberalisation scenario, emissions increase further to 239 Gt.

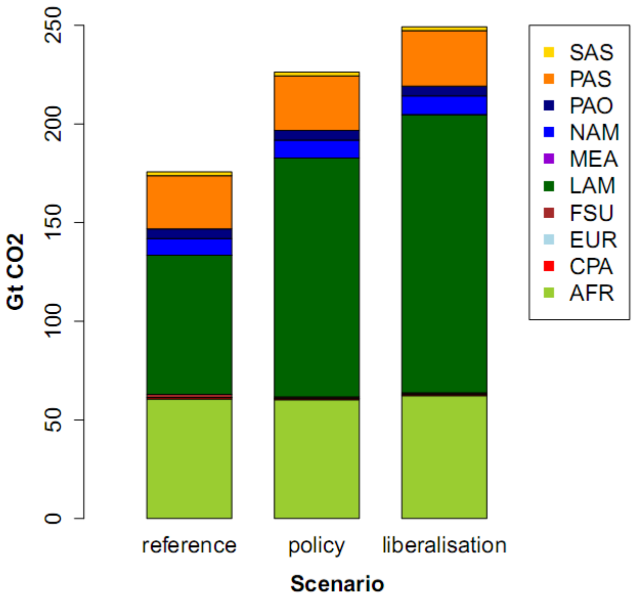

Figure 9: CO_2 Emissions from deforestation in three trade scenarios (2005-2045)

3.5 Non-CO_2 Emissions

MAgPIE provides results of non-CO_2 emissions (CH_4 and N_2O) from livestock, rice production and soil fertilization (see section 2.3). On a global scale, we find a small increase in non-CO_2 emissions with more trade. Total emissions amount to 328.3 Gt CO_2-equivalent emissions in the reference scenario, 329.7 Gt in the policy scenario and 331.3 Gt in the liberalisation scenario. Whereas the global amount of the single emission types does not differ largely, the regional distribution is very dynamic.

Figure 10 shows the regional disaggregation of total emissions displayed in CO_2-equivalent emissions. The main driver in terms of non-CO_2 emissions is the livestock system and the kind of livestock. Both are responsible for CH_4 and N_2O emissions from fermentation and animal waste management. In both cases, most changes occur in CPA, due to a large increase in livestock production and in AFR, where livestock production is decreased. In CPA emissions from fermentation and animal waste management increase by around 70% in the policy scenario and by around 150% in the liberalisation scenario compared to the reference scenario. At the same time emissions decrease in AFR by 26% in the policy and 53% in the liberalisation scenario. Furthermore, emissions decrease in FSU, LAM, MEA, NAM, PAS, and SAS.

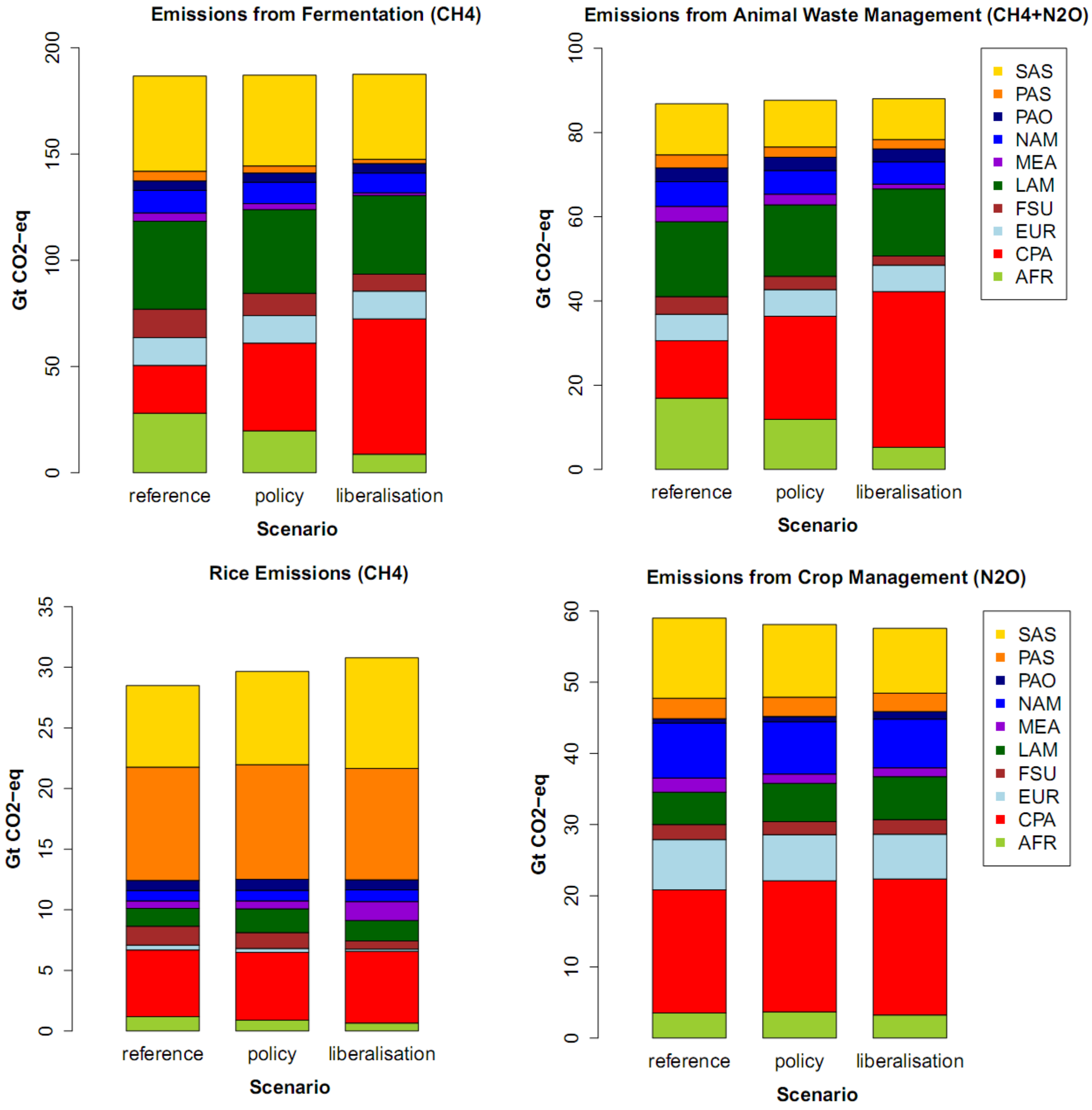

Figure 10: Non-CO_2 Emissions (in CO_2-equivalent) for the three trade scenarios (2005-2045)

Emissions from rice cultivation and crop management play a minor role on a global scale. Only in PAS rice emissions are the major sources, accounting for more than 50% of the emissions in this region. In general emissions from rice cultivation are mostly emitted in the Asian Regions (CPA, PAS, SAS). On a global level they increase continuously with more trade. On the regional level, emissions decrease slightly with more trade in almost all regions except of SAS and MEA, which are the main driver for the overall increase. In the case of N_2O emissions from crop management the global picture looks different, since CPA, EUR, FSU, NAM and SAS reduce emissions with more trade and CPA and LAM increase their emission level. On global level, the emissions decrease slightly.

Figure F.1 in appendix F shows the spatial distribution of non-CO_2 emissions for the three trade scenarios. In the reference scenario, most emissions occur in the Asian regions, especially in North-East China, North India, and the Pacific Islands (Malaysia and Indonesia. Russia, Australia, and Sub-Sahara Africa have the lowest emission levels. Under increased trade emissions increase slightly in South America and China and decrease slightly in USA and Pacific Asia.

3.6 Global Balance

Figure 11 shows the joint picture of environmental and economic impacts on a global scale. Economic benefits are represented by the saved costs of agricultural production due to increased trade (policy and liberalisation scenario). Environmental impacts are represented by additional GHG emissions (in CO_2 equivalent) due to increased trade. The values are aggregated over the ten world regions and over the whole time period (2005-2045).

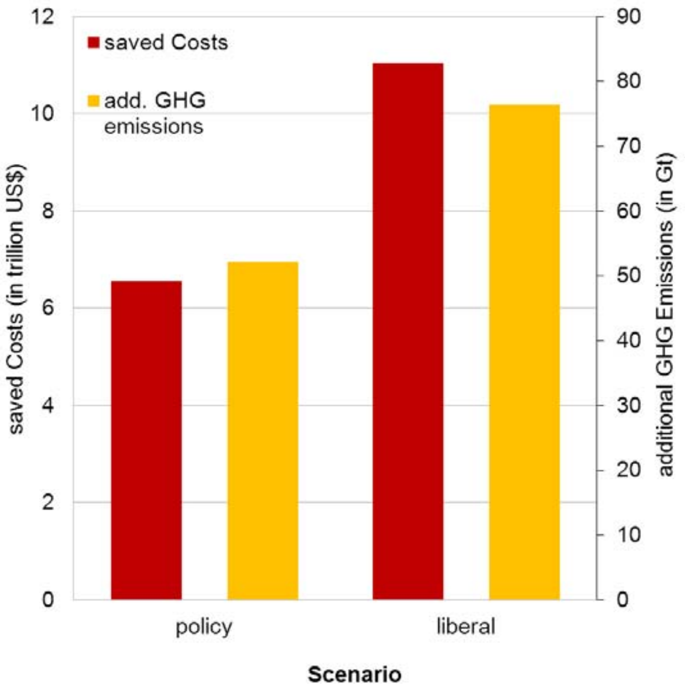

Figure 11: Global cost-savings (red bars) and additional GHG emissions (yellow bars) from the policy and the liberalisation scenario compared to the reference scenario over the period 2005 to 2045.

In the policy scenario 6.5 trillion US$ are saved in the agricultural production sector from 2005 to 2045 but at the same time 52 Gt of additional GHG emissions (in CO_2-equivalent) are emitted. This means for every saved US$ around 7.9 kg GHG emissions are produced. Comparing the liberalisation scenario with the reference scenario, around 11 trillion US$ are saved and around 76 Gt of additional GHG emissions are produced. This decreases the ratio to 6.9 kg CO_2-equivalent per saved US$ production costs.

3.7 Sensitivity Analysis

The results of the sensitivity analysis are summarized in Table 2. The differences in cropland vary between -7% and +3%. Increases in cropland are obtained in the scenarios with low yield elasticity of TC investments (*expensiveTC)* and with low intra-regional transport costs (*lowtrans*) and decreases in the other sensitivity tests. The same holds also in terms of total GHG emissions, although their changes are larger, ranging from -10% (*cheapTC liberal*) to +5% (*lowtrans liberal*). Total costs decrease in the *cheapTC* and *lowtrans* variant and increase in the *expensiveTC* (up to 9%) and *hightrans* (up to 16%) variant. If we set additional GHG emissions in perspective to saved costs between the reference scenario and the two liberalisation scenarios, we observe a variation between 1.3 and 8.9 kg CO_2-eq/US$.

model run		**Total Cropland** *(in million ha)*		**Total Emissions** *(in Gt CO_2-eq)*		**Total Costs** *(in trillion US$)*		**Add. GHG emissions per saved costs** *(kg CO_2-eq/US$)*
standard model	*reference*	1,950		533		100.7		-
	policy	2,105		585		94.1		7.9
	liberal	2,127		609		89.6		6.9
cheapTC	*reference*	1,930	-1%	527	-1%	95.3	-5%	-
	policy	1,947	-7%	533	-9%	90.7	-4%	1.3
	liberal	1,993	-6%	551	-10%	87.0	-3%	2.9
expensiveTC	*reference*	1,957	0%	536	1%	109.6	9%	-
	policy	2,162	3%	601	3%	98.6	5%	5.9
	liberal	2,187	3%	633	4%	92.2	3%	5.6
lowtrans	*reference*	1,973	1%	544	2%	92.9	-8%	-
	policy	2,149	2%	605	3%	86.0	-9%	8.9
	liberal	2,197	3%	638	5%	81.7	-9%	8.4
hightrans	*reference*	1,885	-3%	511	-4%	115.2	14%	-
	policy	2,015	-4%	551	-6%	109.1	16%	6.5
	liberal	2,021	-5%	560	-8%	104.3	16%	4.5

Table 2: Results of standard model version in comparison with sensitivity runs. Percentage numbers are the difference between sensitivity run and the respective run of the standard model version.

In addition, Table G.1 and G.2 in the appendix show the regional disaggregated results for land expansion and TC in the respective sensitivity runs. Most regions show changes of less than 10%. Exceptions are LAM, PAO, and PAS. LAM converts about 35% less land into cropland in the case of high yield elasticity (*cheapTC*) and about 20% less with high transport costs (*hightrans*). In PAO up to 80% additional land is converted in the other two sensitivity tests (*expensiveTC* and *lowtrans*). In PAS between 30 and 40% less land is converted with high transport costs and about 20% more land with low transport costs. Concerning TC rates we observe large increases with higher transport costs in LAM and lower TC rates with lower transport costs in PAO and PAS.

4. Discussion

The issue of agricultural trade and its impacts on climate change faces growing interest and importance, especially regarding international trade and climate negotiations (Tamiotti et al., 2009). This study presents a new approach to tackle this issue by using a spatially explicit global land use model that takes environmental as well as economic indicators into account.

In terms of economic impacts, model results show that further trade liberalisation leads to a shift in export shares in favour of regions with comparative advantages in agriculture. These regions benefit at the expense of highly protected regions. For cereals as well as oilcrops, North America and Europe export less if trade becomes more liberalised. This indicates how much both regions are currently affected by their protective agricultural policies (Gibson et al., 2001). The lower production level in 2045 is mainly due to a drop in technological change (TC) rates in these regions, whereas cropland for cereals and oilcrops is almost not affected. South Asia faces a sharp drop in TC rates. Due to scarce resources and a low comparative advantage, the region imports more and has a lower pressure to increase productivity. In contrast, China imports more due to its increasing demand but TC rates decrease only slightly. Australia, Sub-Saharan Africa, and Latin America are the regions, which take most of the export share from Europe and North America due to their comparative advantage in cereal production.

Overall, Latin America is the region which increases its exports most. In addition to more cereal exports, it will increase its share on the vegetable oil market under more trade liberalisation. The abundant land resource and increasing TC rates lead to a tremendous production increase. In the reference scenario cropland is already expanded from 175 mio ha. in 2005 to 353 mio. ha in 2045. In the policy scenario it increases to 525 mio. ha and in the liberalisation to 546 mio. ha. A similar trend is found by DeFries et al. (2010), who observe a strong correlation between trade activity and deforestation rates in Latin America.

On a global scale the results demonstrate that increased trade liberalisation will lead to lower global costs of food production. Model results show that around 6% (5.4 trillion US$) will be saved in the period of 2005 to 2045 by applying the policy scenario and 10 % (9.4 trillion US$) in the liberalisation scenario. Moreover, our model shows that trade liberalisation leads to a much slower increase in the food scarcity index. This is supported by Federico (2005), who showed that in the past increased trade contributed largely to a reduced pressure on food prices. Nonetheless, these model results do not reflect important policy considerations like food security or domestic socio-economic and environmental implications. In general, we implemented international trade barriers in a rather broad manner, without differentiating between specific measures, like quotas, subsidies, or tariffs. A detailed representation of trade policy is not done in our spatially explicit modelling framework since it would overstrain the model regarding computing capacity.

Regarding environmental impacts we focus on land use change and greenhouse gas emissions as the main indicators in this study. According to FAO 71 million hectares of land have been converted into cropland in the period of 1990-2000 and 225 mio. ha in the period of 1960-2000 (FAOSTAT, 2009). Our model results show that without further regulation of deforestation, future cropland expansion mainly takes place in ecologically sensitive areas of the tropical rainforest. In the reference scenario total cropland expansion (2005-2045) in the three main rainforest areas, the Amazonian rainforest (178 mio. ha), the Central African rainforest (137 mio. ha) and the rainforest on the Pacific islands (37 mio. ha) amounts to 410 mio. ha or 23% of the global cropland area in 2005. Under trade liberalisation this increases further by 175 mio. ha (*policy*) and 198 mio ha (*liberalisation*), mainly in the Amazonian rainforest. Similar results are found by van Meijl et al. (2006) and Eickhout et al. (2009), who show that trade liberalisation leads only to small land-use shifts in Europe but dramatic shifts in developing regions.

CO_2 emissions from tropical deforestation are an important contributor to climate change since tropical forest consists of around 50% more carbon per unit area than any other forest system and faces the highest deforestation rates (Houghton, 2003). At least 25% of all anthropogenic carbon emissions during the 1980s and 1990s origin from tropical deforestation (Malhi and Grace, 2000; Houghton, 2003) and currently they account for almost 20% of total GHG emissions (Grainger, 2008; Gumpenberger et al., 2010). In MAgPIE, the conversion of previous intact forest leads to 192 Gt CO_2 emissions in the period from 2005 to 2045. Additional trade in the future increases emissions from deforestation due to further expansion in Latin America (mainly Brazil). Total carbon emissions rise by 25 Gt CO_2 in the policy scenario and 46 Gt in the liberalisation scenario until 2050 compared to the reference scenario. For non-CO_2 emissions, total emissions amount to 328 Gt CO_2 in the reference scenario and only increase slightly on a global scale with more trade. In terms of regional distribution, China increases its emissions since livestock production shifts from Africa to China due to comparative advantages. Although domestic demand for livestock products rises considerably, China will dominate the export market for meat products under more liberalisation.

In general, our overall results on emissions, except for carbon emissions, in the reference scenario are similar to results of a comparable study of Verburg et al. (2009). They report average annual emissions for their baseline scenario between 2000 and 2005 of 0.8 billion tons for CO_2, 3 billion tons for CH_4 and 1.2 billion tons for N_2O. Our corresponding figures for 2005 are 5.9, 3.8, and 1.9, respectively. However, since they assume full liberalisation already by 2015 the timing of emissions differs considerably. Whereas in their study CO_2 emissions increase until 2015, but are reduced until 2030 and until 2050, in our case CO_2 emissions increase constantly but with lower rates towards the end. Therefore, especially in Latin America, land will be cleared much faster, if trade will already be liberalised by 2015. Regarding non-CO_2 emissions Verburg et al. (2009) report similar mixed results as in our study. Whereas CH_4 emissions increase under trade liberalisation by around 4-5% (mainly due to Brazil), N_2O emissions decrease slightly. In our study the increase in non-CO_2 emissions on a global level is moderate but a major reallocation between different regions takes place. Emissions in China increase due to the increase in livestock production, whereas Africa, Europe, and South/Pacific Asia decrease their emission levels from non-CO_2 sources. In Latin America, emissions increase only over time but not with more trade liberalisation.

Bringing environmental and economic aspects together, our result is that economic benefits are generated at the costs of the environment. If we just consider additional GHG emissions produced by increased trade (and ignore other local environmental damages), the damage amounts to 52 Gt of additional GHG emissions in the policy scenario and more than 76 Gt in the liberalisation scenario. The figures are mainly triggered by increased CO_2 emissions from deforestation in Latin America since non-CO_2 emissions do not change a lot on the global level. To be more certain about the results we have conducted a sensitivity analysis on two key parameters in this process. Although we have chosen extreme values for these parameters, the results of the sensitivity runs show only moderate changes. If the yield elasticity of TC investments is lower or intra-regional transport costs are reduced, cropland and GHG emissions are increased by up to 5% since TC investments are less beneficial and land expansion gets cheaper, respectively. The opposite happens in the other two sensitivity tests, in which cropland and GHG emissions are reduced between 1 and 10%. In general, we obtain that the model behaves moderately with respect to changes in technological change and land expansion costs.

From the generated benefits in both scenarios (cost-savings due to increased trade) the additional GHG emissions could be easily compensated. The current price of CO_2 is around 10-20 US$/t$CO_2$. Future projections about the CO_2 price are highly uncertain but are simulated to be in the range of 100 to 300 U$/t CO_2 (Durand-Lasserve et al, 2010). Our model simulation leads to an ability to pay of up to 126 U$/ t$CO_2$ in the policy scenario and 145 US$/ t$CO_2$ in the liberalisation scenario. However, both figures do not consider several aspects which would decrease the values. First, we ignore other, more local environmental damages generated through increased trade (e.g. loss of biodiversity or environmental services). Second, not all emissions are considered in our calculation. Our modelling approach does not include transport-related emissions which would lead to an increase under trade liberalisation (Hummels, 2009). The same holds for non-CO_2

emissions from chemical fertilizer and pesticide production, which are likely to increase under trade liberalisation as well (Secretariat of the Convention on Biological Diversity, 2005). Finally, the saved production costs do not include international transport costs and other trade related costs, which would reduce the amount of saved costs. On the other side, there are indirect effects which likely decrease the amount of environmental damage with higher income induced by more trade. A first positive effect might be improvements regarding lower emission technology induced by higher income and more international competitiveness (Lucas et al., 2007). However, an often claimed spillover effect of environmental efficiency from developed to developing countries can only be partly confirmed regarding CO_2 and SO_2-efficiency (Perkins and Neumayer, 2009). A second and more deeply studied effect is illustrated by the Environmental Kuznets Curve, which is a U-shaped curve showing the relationship between income and certain environmental measures (Grossman and Krueger, 1993). Grossman and Krueger (1993) were the first to show that trade liberalisation increases the average income level, which leads to the demand of more environmentally friendly goods. Many studies have confirmed this view for air pollution which has a local effect, like SO_2 or NOx (for an overview, see Dasgupta et al, 2002) but not for global emissions, like CO_2 due to the free-rider problem (Frankel and Rose, 2005; Chintrakarn and Millimet, 2006; Kellenberg, 2008). Only recently Frankel (2009) showed that at a very high income level CO_2 emissions might decrease as well.

5. Conclusion

Synthesizing economic and environmental indicators brings us to the conclusion that most of the saved economic costs of trade liberalisation are achieved at the expense of environment and climate. Latin America reaches its increasing export share by converting large parts of the Amazonian rainforest into cropland at low costs. China generates globally most of the non-CO_2 emissions due to rising livestock demand in the region.

As both, climate change mitigation and trade liberalisation, have to be negotiated on a global scale, a major objective for future negotiations should be to account for these environmental and climate externalities and impose the related costs on the produced goods. As Brewer (2010) points out, several interactions between both fields, like lower tariffs on climate-friendly goods or biofuel trade policies, are already in place. More collaboration is needed in order to reduce situations when countries gain from trade by damaging the environment. Since most of the regions where these costs occur are developing countries, compensation policies have to be developed or further improved. Our analysis shows that regions which gain from increased trade are able to pay a sufficient portion of their benefits to account for related environmental damages like deforestation and GHG emissions. An emerging compensation scheme is REDD (Reduced emissions from deforestation and forest degradation), where compensation to countries is paid, if they guarantee protection of the rainforest (Ebeling and Yasue, 2008; Miles and Kapos, 2008). Although REDD has space for improvement, WTO and climate negotiations should adopt similar set-ups in order to cope with negative environmental impacts.

Another important policy implication is the investment into technological change. Higher productivity will lower the pressure on converting further forest land into cropland. Although the need has increased, investments into agricultural Research and Development have slowed down in the past decades resulting in lower agricultural yield growth (Alston et al, 2009). As a consequence, governments are advised to invest more and early into climate and environmentally friendly technological change in order to reduce the pressure on land and the environment for future generations.

References

Alston, J.M., Beddow, J.M. and Pardey, P.G. (2009) Agricultural research, productivity, and food prices in the long run. Science 325 (5945), 1209.

Anderson, K. (1992) Agricultural Trade Liberalisation and the Environment: A Global Perspective. World Economy, 15, 153-171.

Anderson, K. and Tyers, R. (1993) More on welfare gains to developing countries from liberalising world food trade. Journal of Agricultural Economics 44: 189-204.

Anderson, K. (2010) Globalisation’s effects on world agricultural trade, 1960 to 2050. Discussion Paper No. 1011, Centre for International Economic Studies, April 2010.

Antweiler, W., Copeland, B.R. and Taylor, M.S. (2001) Is Free Trade Good for the Environment?. American Economic Review, 91, 877-908.

Baek, J., Cho, Y. and Koo, W. (2009) The environmental consequences of globalisation: A country-specific time-series analysis. Ecological Economics 68 (8-9): 2255-2264.

Brewer, T.L. (2010) Trade Policies and Climate Change policies: A Rapidly Expanding Joint Agenda. The World Economy 33 (6): 799-809.

Bouët, A., Bureau, J.-C., Decreux, Y. and Jean, S. (2005) Multilateral Agricultural Trade Liberalisation: The Contrasting Fortunes of Developing Countries in the Doha Round. The World Economy, 28: 1329–1354.

Chintrakarn, P. and Millimet, D. (2006) The Environmental Consequences of Trade: Evidence from Subnational Trade Flows. Journal of Environmental Economics and Management 52: 430-453.

CIESIN, IFPRI and WRI (2000) Gridded Population of the World (GPW), version 2. Center for International Earth Science Information Network (CIESIN) Columbia University, International Food Policy Research Institute (IFPRI) and World Resources Institute (WRI), Palisades, NY.

Conforti, P. and Salvatici, L. (2004) Agricultural trade liberalisation in the Doha round - Alternative scenarios and strategic interactions between developed and developing countries. FAO Commodity and Trade Policy Research Working Paper No. 10.

Cole, M.A. (2000) Trade Liberalisation, Economic Growth and the Environment. New Horizons in Environmental Economics, Cheltenham: Edward Elgar.

Cole, M.A. and Elliott, R.J.R. (2003) Determining the Trade-Environment Composition Effect: The Role of Capital, Labor and Environmental Regulations. Journal of Environmental Economics and Management 46 (3): 363-383.

Copeland, B.R. and Taylor, M.S. (1994), “North South Trade and the Environment”, Quarterly Journal of Economics, 109 755-787.

Corden, M. (1997), “Trade Policy and Economic Welfare”, Oxford University Press, 1997.

Cox, P.M., Betts R.A., Bunton, C.B., Essery, R.H., Rowntree, P.R. and Smith, J. (1999) The impact of new land surface physics on the GCM simulation of climate and climate sensitivity. Climate Dynamics 15:183-203.

Dasgupta, S., Laplante, B., Wang, H. and Wheeler, D. (2002) Confronting the Environmental Kuznets Curve. Journal of Economic Perspectives 16 (1): 147-168.

DeFries, R., Rudel, T., Uriarte, M. and Hansen, M. (2010) Deforestation driven by urban population growth and agricultural trade in the twenty-first century. Nature Geoscience (3): 178-181.

Dietrich, J.P., Schmitz, C., Müller, C., Fader, M., Lotze-Campen, H., Popp, A. (2010) Measuring agricultural land-use intensity. Under revision for Ecological Modelling.

Dollar, D. and Kraay, A. (2004) Trade, Growth and Poverty. The Economic Journal 114 (February): 22-49.

Döll, P. and Siebert, S. (2000) A digital global map of irrigated areas. ICID Journal 49 (2): 55-66.

Durand-Lasserve, O., Pierru, A. and Smeers, Y. (2010) Uncertain long-run emissions targets, CO_2 price and global energy transition: A general equilibrium approach Energy Policy 38 (9): 5108-5122.

Ebeling, J. and Yasue, M. (2008) Generating carbon finance through avoided deforestation and its potential to create climatic, conservation and human development benefits. Philosophical Transactions of the Royal Society B: Biological Sciences 363, 1917–1924.

Eickhout, B., van Meijl, H., Tabeau, A. and Stehfest, E. (2009) The impact of environmental and climate constraints on global food supply. In: T.W. Hertel, S.K. Rose and R.S.J. Tol, Editors, Economic Analysis of Land Use in Global Climate Change Policy, Routledge, New York, 2009.

Fader, M., Rost, S., Müller, C., Bondeau, A. and Gerten, D. (2010) Virtual water content of temperate cereals and maize: Present and potential future patterns. Journal of Hydrology 384 (3-4), 218-231.

FAOSTAT (2009) Food & Agriculture Organization of the United Nations Statistics Division. URL: http://faostat.fao.org/, accessed 11.06.2009.

FAOSTAT (2010) Food & Agriculture Organization of the United Nations Statistics Division. URL: http://faostat.fao.org/, accessed 15.11.2010.

Federico, G. (2005) Feeding the world: an economic history of agriculture, 1800-2000. Princeton University Press, 2005.

Frankel, J. and Rose, A. (2005) Is Trade Good or Bad for the Environment? Sorting Out the Causality. Review of Economics and Statistics 87 (1) : 85-91.

Frankel, J. (2009) Environmental Effects of International Trade. Harvard Kennedy School Faculty Research Working Paper RWP09-006, January 2009.

Gerten, D., Schaphoff, S., Haberlandt, U., Lucht, W. and Sitch, S. (2004) Terrestrial vegetation and water balance - hydrological evaluation of a dynamic global vegetation model. Journal of Hydrology, 286(1-4): 249-270.

Gibson, P., Wainio, D., Whitley, D. and Bohman, M. (2001) Profiles of Tariffs in Global Agricultural Markets. ERS, USDA, Agricultural Economic Report No. 796.

Grainger, A. (2008) Difficulties in tracking the long-term global trend in tropical forest areas. Proceedings of the National Academy of Sciences 105, 818-823.

Grossman, G.M. and Krueger, A.B. (1993) Environmental Impacts of a North American Free Trade Agreement. In Garber, PM (ed.), The US-Mexico Free Trade Agreement, MIT Press, Cambridge, MA, pp. 13-56.

Gumpenberger, M., Vohland, K., Heyder, U., Poulter, B., Macey, K., Rammig, A., Popp, A. and Cramer, W. (2010) Predicting pan-tropical climate change induced forest stock gains and losses – implications for REDD. Environmental Research Letters 5: 014013.

Hertel, T.W., Keeney, R., Ivanic, M. and Winters, L.A. (2009) Why isn’t the Doha Development Agenda more poverty friendly?. Review of Development Economics 13 (4): 543-559.

Healy, S., Pearce, R. and Stockbridge, M. (1998) The implications of the Uruguay Round Agreement on Agriculture for developing countries. Trainings Material for Agricultural Planning, Food and Agriculture Organization (FAO), Rome.

Houghton, R.A. (2003) Revised estimates of the annual net flux of carbon to the atmosphere from changes in land use and land management 1850–2000. Tellus B 55, 2, 378–390.

Hummels, D. (2007) Transportation Costs and International Trade in the Second Era of Globalization. Journal of Economic Perspectives 21 (3): 131-154.

Hummels, D. (2009) How Further Trade Liberalisation would Change Grennhouse Gas Emissions from International Freight Transport. NBER Working Paper, Prepared for “Global Forum on Trade and Climate Change, June 2009 OECD.

IPCC (1996) Volume 2: Workboook, Chapter 4: Agriculture. In: Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories, Prepared by the National Greenhouse Gas Inventories Programme, Kroeze C., Mosier A., Ehhalt D.H., (eds). Published: IGES, Japan.

IPCC (2006) 2006 IPCC Guidelines for National Greenhouse Gas Inventories. Prepared by the National Greenhouse Gas Inventories Programme, Eggleston H.S., Buendia L., Miwa K., Ngara T. and Tanabe K. (eds). Published: IGES, Japan.

IPCC (2007) Climate Change 2007: Mitigation of Climate Change. In: Metz B, Davidson OR, Bosch PR, Dave R and Meyer LA (eds.), Contribution of Working Group III to the Fourth Assessment Report of the IPCC. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Josling, T., Anderson, K., Schmitz, A. and Tangermann, S. (2010) Understanding International Trade in Agricultural Products: One hundred years of contributions by agricultural economists. American Journal of Agricultural Economics 92 (2): 424-446.

Kellenberg, D. (2008) A re-examination of the role of income for the trade and environment debate. Ecological Economics 68 (1-2): 106-115.

Krause, M., Lotze-Campen, H. and Popp, A. (2009) Spatially-explicit scenarios on global cropland expansion and available forest land in an integrated modelling framework. Selected and reviewed paper at the 27th International Association of Agricultural Economists Conference in Beijing, China, August 16-22, 2009.

Lopez, R. (1994) The Environment as a Factor of Production: The Effects of Economic Growth and Trade Liberalisation. Journal of Environmental Economics and Management, 27, 163-184.

Lotze-Campen, H., Müller, C., Bondeau, A., Jachner, A., Popp, A. and Lucht, W. (2008) Food demand, productivity growth and the spatial distribution of land and water use: a global modeling approach. Agricultural Economics 39, 325-338.

Lotze-Campen, H., Popp, A., Beringer, T., Müller, C., Bondeau, A., Rost, S. and Lucht, W. (2010) Scenarios of global bioenergy production: The trade-offs between agricultural expansion, intensification and trade. Ecological Modelling 221: 2188-2196.

Lucas, P.L., van Vuuren, D.P., Olivier, J.G. and den Elzen, M.G. (2007) Long-term reduction potential of non-CO2 greenhouse gases. Environmental Science and Policy 10: 85-103.

Malhi, Y. and Grace, J. (2000) Tropical forests and atmospheric carbon dioxide. Trends Ecological Evolution 15: 332-337.

Managi, S. (2004) Trade Liberalisation and the Environment: Carbon Dioxide for 1960-1999. Economics Bulletin 17 (1): 1-5.

Martin, W. and Winters, L.A. (eds.) (1996) The Uruguay Round and the Developing Countries. Cambridge University Press.

Miles, L. and Kapos, V. (2008) Reducing greenhouse gas emissions from deforestation and forest degradation: global land-use implications. Science 320, 1454–1455.

Nakicenovic, N., and Swart, R. (eds.) (2000) Special Report on Emisson Scenarios, pp. 1-599. Cambridge University Press, Cambrige, UK.

Narayanan, B. and Walmsley, T.L. (2008) Global Trade, Assistance, and Production: The GTAP 7 Data Base. Center for Global Trade Analysis, Purdue University.

Nelson, A. (2008) Estimated travel time to the nearest city of 50,000 or more people in year 2000. Global Environment Monitoring Unit - Joint Research Centre of the European Commission, Ispra Italy. URL: http://bioval.jrc.ec.europa.eu/products/gam/ (accessed 30/07/2011).

Nelson, G.C., Rosegrant, M.W., Koo, J., Robertson, R., Sulser, T., Zhu, T., Ringler, C., Msangi, S., Palazzo, A., Batka, M., Magalhaes, M., Valmonte-Santos, R., Ewing, M., Lee, D., 2009. Climate change - impact on agriculture and costs of adaptation. International Food Policy Research Institute (IFPRI) Food Policy Report 21.

Pardey, P.G., Beintema, N., Dehmer, S. and Wood, S. (2006) Agricultural Research a Growing Global Divide?. Agricultural Science and Technology Indicators Initiative (ASTI): International Food Policy Research Institute (IFPRI), Food Policy Report.

Perkins, R. and Neumayer, E. (2009) Transnational linkages an the spillover of environment-efficiency into developing countries. Global Environmental Change 19: 375-383.

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

Popp, A., Lotze-Campen, H., Leimbach, M., Knopf, B., Beringer, T., Bauer, N. and Bodirsky, B. (2011a) On sustainability of bio-energy production: integrating co-emissions from agricultural intensification. Biomass & Bioenergy (online available), doi:10.1016/j.biombioe.2010.06.014.

Popp, A., Dietrich, J.P., Lotze-Campen H., Klein, D., Bauer, N., Krause, M., Beringer, T., Gerten, D., Edenhofer, O. (2011b) The economic potential of bioenergy for climate change mitigation with special attention given to implications for the land system. Environmental Research Letters (in press).

Portmann, F., Siebert, S. and Döll, P. (2010) MIRCA2000—Global monthly irrigated and rainfed crop areas around the year 2000: A new high-resolution data set for agricultural and hydrological modelling. Global Biogeochemical Cycles 24, GB1011.

Rost, S., Gerten, D., Bondeau, A., Lucht, W., Rohwer, J. and Schaphoff, S. (2008) Agricultural green and blue water consumption and its influence on the global water system. Water Resources Research 44, W09405.

Schmitz, C., Dietrich, J.P., Lotze-Campen, H., Müller, C. and Popp, A. (2010) Implementing endogenous technological change in a global land-use model. Paper presented at GTAP 13th Annual Conference in Penang (Malaysia), June 9-11 2010, Available at URL: www.gtap.agecon.purdue.edu/resources/download/5584.pdf.

Secretariat of the Convention on Biological Diversity (2005) The impact of trade liberalisation of Agricultural Biological Diversity - Domestic support measures and their effects on agricultural biological diversity. Montreal, SCBD, CBD Technical Series no. 16.

Sohngen, B., Tennity, C. and Hnytka, M., 2009 Global forestry data for the economic modeling of land use. In: Hertel, T.W.; Rose, S.; Tol, R.S.J. (Eds.), Economic analysis of and use in global climate change policy, Routledge, New York. pp 49- 71.

Tamiotti, L., Olhoff, A., The, R., Simmons, B., Kulacoglu, V. and Abaza, H. (2009) Trade and Climate Change. WTO-UNEP Report by the United Nations Environment Programme and the World Trade Organization, Switzerland, 2009.

van Meijl, H., van Rheenen, T., Tabeau, A. and Eickhout, B. (2006) The impact of different policy environments on agricultural land use in Europe. Agriculture, Ecosystems and Environment 114 (2006): 21-38.

van Vuuren, D.P., Isaac, M., Kundzewicz, Z.W., Arnell, N., Barker, T., Criqui, P., Bauer, N., Berkhout, F., Hilderink, H., Hinkel, J., Hochrainer, S., Hof, A., Kitous, A., Kram, T., Mechler, R., and Scrieciu, S. (2009) Scenarios as the Basis for Assessment of Mitigation and Adaptation. In Hulme, M., H. Neufeldt, eds., Making climate change work for us – ADAM synthesis book. Cambridge University Press.

Verburg, R., Stehfest, E., Woltjer, G. and Eickhout, B. (2009) The effect of agricultural trade liberalisation on land-use related greenhouse gas emissions. Global Environmental Change 19, 434-446.

Weindl, I., Lotze-Campen, H., Popp, A., Bodirsky, B. and Rolinski, S. (2010) Impacts of livestock feeding technologies on greenhouse gas emissions. Contributed paper at the IATRC Public Trade Policy Research and Analysis Symposium. “Climate Change in World Agriculture: Mitigation, Adaptation, Trade and Food Security”, Universität Hohenheim, Stuttgart, Germany, June 27-29, 2010.

Wirsenius, S. (2000) Human Use of Land and Organic Materials - Modeling the Turnover of Biomass in the Global Food System. Chalmers University, Göteborg, Sweden.

World Bank (2001) World development indicators (CD-ROM). Washington, DC.

World Bank (2011) World Development Indicators Online (WDI) database. Data retrieved February 25, 2011, Washington, DC.

Appendix

Appendix A: Projected Demand for important crop groups

I. Cereals

year	AFR	CPA	EUR	FSU	LAM	MEA	NAM	PAO	PAS	SAS
2005	128	535	279	128	188	139	248	52	156	322
2015	180	665	302	145	253	180	278	58	196	397
2025	239	795	321	154	322	222	305	64	239	476
2035	300	915	335	155	380	260	328	70	288	550
2045	360	1036	340	155	422	291	347	74	338	622

II. Oilcrops

year	AFR	CPA	EUR	FSU	LAM	MEA	NAM	PAO	PAS	SAS
2005	23	53	29	5	33	13	48	8	24	29
2015	31	63	31	6	40	17	55	9	31	34
2025	40	73	33	6	47	20	63	9	39	39
2035	50	82	34	7	54	24	70	10	49	44
2045	61	91	35	7	61	27	77	10	59	48

III. Starch Plants

year	AFR	CPA	EUR	FSU	LAM	MEA	NAM	PAO	PAS	SAS
2005	65	65	25	12	19	3	7	2	12	9
2015	85	78	27	13	24	4	8	2	16	12
2025	109	88	29	13	28	5	10	3	20	14
2035	134	94	30	13	31	6	12	3	24	16
2045	159	95	31	12	33	6	14	3	29	19

IV. Sugar crops

year	AFR	CPA	EUR	FSU	LAM	MEA	NAM	PAO	PAS	SAS
2005	22	34	40	20	128	26	50	9	32	97
2015	28	37	42	21	152	31	54	9	37	112
2025	36	40	44	21	176	37	59	10	42	126
2035	43	40	45	21	198	42	63	10	46	136
2045	50	40	45	20	219	47	67	10	50	145

V. Meat

year	AFR	CPA	EUR	FSU	LAM	MEA	NAM	PAO	PAS	SAS
2005	5	34	22	6	15	4	18	4	5	5
2015	6	44	24	8	20	5	21	4	7	8
2025	9	53	26	10	24	7	23	5	9	11
2035	12	61	27	10	28	8	26	5	11	13
2045	16	67	28	12	33	10	29	5	14	16

Table A.1: Demand for cereals (I), oilcrops (II), starch plants (III), sugar crops (IV) and meat (V) for the ten world regions from 2005 to 2045 (in mio t.)

Appendix B: Self Sufficiency Ratios

Table B.1 and Table B.2 show the self sufficiency ratios p^{sf} for all regions and crop types obtained from the FAO database. The self sufficiency rates of heavily traded goods like cereals or oilseeds vary to a large extent among the regions. In contrast, crops like potato or cassava are mainly produced for domestic consumption and traded less. [11]

region	tece	maize	trce	rice	soybean	rapeseed	groundn.	sunfl.
AFR	0.47	0.97	0.99	0.64	0.35	0.06	1.10	0.68
CPA	0.90	1.00	1.02	1.04	0.60	0.86	1.08	0.97
EUR	1.12	0.90	0.93	0.59	0.10	1.51	0.06	0.91
FSU	0.81	0.58	0.87	0.72	0.38	1.00	0.17	1.26
LAM	0.70	0.93	0.78	0.94	1.87	0.07	1.92	2.14
MEA	0.58	2.00	0.67	0.68	0.03	0.05	0.91	0.08
NAM	1.78	1.40	1.47	1.57	1.69	2.14	1.26	2.17
PAO	1.42	0.03	0.43	1.10	0.03	0.23	0.25	0.66
PAS	0.06	0.55	0.54	1.06	0.47	0.06	0.78	0.00
SAS	0.95	1.01	1.00	1.04	0.61	0.97	1.04	0.80

Table B.1: Self Sufficiency rates for the ten world regions in 1995 (FAOSTAT, 2010) (I)

region	oilpalm	pulses	potato	cassava	scane	sbeet	cotton	others
AFR	0.96	0.96	0.98	1.00	8	1	1.09	1.06
CPA	0.15	1.23	1.02	0.99	0.88	0.89	0.98	1.01
EUR	0.00	0.85	1.01	0.01	0	1.38	0.92	0.91
FSU	0.00	1.07	0.99	0	0.00	0.75	1.02	0.88
LAM	0.86	0.97	0.96	1.01	1.38	1.40	1.05	1.36
MEA	0.00	0.78	1.00	0.89	0.29	0.49	0.53	0.99
NAM	0.00	1.99	1.07	0.68	0.20	0.95	1.26	0.84
PAO	0.00	1.89	0.88	0.71	1.32	1.32	0.87	0.78
PAS	3.36	0.78	0.82	1.71	1.13	1.00	0.44	1.17
SAS	0.00	0.98	1.00	1.01	1.06	1.06	1.05	1.01

Table B.2: Self Sufficiency rates for the ten world regions in 1995 (FAOSTAT, 2010) (II)

---

[11] Abbreviations for crop types: tece = temperate cereals, trce = tropical cereals, groundn = groundnuts, sunfl = sunflower, scane = sugar cane, sbeet = sugar beet

Appendix C: Export Shares

Table C.1 and Table C.2 show the export share for the ten world regions and all crops in MAgPIE obtained from FAO data for the year 1995 (FAOSTAT, 2010).

region	tece	maize	trce	rice	soybean	rapeseed	groundn.	sunfl.	oilpalm	pulses	potato
AFR	-	-	-	-	-	-	0.23	-	-	-	-
CPA	-	0.01	0.03	0.34	-	-	0.33	-	-	0.23	0.34
EUR	0.30	-	-	-	-	0.47	-	-	-	-	0.16
FSU	-	-	-	-	-	-	-	0.22	-	0.07	-
LAM	-	-	-	-	0.41	-	0.17	0.57	-	-	-
MEA	-	-	-	-	-	-	-	-	-	-	-
NAM	0.61	0.99	0.96	0.12	0.59	0.53	0.15	0.21	-	0.43	0.50
PAO	0.09	-	-	0.06	-	-	-	-	-	0.27	-
PAS	-	-	-	0.23	-	-	-	-	1	-	-
SAS	-	-	0.01	0.25	-	-	0.12	-	-	-	-

Table C.1: Export shares for the ten world regions in 1995 (FAOSTAT, 2010) (I)

region	cassava	sugarc.	sugarb.	others	cotton	ruminant	pig	chicken	egg	milk
AFR	0.03	-	-	0.08	0.07	0.12	0.01	0.02	0.02	0.07
CPA	-	-	-	0.04	-	0.33	0.65	0.21	0.53	0.09
EUR	-	-	0.96	-	-	-	0.14	0.13	0.06	0.17
FSU	-	-	-	-	0.03	-	-	0	0.02	-
LAM	0.02	0.79	0.02	0.60	0.05	0.23	0.03	0.25	0.10	0.07
MEA	-	-	-	-	-	-	-	0.05	0.04	0.01
NAM	-	-	-	-	0.68	0.08	0.11	0.24	0.08	0.05
PAO	-	0.05	0.02	-	-	0.16	-	-	-	0.19
PAS	0.95	0.07	-	0.25	-	-	0.05	0.05	0.06	-
SAS	-	0.09	-	0.03	0.17	0.08	0.01	0.05	0.09	0.35

Table C.2: Export shares for the ten world regions in 1995 (FAOSTAT, 2010) (II)

Appendix D: Validation of Technological Change Rates projected by MAgPIE

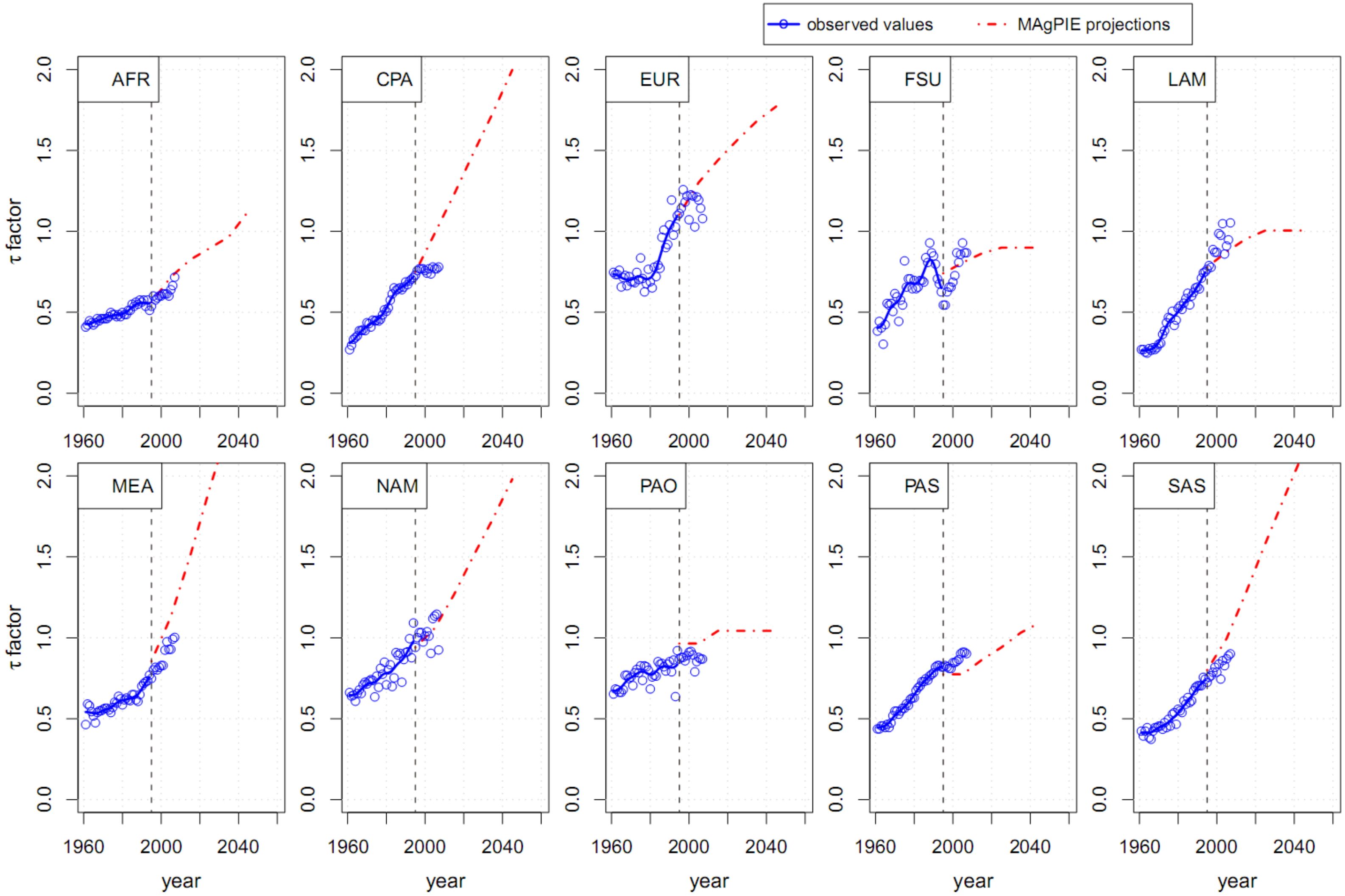

Figure D.1: Validation of MAgPIE technological change projections for the ten world regions from 1995-2060 (red chain line) with FAO observations 1960-2005 (blue dots) and its running mean (blue line) (FAOSTAT, 2009). MAgPIE projections are taken from the reference scenario with constant trade shares.

Appendix E: Net Export Rates for sugar, vegetables and meat

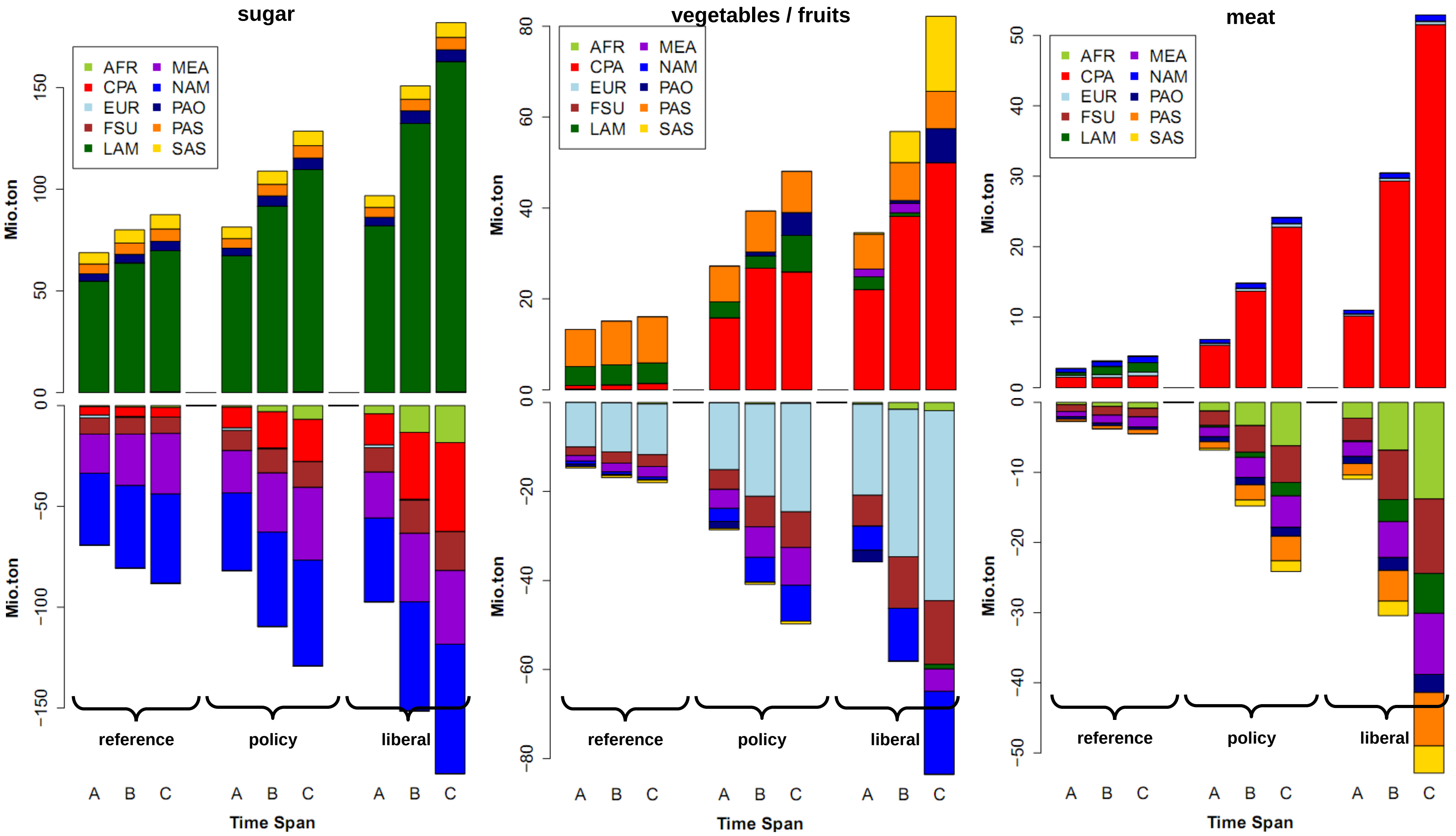

Figure E.1: Net export quantities of sugar, vegetable/fruits and meat (ruminant and non-ruminant) for ten world regions in three trade scenarios and for three time spans (A = 2005-2020; B= 2020-2035; C= 2035-2050)

Appendix F: Mapping of non-CO_2 emissions

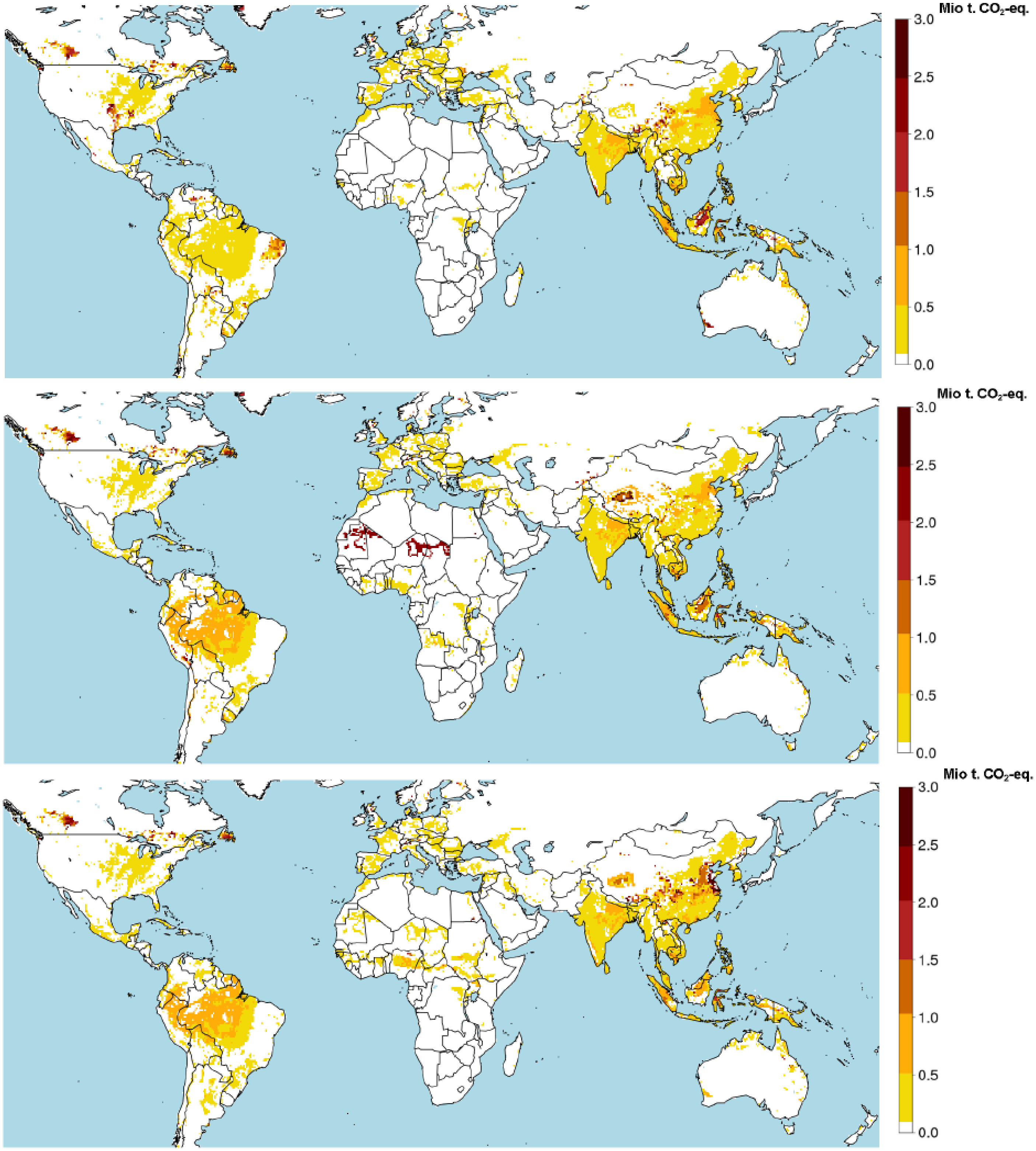

Figure F.1: Mapping of annual Non-CO_2 Emissions (average over 2005-2050) for the three trade scenarios

Appendix G: Sensitivity Analysis

region	**Paper version**			**cheapTC**			**expensiveTC**			**lowtrans**			**hightrans**		
	refer	*pol*	*lib*	*refer*	*pol*	*lib*	*refer*	*pol*	*lib*	*refer*	*pol*	*lib*	*refer*	*pol*	*lib*
AFR	157,0	157,0	157,0	0%	0%	0%	0%	0%	0%	1%	1%	1%	0%	0%	0%
CPA	6,2	6,2	6,2	0%	0%	0%	0%	0%	0%	0%	0%	0%	-4%	-4%	-4%
EUR	0,0	0,0	0,0	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
FSU	5,1	3,9	4,0	0%	-100%	-100%	0%	1%	29%	0%	-100%	-1%	-1%	29%	28%
LAM	215,1	387,2	407,8	-5%	-37%	-30%	2%	5%	3%	5%	5%	6%	-19%	-19%	-19%
MEA	2,5	2,5	2,5	0%	0%	0%	0%	0%	0%	45%	45%	45%	-1%	-1%	-1%
NAM	40,3	40,3	40,3	0%	0%	0%	0%	0%	0%	-2%	-2%	-2%	3%	3%	3%
PAO	62,4	43,0	43,2	-5%	-4%	-4%	3%	78%	78%	1%	30%	71%	-14%	-4%	-15%
PAS	59,9	62,7	63,9	-9%	-12%	-8%	5%	5%	18%	18%	21%	24%	-28%	-29%	-38%
SAS	13,2	13,2	13,2	0%	0%	0%	0%	0%	0%	-2%	-2%	-2%	10%	10%	10%

Table G.1: Land Expansion from 2005 to 2045 in different world regions in the paper and percental differences for the different sensitivity tests

region	**Paper version**			**cheapTC**			**expensiveTC**			**lowtrans**			**hightrans**		
	refer	*pol*	*lib*	*refer*	*pol*	*lib*	*refer*	*pol*	*lib*	*refer*	*pol*	*lib*	*refer*	*pol*	*lib*
AFR	1,4%	1,3%	1,3%	0%	5%	-2%	0%	-1%	2%	0%	-5%	-2%	1%	9%	5%
CPA	2,0%	1,9%	1,8%	1%	13%	20%	0%	-9%	-12%	0%	-3%	-4%	1%	3%	5%
EUR	1,0%	0,7%	0,6%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
FSU	0,4%	0,0%	0,0%	-3%	0%	0%	3%	0%	0%	-3%	0%	0%	0%	0%	0%
LAM	0,5%	0,6%	0,7%	8%	16%	-3%	-2%	-5%	3%	-10%	-6%	-10%	43%	31%	22%
MEA	2,2%	1,0%	0,5%	0%	1%	-6%	0%	-6%	-2%	0%	-2%	-10%	0%	4%	54%
NAM	1,5%	1,4%	1,2%	1%	1%	-1%	0%	1%	-1%	0%	0%	-2%	1%	1%	0%
PAO	0,2%	0,2%	0,2%	25%	0%	-33%	-19%	-5%	8%	-31%	-11%	-21%	75%	21%	0%
PAS	0,7%	0,7%	0,7%	12%	10%	-6%	-6%	-1%	4%	-20%	-18%	-18%	39%	4%	1%
SAS	2,0%	1,6%	1,1%	0%	0%	6%	0%	0%	-8%	0%	0%	-6%	0%	0%	6%

Table G.2: Annual Technological Change Rates from 2005 to 2045 (average) in different world regions in the paper and percental differences for the different sensitivity tests

Appendix H: MAgPIE mathematical description

MAgPIE (Model of Agricultural Production and its Impact on the Environment) is a nonlinear recursive dynamic optimization model that links regional economic information with grid-based biophysical constraints simulated by the dynamic vegetation model LPJmL. A simulation run with the simulation period T can be described as a set

$$X = \{x_t \mid t \in T\} \subseteq \Omega$$

of solutions of a time depending minimization problem, i.e. for every timestep $t \in T$ the following constraint is fulfilled

$$\forall y \in \Omega : g_t(x_t) \leq g_t(y)$$

where the goal function for $t \in T$

$$g_t(x_t) = g(t x_t x_{(t-1)} \ldots x_1 P_t)$$

depends on the solutions of the previous time steps $x_{(t-1)} \ldots x_1$ and a set of time depending parameters P_t. We may interprete a MAgPIE simulation run $X = \{x_t \mid t \in T\} \subseteq \Omega$ as an element of the vector space $\Omega_T = \Omega \times T$.

Sets

The dimension of the domain Ω_T depends on the following sets:

- $T = \{\text{time steps } t\}$: Simulation time steps, where $t$denotes the current time step, $t-1$ the previous time step and so on. The first simulated time step is $t = 1$.
- $I = \{\text{world regions } i\}$: Economic world regions in MAgPIE.
- $J = \{\text{spatial clusters } j\}$: Highest spatial disaggregation level in MAgPIE.
- $K = \{\text{simulated products } k\}$: Union of vegetal products $V$and livestock products L ($K = V \cup L$).
- $L = \{\text{simulated livestock products } l\}$: Products simulated within the livestock sector of MAgPIE.
- $V = \{\text{vegetal products } v\}$: Products simulated within the crop sector of MAgPIE.
- $W = \{\text{water supply types } w\}$: Currently two types are implemented: rainfed 'rf' and irrigated 'ir'
- $C = \{\text{crop rotation groups } c\}$: Groups of crops, which have similar requirements concerning crop rotation criteria.

To highlight the substance of our model equations with regard to the agricultural and economic contents, we split our variable $x_t$into

$$x_t = \left(x_t^{area} \in \Omega^{area} x_t^{prod} \in \Omega^{prod} x_t^{tc} \in \Omega^{tc}\right) \in \Omega$$

where the respective domains can be identified as the following vector spaces

$$\Omega^{area} = \mathbb{R}^{|J|} \times \mathbb{R}^{|V|} \times \mathbb{R}^{|W|}$$

$$\Omega^{prod} = \mathbb{R}^{|J|} \times \mathbb{R}^{|L|}$$

$$\Omega^{tc} = \mathbb{R}^{|I|}$$

As a result, we may specify the dimension of the solution space for each time step as $dim\Omega = |J| \cdot |V| \cdot |W| + |J| \cdot |L| + |I|$ and the dimension of $\Omega_T = \Omega \times T$ as $dim\Omega_T = |T| \cdot dim\Omega = |T| \cdot (|J| \cdot |V| \cdot |W| + |J| \cdot |L| + |I|)$.

In the following, variables and parameters are provided with subscripts to indicate the dimension of the respective sub domains. Subscripts written in quotes are single elements of a set. The order of subscripts in the variable, parameter and function definitions does not change. The names of variables and parameters are written as superscript.

Variables

Since MAgPIE is a recursive dynamic optimization model, all variables refer to a certain time step $t \in T$. In each optimization step, only the variables belonging to the current time step are free variables. For all previous time steps, values were fixed in earlier optimization steps. As we have seen above, we currently distinguish three variables $x_t^{area} \in \Omega^{area}$, $x_t^{prod} \in \Omega^{prod}$and $x_t^{tc} \in \Omega^{tc}$that can be described as follows:

- x_{tjvw}^{area}: The total area of each vegetal production activity $v$for each water supply type w, each cluster $j$and each time step t[ha]
- x_{tjl}^{prod} : The total production of each livestock product l, for each cluster $j$at each time step t[ton dry matter]
- x_{ti}^{tc}: The amount of yield growth triggered by investments in R&D [-]

Parameters

Besides variables, the model is fed with a set of parameters P_t. These parameters are computed exogenously and are in contrast to variables of previous time steps fully independent of any simulation output. Although most parameters are time independent, there exist also some parameters which are time dependent.

- p_{tjvw}^{yield}: Yield potentials for each time step, each cluster, each crop and each water supply type taking only biophysical variations into account and excluding changes due to technological change [ton/ha]
- p_{tik}^{dem} : Regional food and material demand in each time step for each product [10^6 ton]
- p_{ilk}^{fbask} : Feed basket parameter describing the share of each product $k$in the feed basket related to livestock product $l$and corresponding transformation from GJ feed in ton dry matter [ton/GJ]
- p_{il}^{feed} : Feed requirements for each livestock product $l$in each region i[GJ/ton]
- p_{ikl}^{byprod} : Feed energy delivered by the byproducts of $k$that are avaiable as feedstock for the livestock product l[GJ/ton]

- p_{iv}^{frv} : Area related factor requirements for each crop and each region based on the technological development level in the initial time step [US$/ha]
- p_{il}^{frl} : Production related factor requirements for livestock products for each livestock type and each region [US$/ton]
- p_{i}^{lcc}: Area related land conversion costs for each region [US$/ha]
- p^{tcc}: Technological change cost factor accounting for interest rate, expected lifetime and general costs [US$/ha]
- $p_{iv}^{\tau 1}$: τ-Factor representing the agricultural land use intensity in the first simulation time step for each crop in each region [-]
- p^{cxp}: Correlation Exponent between τ-Factor and technological change costs [-]
- p_{iv}^{seed}: Share of production that is used as seed for the next period calculated for each crop in each region [-]
- p_{tik}^{xs}: Regional excess supply for each product and each time step describing the amount produced for export [10^6 ton]
- p_{ik}^{sf}: Regional self sufficiencies for each product [-]
- p^{tb}: Trade balance reduction factor with $0 \leq p^{tb} \leq 1$which is used to relax the trade balance constraints depending on the particular trade scenario.
- p_{j}^{land}: Total amount of land available for crop production in each cluster [10^6 ha]
- $p_{j}^{ir.land}$: Total amount of land equipped for irrigation in each cluster [10^6 ha]
- p_{jk}^{watreq}: Cluster-specific water requirements for each product [$m^3/ton/a$]
- p_{j}^{water}: Amount of water available for irrigation in each cluster [$m^3/ton/a$]
- p_{c}^{rmax}: Maximum share of crop groups in relation to total agricultural area [-]
- p_{c}^{rmin}: Minimum share of crop groups in relation to total agricultural area [-]

[all ton units are in dry matter]

Sub-Functions

To simplify the general model structure, some model components which appear more than once in the model description and depend on the variables of the current time step t are arranged as functions:

$$f_{ti}^{growth}(x_t) = \prod_{\tau=1}^{t} (1 + x^{tc})$$

$$f_{tik}^{prod}(x_t) = \sum_{j_i} \begin{cases} x_{tjk}^{prod} & : k \in L \\ \sum_w x_{tjkw}^{area} p_{tjkw}^{yield} f_{ti}^{growth}(x_t) & : k \in V \end{cases}$$

$$f_{tik}^{dem}(x_t) = p_{tik}^{dem} + \sum_{l} p_{ilk}^{fbask} \left(p_{il}^{feed} f_{til}^{prod}(x_t) - \sum_{\kappa} p_{i}^{byprod} f_{ti\kappa}^{prod}(x_t) \right)$$

f_{ti}^{growth}: Growth function describing the aggregated yield amplification due to technological change compared to the level in the starting year for each year $t$and region i .

f_{tik}^{prod}: Function representing the total regional production of a product $k$in region $i$at timestep t. In the case of vegetal products, it is derived by multiplying the current yield level with the total area used to produce this product. In the case of livestock products, it is represented by the related production variable.

f_{tik}^{dem}: Function defining the demand for product $k$in region $i$at timestep t. It consists of an exogenous demand for food and materials $p_{tik}^{dem}$and an endogenous demand for feed, which is calculated as the feed demand generated by the livestock production minus the feed supply gained through byproducts.

Goal Function

$$g_t(x_t) = g(tx_t x_{(t-1)} ... x_1 P_t)$$

The goal function describes the value that is minimized in our recursive dynamic optimization model structure in each timestep. It is time dependent, i.e. it differs for each time step, depending on the solutions of the previous time steps. We define the goal function as follows:

$$\begin{aligned} g_t(x_t) = &\sum_{iv} \left(p_{iv}^{frv} f_{ti}^{growth}(x_t) \sum_{j_i w} x_{tjvw}^{area} \right) \\ &+ \sum_{il} \left(p_{il}^{frl} f_{til}^{prod}(x_t) \right) \\ &+ \sum_{i} \left(p_i^{lcc} \sum_{j_i vw} \left(x_{tjvw}^{area} - x_{t-1jvw}^{area} \right) \right) \\ &+ p^{tcc} \sum_{i} \left(x_{ti}^{tc} \left(\frac{1}{|V|} \sum_{v} p_{iv}^{\tau 1} f_{ti}^{growth}(x_t) \right)^{p^{exp}} \sum_{j_i vw} x_{t-1jvw}^{area} \right). \end{aligned}$$

The function describes the total costs of agricultural production. The total costs can be split in four terms: 1. area depending factor costs of vegetal production, which increase with the yield gain due to technological change; 2. factor costs of livestock production depending on the production output; 3. land conversion costs which arise, when non-agricultural land is cleared and prepared for agricultural production; 4. investment costs in technological change to increase yields by improvements in management strategies and other inventions. The technological change costs are proportional to total cropland area of a region and increase disproportionately with yield growth bought in the current timestep and the agricultural land-use intensity.

Constraints

Constraints describe the boundary conditions, under which the goal function is minimized.

Global demand constraints

(for each activity k)

$$\sum_i \frac{f^{prod}_{tik}(x_t)}{1+p^{seed}_{ik}} \geq \sum_i f^{dem}_{tik}(x_t)$$

These constraints describe global demand for agricultural commodities: Total production of a commodity $k$adjusted by the seed share required for the next production iteration has to meet the demand for this product.

Tradebalance

(for each region i and product k)

$$\frac{f^{prod}_{tik}(x_t)}{1+p^{seed}_{ik}} \geq p^{tb} \begin{cases} f^{dem}_{tik}(x_t) + p^{xs}_{tik} & : p^{sf}_{ik} \geq 1 \\ f^{dem}_{tik}(x_t) p^{sf}_{ik} & : p^{sf}_{ik} < 1 \end{cases}$$

The trade balance constraints are similar to the global demand constraints, except that they act on a regional level. In the case of an exporting region (self sufficiency for the product $k$is greater than 1), the production has to meet the domestic demand supplemented by the demand caused due to export. In the case of importing regions (self sufficiency less than 1), the domestic demand is multiplied with the self sufficiency to describe the amount which has to be produced by the region itself. In both cases the demand is multiplied with a so called "trade balance reduction factor". This factor is always less than or equal to 1 and is used to relax the trade balance constraints depending on the particular trade scenario for the future.

Land constraints

(for each cluster j)

$$\sum_{vw} x^{area}_{tjvw} \leq p^{land}_j$$

$$\sum_{v} x^{area}_{tjv'ir'} \leq p^{ir.land}_j$$

The land constraints guarantee that no more land is used for production than available. The first set of land constraints ensures the land availability for agricultural production in general. The second one secures that irrigated crop production is restricted to areas that are equipped for irrigation.

Water constraints

(for each cluster j)

$$\sum_v x^{area}_{tjv'ir'} p^{yield}_{tjv'ir'} f^{growth}_{ti(j)}(x_t) p^{watreq}_{jv} + \sum_l x^{prod}_{tjl} p^{watreq}_{jl} \leq p^{water}_j$$

The output of animal products as well as vegetal products under irrigated conditions requires water. The required amount of water is proportional to the production volume. The whole water demand in each cluster must be less or equal to the water available for production in this cluster.

Rotational constraints

(for each crop rotation group c, cluster j and irrigation type w)

$$\sum_{v_c} x^{area}_{tjvw} \leq p^{rmax}_{c} \sum_{v} x^{area}_{tjvw}$$

$$\sum_{v_c} x^{area}_{tjvw} \geq p^{rmin}_{c} \sum_{v} x^{area}_{tjvw}$$

The rotational constraints are used to prescribe typical crop rotations by defining for each vegetal product a maximum and minimum share relative to total area under production in a cluster.