Draft Version

Increased Agricultural Trade and its Impacts on Food System, Land-use and Greenhouse Gas Emissions

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Abstract

The volume of agricultural trade increased by more than ten times throughout the past six decades and is likely to continue with similar rates in the future. Thereby the issue of environmental and climatic impacts of this development is a recently discussed concern in literature. We analyse future trade scenarios covering the next five decades by evaluating economic and environmental effects using the global land-use model MAgPIE ("Model of Agricultural Production and its Impact on the Environment"). The model predicts global landuse patterns in a spatially explicit way and uses endogenously derived technological change and land expansion rates. Our study is the first which combines trade analysis with a spatially explicit mapping of landuse patterns and greenhouse gas emissions. By implementing self-sufficiency rates in the regional demand and supply equations, we are able to simulate different trade settings. We focus on three scenarios: the default scenario fixes current trade patterns until the year 2045, the liberalisation scenario assumes a path of increasing trade liberalization which ends with no trade barriers in 2045 and the policy scenario follows a historically derived pathway by reducing trade barriers by 10% in each decade.

Results show lower global costs of food production and lower rates of food price rises due to liberalisation. Regions with comparative advantages like Latin America for oilcrops and China for cereals 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 coming from further trade liberalisation. Non-CO_2 Emissions will increase most in China due to rising livestock demand in the region. In general, the model predicts a non-continous behaviour in terms of environmental damages when trade increases continously.

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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 has reduced transport and transaction costs for trading significantly and second, agricultural trade has been liberalized 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 the welfare level (e.g. Hertel et al., 2009; Bouët et al., 2005; Corden, 1997; Martin and Winters, 1996; Anderson and Tyers, 1993). 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 freer trade on the environment (Anderson, 1992; Antweiler et al., 2001) or draw a mixed picture (Cole, 2000). 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) comes to the conclusion that trade increases resource degradation if producing countries are not including production externalities in the product price. More sophisticated econometric studies indicate a clear positive relationship between trade liberalization and CO_2 emissions (Cole and Elliot, 2003; Frankel and Rose, 2005; Managi, 2004).

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 liberalization. Verburg et al. (2009) used the coupled LEITAP-IMAGE model to analyze 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.

However, in contrast to these studies, our analysis takes environmental as well as economic indicators into account to get a more comprehensive picture. We use a spatially explicit economic landuse model, called MAgPIE ("Model of Agricultural Production and its Impact on the Environment") to run different trade liberalization scenarios. As a result maps on a 0.5 degree resolution are generated which helps to locate the results on a sub national level. To our knowledge no study before has mapped results from trade analysis in such a way. Our global landuse model differs significantly to comparable model frameworks by considering the interplay of land expansion and yield increasing technological change in an endogenous way (Dietrich et al., 2010b). The environmental impacts are included by considering deforestation rates as well greenhouse gas emissions from landuse change, the livestock sector and the application of different chemical and organic fertilizers.

The main goal of our study is to investigate the implications of different trade liberalisation scenarios on food prices, technological change rates, landuse 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) and applied scenarios (section 2.3) as well as illustrate the method of calculation environmental effects (section 2.4). Chapter three illustrates the results of the analysis. In chapter four the results are discussed regarding economic impacts (section 4.1), environmental impacts (section 4.2), model uncertainties (section 4.3) and policy implications (section 4.4).

2. Model and Scenarios

2.1 The Model

The global land-use model MAgPIE ("Model of Agricultural Production and its Impact on the Environment") 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 spatial explicit programming allows to model the supply side of the model with cell resolutions up to 0.5 degree (approximately 50x50km grid).

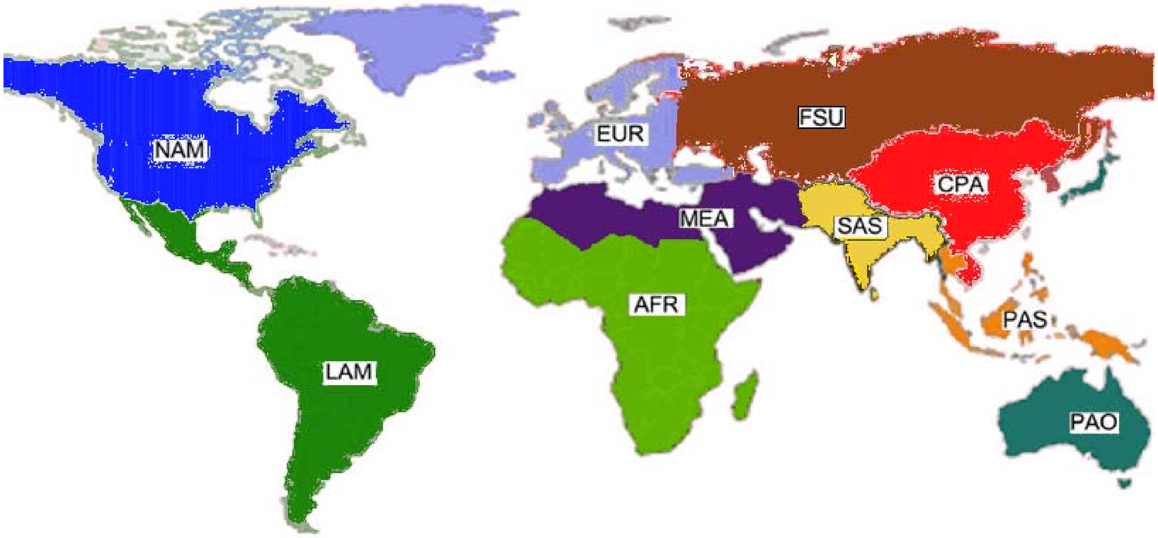

Figure 1: The ten world regions in MAgPIE [2]

The demand side is represented by ten world regions (see Figure 1). The required calories in the demand categories are derived from future population (CIESIN et al., 2000) and income growth scenarios (Gross Domestic Product per capita) (World Bank, 2001). These data are regressed on cross-sectional basis with country data on food and non-food energy intake. The resulting demand calories are produced by 16 cropping[3] and 5 livestock activities[4]. 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.

Three categories of costs arise for the production: production costs for livestock and vegetal production, yield increasing technological change costs and land conversion

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

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

costs. The model is optimized by minimizing these three cost components on a global scale. MAgPIE can invest in yield-increasing technological change or in land expansion in order to meet future agricultural demand quantities. The endogenous implementation of technological change (TC) is based on a surrogate measure for agricultural landuse intensity (Dietrich et al., 2010a). We have related this measure to empirical data on investments in TC, like Research & Development and infrastructure investments (Dietrich et al., 2010b). The other alternative for MAgPIE to increase production is to expand into cropland from a pool of non-agricultural land. The expansion involves land-conversion costs which account for the preparation of new land and basic infrastructure investments. For instance, if MAgPIE has to increase the production by one ton it decides on the basis of the shadow prices minus the costs. Cropland expansion leads to the shadow price of the new land minus the land conversion costs. Technological change means the shadow price of the existing cropland after the productivity gain minus the costs for TC. Since MAgPIE minimizes costs, it will consider the cheaper alternative.

The biophysical inputs (e.g. yields) for MAgPIE are derived from the grid-based dynamic vegetation model Lund-Potsdam-Jena 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 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 further irrigation area expansion in MAgPIE.

More information on the model framework is presented in a mathematical description of MAgPIE in the appendix of this paper.

2.2 Trade Implementation

We have implemented international trade in MAgPIE by using self sufficiency ratios. Self-sufficiency ratios describe how much of the regional agricultural supply quantity has to be produced within a region. For example, a ratio for cereals of 0.65 means that 65% of cereals are produced domestically, whereas 35% are imported. To represent the trade situation of 1995 we have calculated the self-sufficiency ratios ($p_{i,k}^{sf}$) for each region *i* and production activity *k* from the food balance sheets of FAO for the year 1995 (FAOSTAT, 2010) (see Appendix A). We first explain the implementation with the help of an illustration (Figure 2) and afterwards in mathematical terms.

We have 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 determined how much is produced domestically and export shares determine how much is produced for the export. The export shares are generated for every crop for the year 1995 and are taken from FAO (FAOSTAT, 2010) (see Appendix B). The demand which enters the second pool is allocated according to comparative advantage criteria to the supply regions. The parameter p^{tb} defines the share of trade which flows in both pools. If p^{tb} is equal to 1, the total demand will be distributed according to the fixed self sufficiencies and the export shares to the supply regions. If r is equal to 0, all trading quantity will end up in the second pool and is distributed according to comparative advantage criteria to the supply regions.

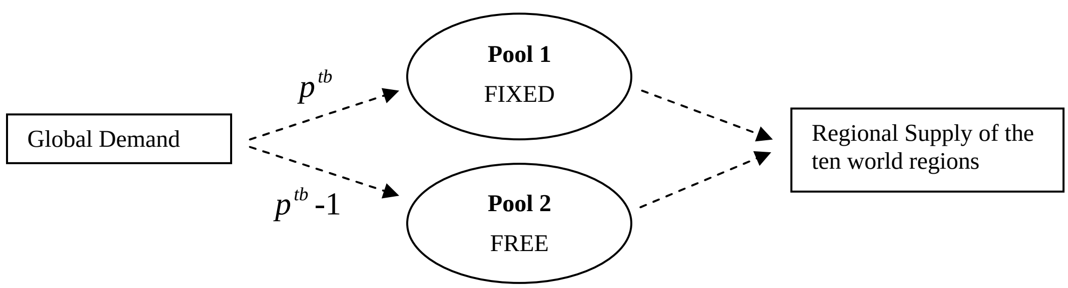

Figure 2: Trading pools in MAgPIE. The fixed pool allocates demand according to fixed criteria (self sufficiency ratios and export shares). The free pool allocates it according to comparative advantage criteria.

The 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} 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 regions, t as time and k as production activities.

Subsequently, we have 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 ($p^{sf} < 1$) (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 is balanced on the regional scale. In the case of an exporting region, the regional supply has to be bigger or equal than the domestic demand plus the exported quantity. In the case of an importing region, the regional supply has to be bigger or equal than the domestic demand times the self sufficiency. This holds true, if the trade balance reduction factor p^{tb} is equal to one. As explained above the trade balance reduction factor determines the amount of demand which is traded with fixed shares and which amount is freely traded. If p^{tb} is equal to zero, the equation becomes zero and everything is solved is via the global trade balance (equation 1).

Trade Balance Equation:

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

2.3 Implementation of GHG emissions

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

Two types of CO_2 emissions are implemented: carbon emissions from deforestation and from vegetal production. CO_2 emissions from deforestation occur by converting the intact and frontier forest into cropland. Furthermore, as long as the land is used for agricultural activities less carbon emissions are captured as compared to a possible regrowth of natural vegetation. The impacts of changes in the vegetal production and the resulting changes in CO_2 emissions are calculated by taking the changes in carbon stocks between the current and last period as an indicator for the released CO_2 emissions. However, this effect is less substantial compared to the deforestation effect.

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, the effect is influenced by the temperature, the kind of livestock and the development status 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 by flooding the fields. This permits the soils to absorb the CH_4. Besides the amount of rice cultivation, this emission type depends on the water management practices and a specific regional factor.

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 the amount is dependent on the amount of livestock and the type of livestock system. The second source is N_2O emissions from cultivated soils. These are affected directly by the kind of nitrogen fertilizer used (synthetic fertilizer, manure, crop residues and N-fixing crops). In addition, indirect effects occur through the atmospheric deposition of NO_x and NH_3 and through leaching of nitrogen fertilizer.

Further information on the detailed calculation of these emissions within MAgPIE is provided in Popp et al. (2010).

2.4 Scenarios

We consider three scenarios: The baseline scenario keeps the self sufficiency rates constant over time. The policy scenario follows a historically derived pathway of trade liberalization. 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; Hinkelman, 2005). This is also supported by the general trade study of Dollar and Kraay (2004), who found out a 22% tariff cut for non-globalizing countries, 11% for globalizing countries and 0% for rich countries[5] between the 1980s and 1990s.

The liberalisation scenario allows for full trade liberalisation in 2045 by reducing the self sufficiency rates to zero over time. The quite ambitious goal is that the world will be fully liberalized in 2045 and everything is traded according to comparative advantage rules.

As explained in the previous chapter the scenarios differ by changing the factor p^{tb}. Table 1 gives the values for p^{tb} in each period and scenario. As mentioned, the baseline scenario keeps the self sufficiencies for 1995 constant over time. Therefore, the value for p^{tb} is 1 in all time steps. In the policy scenario this factor is reduced by 10% in each decade and in the liberalisation scenario p^{tb} is reduced continuously to 0 in 2045.

Year	**1995**	**2005**	**2015**	**2025**	**2035**	**2045**
baseline 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 Scenarios

[5] „Rich countries refer to the 24 OECD economies before recent expansion plus Chile, Hong Kong, Korea, Taiwan, and Singapore. Globalizers 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 refers to the remaining developing countries in this group.“ (Dollar and Kraay, 2004)

3. Results

3.1 Trade Balances

Trade balances (in million tones) are calculated by taking the difference between exports and imports of a region. We decided to take cereals (incl. rice) and oilcrops as they are the most important crop groups for international trade.

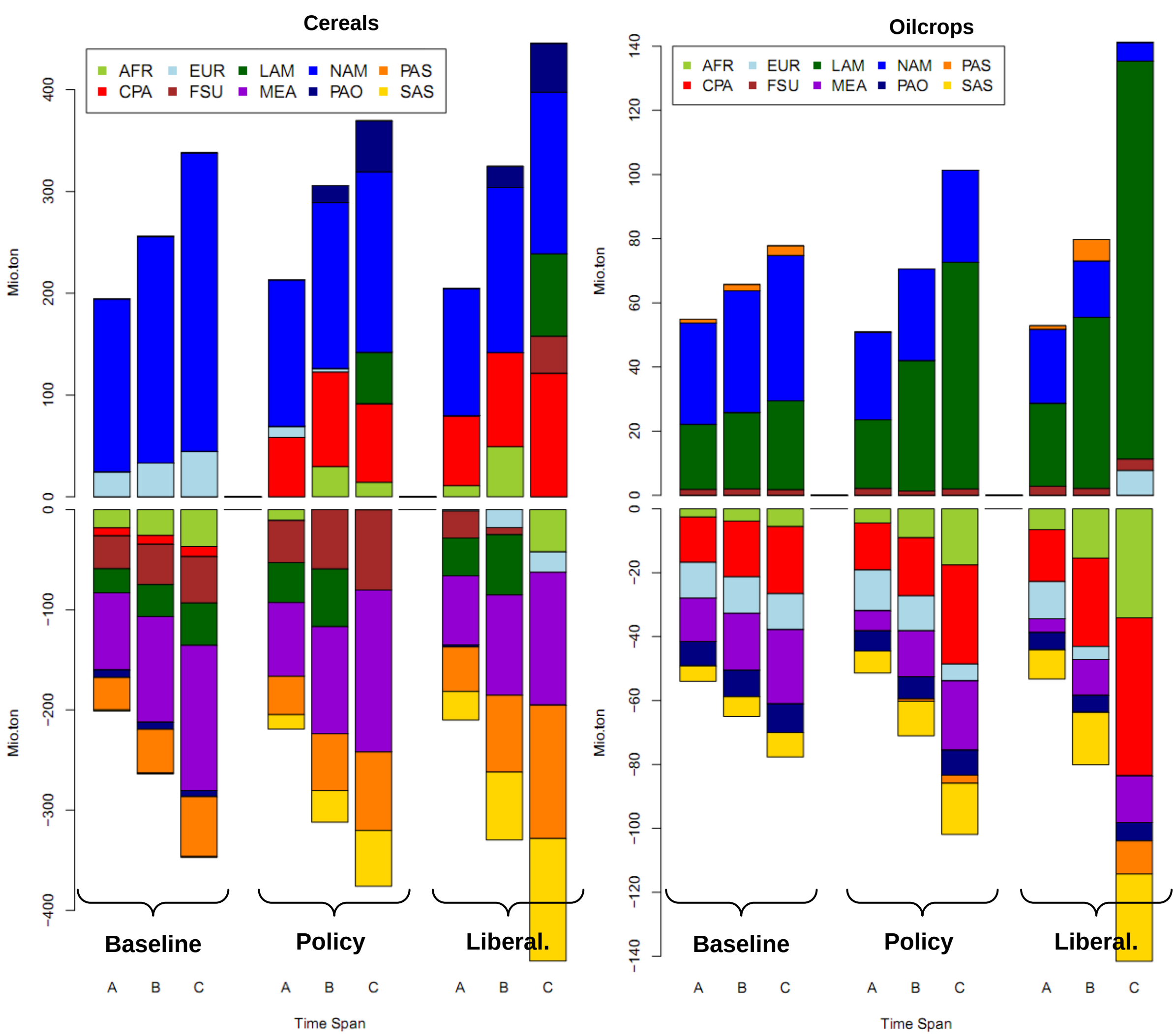

Figure 3: Net Export Rates of cereals (incl. rice) and oilcrops for the ten world regions in the three trade scenarios and for the three time spans

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 (baseline on the right, policy in the middle and liberalization on the left). The three bars in each scenario cover the three time spans: 2005-2020 (A), 2020-2035 (B) and 2035-2050 (C).

In the baseline scenario, EUR and NAM dominate the cereal market. The imports are shared among the other regions, lead by MEA. This situation changes in the other two scenarios when CPA, PAO, AFR, LAM and FSU join the export group at the expenses of EUR, who becomes partly a net importer. On the import side PAS and SAS increase their quantities most. The overall trade volume in the years 2035 till 2050 increases to over 450 mio. tons in the liberalization scenario (compared to 200 mio. tons in the baseline). Focusing on oilcrops, these crops are mostly dominated by NAM and LAM. With more trade LAM increases its export volume significantly (increase of more than four times in the last time step comparing liberalization with baseline). On the import side CPA, AFR and SAS face the highest increases.

3.2 Total Costs and Food Price Index

Since MAgPIE is a mathematical programming model which minimizes agricultural production costs, we can compare these global costs between the different scenarios and with measured data from the past (Figure 4).

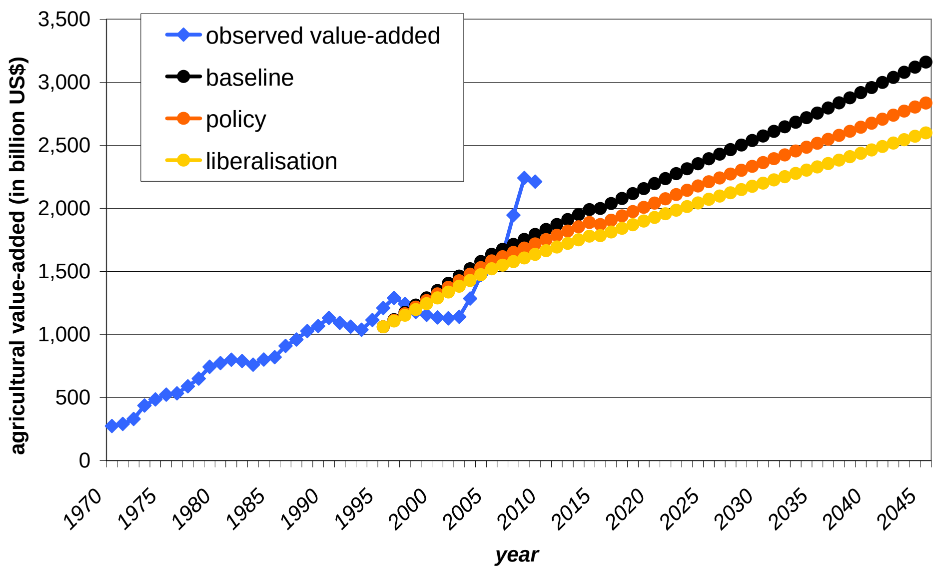

Figure 4: Total production costs in each scenario compared with historic data from (World Bank, 2011)

The historic data (1970-2009) are agricultural value-added output, which measure 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 and comprises value added from cultivation of crops and livestock production as well as forestry, hunting, and fishing. The figures are taken from the World Development Indicators Database (World Bank, 2011).

From 1995 till 2009 historic data and projected data from MAgPIE overlap and are in a good agreement with each other. The long-term term shows as well that the MAgPIE projections are in line with past measurements. In terms of future projection, more liberalisation leads to lower global production. In the baseline scenario production costs more than triple from 1 trillion US$ in 2005 to 3.15 trillion US$ in 2045. In contrast, the liberalization scenario shows a significant lower increase to 2.65 trillion US$ in 2045.

The total food price index for agricultural products in Figure 5 shows a sharp increase by 70% until 2045 for the baseline scenario. In the policy scenario the food prices increase continuously by about 5 to 10% per decade and ends up at 130 index points in 2045. For the liberalization scenario we obtain a slow and uneven increase to an index value of 112 in 2045.

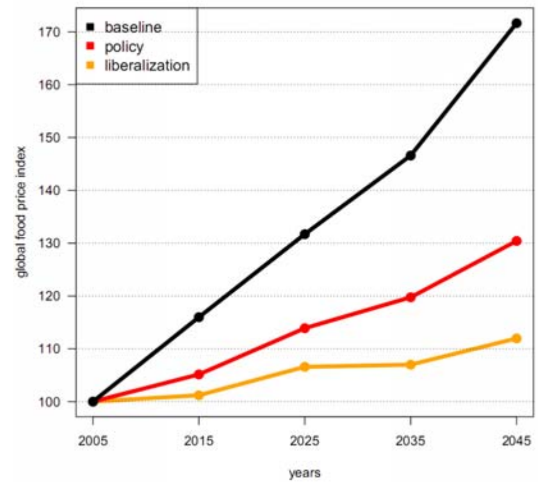

Figure 5: Global Food Price Index over time in each scenario

If we disaggregate the global food price index, we get very different results for the single world regions. Figure 6 shows the regional food price indices for the baseline scenario. The figures on the right and left differ just in scale. We obtain a 3.5-fold increase in food prices in the Middle East and North Africa. North America and South Asia face a two-fold increase. The increase in Sub-Saharan Africa is moderate until 2035 but jumps up to almost 160 in 2045. Latin America and Europe are not challenged by higher food prices until 2045.

If we allow for more trade in food products, the range between the regions is reduced significantly. Figure 6 shows the results for the policy and liberalization scenario. In the policy scenario all regional indices end up between values of 110 and 160 in 2045. Highest values are for South Asia and the Former Soviet Union. In the full liberalization scenario the indices develop very closely and differ only by 25 index points in 2045.

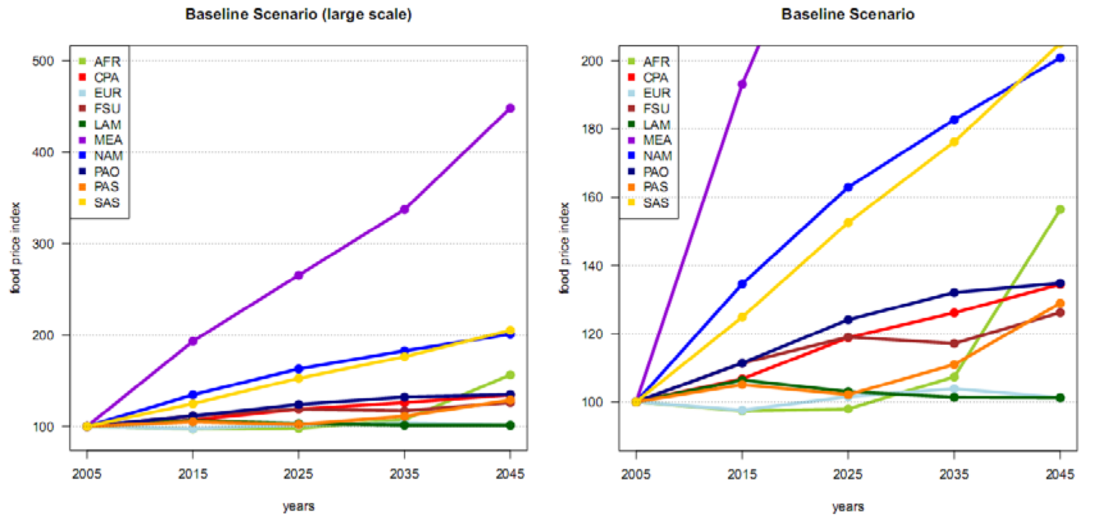

Figure 6: Regional Food Price Index over time for the baseline scenario in large scale (left) and normal scale (right)

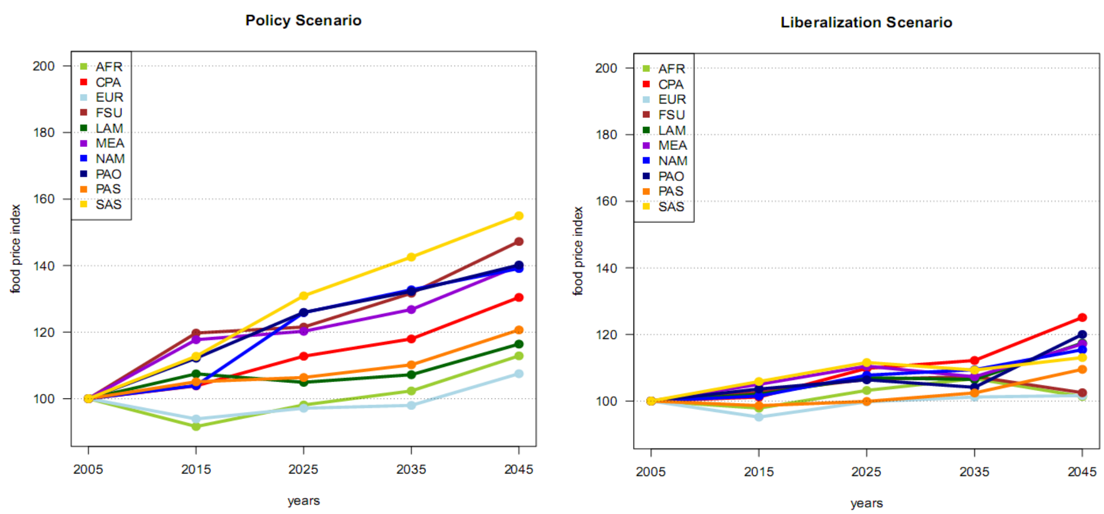

Figure 7: Regional Food Price Index over time for the policy scenario (left) and the liberalization scenario (right)

3.3 Technological Change Rates

Figure 8 shows the technological change (TC) rates of the ten world regions. In all cases, except PAO, LAM and CPA the technological change rates are reduced continuously if more trade is allowed. FSU and MEA face the strongest decreases. In MEA the annual rate is decreased from 2.1% in the baseline to 0.3% in the liberalisation scenario. AFR shows slightly decreases in the policy scenario and the liberalization scenario. The opposite holds true for CPA and LAM where TC rates slightly increase. PAO shows no technological change in all scenarios. Under trade liberalisation, China, Sub-Sahara Africa and India face the highest technological change rates over the whole period.

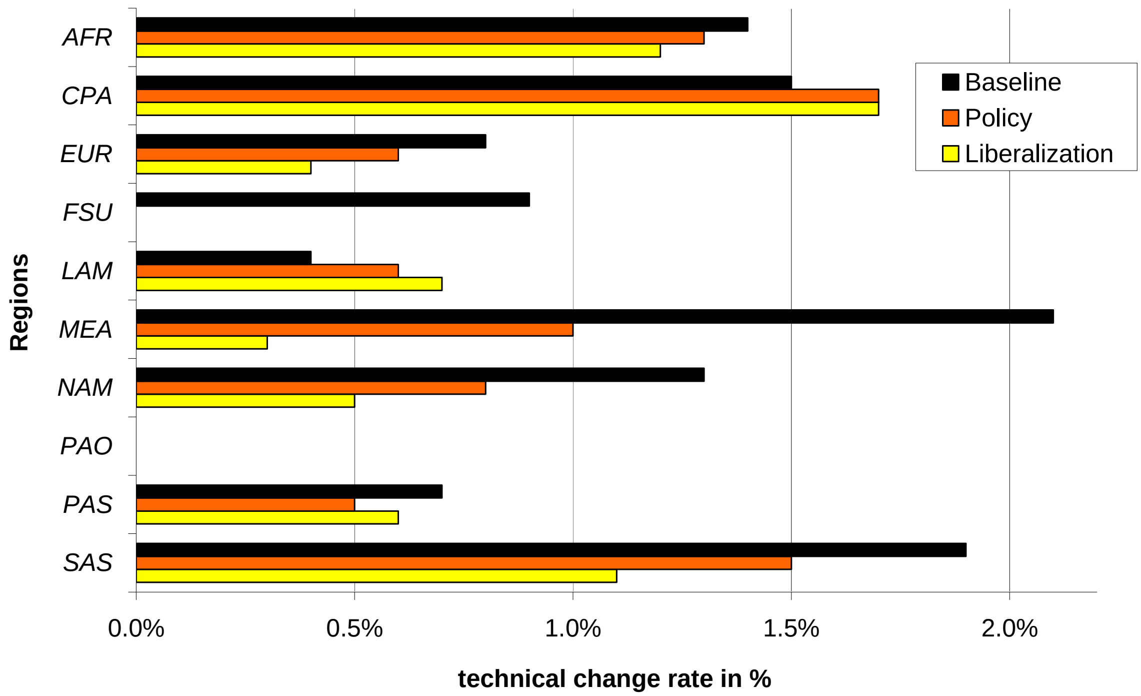

Figure 8: Average annual technical change from 2005 to 2045. The black bars represent the rates under the constant trade scenario (Baseline), the orange bars the moderate trade liberalisation scenario (Policy) and the yellow bars the full liberalisation scenario.

3.4 Landuse Change

The following maps show the physical crop area change in 2045 (in percentage) between the baseline scenario and one of the trade scenarios for cereals (incl. rice) and oilcrops. If the number is positive (green colour), MAgPIE uses more cropland in the trade scenario compared to the baseline scenario. If the number is negative (yellow/red colour), MAgPIE uses less cropland in the trade scenario compared to the baseline scenario.

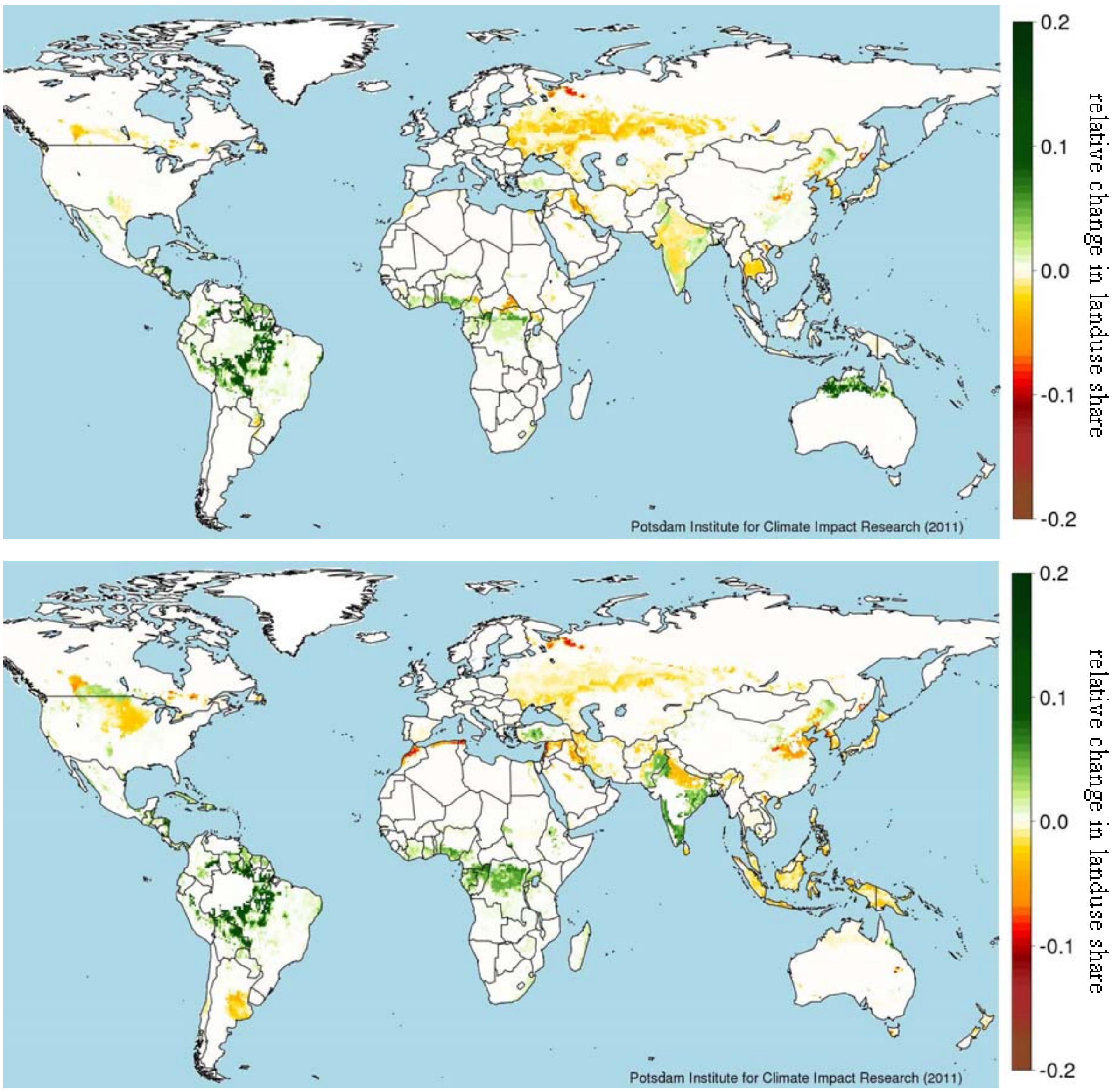

Figure 9: Relative change in landuse share of cereals per grid cell (0.5°) between baseline and policy scenario (top) and between baseline and liberalisation scenario (down) in 2045

Figure **9** shows the physical cropland changes for cereals. The policy and liberalization scenario show similar behaviour in the cases of the Amazonian rainforest and rainforest Central Africa, although the landuse changes are stronger in the liberalization scenario. In Pacific Asia (Malaysia/Indonesia/Thailand) and Russia cereal area is significantly reduced, whereas North America, China and India show mixed effects. Contrasting effects between both scenarios can be obtained for India and Australia. Especially Australia increases its cereal area in the policy scenario and decreases it in the liberalization scenario.

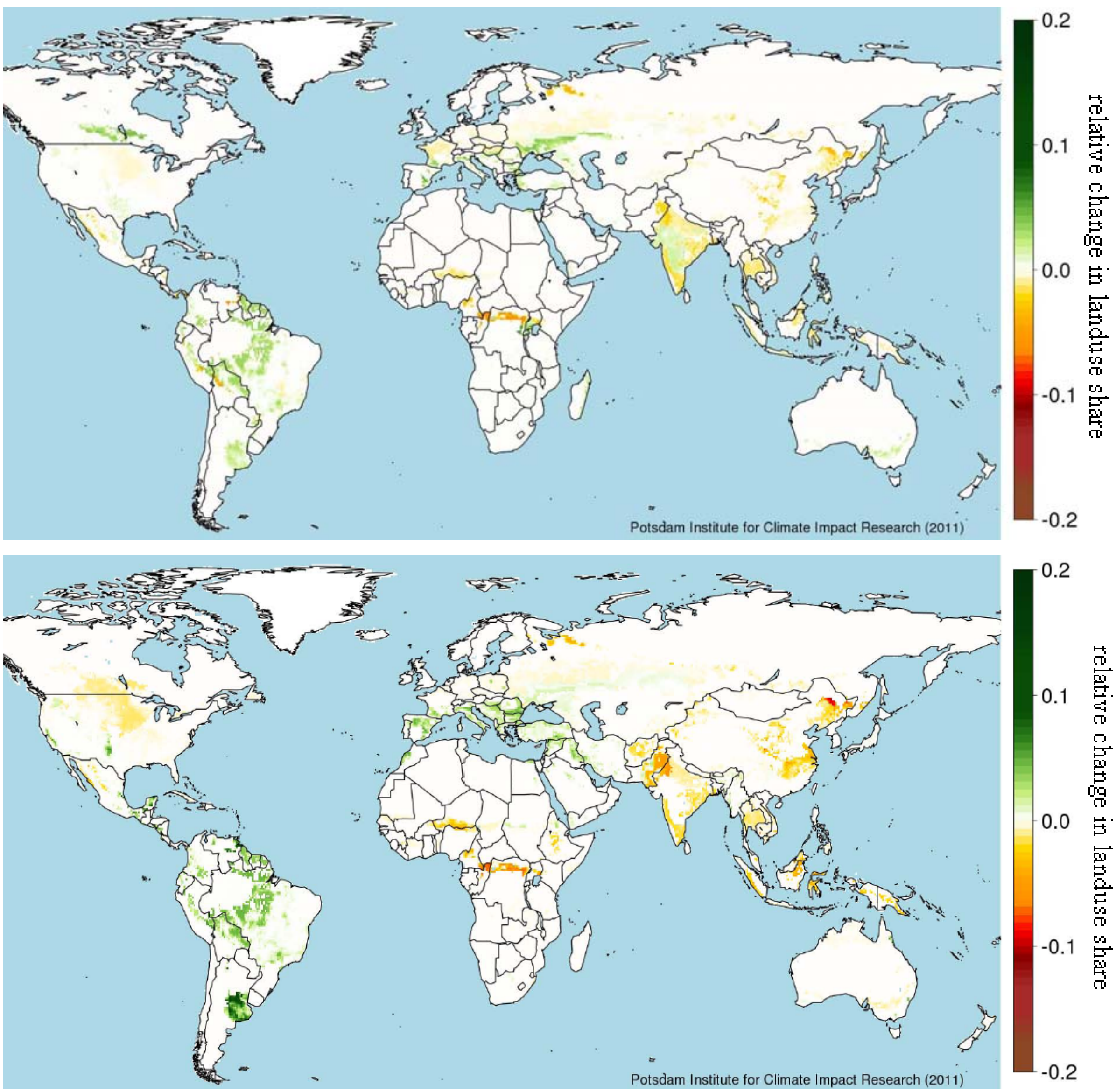

Figure 10: Relative change in landuse share of oilcrops per grid cell (0.5°) between baseline and policy scenario (top) and between baseline and liberalisation scenario (down) in 2045

Figure 10 shows the area differences for oilcrops. between the policy and baseline scenario (top) and the liberalization and baseline scenario (bottom). In the policy scenario oilcrop area is increased in Latin America and this happens even to a larger extent in the liberalization scenario. With the latter the oilcrop area in Argentina increases in parts by almost 20%. Under liberalization Southern Europe and the Middle East expand oilcrop area as well. Whereas Russian and Canadian oilcrop area sees increases under the policy scenario. Oilcrop area in Central Africa, China, India, and Pacific Asia is reduced, although we obtain increases in Central India under the policy scenario.

3.5 Deforestation and Carbon Emissions

Besides technological change MAgPIE has also the option of expanding cropland in order to increase production. Figure 11 illustrates the cumulative amount of crop land expansion into forest land (in relative landuse shares) from 2005 till 2045. 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 Canada and North Russia.

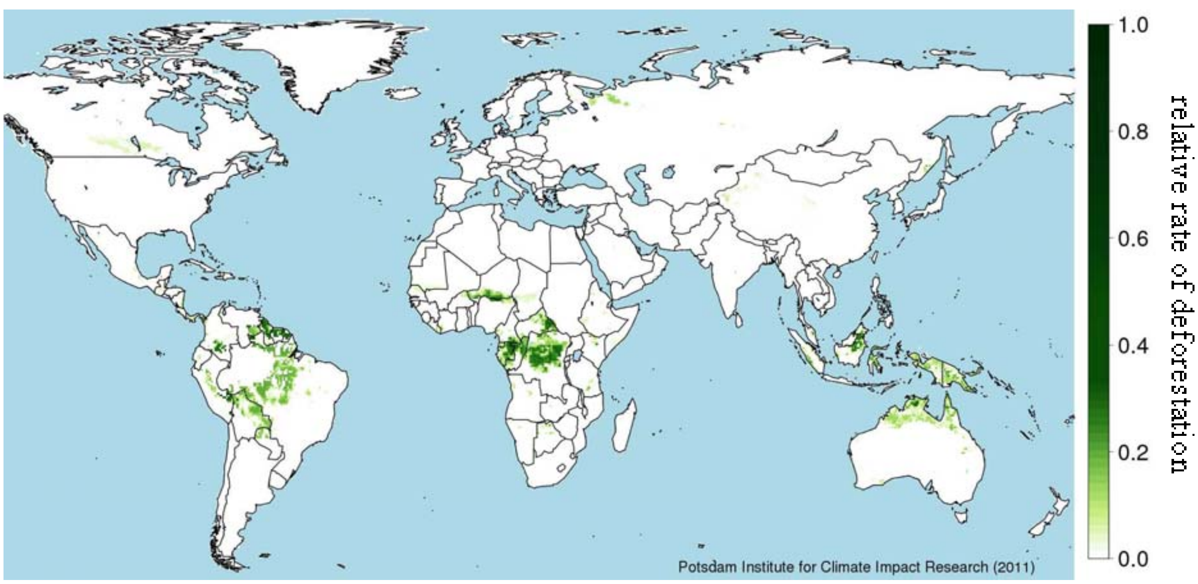

Figure 11: Relative rate of cropland expansion (change in landuse share of all crops) per grid cell (0.5°) in the baseline scenario between 2005 till 2045

Figure 12 illustrates the difference in cropland expansion between the baseline and policy scenario (top) and the baseline and liberalization scenario (bottom). In both cases total cropland expansion increases and the expansion in Africa is almost constant. In the policy scenario more area is converted into cropland in North Australia and the Amazonian

Rainforest. Less area is converted in the Pacific Asian countries and North Russia. In the liberalization scenario, the expansion in Australia does not take place and also in the Savannah Region of West Africa no cropland expansion happens. In total less land is converted in the liberalization scenario compared to the policy scenario.

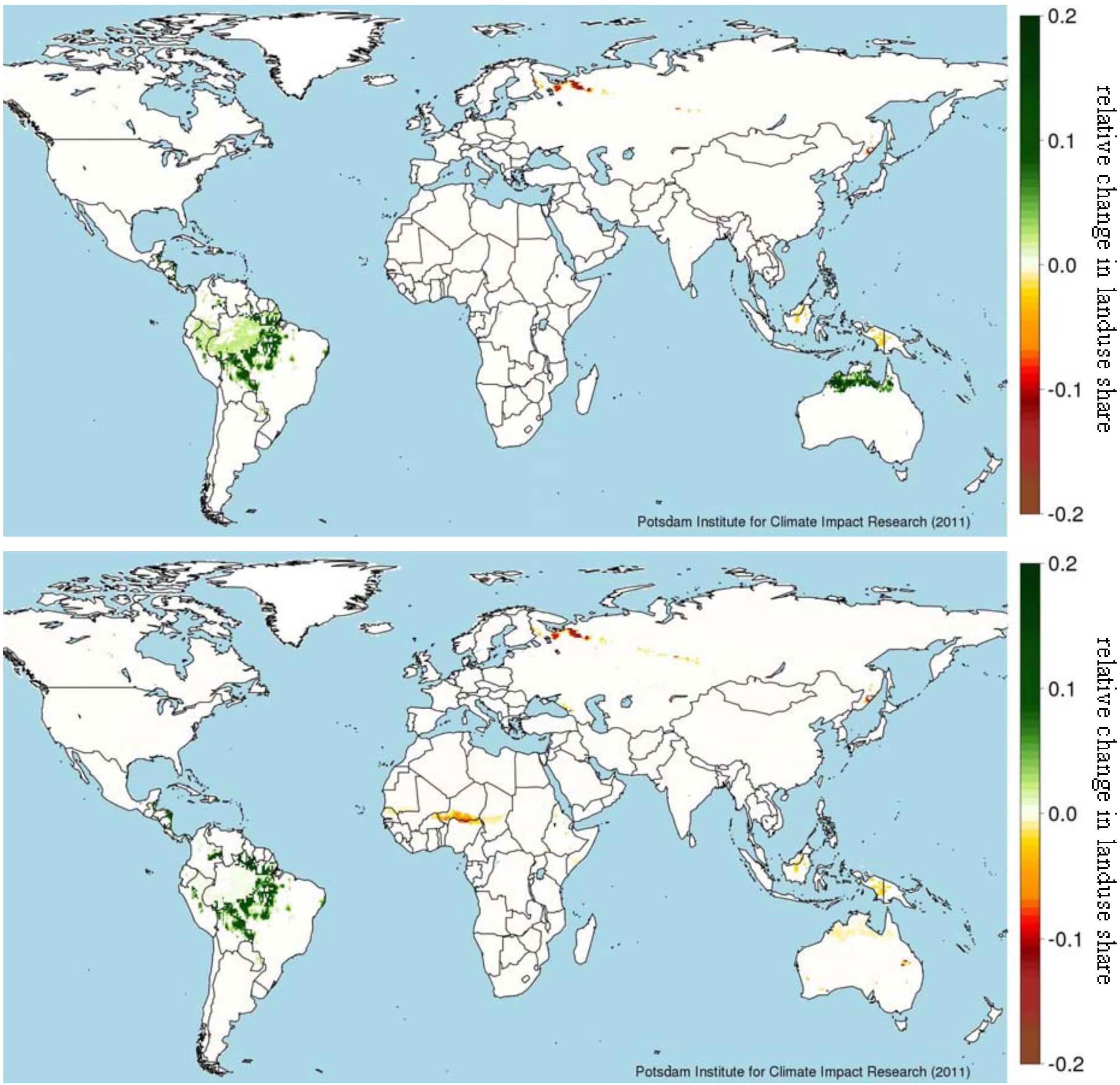

Figure 12: Relative change in landuse share of all crops per grid cell (0.5°) between baseline and policy scenario (top) and between baseline and liberalisation scenario (down) in 2045

Expansion of cropland into forest results in a significant amount of carbon emissions (see Figure 13). The rainforest regions LAM, AFR and PAS emit most carbon emissions till 2045. When these emissions are emitted depends to a certain extent on the trade scenario. Under the policy scenario, total emissions increase in all three time spans (A=2005-2020, B=2020-2035 and C=2035-2050). AFR will emit more in the first time span, whereas carbon emissions in LAM are increased most between 2035 and 2050. Under full liberalization we see a mixed picture. From 2005-2020 carbon emissions are even reduced, mostly in PAS and LAM compared to the other two scenarios. In the second period carbon emissions increase, which is the only case when total carbon emissions increase from one time step to the other. The last period is again dominated by carbon emissions from LAM.

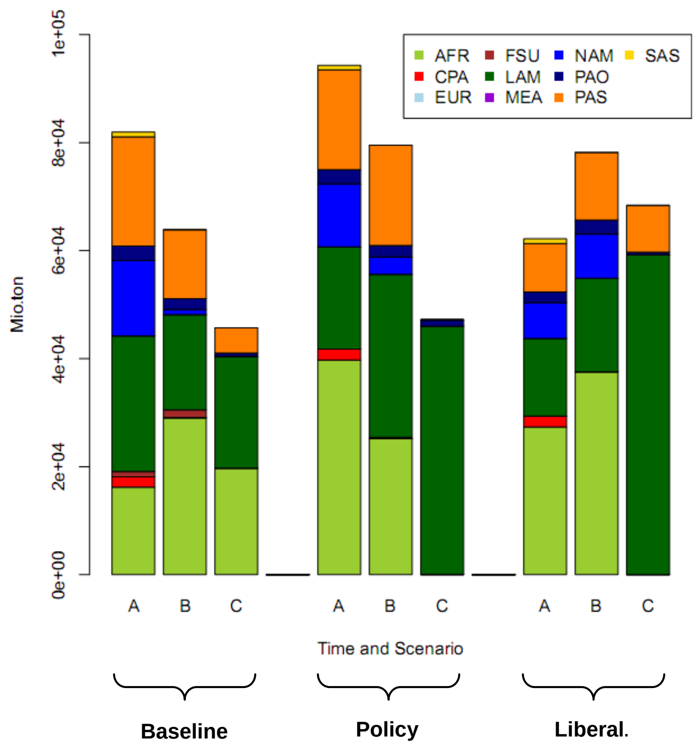

Figure 13: Carbon Emissions in time steps from 2005 to 2050 in three trade scenarios

3.6 Non-CO_2 Emissions

Table 2 lists the non-CO_2 emissions (CH_4 and N_2O) coming from livestock, rice production and soil fertilization, which are explained in section 2.4.
All emissions are calculated in CO_2-equivalent values using the calculation of the "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.

Regions	**Baseline Scenario**	**Policy Scenario**	**Liberalization Scenario**
Rice (CH4)	31,183	30,691	30,217
Fermentation (CH4)	174,324	181,833	173,094
AWMS (CH4 + N2O)	81,099	84,322	79,168
Crop (N2O)	48,790	48,217	47,091
Total	**335,396**	**345,063**	**329,570**

Table 2: Non-CO_2 Emissions (in mio. t CO2-equivalent) from 2005 to 2050 in both trade scenarios

We find very mixed results in terms of non-CO_2 emissions by comparing the different trade scenarios. Whereas total emissions increase in the policy scenario (compared to the baseline), they decrease in the full liberalization scenario. In the policy scenario CH_4-emissions from enteric fermentation and from animal waste management (AWMS) are the main driver for the increase. In the liberalization scenario these emissions are reduced significantly. In contrast, CH_4 emissions from rice cultivation and N_2O from cropping activities through fertilizing decrease slightly and continuously with more liberalisation.
Disaggregating these figures to the regional level and the time spans (Figure 14), gives us more detailed insights. The composition of non- CO_2 emissions varies largely among the different regions. Emissions from rice cultivation play a minor role, except in PAS where it accounts for more than 50%. In all other regions, the livestock system and the kind of livestock are the crucial factors determining the amount of emissions. Most changes over time occur in Africa, where total non-CO2 emissions are reduced considerably under the liberalization scenario. In contrast, CPA and SAS increase their emission level constantly over time and with more trade. Emissions in LAM increase over time but decrease slightly with more trade.

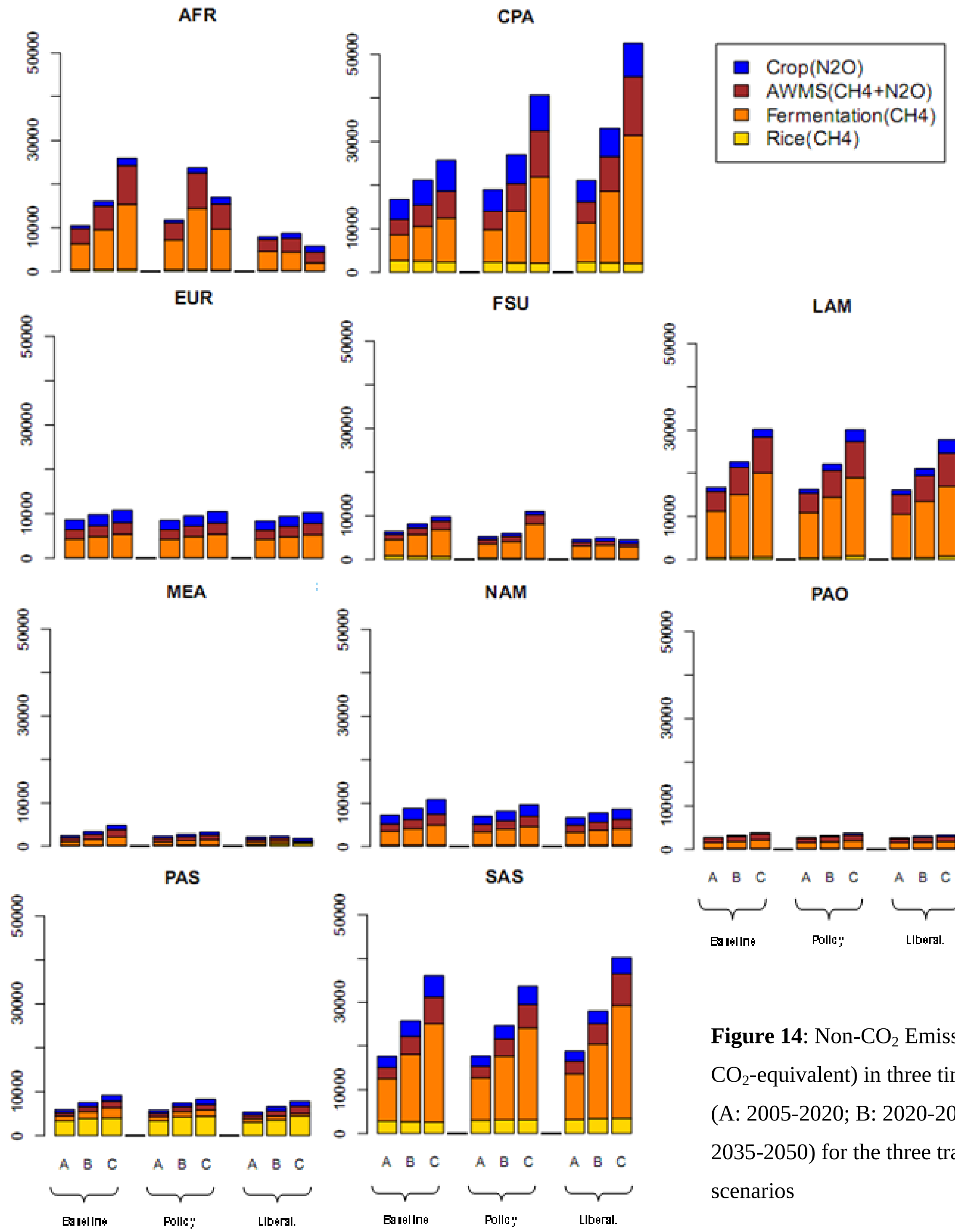

Figure 14: Non-CO_2 Emissions (in CO_2-equivalent) in three time steps (A: 2005-2020; B: 2020-2035; C: 2035-2050) for the three trade scenarios

Figure 15 shows the spatial distribution of non-CO_2 emissions for the three trade scenarios. Most emissions occur in the Asian region (China, India, Pacific) followed by Europe and North America. Lowest levels can be obtained in Latin America, Africa and Australia. Under more liberalization emissions in Europe, Russia and to some extent in

Latin America (especially Brazil) are reduced. In Africa more is emitted with more trade, especially in Central and West Africa.

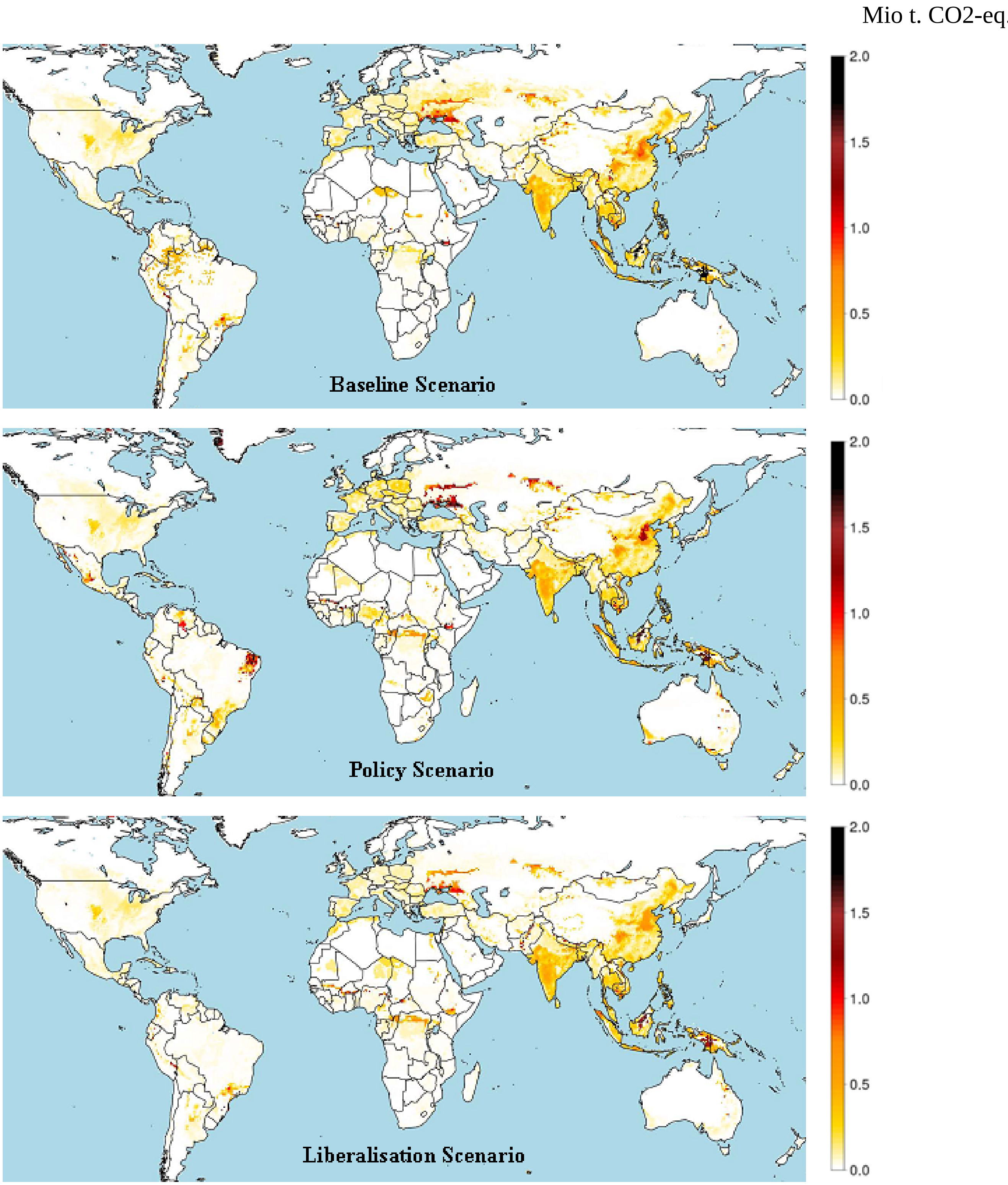

Figure 15: Mapping of annual Non-CO_2 Emissions (average over 2005-2050) for the three trade scenarios

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. This study presents a new approach to tackle this issue by using a spatially explicit global land use model and a comprehensive focus on environmental as well as economic indicators.

4.1 Economic Impacts

Model results show that further trade liberalisation leads to a shift in the balance of power in terms of export shares. Regions with comparative advantages in agriculture benefit at the expense of highly protected regions. For cereals, as well as oilcrops, North America and Europe export less if trade becomes more liberalized. This indicates how much both regions profit from their high tariffs currently applied in most of their agricultural markets. The lower production level until 2045 is mainly due to a sharp drop of technological change rates in these regions, whereas cropland for cereals and oilcrops is almost not affected. Australia and China are the regions which take most of the export share from Europe and North America. China will mainly benefit due to its lower food demand increase coming from a lower population pressure after 2025 and Australia profits from its comparative advantages in cereal production. India and its surrounding countries have low competitive advantages concerning staple crops. Therefore, technological change rates decrease and more will be imported under liberalisation.

Latin America is the region which benefits most in economic terms since it will dominate the oil market, if more trade liberalization occurs. The abundant land resource and increasing technological change rates lead to a tremendous production increase. In the baseline scenario cropland is already expanded from 145 mio ha. in 1995 to 327 mio. ha in 2045. In the policy scenario it increases to 406 mio. ha and in the liberalisation to 390 mio. ha. The related emissions are discussed in the next section.

On a global scale, the results demonstrate that increased trade liberalisation will lead to lower global costs of food production. In 2005, the model predicts that global food production costs between 1.5 and 1.6 trillion US$. According to the World Bank the agricultural value-added in 2005 was 1.526 trillion US$ (World Bank, 2011) which shows the good validation of our output (see Figure 4). In MAgPIE, this figure increases over time to 2.5 to 3.2 trillion US$ depending on the trade scenario. The model predicts that around 0.7 trillion US$ (22%) can be saved annually with producing the same quantity of food by fully liberalizing trade in 2045. Of course, these are hard figures, which do not take into account important policy considerations like food sovereignty or domestic socio-economic and environmental implications.

In terms of global food security, however, this view is supported since trade liberalization leads to a significant reduction of the food price index (Figure 5). Additionally, the range of the price index between regions is narrowed down under trade liberalisation (Figure 6 and Figure 7). The Middle East / North Africa region is the most extreme region, where food prices increase until 2045 by more than 300% in the baseline scenario due to unfavourable cropping conditions. This is reduced to a 40% increase in the liberalisation scenario. South Asia is another hotspot, where prices rise by more than 100% in the baseline scenario. Both regions have in common that their agricultural sectors have low competitive advantages on the world market. This leads to the highest increases of imports under liberalisation (Figure 3) and significantly lower technological change rates (Figure 8) since the pressure to increase productivity is reduced. The strong price increase in North America in the baseline scenario indicates that it faces problems in the future to keep its currently strong export position. Since the baseline scenario assumes that the export position is constant over time, the level of the food price index in this scenario is a valuable indicator of the competitiveness in the future.

4.2 Environmental Impacts

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 future cropland expansion mainly takes place in ecological sensible area of the rainforest causing significant environmental damages (Figure 11 and Figure 12). In the baseline scenario total cropland expansion in the three main rainforest areas, the Amazonian rainforest (180 mio. ha), the Central African rainforest (170 mio. ha) and the rainforest on the Pacific islands (60 mio. ha) amounts to 410 mio. ha or 21.4% of the global cropland area between 1995 and 2045. Under trade liberalisation this increases by further 55 mio. ha, 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.

An important environmental damage resulting from deforestation are carbon emissions. 11% to 39% of all carbon emissions from human origin come from the forest sector (Hao et al., 1990) and they account for 12-20% of total GHG emissions (Gumpenberger et al., 2010). The conversion of previous intact forest leads to 160 billion tons of CO_2 emissions in the period from 1995 to 2045. Under additional trade, this amount increases due to further expansion in Latin America (mainly Brazil). Total carbon emissions rise by 30 billion tons in the policy scenario and 15 billion tons in the liberalization scenario. This shows that more liberalisation increases emissions but not necessarily in a continous way. We obtain a similar behaviour in terms of non-CO_2 emissions, where total emissions in the baseline scenario amount to 335 billion tons over the whole period. This increases by 10 billion tons in the policy scenario but decreases by 6 billion tons in the liberalisation scenario. This non-continous behaviour can be also observed in results by Verburg et al. (2009). The main reason in our case is the trade-off between technological change and land expansion. If a moderate level of liberalisation is allowed, like in the policy scenario, the model uses the cheapest possibility, which is cropland expansion into rainforest and increasing livestock in China and Sub-Sahara Africa. If even more liberalisation is happening, like in the liberalisation scenario, more specialisation of the regions leads to higher investments in technological change in Latin America. Therefore, in Latin America less environmental damage occurs compared to the policy scenario. Concerning non-CO_2 emissions the shift of livestock production from Sub-Sahara Africa to China in the liberalisation scenario leads to lower emissions since the livestock system in China is more efficient although on a low level. If future climate negotiations will incorporate GHG emissions from agriculture in the trading system, this non-continous behaviour would be reduced. Therefore, future research should incorporate the costs for environmental externalities like GHG emissions to test this hypothesis.

In general, our results on emissions largely confirm the results of a comparable study of Verburg et al. (2009). They report average annual emissions for their baseline scenario between 2000 and 2050 of 0.8 billion tons for CO_2, 3 billion tons for CH_4 and 1.2 for N_2O. Our corresponding figures are 4.1, 4.5 and 1.9, respectively. However, looking more into depth, the timing of CO_2 emissions differs significantly between both studies. In the liberalisation scenario by Verburg et al. (2009), CO_2 emissions increase by more than 50% in 2015, but are reduced by 15% in 2030 and by around 35% in 2050. In our case carbon emissions decrease by 20% (2005-2020), increase by 25% (2020-2035) and increase by 45% (2035-2050) under trade liberalisation. The reason for the totally different results is that Verburg et al. (2009) assume full trade liberalisation by 2015, whereas our study assumes it by 2045. Therefore, especially, in Latin America land will be cleared much faster, if trade will be liberalized already 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 liberalization by around 4-5% (mainly due to Brazil), N_2O emissions decrease slightly. In our case the non-CO_2 emission increase is mainly triggered by China and India, whereas Latin America increases only over time but not with more trade liberalisation.

4.3 Model Uncertainty and Gaps

Our modelling approach has the strength of combining environmental and economic aspects and to generate spatially explicit results. However, this comes at the costs of other limitations. First, the implementation of international trade is rather broad. We do not differentiate between specific trade barriers, like quotas, subsidies or tariffs. This would require a detailed incorporation of the different measures, which would overstrain the model especially regarding computing capacity. Second, we have not considered interregional transport costs in this study. However, Biewald et al. (2010) presented an updated version of the MAgPIE model, which includes transport costs between regions.

Besides new simulations regarding changes in the transport sector, it allows MAgPIE to consider transport related emissions. This would lead to further increases of GHG emissions if more trade is allowed. Third, we do not account for indirect effects like the income effect. According to Grossman and Krueger (1993) trade liberalisation increases the average income level, which leads to the demand of more environmental-friendly goods since environment is considered to be a normal good[6]. A second positive effect might be improvement regarding lower emission technology induced by higher income and more international competitiveness (Lucas et al., 2007). Finally, we have not considered any forest protection policies. This will be picked up by a follow-up study.

4.4 Policy Implications

Synthesizing our economic and environmental results brings us to the conclusion that most of the economic benefits of the competitive regions is achieved at the expense of the environment and climate. Latin America reaches its increasing export share by converting large parts of the Amazonian rainforest into cropland at low costs. Only a significant smaller part of its budget is invested in additional technological change. China has almost no additional cropland to convert but it generates globally most of the non-CO_2 emissions. The reason for that lies in its cheap but inefficient livestock system regarding emission efficiency and the rising livestock demand domestically and in its neighbouring countries.

As climate change and trade liberalisation are both negotiated on a global scale, their main objective for future negotiations should be to account for these environmental and climate externalities and impose the related costs on the produced goods. However, since most of the regions, where these costs occur, are developing countries, compensation policies have to be developed or even improved. A positive example is REDD (Reduced emissions from deforestation and forest degradation), where compensation to countries is paid, if they guarantee protection of the rainforest. More of these global deals between developed and developing countries are needed. Another important policy implication is the investment into technological change. Higher productivity will reduce food prices and therefore, the need for converting further forest land into cropland. As discussed in Dietrich et al. (2010b) historical technological change rates have been triggered by R&D investments 15 years earlier and investments into infrastructure. Therefore, governments are advised to invest early into technological change in order to reduce the pressure on land and the environment for future generations.

[6] normal goods are defined in economics as goods, whose demand increases if income rises.

References

Anderson K (1992), “Agricultural Trade Liberalization 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 liberalizing 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 BR and Taylor MS (2001), “Is Free Trade Good for the Environment?”, *American Economic Review*, 91, 877-908.

Biewald A, Schmitz C and Lotze-Campen H (2010): “Transportation costs and bilateral international trade in a global land use model” GTAP Paper 3326, April 2010.

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.

CIESIN, IFPRI,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 MA (2000), “Trade Liberalisation, Economic Growth and the Environment”, New Horizons in Environmental Economics, Cheltenham: Edward Elgar.

Cole MA and Elliott RJR (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 BR and Taylor MS (1994), “North South Trade and the Environment”, *Quarterly Journal of Economics*, 109 755-787.

Copeland BR and Taylor MS (2001), “International Trade and the Environment: A Framework for Analysis”, *National Bureau of Economic Research Working Paper* N. 8540.

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

Dietrich J. P., Schmitz C., Müller C., Fader M., Lotze-Campen M., Popp A. (2010a) "Measuring agricultural land-use intensity." Paper presented at HAWEPA 2010 workshop in Halle, Germany, June 28-29, 2010

Dietrich JP, Schmitz C, Lotze-Campen H, Popp A and Müller C (2010b): “An outlook on agricultural productivity – Implementing endogenous technological change in a global land-use model”, Under revision for *Environmental and Resource Economics*.

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.

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.

Ekins P, Folke C and Costanza R (1994), “Trade, Environment and Development: The Issues in Perspective”, *Ecological Economics*, 9, special issue: 1-12.

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.

Galeotti M and Kemfert C (2004), "Interactions between Climate and Trade Policies", *FEEM Working Paper* No. 88.04, May 2004.

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.

Grossman GM and Krueger AB (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 (2010).

Hao WM, Liu MH and Crutzen PJ (1990), "Estimates of Annual and Regional Release of CO2 and Other Trace Gases to the Atmosphere from Fires in the Tropics", in Goldammer, J. G. (ed.), Fire in the Tropical Biota, Springer-Verlag, Berlin, pp. 440–462.

Hertel TW, Keeney R, Ivanic M and Winters LA (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.

Hinkelman EG (2005): "Dictionary of International Trade: Handbook of the Global Trade Community", World Trade Press, 6th edition, 2005.

Huang H and Labys W (2002), "Environment and trade: a review of issues and methods", *International Journal of Global Environmental Issues* 1,1: 1-62.

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

IPCC (2007): "Climate Change 2007: Mitigation", 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.

Lopez R (1994), “The Environment as a Factor of Production: The Effects of Economic Growth and Trade Liberalization”, *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 PL, van Vuuren DP, Olivier JG and den Elzen MG (2007), “Long-term reduction potential of non-CO2 greenhouse gases”, *Environmental Science and Policy* 10: 85-103.

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

Martin W and Winters LA (eds.) (1996), “The Uruguay Round and the Developing Countries”, Cambridge University Press.

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

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.

Tamiotti L, Olhoff A, Teh 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.

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.

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: Self Sufficiency Ratios

Table 3 and Table 4 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. [7]

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	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	0.17	1.26
LAM	0.70	0.93	0.78	0.94	1.87	0.07	1.92	2.14
MEA	0.58	0.20	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
SAS	0.95	1.01	1	1.04	0.61	0.97	1.04	0.80

Table 3: Self Sufficiency rates for the ten world regions in 1995 (FAOSTAT, 2010) (I)

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

Table 4: Self Sufficiency rates for the ten world regions in 1995 (FAOSTAT, 2010) (II)

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

Appendix B: Export Shares

Table 5 and Table 6 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	maiz	trce	rice	soybean	rapeseed	groundn.	sunfl.	oilpalm	pulses	potato
AFR	-	-	-	-	-	-	0.23	-	-	-	-
CPA	-	0.01	0.03	0.35	-	-	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	0.62	0.99	0.96	0.12	0.59	0.54	0.15	0.21	-	0.44	0.50
PAO	0.09	-	-	0.06	-	-	-	-	-	0.27	-
PAS	-	-	-	0.23	-	-	-	-	1	-	-
SAS	-	0.00	0.01	0.26	-	-	0.13	-	-	-	-

Table 5: 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	-	0.34	0.64	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 6: Export shares for the ten world regions in 1995 (FAOSTAT, 2010) (II)

Appendix C: Validation of Technological Change Rates projected by MAgPIE

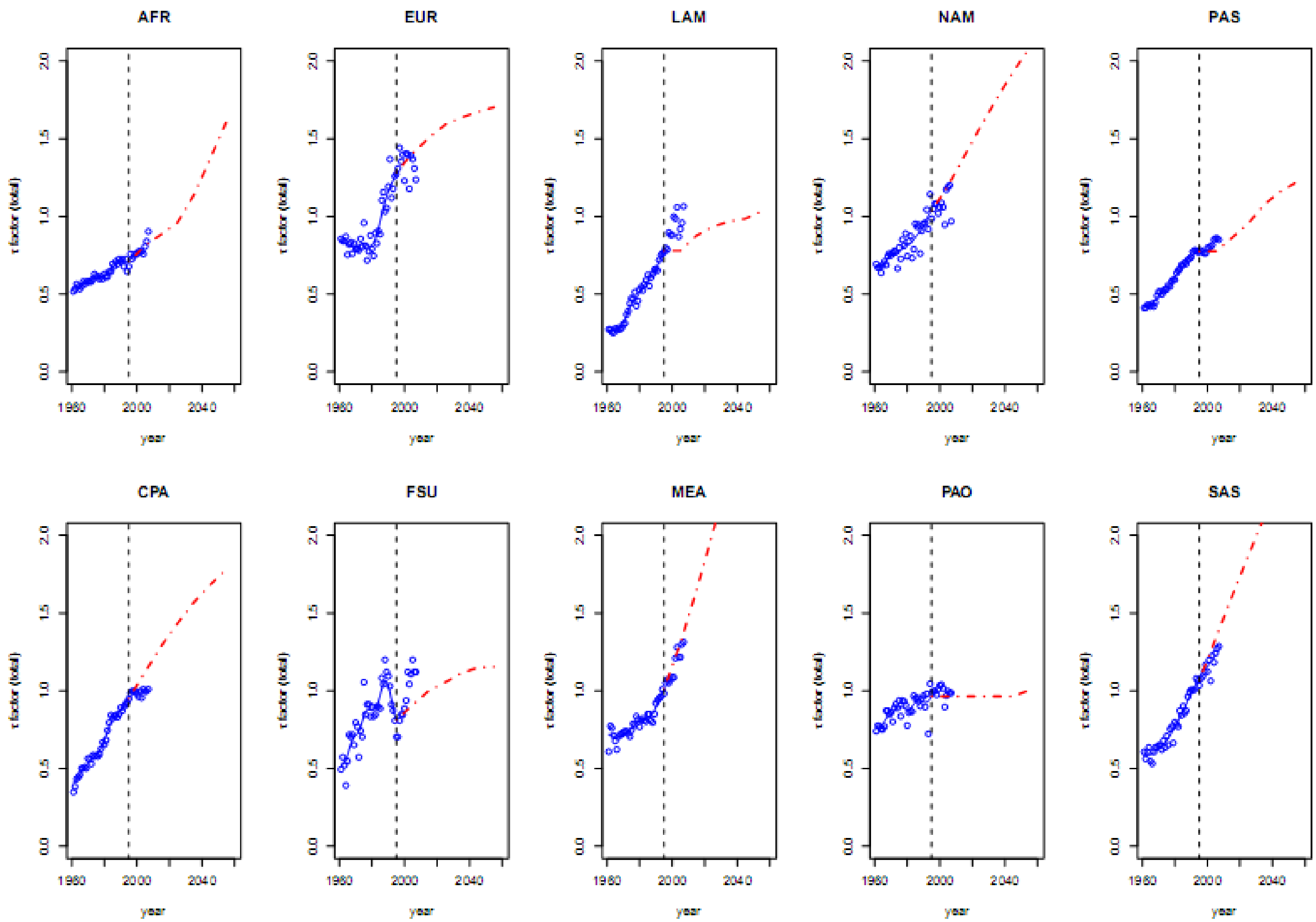

Figure 16: Validation of MAgPIE technological change projections for the ten world regions from 1995-2060 (red chain line) with FAO observations 1960-2005 (blue dots) and its running mean (blue line) (FAOSTAT, 2009)

MAgPIE mathematical description

PIK Landuse Group

March 1, 2011

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

$$X = \{x_t \mid t \in T\} \subseteq \Omega \tag{1}$$

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

$$\forall y \in \Omega : g_t(x_t) \leq g_t(y), \tag{2}$$

where the goal function for $t \in T$

$$g_t(x_t) = g(t, x_t, x_{(t-1)}, ..., x_1, P_t) \tag{3}$$

depends on the solutions of the previous time steps $x_{(t-1)}, ..., x_1$ 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 $\Omega_T = \Omega \times T$.

$$\Omega^{area} = \mathbb{R}^{|J|} \times \mathbb{R}^{|V|} \times \mathbb{R}^{|W|} \tag{5}$$

$$\Omega^{prod} = \mathbb{R}^{|J|} \times \mathbb{R}^{|L|} \tag{6}$$

$$\Omega^{tc} = \mathbb{R}^{|I|} \tag{7}$$

As a result, we may specify the dimension of the solution space for each timestep 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 subdomains. 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.

2 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:

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

3 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.

- $p^{yield}_{t,j,v,w}$: Yield potentials for each time step, each cell, each crop and each water supply type taking only biophysical variations into account and excluding changes due to technological change [ton/ha]
- $p^{dem}_{t,i,k}$: Regional food and material demand in each time step for each product [10^6 ton]
- $p^{fbask}_{i,l,k}$: 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]
- $p^{feed}_{i,l}$: Feed requirements for each livestock product l in each region i [GJ/ton]
- $p^{byprod}_{i,k,l}$: Feed energy delivered by the byproducts of k that are avaiable as feedstock for the livestock product l [GJ/ton]
- $p^{frv}_{i,v}$: Area related factor requirements for each crop and each region based on the technological development level in the initial time step [US$/ha]
- $p^{frl}_{i,l}$: Production related factor requirements for livestock products for each livestock type and each region [US$/ton]
- p^{lcc}_{i}: Area related land conversion costs for each region [US$/ha]
- p^{tcc}: Technological change cost factor accounting for interest rate, expected lifetime and general costs [US$/ha]
- $p^{\tau 1}_{i,v}$: τ-Factor representing the agricultural land use intensity in the first simulation time step for each crop in each region [-]
- p^{exp}: Correlation Exponent between τ-Factor and technological change costs [-]

- $p^{seed}_{i,v}$: Share of production that is used as seed for the next period calculated for each crop in each region [-]

- $p^{xs}_{t,i,k}$: Regional excess supply for each product and each time step describing the amount produced for export [10^6 ton]

- $p^{sf}_{i,k}$: 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^{land}_{j}: Total amount of land available for crop production in each cell [10^6 ha]

- $p^{ir.land}_{j}$: Total amount of land equipped for irrigation in each cell [10^6 ha]

- $p^{watreq}_{j,k}$: Cellular water requirements for each product [$m^3/ton/a$]

- p^{water}_{j}: Amount of water available for irrigation in each cell [$m^3/ton/a$]

- p^{rmax}_{c}: Maximum share of crop groups in relation to total agricultural area [-]

- p^{rmin}_{c}: Minimum share of crop groups in relation to total agricultural area [-]

[all ton units are in dry matter]

4 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:

$$f_{t,i}^{growth}(x_t) = \prod_{\tau=1}^{t} (1 + x_{\tau,i}^{tc}) \tag{8}$$

$$f_{t,i,k}^{prod}(x_t) = \sum_{j_i} \begin{cases} x_{t,j,k}^{prod} & : k \in L \\ \sum_w x_{t,j,k,w}^{area} p_{t,j,k,w}^{yield} f_{t,i}^{growth}(x_t) & : k \in V \end{cases} \tag{9}$$

$$f_{t,i,k}^{dem}(x_t) = p_{t,i,k}^{dem} + \sum_l p_{i,l,k}^{fbask} \left(p_{i,l}^{feed} f_{t,i,l}^{prod}(x_t) - \sum_\kappa p_{i,\kappa,l}^{byprod} f_{t,i,\kappa}^{prod}(x_t) \right). \tag{10}$$

- $f_{t,i}^{growth}$: 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.
- $f_{t,i,k}^{prod}$: 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.
- $f_{t,i,k}^{dem}$: Function defining the demand for product k in region i at timestep t. It consists of an exogenous demand for food and materials $p_{t,i,k}^{dem}$ 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.

5 Goal function

$$g_t(x_t) = g(t, x_t, x_{(t-1)}, ..., x_1, P_t) \tag{11}$$

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:

$$
\begin{aligned}
g_t(x_t) = &\sum_{i,v}\left(p^{frv}_{i,v} f^{growth}_{t,i}(x_t) \sum_{j_i,w} x^{area}_{t,j,v,w}\right) \\
&+ \sum_{i,l}\left(p^{frl}_{i,l} f^{prod}_{t,i,l}(x_t)\right) \\
&+ \sum_{i}\left(p^{lcc}_{i} \sum_{j_i,v,w}\left(x^{area}_{t,j,v,w} - x^{area}_{t-1\,j,v,w}\right)\right) \\
&+ p^{tcc}\sum_{i}\left(x^{tc}_{t,i}\left(\frac{1}{|V|}\sum_{v} p^{\tau 1}_{i,v} f^{growth}_{t,i}(x_t)\right)^{p^{exp}} \sum_{j_i,v,w} x^{area}_{t-1\,j,v,w}\right).
\end{aligned} \tag{12}
$$

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.

6 Constraints

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

6.1 Global demand constraints (for each activity k)

$$
\sum_{i} \frac{f^{prod}_{t,i,k}(x_t)}{1 + p^{seed}_{i,k}} \geq \sum_{i} f^{dem}_{t,i,k}(x_t) \tag{13}
$$

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.

6.2 Tradebalance (for each region i and product k)

$$\frac{f^{prod}_{t,i,k}(x_t)}{1+p^{seed}_{i,k}} \geq p^{tb} \begin{cases} f^{dem}_{t,i,k}(x_t) + p^{xs}_{t,i,k} & : p^{sf}_{i,k} \geq 1 \\ f^{dem}_{t,i,k}(x_t) p^{sf}_{i,k} & : p^{sf}_{i,k} < 1 \end{cases} \tag{14}$$

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.

6.3 Land constraint (for each cell j)

$$\sum_{v,w} x^{area}_{t,j,v,w} \leq p^{land}_{j} \tag{15}$$

$$\sum_{v} x^{area}_{t,j,v,'ir'} \leq p^{ir.land}_{j} \tag{16}$$

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.

6.4 Water constraints (for each cell j)

$$\sum_{v} x^{area}_{t,j,v,'ir'} p^{yield}_{t,j,v,'ir'} f^{growth}_{t,i(j)}(x_t) p^{watreq}_{j,v} + \sum_{l} x^{prod}_{t,j,l} p^{watreq}_{j,l} \leq p^{water}_{j} \tag{17}$$

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 cellular water demand must be less or equal to the water available for production in this cell.

6.5 Rotational constraints (for each crop rotation group c, cell j and irrigation type w)

$$\sum_{v_c} x^{area}_{t,j,v,w} \leq p^{rmax}_c \sum_{v} x^{area}_{t,j,v,w} \tag{18}$$

$$\sum_{v_c} x^{area}_{t,j,v,w} \geq p^{rmin}_c \sum_{v} x^{area}_{t,j,v,w} \tag{19}$$

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 cell.