



Global food efficiency of climate change mitigation in agriculture

By

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Concerns exist regarding potential trade-offs between climate change mitigation in agriculture and food security. Against this background, the Global Biosphere Management Model (GLOBIOM) is applied to a range of scenarios of mitigation of emissions from agriculture to assess the implications of climate mitigation for agricultural production, prices and food availability. The “food efficiency of mitigation” (FEM) is introduced as a tool to make statements about how to attain desired levels of agricultural mitigation in the most efficient manner in terms of food security. It is applied to a range of policy scenarios which contrast a climate policy regime with full global collaboration to scenarios of fragmented climate policies that grant exemptions to selected developing country groups. Results indicate increasing marginal costs of abatement in terms of food calories and suggest that agricultural mitigation is most food efficient in a policy regime with global collaboration. Exemptions from this regime cause food efficiency losses.

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1. Introduction

Manifold linkages exist between agriculture and climate change. On the one hand, the agricultural sector worldwide sees itself affected by climate change. With a view to the future, this implies challenges for the sufficient provision of food and biomass for a growing and more prosperous global population and determines the need for adaptive action (Iglesias, Quiroga, and Diz 2011; IPCC 2014b; Nelson et al. 2010; Stern 2007). On the other hand, the agricultural and land use sector also is an important contributor to climate change, accounting for almost one quarter of anthropogenic greenhouse gas (GHG) emissions (IPCC 2014a). Thus, agriculture necessarily has to be an integral part of any global strategy for climate change mitigation. Since mitigation potential in agriculture and land use not only lies in the reduction of emissions but also in the enhancement of GHG sequestration, the sector plays a particular role in such a strategy (IPCC 2014a; Smith et al. 2013).

At the same time, requirements for climate change mitigation may constitute an additional burden to the agricultural sector and limit the potential for the necessary expansion of food and biomass supply and the continued support of rural livelihoods in the decades ahead (Smith et al. 2013; Valin et al. 2013). Of particular concern is the impact of climate policy regimes involving the agricultural sector on food security in vulnerable regions of the world (FAO 2009).

Against this background, the present analysis seeks to shed light on the trade-off between climate change mitigation in agriculture on the one hand and food security on the other hand. To pursue this objective, the Global Biosphere Management Model (GLOBIOM, Havlik et al., 2014a) is applied to a range of scenarios of agricultural mitigation. Global GHG abatement requirements that are consistent with a selected shared socioeconomic pathway (SSP) and representative concentration pathways (RCPs) of the new scenario framework for climate change research (O'Neill et al. 2014) are calculated and the implications of climate mitigation for agricultural production, food prices and food availability are assessed. The “food efficiency of mitigation” (FEM) is introduced as a measure for the assessment of the trade-off between agricultural mitigation and food security and applied to a range of policy scenarios which contrast a climate policy regime with full global collaboration to scenarios of fragmented climate policies that grant exemptions to selected developing and emerging economy country groups. The FEM is proposed

as a tool to make statements about how to attain desired levels of agricultural mitigation in the most efficient manner in terms of food security. It is actually a mirror measure of the Total Abatement Calorie Cost (TACC) curves proposed by Havlík et al. (2014).

The paper proceeds with a short overview on the GLOBIOM model, followed by a section that introduces the FEM measure. The subsequent Section 3 describes the scenarios of climate mitigation and climate policy that are analyzed, focusing first on a set of standard scenarios and second on scenarios with policy exemptions for developing and emerging country regions. The results are presented in Section 4, dealing first with the effects of climate policy on agricultural mitigation and food production. A second part of the results section discusses the trade-offs between mitigation and food security under the different policy regimes. A final section presents a short summary and concludes.

2. Method

2.1. Modeling approach

For the present analysis we apply the Global Biosphere Management Model (GLOBIOM) (Havlík et al. 2011, 2014). GLOBIOM is a partial equilibrium model of the global agricultural and forestry sectors that has been used extensively for analyses of future trends in the world agriculture and food sector (Mosnier et al. 2014; Schneider et al. 2011), bioenergy and biofuels (Frank et al. 2013; Havlík et al. 2011; Kraxner et al. 2013; Mosnier et al. 2013) and climate change and GHG mitigation (Cohn et al. 2014; Havlík et al. 2013; Havlík et al. 2014; Mosnier et al. 2013; Valin et al. 2013). A detailed description of the model can be found in Havlík et al. (2011) and Havlík et al. (2014), here we just highlight the most important aspects for the present study. In GLOBIOM, crop and livestock production are represented with a high spatial resolution at the level of Simulation Units (SimU) going down to 5x5 minutes of arc, which depict different production and management systems, differences in natural resource and climatic conditions as well as differences in cost structures and input use. Here, these units are aggregated to 2x2 degrees. The model explicitly covers 18 major crops that together represent over 70% of harvested area and 85% of vegetal calorie supply. Crops are produced in four management systems whose input structure is defined by Leontieff production functions and which are parameterized using the Environmental Policy Integrated Model (EPIC) model (Williams and

Singh 1995). The crop sector supplies food products and feed for livestock. In the livestock sector, four species aggregates (bovines, small ruminants, pigs, and poultry) are distinguished. Ruminants can be produced in eight alternative production systems and monogastrics in two. For each species, production system and SU, livestock production is characterized in terms of yields, feed requirements, GHG emissions, manure production and nitrogen excretion (Havlík et al. 2014). The parameterization of the livestock sector is done with the RUMINANT model (Herrero et al. 2008; Herrero et al. 2013). The forestry sector represents the source for logs (for pulp, sawing and other industrial uses), biomass for energy, and traditional fuel wood, which are supplied from managed forest or short rotation plantations (SRP).

Demand in GLOBIOM is modeled at the level of aggregate economic regions and income elasticities are calibrated to mimic projections of the Food and Agriculture Organization of the United Nations (Alexandratos and Bruinsma 2012). Prices are endogenously determined at the regional level to establish market equilibrium to reconcile demand, domestic supply and international trade. The latter is included in the model following a spatial equilibrium modeling approach which depicts bilateral trade flows between regions based on a simple criterion of cost competitiveness (Takayama and Judge 1971; Schneider, McCarl, and Schmid 2007).

Land and other resources are allocated to the different production and processing activities to maximize a social welfare function which consists of the sum of producer and consumer surplus (Havlík et al. 2014). Changes in socioeconomic and technological conditions, such as economic growth, population changes, and technological progress, lead to adjustments in the product mix and the use of land and other productive resources. By solving the model in a recursive dynamic manner for 10 year time steps, decade-wise detailed trajectories of variables related to supply, demand, prices, and land use are generated. The simulation period is from 2000 to 2050.

GLOBIOM provides for a detailed representation of the relevant GHG emissions from agricultural production, land use change (LUC), and from the bioenergy sector. In crop production, emissions of Nitrous Oxide (N_2O) from the application of synthetic fertilizer to soils as well as methane (CH_4) from flooded rice cultivation are considered. Emissions from livestock production include N_2O and CH_4 from the management and application of manure and CH_4 from enteric fermentation. Emissions from LUC include emissions of Carbon Dioxide (CO_2)

originating from the conversion of land between the different land use types as well as carbon sequestration from the establishment of SRPs¹. With respect to the bioenergy sector, CO₂ from biofuels processing is taken into consideration. For each emissions account, specific coefficients are defined at the SU level. With this approach it is possible to trace and determine emissions that arise from changes in cropping area and livestock numbers, changes in the crop and livestock production systems, the location of production, and LUC that occur in response to exogenous socioeconomic and technological drivers.

For the current analysis, a regional aggregation of 30 economic regions has been chosen, corresponding to earlier applications of the model to climate change and GHG mitigation (Havlík et al. 2013; Havlík et al. 2014; Valin et al. 2013). For the scenario analysis as described below, GLOBIOM uses inputs of biomass demand for bioenergy production and GHG emissions prices (carbon prices) from the MESSAGE energy system model (Riahi et al. 2011).

2.2. Food efficiency of climate change mitigation

To address the objective of the present analysis of assessing the cost of climate change mitigation under alternative policy regimes in terms of food security we refer to the traditional economic concept of efficiency and propose the “food efficiency of mitigation” as a main measure for the analysis.

In production economics, efficiency in most general terms is defined as the ratio of outputs over inputs

$$E = \frac{Q}{I} \tag{1}$$

where E is efficiency, Q is the quantity of output produced and I is the quantity of input used.

For the application of this general concept to the analysis of climate change mitigation and food security, the output of interest is the quantity of GHG that is abated in a specific climate policy scenario compared to a reference without any climate policy. The quantity of input is the loss in available food calories, i.e. the difference between the calorie availability in a scenario with

¹ In detail, the emissions accounts related to LUC comprise CO₂ from the conversion of grassland, natural land or forest to cropland, of natural land and forest to grassland, and the afforestation of cropland, grassland or natural land to SRPs.

climate policies and the calorie availability without such policies. In general terms, this measure can be expressed as

$$FEM_c = \frac{QA}{CC} = \frac{QE_{REF} - QE_c}{QF_{REF} - QF_c} \quad (2)$$

In (2), the food efficiency of mitigation (FEM_c) for any climate policy scenario c is the quotient of the quantity of GHG abated QA and the cost in terms of food calories CC . QE is the amount of GHG emissions in the reference scenario REF and a scenario c with mitigation policies. QF is the amount of food calories available under the respective scenarios.

For the specific case of an assessment with multiple emission producing sectors, regions and time periods as provided by the GLOBIOM model, we calculate a global measure FEM_c :

$$FEM_c = \frac{\sum_{t=1}^T \sum_{r=1}^R \sum_{s=1}^S (QE_{r,s,t,REF} - QE_{r,s,t,MITIG})/T}{\sum_{t=1}^T (\sum_{r=1}^R QF_{r,t,REF} / \sum_{r=1}^R POP_r - \sum_{r=1}^R QF_{r,t,MITIG} / \sum_{r=1}^R POP_r) / T} \quad (3)$$

In (3), the sum of abatement over all emission producing sectors s and regions r , is averaged over the number of time periods T and divided by the difference in the global food calories per capita between the climate policy scenario c and the reference scenario. Per capita food calories for both scenarios are calculated as the absolute levels of calories available QF divided by the population POP . Taking the units of measurement as used in the analysis, FEM_c thus is the food efficiency of mitigation in $GtCO_2eq/Kcal \times Cap^{-1}$.

3. Scenarios

Two sets of scenarios have been designed. The first set generates the emissions pathways that are consistent with different RCPs for a selected socioeconomic development path. A second set of simulations is carried out to assess the effects of exemptions from mitigation action for four selected groups of developing and emerging economies, namely the BRICS group of countries, a group of humid tropical forest basin countries, the group of least developed countries (LDC) and all developing economies (DC).

3.1. Standard Scenarios

The standard scenarios offer insights into the extent of mitigation from the GHG abatement from the agricultural and land use sector that is required to meet different future climate mitigation targets under a given socioeconomic development pathway. For the socioeconomic development pathway, a scenario of the family of shared socioeconomic pathways (SSPs) that has been developed as part of the new scenario framework for climate change research (O'Neill et al. 2014) has been selected. The SSP chosen for the analysis is SSP 2 "Middle of the Road". The emissions ceilings that are given as climate mitigation targets correspond to five representative concentration pathways (RCPs) that form part of the same scenario framework (Moss et al. 2010). The RCPs included in the analysis are RCP 2.6, RCP 3.7, RCP 4.5 and RCP 6.0. These RCPs reflect year-2100 radiative forcing values from 2.6 to 6.0 W/m² (Vuuren et al. 2011). In addition, a fifth RCPRef represents a pathway in which, akin to RCP 8.5 with a radiative forcing of around 8.5 W/m² in 2100, no climate policies are implemented.

SSP 2, also called "Middle of the Road", describes a business-as-usual development pathway with middle challenges to adaptation and mitigation (O'Neill et al. 2012). SSP 2 has moderately high population growth up to around 9.2 bn people by 2050, a peak of around 9.3 bn people by 2070, and a weak decline to 8.8 bn thereafter. GDP growth is moderate with a compound annual growth rate of about 2.5%. For food demand, elasticities are calibrated such that the trajectories for this pathway follow projections by FAO up to 2050 (Alexandratos and Bruinsma 2012). Demand for animal protein is relatively high, due to comparatively strong income and population growth. Moderate reductions in food waste and losses over time add to the availability of agricultural products.

On the agricultural production side, crop yields and livestock feed conversion efficiencies are assumed to increase at a medium pace in line with past trends. Fertilizer use and costs of agricultural production increase in proportion with yields. Transition towards more efficient livestock production systems takes place at a moderately fast pace.

The drivers of climate change mitigation that are differentiated by the RCPs used in GLOBIOM include trajectories of demand for solid biomass for bioenergy production and prices for CO₂ emissions from agriculture and LUC (Figure 1). The quantities of biomass demand are obtained

from the MESSAGE energy system model (Riahi et al. 2011). Both biomass demand and emissions prices are consistent with pathways of the global energy and emissions price regimes required for attaining the individual RCPs. The policy assumption implicit to these scenarios is one of full global collaboration in where a global carbon price regime is established to limit emissions to the necessary levels to achieve a given RCP. All countries participate in this regime from the onset.

The pathways of biomass demand for energy production generally follow the order of the stringency of the limits to radiative forcing that correspond to each RCP (Figure 1, panel (a)). RCPs with higher limits on radiative forcing imply higher demands for biomass since the use of bioenergy forms an integral part of a low-carbon energy strategy (Vuuren et al. 2011). The final levels of bioenergy demand in terms of primary energy in 2050 range between 51.1 EJ for RCPRef and 101.5 EJ for RCP 2.6.

[Figure 1 about here]

In GLOBIOM, demand for biomass for bioenergy has a direct effect on cultivated area. Higher demand for energy biomass from managed forests leads to increased forest area related to increasing afforestation efforts and the development of short rotation plantations. Regional increases in bioenergy demand change the development of short rotation plantations in the respective areas. The level of total demand for solid biomass in addition affects deforestation, the use of solid non-commercial biomass and trade flows.

Emissions prices vary according to the RCP (Figure 1, panel (b)) and increase from RCP 6.0 to RCP 2.6. By 2050, the emissions price for RCP 6.0 is low, at around 2 USD. For RCP 2.6, which requires substantially the most ambitious emissions reductions, the price in 2050 is 100 USD.

In the model, emissions prices drive up the costs of emissions and the benefits from carbon sequestration. Higher costs of emissions and demand for land for biomass production and afforestation set incentives to reduce areas of production of the crops associated with emissions, or to decrease animal numbers and slow down LUC, thus triggering adjustments in the food system.

3.2. Scenarios of exemptions from mitigation action for selected developing and emerging country regions

In addition to the standard scenarios of GHG mitigation that describe a policy scenario of full global cooperation for the different RCPs, a second set of scenarios are simulated that aim to test the effects of exemptions for particular groups of countries from mitigation action. In the formulation of these scenarios, we follow general guidelines for generic Shared Policy Assumptions (SPAs) for the land use sector that have been formulated for the integrated assessment modeling of shared socio economic pathways (Anonymous 2014). We implement a policy assumption that considers that all pricing of land use emissions follows the levels of carbon prices in the energy sector. However, the setting of carbon prices in the energy sector follows a sequence of fragmentation, accession and cooperation in which single groups of countries opt out from a global carbon price regime before they join following a transition period². The general rule for the exemption from carbon prices is that countries which have a per capita income of 12,600 USD or higher (i.e. high-income economies according to the World Bank's country classification) by 2020 participate in the global carbon price regime with a period of linear transition up to 2040. Countries with per capita incomes below that threshold start the transition toward the global carbon price in 2030 and follow a linear transition path up to 2050, when the global carbon price level is reached.

For our analysis, we focus on four country groups: the BRICS, humid tropical forest basin countries, the group of least developed countries (LDC), and the group of all developing countries (DC). The BRICS comprise the emerging economies of Brazil, Russia, India, China, and South Africa. Humid tropical forest basin countries include Brazil as the most important country of the Amazon Basin, the Congo Basin (Cameroon, Central African Republic, Democratic Republic of the Congo, Republic of the Congo, Equatorial Guinea, and Gabon) and countries of South East Asia (Malaysia, Indonesia, Philippines, Papua New Guinea). For the LDC and DC, the respective country lists of the United Nations are used^{3 4}. For the four country

² This assumption broadly corresponds to the F3 SPA for the fossil fuels and energy sectors combined with the LP SPA for the land use sector as described in Anonymous (2014).

³ The complete list can be accessed at http://www.un.org/en/development/desa/policy/cdp/lcd/lcd_list.pdf.

⁴ Due to the regional aggregation of the GLOBIOM model, the country groups for which the simulations are implemented differ from the above lists as follows: BRICS as above plus Armenia, Azerbaijan, Belarus, Georgia, Kazakhstan, Kyrgyzstan, Moldova, Tajikistan, Turkmenistan, Ukraine, and Uzbekistan; South East Asia as above plus Brunei Darussalam, Myanmar, Singapore, Thailand, Timor Leste, Fiji,

groups, scenarios with exemptions from mitigation action are designed following the general guidelines outlined above. Within each group, countries are classified according to their income level, taking the scenario of country level purchasing power parity GDP of the OECD for SSP2 as the reference (Anonymous 2012). Countries/regions that have reached high-income economy status by 2020, have carbon prices of zero up to 2020, apply half the 2040 price during the decade of 2030 and reach the full level of the global carbon price by 2040. Compared to other countries, which apply the full global carbon price, this means a later start of implementation and a lower price level during the transition period in the 2030s. Countries that have not attained the status of a high-income economy by 2020 maintain a carbon price of zero up to 2030, when they start joining the global regime. Carbon prices in the 2040 decade are at half the level of the 2050 prices. By 2050, these countries also apply the global price. This approach implies that the countries of this group are exempt from the global carbon price regime for a longer time and apply lower prices than the global level during their transition period from 2030 to 2050.

For the BRICS group and the humid tropical forest basin countries, two individual blocks of scenarios are designed. In the BRICS group, Brazil, China, Russia and South Africa apply carbon prices according to the scheme for high-income economies. India, as an upper-middle-income economy in 2020, applies carbon prices according to the second scheme. In the group of humid tropical forest basin countries, Brazil falls under the high-income economy regime. For the Congo Basin and the countries of South East Asia, the more delayed accession to the global carbon price is applied. For the LDC group, all countries will remain low income countries by 2020 and hence apply carbon prices of the second scheme. All other regions of the world are subject to a carbon price according to the standard scenarios.

Results from the simulations of all RCPs for the four country groups are contrasted to the standard scenarios to answer the principal questions about the effects of regional exemptions from mitigation action on the abatement of GHG emissions from agriculture and LUC, on the costs of abatement in terms of food calories, and on the food efficiency of climate mitigation under alternative policy regimes.

French Polynesia, New Caledonia, Samoa, Solomon Islands, and Vanuatu. LDCs are the GLOBIOM regions of Congo Basin, Rest of South Asia (RSAS), South East Asia-Pacific (RSEA_PAC), Eastern Africa, Southern Africa, and Western Africa. See Table 1.A. in the Annex for a detailed list of GLOBIOM regions.

4. Results

4.1. Agricultural mitigation, and food production

At the world level, policy efforts for climate change mitigation in the agricultural and land use sector lead to demands for GHG abatement, i.e. the reductions in emissions in the policy scenario relative to the emissions amount in the reference scenario, that start from 3.0 GtCO₂eq/yr on average for the period from 2020-2050 under RCP 6.0 and reach up to 10.1 GtCO₂eq/yr under RCP 2.6 (see the four left columns of Figure 2). This compares to current annual emission from agriculture, forestry and other land use (AFOLU) of around 10-12 GtCO₂eq/yr (Smith et al. 2014). Regarding the contribution of individual emissions sources to global abatement, the different types of LUC (deforestation for crop land and grassland, afforestation of cropland and grassland to short rotation plantations (SRPs), other LUC) which are marked by the green sections of the bars in Figure 2, make up for the highest shares. These shares range from 91% under RCP 2.6 to 98% under RCP 6.0. The high shares of abatement of LUC emissions can be explained by the comparatively low cost of GHG emissions reduction from the associated sources as compared to the higher cost of abatement of emissions from sources related to agricultural or livestock production. Accordingly, the required contributions to abatement from crop and livestock production at the global level are much lower, ranging between around 0% in RCP 6.0 and 1 and 8 % in RCP 2.6, respectively. The contribution of crop and livestock production, however, increases with the stringency of the mitigation targets. This suggests rising marginal costs of LUC abatement and increasing cost competitiveness of emissions reductions in agricultural production once mitigation demands get higher.

[Figure 2 about here]

The required levels of abatement for the four country groups at the focus of the analysis follow the pattern already observed at the global level: Abatement demands are lowest under RCP 6.0 and increase when moving towards RCP 2.6. Also, mitigation of emissions from LUC contributes the highest share to total abatement in the regions. Differences exist; however, in the contribution of crop and livestock production total abatement, in particular for the tighter emissions ceilings under RCP 2.6. In the BRICS countries, crop and livestock production account for 1.3 and 14% of total abatement, respectively. These comparatively high shares owe

themselves mostly to a low potential for the reduction of emissions from deforestation in China and India. In both countries, reduction of CH₄ from rice production is important. In contrast, as a consequence of the high potential to halt deforestation in the tropical areas the share of LUC abatement is disproportionately high in the tropical forest basin countries. The LDC occupy middle ground in terms of the composition of abatement.

During the period from 2020 to 2050, agricultural supply increases for the world as a whole and for the regions under consideration (Figure 3). Global supply of crop products is around 2 bn tons higher in 2050 than in 2020 in the scenario without any climate change mitigation efforts (RCPref). This corresponds to an increase by 31% during that period. Global livestock supply rises by 0.6 bn tons between 2000 and 2050, which is an increase by 26%.

Figure 3, however, also illustrates that GHG mitigation in the agricultural sector goes hand in hand with negative impacts on the supply of farm products. When moving towards more stringent mitigation targets, the supply increase from 2000-2050 is dampened for the world as a whole and for the four regions under consideration. This reflects both the increasingly stringent restrictions on LUC as well as the higher taxes on emissions from agricultural production. At this, the effects on the livestock sector are more pronounced. This is a consequence of the high emissions intensity of livestock production compared to crop production and the correspondingly strong impact of mitigation policies on that sector.

[Figure 3 about here]

Stringent mitigation targets also neutralize the price reducing effects of supply increases. Increasing productivity and the expansion of agricultural area lead to reductions in prices for both crop and livestock products from the 2020 decade onwards for all scenarios but RCP 2.6 and RCP 3.7 (Figure 4). Under RCP 3.7, prices of livestock products increase slightly towards 2050, as reflected by an increase in the price index from 1.04 to 1.07. Under RCP 2.6, both crop and livestock prices show pronounced increases to index levels of 1.11 and 1.22, respectively, by 2050.

[Figure 4 about here]

4.2. Food security tradeoffs under alternative policy regimes

The preceding discussions show that there is a tradeoff between climate change mitigation and food security. While the agricultural sector clearly holds substantial potential to contribute to achieving global mitigation targets and to operate even under stringent emissions ceilings, this comes at the cost of reductions in food production when compared to a scenario without climate change mitigation efforts.

Havlík et al. (2014) provided a first rigorous assessment of the trade-offs between mitigation in AFOLU and food availability within their framework of TACCs. Here, we reverse the two axis, and put the calorie cost on the x-axis and the GHG abatement on the y-axis, to have another look on this important issue. Figure 5 puts the quantities of GHG abated against the loss in food calories available per capita and day for the different mitigation targets. The solid line in the figure shows the results for the standard scenario in which all countries participate in a global climate policy regime. The remaining lines represent abatement and calorie costs for the different policy scenarios, where the BRICS, the tropical forest basin countries, the LDC or the DC do not participate in the regime.

[Figure 5 about here]

As a first observation, a large quantity of abatement can be achieved at a relatively low calorie cost. Abatement levels as required for RCP 4.5, at around 11 GtCO₂eq/yr require only calorie losses of around 20 Kcal/cap/day at the global level. Moving from RCP 4.5 (~11.0 GtCO₂eq/yr) to RCP 3.7 (~ 13.0 GtCO₂eq/yr), however, doubles calorie cost and going from RCP 3.7 to RCP 2.6, which requires an additional abatement of around 2 GtCO₂eq/yr, increases calorie cost to almost 115 Kcal/cap/day. This implies that additional abatement beyond a certain level comes at an increasing marginal cost in terms of food calories. The corollary of this interpretation is that there are diminishing returns to scale in agricultural mitigation.

A principal reason for the diminishing returns to scale can already be found in the discussions above: Low levels of mitigation can be achieved by reducing emissions from LUC, which is less costly in terms of food calories. At higher levels of mitigation, however, the contribution of reduction in emissions from agricultural sources becomes more important. This requires adjustments in production practices, i.e. the shift towards production systems with lower

emissions intensities per unit of output produced, but mainly reductions in cropping areas and livestock numbers. The consequences of these adjustments are stronger reductions in food supply and higher calorie costs per unit of GHG.

The results for the scenarios for more fragmented climate policy regimes as represented by the remaining lines in Figure 5 show that in general the standard scenario of global policy cooperation provides an envelope for scenarios in which selected regions do not participate. At a given food calorie loss, levels of abatement are lower, which means that calorie costs per unit of abated GHG are higher. Thereby, there are clear differences between the different policy scenarios. The BRICS scenario comes closest to the optimal case of a global policy, followed by the tropical forest basin countries and the LDC. The scenario with exemptions for the DC shows the strongest shortfall in abatement per calorie cost.

The reasons for the differences between the scenarios can be found in the design of the policy scenario and in the size of the contribution to global abatement of the non-participating region in the standard scenario. With respect to policy design, scenarios in which countries phase in the global emissions price at a later point in time, i.e. scenarios with many and large low-income countries fall further below the standard scenario. The scenarios for the tropical forest basin countries and the LDC represent examples. With respect to the potential contribution to global abatement, higher potential abatement leads to higher abatement loss for each level of calorie costs when a country or region does not participate in the global regime.

Figure 6 provides an interpretation of Figure 5 in terms of the food efficiency. It shows the food efficiency of mitigation for the different levels of abatement imposed by the mitigation targets of different stringency for the different RCPs. The solid line once more represents the standard scenario with full global climate policy collaboration. At less stringent climate policies as for RCP 4.5, marked by the black triangle in the figure, mitigation can be achieved at a relatively high food efficiency of around $0.5 \text{ GtCO}_2\text{eq/Kcal}\times\text{Cap}^{-1}$. This level of food efficiency, however, declines quickly as mitigation demands become stronger. Mitigation for RCP 2.6 in the standard scenario, marked by the black circle in the figure, has a food efficiency of only around $0.13 \text{ GtCO}_2\text{eq/Kcal}\times\text{Cap}^{-1}$. This again illustrates the abovementioned rising marginal food cost of climate change mitigation.

[Figure 6 about here]

The comparison of the standard scenario with the scenarios in which selected country groups do not take part in mitigation action highlight the food efficiency losses caused by fragmentation in the climate policy regime. The subsequent inward shifts of the curves against the standard scenario show that the BRICS scenario has the lowest food efficiency losses, followed by the humid tropical forest basin countries and the LDC. The DC scenario is the least efficient one. The ordering of the scenarios with respect to food efficiency is once more determined by the extent of the policy exemptions with respect to timing and geographical coverage and by the abatement potential of the non-participating country groups.

A vertical comparison of food efficiency across the interpolated lines for each policy scenario at a given level of abatement allows quantifying the losses in food efficiency. At an abatement level consistent with RCP 4.5, for example, policy exemptions for the BRICS reduce the FEM to around $0.47 \text{ GtCO}_2\text{eq/Kcal}\times\text{Cap}^{-1}$. When the humid tropical forest basin countries do not participate, the FEM declines to about $0.41 \text{ GtCO}_2\text{eq/Kcal}\times\text{Cap}^{-1}$ and the exemptions for the LDC would cause a reduction to around $0.16 \text{ GtCO}_2\text{eq/Kcal}\times\text{Cap}^{-1}$. In the DC scenario, the FEM for RCP 4.5 abatement would go towards zero. As the mitigation targets become more stringent and the FEM even of the standard scenario becomes low, the FEM with policy exemptions are even below those levels. In the extreme case of RCP 2.6, which can only be assessed with the present results by extrapolating the lines towards the bottom right of Figure 6, FEM are consistently below $0.10 \text{ GtCO}_2\text{eq/Kcal}\times\text{Cap}^{-1}$.

5. Summary and conclusions

The present analysis proposed the food efficiency of mitigation (FEM) as the mirror measure to the total abatement calorie cost (TACC) curves for the assessment of the trade-off between climate change mitigation in agriculture and food security. It has been shown that climate change mitigation in agriculture is most food efficient in a policy regime with global collaboration. Exemptions from this regime cause food efficiency losses which increase as the number of countries that do not take mitigation action gets larger. Most notably, in the combined scenario, which is comparable to a regime in which only the Annex 1 countries of the UNFCCC participate, and for mitigation targets consistent with RCP 3.7 or RCP 2.6, food efficiency goes

towards zero. This implies that in such a scenario, climate change mitigation in the agricultural and land use sector can only be achieved at high food calorie costs. Thus, from a food efficiency point of view a global climate policy framework which includes all countries of the world but which has more modest mitigation targets may be preferable to a more ambitious policy pursued by only a few countries or regions.

As a second best solution in the case a global accord is out of reach, the FEM approach can help identifying those countries or regions which should be included in a less comprehensive agreement. The present analysis already showed that food efficiency losses from policy exemptions tend to be highest for regions with generally high potentials for abatement and with a high contribution of emissions reductions from land use change to total abatement. A more thorough analysis would establish a ranking of regions based on region specific food efficiency losses derived from the calculation of FEM for a series of scenarios with exemptions for individual regions. Such analysis is subject for future research.

An additional aspect worth noting is that average food calorie costs of mitigation at the global level tends to be modest for the simulated scenarios, even in case of the most stringent mitigation targets. The calorie cost of around 115 kcal/cap/day of mitigation for RCP 2.6 in the standard scenario account for only 7.5% of a diet of 2000 kcal/day. It has been shown, however, that calorie costs can increase sharply when there is no global collaboration in climate policies. Further, the global figures conceal differences between regions with respect to calorie costs on the one hand and the point of departure of food availability of individual regions on the other hand. For regions with already high food availability (e.g. USA or Canada with around 3600 kcal/cap/day) calorie reductions of the scale as presented in Figure 5 would be negligible. In presently food insecure regions like the Congo Basin or Eastern Africa the described calorie costs may weigh more heavily.

The analysis also only deals with food availability. Other dimensions of food security like access, utilization, and stability (FAO, 2006) are not taken into consideration. One implication is that reductions in food availability from climate change mitigation can be counteracted by improvements in the other dimensions of food security. This is especially valid in situations which are characterized by moderate levels of average food availability but limited food access by vulnerable population groups. Specific support to these groups would help cushioning

negative impacts of climate mitigation. Since this analysis is carried out at an aggregated level and does not include dimensions of food security other than availability, however, it should be complemented by more detailed examinations at a more disaggregate sub-national level to make more precise statements.

A further extension to the analysis would be to consider not only exemptions from the global carbon price, but also from bioenergy policy. Exemptions from bioenergy policy, i.e. the obligation to provide determined levels of biomass as part of a low-carbon strategy for the energy sector, along with exemptions from the carbon price would accentuate the results both with respect to larger abatement shortfalls and stronger reductions in calorie costs.

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Annex: List of GLOBIOM regions

Table A.1: List of GLOBIOM regions

Macro region (MESSAGE)	Region (GLOBIOM)	Country
Central and Eastern Europe	EU_CentralEast	Bulgaria, Czech Republic, Hungary, Poland, Romania, Slovakia, Slovenia
	RCEU	Albania, Bosnia and Herzegovina, Croatia, Macedonia, Serbia and Montenegro
Western Europe	EU_MidWest	Austria, Belgium, France, Germany, Luxembourg, Netherlands
	EU_North	Denmark, Finland, Ireland, Sweden, United Kingdom
	EU_South	Cyprus, Greece, Italy, Malta, Portugal, Spain
	ROWE	Greenland, Iceland, Norway, Switzerland
	TurkeyReg	Turkey
Former Soviet Union	EU_Baltic	Estonia, Latvia, Lithuania
	Former_USSR	Armenia, Azerbaijan, Belarus, Georgia, Kazakhstan, Kyrgyzstan, Moldova, Russian Federation, Tajikistan, Ukraine, Uzbekistan
Latin America and the Caribbean	BrazilReg	Brazil
	MexicoReg	Mexico
	RCAM	Bahamas, Belize, Costa Rica, Cuba, Dominican Republic, El Salvador, Guadeloupe, Guatemala, Haiti, Honduras, Jamaica, Nicaragua, Panama, Trinidad and Tobago
	RSAM	Argentina, Bolivia, Chile, Colombia, Ecuador, Falkland Islands, French Guyana, Guyana, Paraguay, Peru, Suriname, Uruguay, Venezuela
North America	CanadaReg	Canada
	USAREg	Puerto Rico, USA
Middle East and North Africa	MidEastNorthAfr	Algeria, Bahrain, Egypt, Iran, Iraq, Israel, Jordan, Kuwait, Lebanon, Libya, Morocco, Oman, Palestine, Qatar, Saudi Arabia, Syria, Tunisia, United Arab,

Macro region (MESSAGE)	Region (GLOBIOM)	Country
		Emirates, West Sahara, Yemen
Sub Saharan Africa	CongoBasin	Cameroon, Central African Republic, DR Congo, Republic of the Congo, Equatorial Guinea, Gabon
	SouthAfrReg	South Africa
	EasternAf	Burundi, Ethiopia, Kenya, Rwanda, Tanzania, Uganda
	SouthernAf	Angola, Botswana, Comoros, Lesotho, Madagascar, Malawi, Mauritius, Mozambique, Namibia, Reunion, Swaziland, Zambia, Zimbabwe
	WesternAf	Benin, Burkina Faso, Cape Verde, Chad, Cote d'Ivoire, Djibouti, Eritrea, Gambia, Ghana, Guinea, Guinea Bissau, Liberia, Mali, Mauritania, Niger, Nigeria, Senegal, Sierra Leone, Somalia, Sudan, Togo
Pacific OECD	ANZ	Australia, New Zealand
	JapanReg	Japan
Planned Asia and China	ChinaReg	China
	RSEA_PAC	Cambodia, DPR Korea, Laos, Mongolia, Vietnam
South Asia	IndiaReg	India
	RSAS	Afghanistan, Bangladesh, Bhutan, Nepal, Pakistan, Sri Lanka
Other Pacific Asia	Pacific_Islands	Fiji Islands, French Polynesia, New Caledonia, Papua New Guinea, Samoa, Solomon Islands, Vanuatu
	RSEA_OPA	Brunei Darussalam, Indonesia, Malaysia, Myanmar, Philippines, Singapore, Thailand, Timor Leste
	SouthKorea	Republic of Korea

Figures

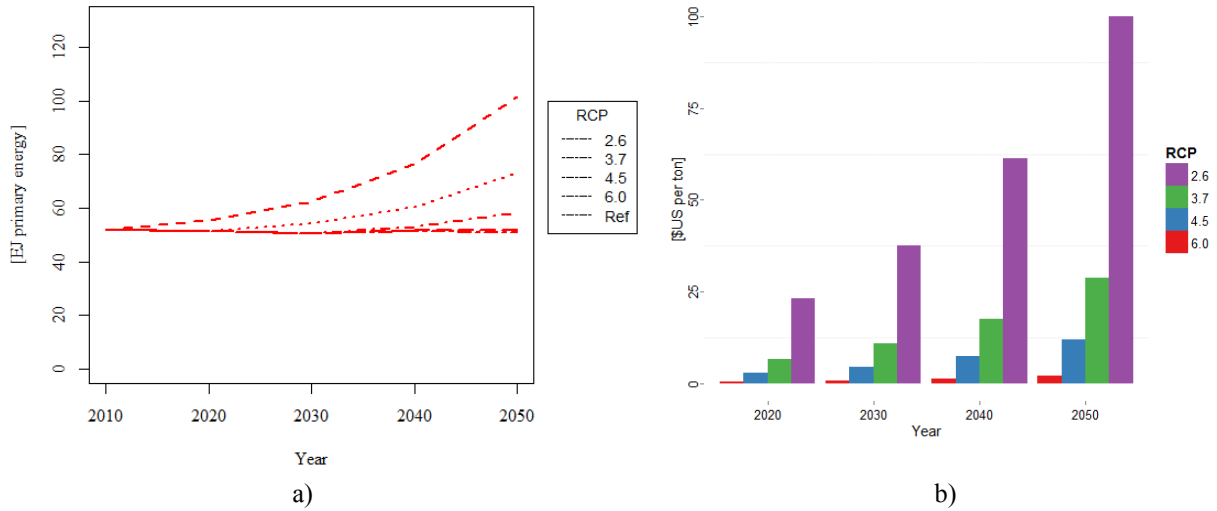


Figure 1: Drivers of climate change mitigation by RCP, SSP 2: (a) total biomass demand and (b) CO₂ price.

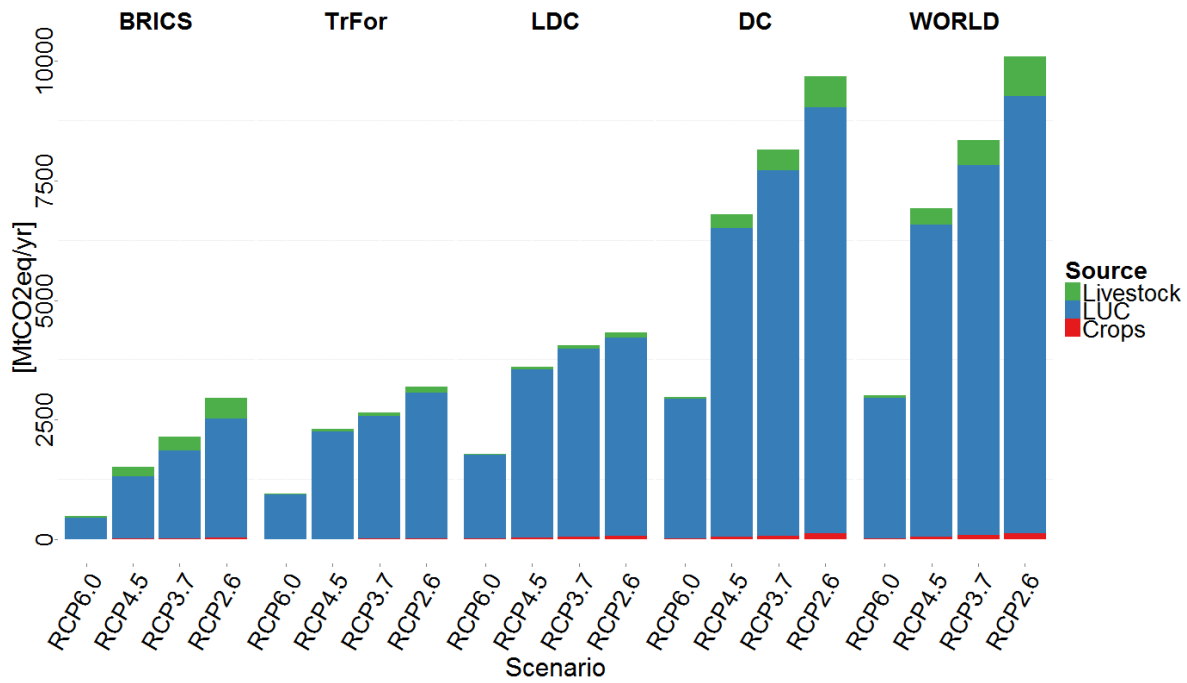
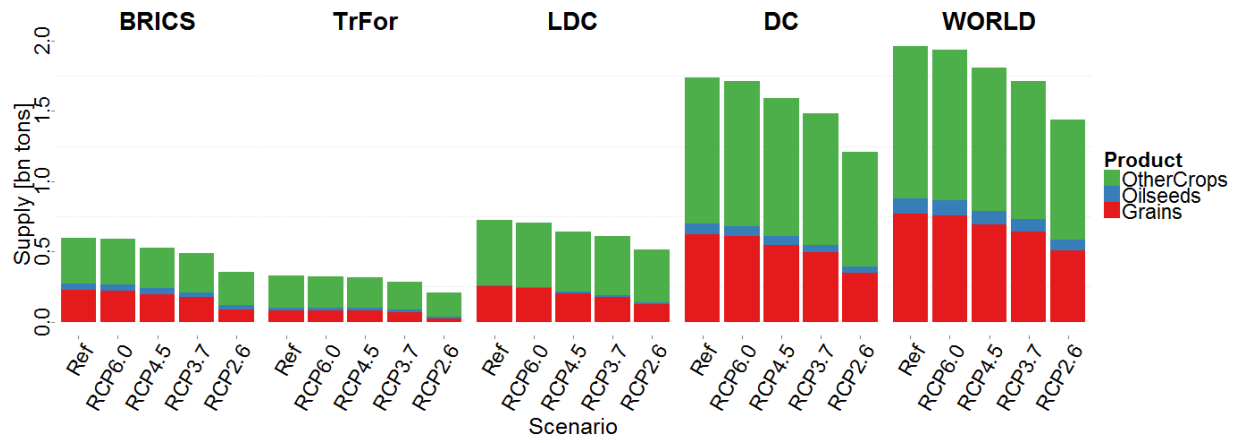
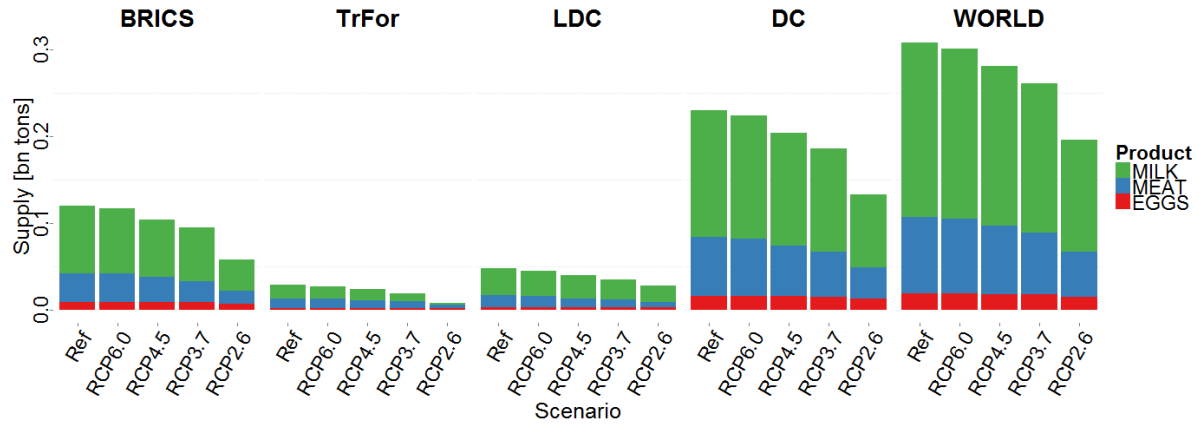


Figure 2: Average annual abatement of GHG emissions, by region and emissions source, 2020-2050, SSP 2.



a)



b)

Figure 3: Change in agricultural supply from 2020 to 2050 for different emissions ceilings, SSP 2: a) crop production, b) livestock production.

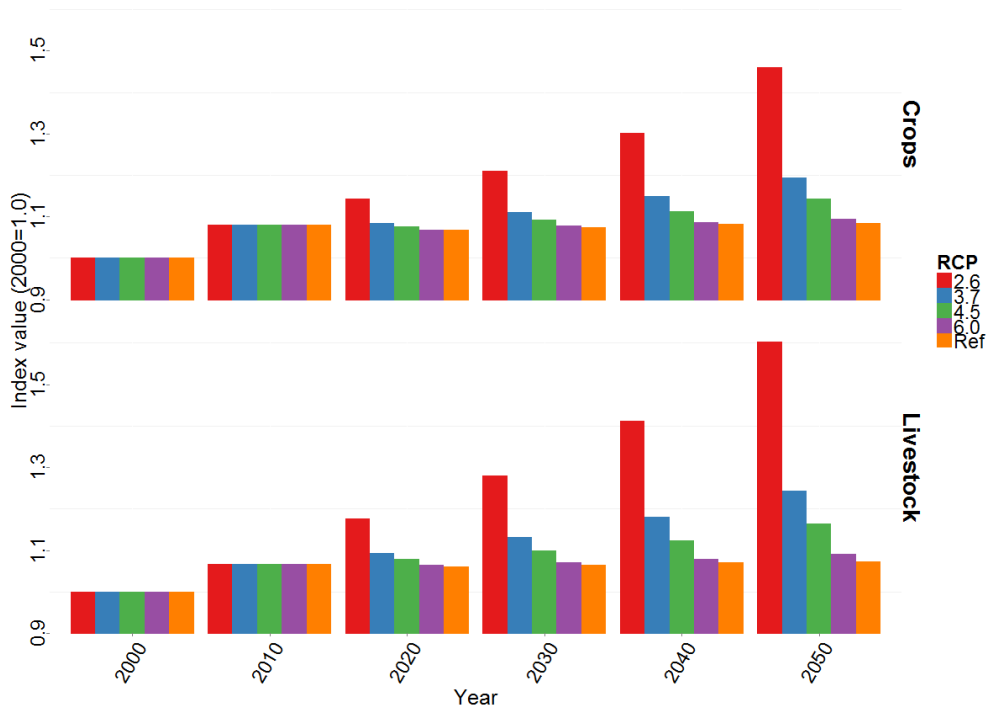


Figure 4: Food price impacts of climate change mitigation, SSP 2 (Fisher price index).

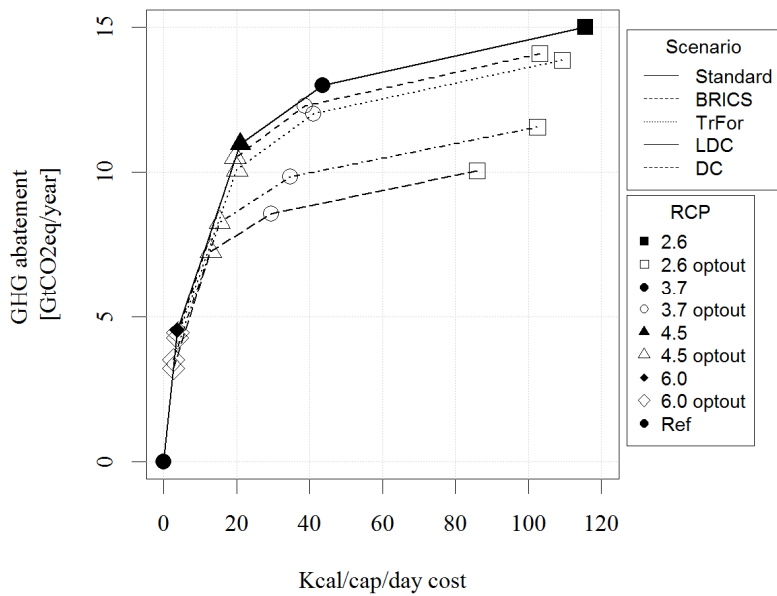


Figure 5: Agricultural mitigation and food calorie cost, global level, SSP 2.

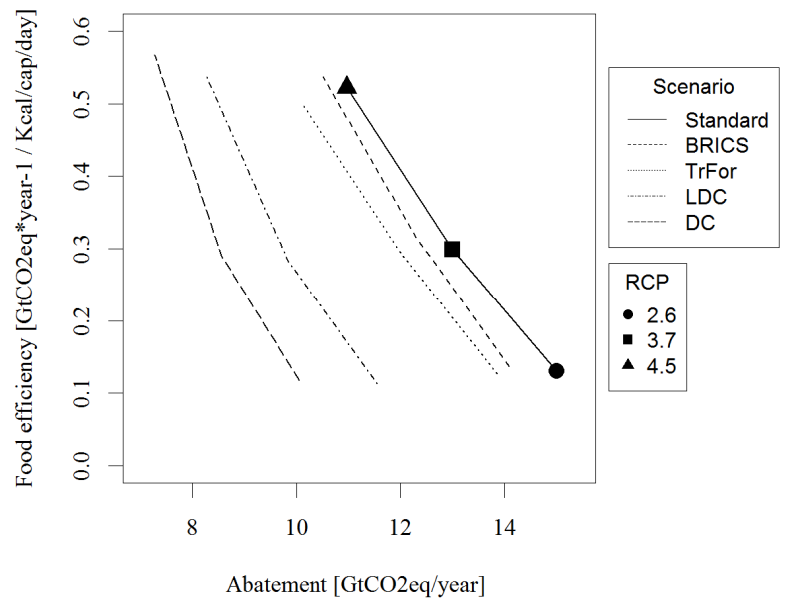


Figure 6: Global food efficiency of climate change mitigation in agriculture, SSP 2.