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# Reducing greenhouse gas emissions in agriculture without compromising food security?

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## Abstract

To keep global warming possibly below 1.5 °C and mitigate adverse effects of climate change, agriculture, like all other sectors, will have to contribute to efforts in achieving net negative emissions by the end of the century. Cost-efficient distribution of mitigation across regions and economic sectors is typically calculated using a global uniform carbon price in climate stabilization scenarios. However, in reality such a carbon price would substantially affect food availability. Here, we assess the implications of climate change mitigation in the land use sector for agricultural production and food security using an integrated partial equilibrium modelling framework and explore ways of relaxing the competition between mitigation in agriculture and food availability. Using a scenario that limits global warming cost-efficiently across sectors to 1.5 °C, results indicate global food calorie losses ranging from 110–285 kcal per capita per day in 2050 depending on the applied demand elasticities. This could translate into a rise in undernourishment of 80–300 million people in 2050. Less ambitious greenhouse gas (GHG) mitigation in the land use sector reduces the associated food security impact significantly, however the 1.5 °C target would not be achieved without additional reductions outside the land use sector. Efficiency of GHG mitigation will also depend on the level of participation globally. Our results show that if non-Annex-I countries decide not to contribute to mitigation action while other parties pursue their mitigation efforts to reach the global climate target, food security impacts in these non-Annex-I countries will be higher than if they participate in a global agreement, as inefficient mitigation increases agricultural production costs and therefore food prices. Land-rich countries with a high proportion of emissions from land use change, such as Brazil, could reduce emissions with only a marginal effect on food availability. In contrast, agricultural mitigation in high population (density) countries, such as China and India, would lead to substantial food calorie loss without a major contribution to global GHG mitigation. Increasing soil carbon sequestration on agricultural land would allow reducing the implied calorie loss by 65% when sticking to the initially estimated land use mitigation requirements, thereby limiting the impact on undernourishment to 20–75 million people, and storing significant amounts of carbon in soils.

## 1. Introduction

Numerous linkages exist between agriculture and climate change. On the one hand, global agriculture is affected by climate change that could significantly impact productivity, especially in the tropics (Lobell *et al* 2011, Challinor *et al* 2014, Rosenzweig *et al* 2014). In addition, large-scale afforestation and biomass for energy production (Kreidenweis *et al* 2016, Popp *et al* 2017), as well as population and income growth will exacerbate the competition for land. This raises challenges for the sufficient provision of food and biomass for a growing and richer world population with different dietary and energy demands, and requires adaptive action and climate change mitigation (Wheeler and von Braun 2013, Leclère *et al* 2014, Hertel 2015). On the other hand, agriculture is an important contributor to climate change, accounting directly for 10%–12% of anthropogenic greenhouse gas (GHG) emissions and also for around 70% of land use change emissions, mainly through deforestation (Hosonuma *et al* 2012, IPCC 2014, Tubiello *et al* 2015). Thus, the agricultural sector has to be an integral part of any global strategy to stabilize the climate.

Despite the need to stabilize the climate by achieving net negative emissions by the end of the century (IPCC 2014, Schleussner *et al* 2016), a major concern about implementing mitigation requirements in agriculture is that this could limit the potential for the increase of food and biomass supply and the continued support of rural livelihoods in the decades ahead (Smith *et al* 2013, Hasegawa *et al* 2015, Herrero *et al* 2016). Cost-efficient distribution of mitigation efforts across regions and sectors is typically calculated in integrated assessment models using a global uniform carbon price (IPCC 2014). However, such a uniform carbon price would, in reality, lead to substantial impacts on food availability (Golub *et al* 2013, Hasegawa *et al* 2015, Havlík *et al* 2015). Of particular concern is the impact on food security if climate mitigation targets were also to encompass the agricultural sector in vulnerable regions of the world (FAO 2009). Mitigation requirements would affect food availability via (i) diversion of land from food to energy uses, (ii) limited land availability for agricultural expansion due to the need for avoided conversion of high carbon landscapes, (iii) shift towards less GHG-intensive agricultural commodities i.e. away from ruminant production, and (iv) adoption of GHG-efficient management practices that may either directly (i.e. reduced fertilizer application, reduced livestock density) or indirectly (i.e. increased production costs) impact product prices and food production (Smith *et al* 2013, Havlík *et al* 2014, Hertel 2015, Searchinger *et al* 2015, Kreidenweis *et al* 2016, Popp *et al* 2017).

Hence, to distribute efforts across sectors and regions, other aspects besides cost-efficiency i.e. equity should be considered (Höhne *et al* 2014, Tavoni *et al* 2015) to determine how to best meet policy objectives in addition to climate change mitigation. Proposed mechanisms for enabling development in developing countries under mitigation include climate finance, low emissions development, exempting countries below a given emissions threshold from mitigation requirements (Chakravarty *et al* 2009, Wollenberg *et al* 2016) and 'win-win' mitigation options i.e. soil carbon (SOC) sequestration or sustainable intensification (Smith *et al* 2008, Tilman *et al* 2011, Valin *et al* 2013) that both reduce agricultural emissions and increase food production. SOC sequestration through improved crop- and grassland management offers the possibility to sequester significant amounts of carbon in the soil, while at the same time improving soil quality and productivity, and subsequently food security (Lal 2010, Smith *et al* 2013, Paustian *et al* 2016). For example, the French government proposed in the '4 per 1000, Soils for Food Security and Climate' initiative (www.4p1000.org) to offset global anthropogenic GHG emissions by increasing the SOC content of soils annually by 0.4% through improved farming and forestry practices. However, despite the potential for climate change mitigation, SOC sequestration is currently not considered in global climate stabilization scenarios (Fuss *et al* 2016, Smith 2016). Concerns about the length of time required to build up SOC, the reversibility of sequestered carbon, competition for soil inputs and difficulties of detecting improvements have limited attention to SOC thus far.

In the light of the Paris Agreement to limit global warming well below 2 °C, possibly to 1.5 °C, this paper explores the trade-offs between food security and the potential contribution of the land use sector to climate change mitigation. We apply a uniform carbon price in the Global Biosphere Management Model (GLOBIOM) (Havlík *et al* 2014) to assess the implications of the 1.5 °C target for the agriculture, forestry, and other land use (AFOLU) sector, agricultural production, food prices and dietary energy consumption. To inform climate policy design with respect to agriculture, we test if trade-offs with food security can be reduced through (i) regional exemptions of the land use or agricultural sector from mitigation efforts and (ii) incentivizing SOC sequestration on agricultural land that generates production subsidies for farmers under a carbon price scheme.

## 2. Methodology

### 2.1. Model framework

GLOBIOM (Havlík *et al* 2014) is a partial equilibrium model that covers the agricultural and forestry sectors, including the bioenergy sector. Commodity markets and international trade are represented in this study at the level of 30 economic regions. Commodity demand is specified as stepwise linearized downward sloped function based on Schneider *et al* (2007) with constant own-price elasticities parameterized using FAOSTAT data on prices and quantities, and price elasticities as reported in Muhammad *et al* (2011). The spatial resolution of the supply side relies on the concept of simulation units, which are aggregates of 5 to 30 arcmin pixels belonging to the same altitude, slope, and soil class, and also the same country (Skalský *et al* 2008). For crops, livestock, and forest products, Leontief production functions covering a comprehensive set of alternative production systems with different intensities are parameterized using biophysical models like EPIC (Williams 1995), G4M (Kindermann *et al* 2008, Gusti 2010), or RUMINANT (Herrero *et al* 2013). For the present study, the supply side spatial resolution was aggregated to 2 degrees (about 200 × 200 km at the equator). The model includes six land cover types: cropland, grassland, short rotation tree plantations, managed forests, unmanaged forests, and other natural vegetation land. Depending on the relative profitability of primary, by-, and final products, the model represents land use changes from one land cover type to another.

The model represents the relevant GHG emissions from agricultural production, forestry, and other land use in detail. Agricultural emissions include $N_2O$ emissions from the application of synthetic fertilizer to soils, $CH_4$ from flooded rice cultivation, $N_2O$ and $CH_4$ from the management and application of manure, and $CH_4$ from enteric fermentation. Emissions from forestry and other land use (FOLU) include emissions of $CO_2$ originating from the conversion of land between different land use types, and carbon sequestration from the establishment of short-rotation tree plantations, afforestation, and forest management, the latter estimated by the G4M model (Kindermann *et al* 2008, Gusti 2010). For each emissions account, specific coefficients are defined at the grid level.

GLOBIOM endogenously represents three major mitigation mechanisms in the agricultural sector: (i) technological mitigation options, (ii) structural changes such as switches in production systems or international trade, and (iii) feedback on the demand side through consumers' response to price changes. Technical non-$CO_2$ ($CH_4$ and $N_2O$) mitigation options such as anaerobic digesters or feed supplements are based on the EPA database (Beach *et al* 2008) while SOC sequestration options such as improved crop rotations, conservation tillage etc for agricultural land are based on Smith *et al* (2008). Structural mitigation options (Havlík *et al* 2014) are explicitly represented in the model via four different crop management systems ranging from subsistence farming to high input systems with irrigation technology. For the livestock sector, a comprehensive set of production systems from extensive to intensive management practises is available based on Herrero *et al* (2013). This allows the model to switch between management practises in response to e.g. a carbon price and hence decrease emissions through GHG efficient intensification. The model may also reallocate production to more productive areas within a region or even across regions through international trade. The impact of changes in commodity prices on the demand side is explicitly considered and consumers' react to increasing prices by decreasing consumption depending on the region specific price elasticities. Impact on undernourishment is calculated based on the FAOSTAT methodology. More information on main model characteristics relevant for this study is provided in the supplementary material available at stacks.iop.org/ERL/12/105004/mmedia.

### 2.2. Scenario analysis

#### *2.2.1. Global climate stabilization scenarios*

The global climate stabilization scenarios offer insights into the extent of GHG mitigation from the AFOLU sector that is required to meet different future climate mitigation targets compared to a baseline scenario without climate policies. Socio-economic developments in all scenarios are based on the SSP2 'Middle of the Road' scenario (O'Neill *et al* 2014, Fricko *et al* 2016), which is characterized by moderate population and GDP growth (up to around 9.2 billion people by 2050 and about 2.5% annual GDP growth). For food demand, income elasticities are calibrated such that the trajectories follow projections by FAO up to 2050 (Alexandratos and Bruinsma 2012). On the agricultural production side, projected crop productivities are based on 18 crop specific yield responses function to GDP per capita growth estimated for different income groups using a fixed effects model. For the livestock products, feed conversion efficiency increases (feed intake per output unit) for five livestock products (ruminant, pig and poultry meat, milk, and eggs) follow on Bouwman *et al* (2005).

Global climate stabilization targets correspond to the representative concentration pathways (RCPs, 2.6 W $m^{-2}$ scenario, 4.5 W $m^{-2}$ scenario, 6 W $m^{-2}$ scenario) (Moss *et al* 2010). These RCPs reflect year 2100 radiative forcing values from 2.6–6 W $m^{-2}$ and temperature increases from 2 °C–3.1 °C by 2100 (van Vuuren *et al* 2011). In addition, a 3.4 W $m^{-2}$ scenario (Riahi *et al* 2016) and 1.9 W $m^{-2}$ scenario ('1.5 °C scenario'), which is likely to limit global warming to 1.5 °C, were included in the analysis. All stabilization scenarios were quantified using the MESSAGE-GLOBIOM modelling framework (Fricko *et al* 2016). The baseline represents a pathway with no climate policies in place. To achieve the respective global climate stabilization, GLOBIOM includes RCP specific trajectories of solid biomass demand for bioenergy production and AFOLU sector carbon prices (implemented as additional cost/subsidy per $tCO_2eq$ emitted/sequestered on the supply side irrespective of where products eventually get consumed) based on the MESSAGE-GLOBIOM iterations. First generation biofuel demand is exogenous and based on Lotze-Campen *et al* (2014). The final levels of bioenergy demand in terms of primary energy in 2050

Table 1. Climate stabilization scenarios drivers derived from MESSAGE-GLOBIOM framework.

| Scenario name | Radiative forcing levels in 2100 | Carbon price in 2050 | Bioenergy in 2050 |
|---|---|---|---|
| 3.1 °C scenario | 6.0 W $m^{-2}$ | 2 \$/t$CO_2$eq | 53 EJ |
| 2.6 °C scenario | 4.5 W $m^{-2}$ | 10 \$/t$CO_2$eq | 61 EJ |
| 2.2 °C scenario | 3.4 W $m^{-2}$ | 25 \$/t$CO_2$eq | 70 EJ |
| 2.0 °C scenario | 2.6 W $m^{-2}$ | 65 \$/t$CO_2$eq | 81 EJ |
| 1.5 °C scenario | 1.9 W $m^{-2}$ | 190 \$/t$CO_2$eq | 103 EJ |

range between 53 EJ for the baseline and 103 EJ for the 1.5 °C scenario and carbon prices of up to 190 \$/t$CO_2$eq (USD per t$CO_2$ equivalent) by 2050 (table 1).

### 2.2.2. Regional mitigation pathways

A second set of scenarios is simulated only in GLOBIOM to test the effects of exemptions for groups of lower-income countries from the mitigation efforts in the land use sector. In the regions implementing carbon policy, the scenarios have been implemented using the regional carbon prices and biomass demands from the 1.5 °C scenario with global participation. For regions not participating, we stick to the baseline bioenergy demands and no carbon price. In the regional scenarios, we usually consider as a 'benchmark' scenario the case where the carbon price is implemented on the AFOLU sector only in developed countries, represented in our analysis by Annex-I countries. Alternative scenarios are created considering under the mitigation scheme, one by one, also other countries or regions in addition to the developed (Annex-I) countries. These scenarios thus allow assessing the climate change potential and the collateral effects of mitigation alternatives with specific countries or regions:

a. Carbon price for AFOLU in Annex-I countries only.
b. Carbon price for AFOLU in Annex-I countries and Brazil.
c. Carbon price for AFOLU in Annex-I countries and India.
d. Carbon price for AFOLU in Annex-I countries and China.
e. Carbon price for AFOLU in Annex-I countries and Congo Basin countries.
f. Carbon price for AFOLU in Annex-I countries and BRICS.
g. Carbon price for AFOLU in all countries except least developed countries.
h. Global carbon price on AFOLU $CO_2$ emissions, agricultural $CH_4$ and $N_2O$ emissions are only taxed in Annex-I countries.

### 2.2.3. Soil carbon sequestration

Three scenarios for SOC sequestration were used to assess the potential contribution of SOC sequestration on agricultural land (including improved crop- and grassland management, restoration of organic soils and degraded lands) to climate change mitigation and its impacts on food security. The three scenario variants were built incrementally; first, SOC mitigation options were not considered (no SOC, default option), second, these options and their associated effect on carbon sequestration based on Smith *et al* (2008) were considered and they were enrolled under the global and regional mitigation schemes (SOC) and finally, in the optimistic variant in addition to the SOC effects, positive effects of SOC accumulation on yields were considered (SOC+):

a. No SOC: No SOC options considered for climate change mitigation (default option).
b. SOC: SOC options considered for mitigation but their yield effects ignored.
c. SOC+: SOC sequestration options considered, including their yield effects on all cropland with SOC increase (optimistic option).

Results from the simulations of all climate stabilization scenarios, regional groups and SOC variants were compared to the baseline scenario without climate policies or to the climate regime in developed countries only to answer the principal questions about the effects of alternative climate policy regimes on the AFOLU mitigation potential and on the costs of abatement in terms of food calories. More information on the implementation of the mitigation options and scenarios is provided in the supplementary material.

### 2.2.4. Sensitivity analysis

A sensitivity analysis was performed with respect to the applied own-price elasticities and SOC sequestration rates. To test the impacts of a more inelastic response of consumers to price changes, we shifted product-specific, regional own-price elasticities in GLOBIOM to median values as reported in Valin *et al* (2014) calculated across several global agricultural sector models (−0.1 for crops, and −0.25 for livestock products, see the supplementary material for details). We also tested more conservative assumptions on SOC sequestration and halved the assumed SOC sequestration rate in the SOC- scenario compared to Smith *et al* (2008).

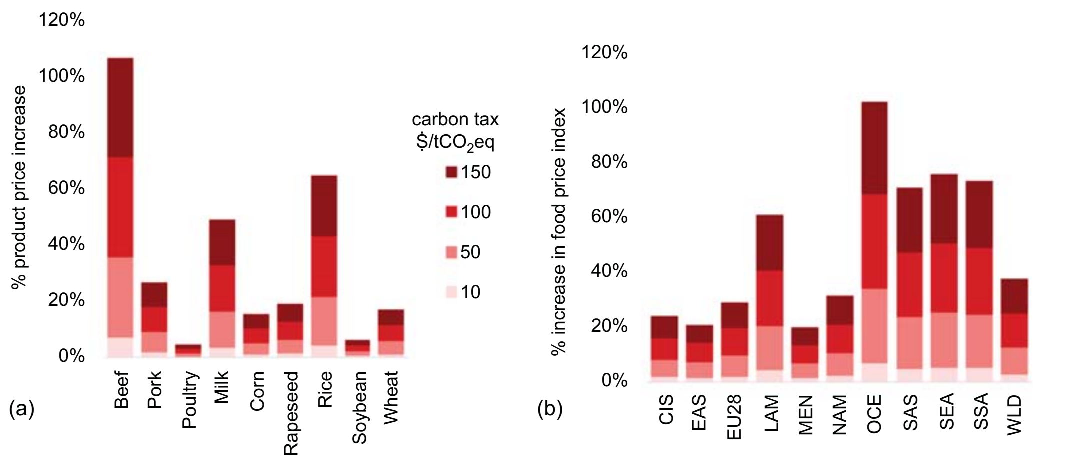


**Figure 1.** Relative price impact of a carbon tax (0–150 \$/t$CO_2$eq) on emissions from agriculture on global commodity prices (*a*) and regional food price index (*b*). Taxed livestock emissions include direct $CH_4$ and $N_2O$ emissions from livestock production (enteric fermentation, manure management and application, excluding emissions associated to the production of feed requirements). Crop emissions include $CH_4$ emissions from rice cultivation and $N_2O$ emissions from soils. CIS—Commonwealth of Independent States, EAS—East Asia, EU28—European Union, LAM—Latin America, MEN—Middle East and North Africa, NAM—North America, OCE—Oceania, SAS—South Asia, SEA—South East Asia, SSA—Sub-Saharan Africa. WLD—World.

## 3. Results

### 3.1. AFOLU mitigation requirements to stabilize the climate

To stabilize the climate well below 2 °C, a significant contribution from the AFOLU sector for GHG abatement is foreseen (van Vuuren *et al* 2011, IPCC 2014, Fricko *et al* 2016, Riahi *et al* 2016). In line with other studies (IPCC 2014, Fricko *et al* 2016, Wollenberg *et al* 2016), our analysis shows that the AFOLU sector needs to significantly reduce current emissions of around 10–12 Gt$CO_2$eq yr$^{-1}$ to around 0.6 Gt$CO_2$eq yr$^{-1}$ in 2050. This translates into GHG mitigation requirements of up to 7.9 Gt$CO_2$eq yr$^{-1}$ in 2050 compared to a baseline scenario without climate stabilization target in GLOBIOM to achieve the 1.5 °C target (scenario with radiative forcing value of 1.9 W m$^{-2}$ by 2100) cost-efficiently by the end of the century. This reduction of AFOLU emissions is mainly achieved through the mitigation of land use change (mainly deforestation) and carbon sequestration in existing and newly established forests (5.2 Gt$CO_2$eq yr$^{-1}$ in 2050) as land-use related mitigation options are highly cost-effective (Kindermann *et al* 2008, Golub *et al* 2013, Havlík *et al* 2014), while agriculture contributes only emission savings of around 2.7 Gt$CO_2$eq yr$^{-1}$ in 2050. Across world regions, around 80% of the global mitigation from land use change and forestry is located in Latin America and Sub-Saharan Africa, while East Asia and Latin America contribute half of the total global mitigation potential in agriculture, mainly related to livestock-sector emission savings.

### 3.2. Food security trade-offs

Although agriculture clearly holds substantial potential to contribute to global mitigation targets within the AFOLU sector (Herrero *et al* 2016, Paustian *et al* 2016), this may come partly at the cost of food availability if driven by a uniform carbon tax across sectors or other policies that affect agricultural prices and market equilibrium. If direct non-$CO_2$ ($N_2O$ and $CH_4$) emissions from livestock or crop production were taxed, product prices, especially of ruminants and rice, would significantly increase, while poultry meat and crop prices would only change slightly due to their lower GHG intensity (GHG emission per output unit produced). Figure 1 shows relative product price changes driven by a global carbon tax on agricultural GHG emissions across world regions calculated ex-ante using the GLOBIOM dataset on production systems for the base year 2000 (Havlík *et al* 2014). We calculated emission intensities for the average current production system. Using different illustrative carbon price levels, and FAOSTAT data on commodity prices, we estimated the impact on food prices if a carbon tax were imposed on agriculture. This back-of-the-envelope calculation simply serves the purpose to illustrate potential implications for food prices but assumes no shifts in production to more GHG efficient systems or other dynamics in the sector, and hence overestimates price impacts.

Across world regions, the food price index is least impacted in regions with highly efficient production systems i.e. North America and the European Union, or regions with moderately efficient production systems but lower shares of GHG intense products in the food basket. However, regions with poor productivities and consequently higher GHG emissions per unit of output produced especially in the livestock sector i.e. Sub-Saharan Africa, South Asia, and South East Asia could experience a significant increase in agricultural commodity prices if they continue with their current inefficient production systems. This is consistent with Herrero *et al* (2013) and Avetisyan *et al* (2011),

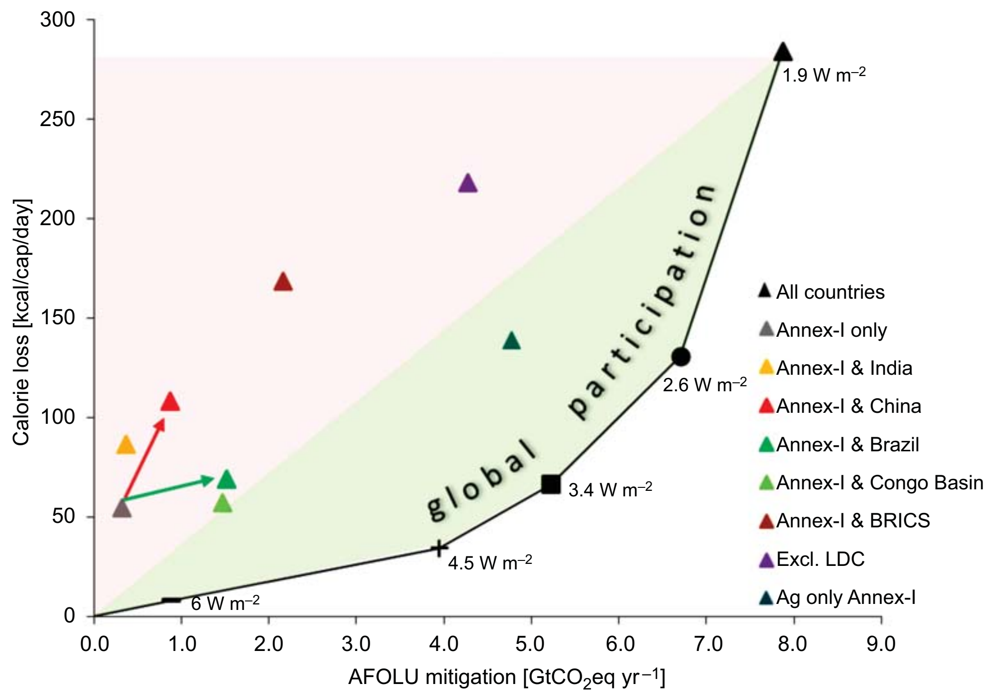


**Figure 2.** Trade-offs and synergies between annual AFOLU mitigation and dietary energy consumption by 2050 under a uniform carbon price. Global annual mitigation potential in $GtCO_2eq\,yr^{-1}$ in 2050 vs. global average loss in daily dietary energy (kcal per capita per day) consumption, compared to a baseline scenario without mitigation efforts. The convex line represents policies where all countries participate to achieve increasingly ambitious climate stabilization targets and the corresponding radiative forcing values. For a 1.5 °C target (1.9 W $m^{-2}$ scenario), implications of eight regional mitigation policies are shown for: Annex-I countries only (grey), Annex-I and Brazil (dark green) and Annex-I and China (red), Annex-I and India (yellow) and Annex-I and Congo Basin (light green), Annex-I and BRICS (brown), world excluding least developed countries (Excl. LDC, violet), world but agriculture only in Annex-I (Ag only Annex-I, turquoise). Green arrow—impact of including Brazil in a climate regime in addition to Annex-I countries, red arrow—impact of including China in a climate regime in addition to Annex-I countries. Green background colour indicates relatively efficient mitigation pathways (calorie loss/AFOLU mitigation), red colour inefficient ones compared to the 1.5 °C scenario with global participation.

who show substantial variation in emission intensities across regions with high GHG emission intensities in Africa and Asia mainly related to poor productivities and low-quality feed practises.

Moving from this static assessment to a dynamic modelling analysis using GLOBIOM, figure 2 presents the trade-offs between global and regional AFOLU mitigation targets and global average calorie consumption by 2050. The convex line represents global climate stabilization scenarios (without SOC sequestration options), emulated by a uniform global carbon price up to 190 $/$tCO_2$eq by 2050 to achieve the corresponding radiative forcing values. Implications of eight regional climate regimes (regional scenarios a–h) are shown for a scenario that achieves under full global participation the 1.5 °C target (1.9 W $m^{-2}$ scenario).

While low levels of AFOLU GHG abatement can be cost-efficiently achieved with a global carbon price at relatively little cost in terms of calorie loss per capita, a uniform carbon price across sectors does lead to trade-offs with food security at increasingly ambitious stabilization targets. This results from rising food prices driven by the adoption of GHG (i.e. $CH_4$, $N_2O$, and land use change $CO_2$) abatement strategies in the AFOLU sector, which limit agricultural land expansion and increase production costs for farmers targeted by the implementation of a carbon price. Hence, farmers adjust their production practices, i.e. the shift towards production systems with lower emissions intensities per unit of output produced, but also abandon GHG intensive cropping areas and livestock production systems. While in developed countries agricultural demand is rather inelastic to price changes induced by high carbon prices, food insecure countries could experience a more significant reduction of calorie availability due to higher demand elasticities. In the default model set-up, calorie availability could drop on global average by up to 285 kcal per capita per day (−9%) in a 1.5 °C scenario compared to a baseline without mitigation efforts in 2050. This would translate into a rise of 300 million people in the global number of chronically undernourished to 500 million people (~5.5% of total population in 2050) according to the FAO methodology. Our results are similar to Havlík *et al* (2014), who identified calorie losses of up to 200 kcal per capita per day globally when introducing a carbon price of 100 $/$tCO_2$eq. Also Springmann *et al* (2016) report average calorie losses of around 80 kcal per capita per day at 50 $/$tCO_2$eq while Hasegawa *et al* (2015) find significantly lower calorie loss of maximum up to 60 kcal per capita per day globally in 2050 in a 2 °C scenario, however with strong regional impacts of up to 170 kcal per capita per day in India. This sizable difference compared to the latter study can be explained by different assumptions on the implementation of mitigation policies as the carbon tax does not cover agricultural non-$CO_2$ emissions in Hasegawa *et al* (2015). Hence, impacts on food security are only driven by indirect impacts of the carbon price in other sectors and not through a direct tax on agricultural emissions as done in this study. Kreidenweis *et al* (2016) show potential food price increases by up to 80% by 2050 when applying a carbon price of 130 \$/t$CO_2$ on afforestation and deforestation compared to a baseline scenario. Applying this price increase to the calorie consumption levels in our baseline scenario and assuming an inelastic price elasticity of −0.1 this would also translate into a decrease in food consumption of 245 kcal per capita per day. Tabeau *et al* (2017) found consumption losses of up to 1.6% on global average by 2030 for a scenario restricting agricultural land expansion into forest, however with developing regions facing much higher decreases (up to 5% for Sub-Saharan Africa). Also Popp *et al* (2017) observe food price increases driven by mitigation policies driven by land competition especially towards the end of the century, but stress high uncertainties across the applied models.

Given the importance of price elasticities for food security results and the range uncertainty, we performed a demand sensitivity analysis to test the robustness of our results. When assuming more inelastic response of consumers, the expected calorie loss significantly declines. Global average calorie loss decreases from around 285 to 110 kcal per capita per day in the 1.5 °C scenario which results in a drop of additional undernourishment from 300 million people in the default set-up to around 80 million people in the sensitivity analysis. Nevertheless, this still represents a non-negligible increase in people undernourished by 35% in 2050 compared to the baseline without mitigation efforts. In line with decreasing calorie loss, the total AFOLU mitigation potential also declines slightly from 7.9 to 7.5 $GtCO_2eq\,yr^{-1}$ in 2050 due to foregone mitigation in the agricultural sector, which would need to be compensated to remain on track with the 1.5 °C target. Even though the absolute magnitude of food security impacts decrease in the sensitivity analysis, we observe the same curvature and positioning of the regional and global climate scenario in figure 2 (see supplementary material), which supports the findings and drawn conclusions.

### 3.3. Regional mitigation hot spots

Excluding countries from the global carbon price regime reduces not only the ability to meet mitigation targets, but also affects food security depending on which countries are targeted. Country-level impacts reflect the extent to which countries can contribute to GHG mitigation through avoided land use change or need to mostly reduce emissions in agriculture. We can distinguish two major groups of countries: (i) land-rich countries with extensive agriculture and large amounts of emissions from land use change, in particular deforestation and forest degradation, such as Brazil or the countries of the Congo Basin, and (ii) densely populated countries with intensive agriculture, such as China or India. Reducing emissions from land use change in the land rich countries represents a cost-efficient mitigation option with large mitigation potential and limited trade-offs with food security. For instance, if Brazil and Annex-I countries adopted mitigation efforts consistent with reaching a 1.5 °C scenario cost-efficiently under global participation, the global mitigation potential from the AFOLU sector would increase by 1.2 $GtCO_2eq\,yr^{-1}$ (compared to a scenario where only Annex-I countries take action). Impact on the calorie availability (green arrow, figure 2) is marginal, as additional GHG abatement is mainly achieved through reduced deforestation (figure 3 present additional mitigation potential by emission source when expanding the climate regime beyond Annex-I countries). Agricultural production is hardly impacted as these regions offer significant potentials to intensify GHG efficiently on existing crop- and grasslands (Cohn *et al* 2014, Havlík *et al* 2014, Henderson *et al* 2015).

On the other hand, if China enrolled its AFOLU sector into the mitigation effort consistent with a 1.5 °C scenario in addition to Annex-I countries, the mitigation potential would increase by only 0.6 $GtCO_2eq\,yr^{-1}$, while the calorie availability in food insecure countries would decrease by an additional 50 kcal per capita per day (red arrow, figure 2). This could translate into a rise in the global number of chronically undernourished by 45 million people in 2050. In the demand sensitivity analysis less pronounced effects can be observed with an average calorie loss of 20 kcal per capita per day (+13 million undernourished people). As GHG mitigation in China would be mostly achieved in the agricultural sector (figure 3), a high impact on food security can be observed within China when joining a climate regime, with increased calorie losses of around 420 kcal per capita per day (140 kcal per capita per day in the demand sensitivity analysis) due to price effects when compared to the baseline without mitigation efforts as ruminant meat production is expected to decline by 45%, milk by 38%, and rice by 21%.

Limited regional coverage of the mitigation efforts also results in emission leakage, which offsets part of the domestic emission savings within a climate regime and reduces global GHG mitigation. Hence, regional climate regimes perform worse both with respect to GHG abatement and food security compared to scenarios with moderate mitigation efforts but global participation. Across regional climate regimes leakage effects vary between 0.8 $GtCO_2eq\,yr^{-1}$ for Annex-I and Congo Basin up to 1.8 $GtCO_2eq\,yr^{-1}$ for Annex-I and BRICS. Leakage effects are mainly

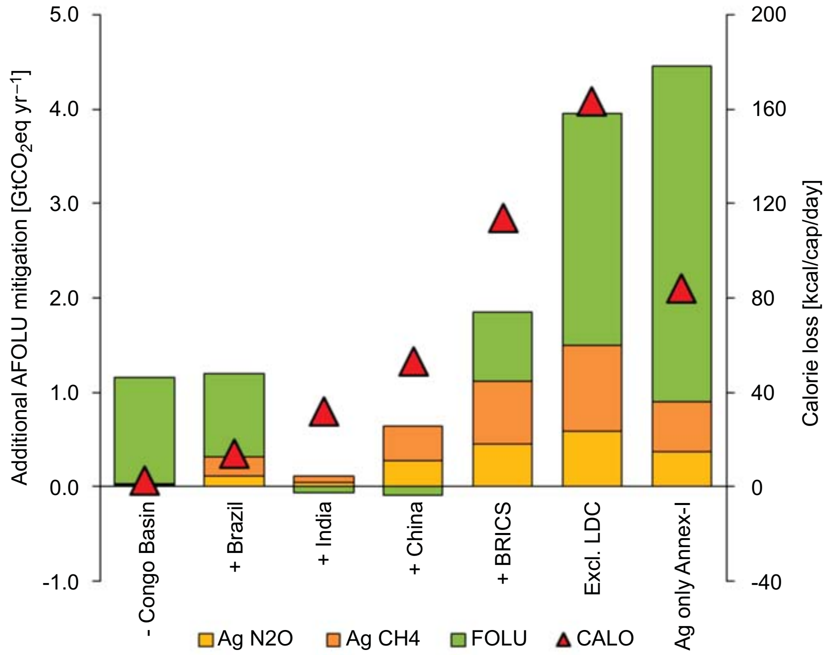


**Figure 3.** Additional global AFOLU mitigation in $GtCO_2eq\ yr^{-1}$ and loss in global average daily dietary energy (kcal per capita per day) consumption when expanding the climate regime beyond Annex-I countries in a 1.5 °C scenario. Ag N2O—$N_2O$ mitigation from agriculture, Ag CH4—$CH_4$ mitigation from agriculture, FOLU—$CO_2$ mitigation from forestry and other land use, CALO—calorie loss per capita per day.

resulting from land use change emissions. Consequently, climate regimes that include i.e. the Congo Basin (35%) countries or Brazil (45%) show much smaller relative leakage shares (leakage/domestic emission reduction). Exempting agricultural $CH_4$ and $N_2O$ emissions in non-Annex-I countries from the global AFOLU GHG tax (scenario 'Ag only Annex-I') enables to achieve 4.8 $GtCO_2eq\ yr^{-1}$ of mitigation with limited impacts on food security (default calorie loss of 140 kcal per capita per day compared to the baseline, 55 kcal per capita per day in the demand sensitivity analysis). This scenario outperforms both with respect to GHG mitigation and food security the scenario 'Excl. LDC', which ends up with high food security impacts even though it exempts the AFOLU sector in least developed countries from the carbon tax. Results show that all regional scenarios perform worse with respect to food security compared to the global scenarios with e.g. moderate AFOLU mitigation targets but adopted by all countries, as inefficient GHG mitigation increases agricultural production costs and consequently food prices. Since the highly productive agricultural sector in developed countries is included in the mitigation efforts of the regional climate regimes (which affects competitiveness), food availability is indirectly impacted through international trade in regions outside the climate regime, resulting in higher calorie losses and food security impacts compared to global mitigation scenarios with less ambitious targets where all countries participate. Hence, exempting countries from the land use mitigation efforts does not necessarily reduce regional food security impacts of a mitigation policy. Either coordinating mitigation efforts globally or alternatively as a second best policy targeting cost-effective regional mitigation hot spots comprehensively, such as land-rich countries with significant emissions from land use change, is key for any efficient climate policy design with respect to food security and GHG abatement.

### 3.4. Relaxing food security trade-offs through soil carbon sequestration

SOC sequestration on crop- and grassland is considered an important negative emission technology with significant co-benefits for food security (Paustian *et al* 2016). Nevertheless, the mitigation potential of SOC sequestration is not considered in current climate stabilization scenarios (Smith 2016). Figure 4 presents the implications of considering SOC sequestration in the mitigation portfolio, based on the mitigation potentials from Smith *et al* (2008). Results show that if agricultural SOC sequestration options were incentivized under a mitigation policy, the cost-efficient contribution of the AFOLU sector to achieve the 1.5 °C target could increase from 7.9 $GtCO_2eq\ yr^{-1}$ to up to 11.4 $GtCO_2eq\ yr^{-1}$ by 2050 when applying the same carbon price levels consistent with a least-cost achievement of the 1.5 °C target without SOC sequestration measures (thereby even overshooting the initially derived AFOLU mitigation requirements), while at the same time improving food availability in food insecure countries. Similarly, Paustian *et al* (2016) identify a mitigation potential between 3 $GtCO_2eq\ yr^{-1}$ (20\$/$tCO_2$eq) up to a maximum of 8 $GtCO_2eq\ yr^{-1}$ (technical potential)

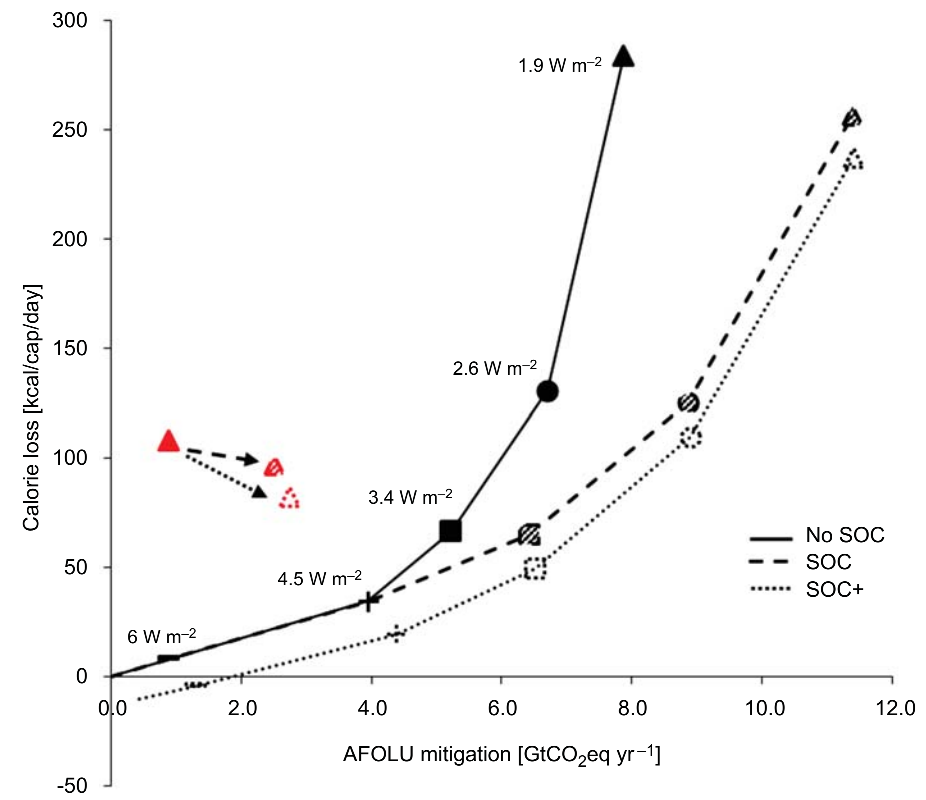


**Figure 4.** Trade-offs and synergies between annual land sector mitigation and dietary energy consumption by 2050 under a uniform carbon price. Global annual mitigation potential in $GtCO_2eq\ yr^{-1}$ in 2050 vs. loss in global average daily dietary energy (kcal per capita per day) consumption, compared to a baseline scenario without mitigation efforts. The convex lines represent policies where all countries participate in the mitigation effort assuming three alternative mitigation policies: no SOC sequestration incentives (No SOC, straight line); SOC sequestration incentives without considering associated yield improvements (SOC, dashed line); SOC sequestration incentives considering yield improvements (SOC+, pointed line). For a 1.5 °C scenario, implications of a regional mitigation policy are shown for Annex-I and China (red). Arrows indicate the impact in the climate policy for the three policy variants (no SOC, filled triangle; SOC, dashed triangle; SOC+, pointed triangle).

related to improved cropland- and grassland management, biochar application, enhanced root phenotypes, and restoration of degraded lands and organic soils. As we apply in the SOC scenarios the carbon price from the no-SOC scenarios, we implicitly assume a mitigation policy with cost-efficient distribution of efforts across sectors. However, we do not consider the impact of the SOC sequestration on the carbon price required to meet the 1.5 °C target, which could be expected to decrease due the availability of additional SOC mitigation potential.

Aside from increased GHG mitigation, SOC sequestration delivers co-benefits for food security, even in the scenarios that do not consider explicitly yield gains associated to SOC sequestration (SOC). Sequestration policies would increase the value of carbon-enhancing production systems by paying farmers for the carbon sink provided and thus allow for more agricultural land to remain in production under climate policies, thereby benefitting food security. At the global level, the implied calorie loss in the SOC scenario could be reduced by 10% (around 40 million people undernourished less) compared to the 1.5 °C scenario without SOC sequestration. Taking into account the positive effects of SOC sequestration on crop yields (Lal 2006) (SOC+ scenario), food security could be further improved (−17% implied calorie loss) while maintaining the level of GHG abatement. However, impacts in the SOC+ scenario (+0.9% yield increase per $tCO_2\ ha^{-1}$ sequestered) are indeed very optimistic. Hence, results should only be considered as the hypothetical upper limit as yield increases are assumed to materialize on all cropland which sequester SOC (and not only on degraded lands).

The importance of enrolling SOC sequestration options under the mitigation policies in reducing the food security and climate change mitigation trade-offs is even more visible at regional scales. The abatement potential if Annex-I countries and China mitigated AFOLU emissions and sequestered soil carbon would almost triple with SOC sequestration while decreasing the calorie loss by up to 20%, depending on whether the related crop yield increases through enhanced SOC sequestration could be realized (pointed and dashed arrow, figure 4). In the demand sensitivity analysis the effect is less pronounced but could still decrease the calorie loss by up to 15%.

While figure 4 presents the cost-efficient AFOLU mitigation potential that could be expected with SOC

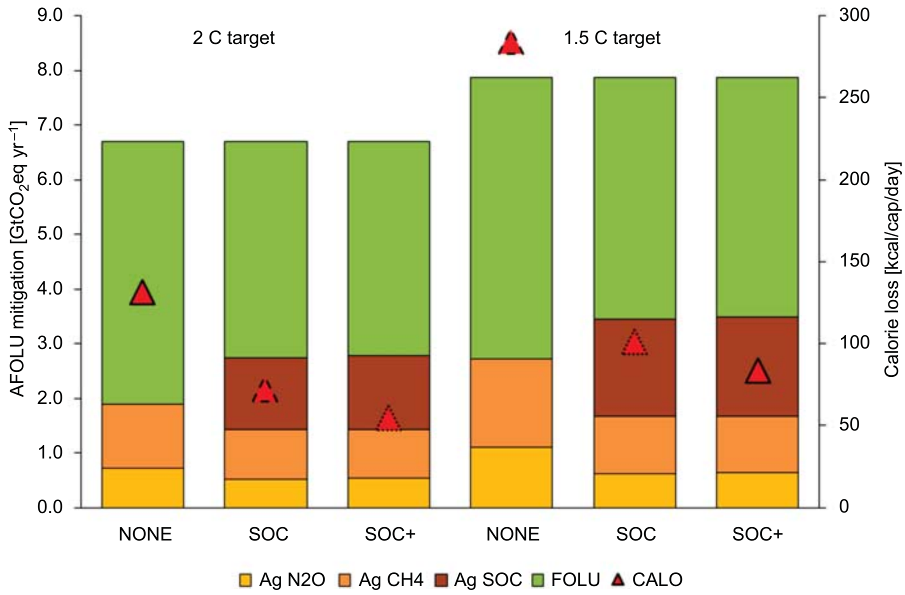


**Figure 5.** Global AFOLU mitigation option portfolio under two climate stabilization targets (2.6 W $m^{-2}$—2 °C target, 1.9 W $m^{-2}$—1.5 °C target) and loss in global average daily dietary energy (calorie loss, kcal per capita per day) consumption. SOC variants: NONE—no SOC sequestration considered, SOC—SOC sequestration but no yield improvements considered, and YLDC+ - SOC sequestration and crop yield improvements considered. GHG mitigation potentials: Ag N2O—$N_2O$ mitigation from agriculture, Ag CH4—$CH_4$ mitigation from agriculture, Ag SOC—$CO_2$ sequestration from agriculture, FOLU—$CO_2$ mitigation from forestry and other land use.

sequestration given different carbon prices, figure 5 shows the minimum AFOLU abatement required, consistent with reaching 1.5 °C and 2.0 °C climate stabilization targets cost-efficiently (1.9 W $m^{-2}$ and 2.6 W $m^{-2}$ scenario respectively). Depending on how the mitigation policy is designed i.e. the distribution of mitigation efforts across economic sectors, impacts of SOC sequestration will be similar to either figure 4 or figure 5. Under the assumption that emission reduction targets from other sectors are decoupled from the GHG mitigation potential in the AFOLU sector[11], the carbon price in the 1.5 °C scenario could drop for the AFOLU sector due to the availability of SOC sequestration from 190 \$/t$CO_2$eq to 50 \$/t$CO_2$eq, while maintaining GHG abatement levels. Even though the total contribution from the agriculture increases from 2.7 up to 3.5 Gt$CO_2$eq $yr^{-1}$ (including SOC) in 2050, the decrease in calorie availability is reduced from 285 to up to 100 kcal per capita per day (−65%) when SOC sequestration measures are adopted in agriculture (SOC scenario). This buffers the impact on undernourishment which decreases from additional 300 (in the no SOC scenario) to only around 75 million people. In the demand sensitivity analysis calorie loss declines from 110 to 35 kcal per capita per day (corresponding impact on undernourishment decreases from 80 to 20 million people). Since SOC sequestration delivers additional GHG mitigation that would have been otherwise anticipated through direct cuts in agricultural non-$CO_2$ emissions, production levels and food availability are less impacted.

However, SOC saturation and permanence of the sink are two important aspects which need to be taken into account. SOC enhancing management practises are characterized by decreasing sequestration rates over time as soil can only store finite amounts of carbon and sequestration rates decline once approaching the new SOC equilibrium. Hence, most practises considered deliver additional SOC sequestration only over a limited time span of around 20–30 years (Paustian *et al* 2016). In addition, SOC practices need to be maintained even beyond the saturation point to keep the carbon stored in the soil (Paustian *et al* 2016, Smith 2016). Since recent studies show a potential overestimation of mitigation potentials e.g. in the case of crop- and grasslands (Powlson *et al* 2014, Frank *et al* 2015, Henderson *et al* 2015), we tested a more conservative assumption on sequestration rates. Halving SOC sequestration rates from Smith *et al* (2008) would, not surprisingly, significantly reduce the GHG mitigation potential from SOC sequestration. Nevertheless, the impact on food security in the 1.5 °C scenario could still be reduced from 285 to 130 kcal per capita per day in 2050 (from 110 to 50 kcal per capita per day in the demand sensitivity analysis) corresponding to only additional 100 million people undernourished (30 million people in the demand sensitivity analysis). Hence,

[11] For figure 5 we assume that once the mitigation efforts have been distributed cost-efficiently across sectors without considering any mitigation coming from SOC sequestration, targets across sectors would not change even if SOC sequestration could deliver additional GHG abatement. This assumption also reflects current EU policies design. In 2016, the European Commission put forward a proposal to allow the restricted use of carbon credits from the land use sector for reaching emission reduction targets without revising overall effort levels (EC 2016).

a policy-rich mitigation portfolio that includes win-win options like SOC sequestration is indispensable to achieve ambitious climate change mitigation with optimal cost-efficiency and avoid that AFOLU mitigation results in higher food costs.

### 3.5. Limitations and uncertainties

Results need to be considered within limitations of the modelling approach applied. Macro-economic feedbacks from other sectors driven by the mitigation policy i.e. on urban- and agriculture dependant household income, were not considered, an important issue raised also in other studies (Swinnen and Squicciarini 2012, Hertel 2016). The absence of macro-economic feedbacks and simplified representation of households may result in an overestimation of food security impacts in both global and regional scenarios i.e. countries outside the regional climate regimes may experience an actual increase in income related to improved competitiveness while countries with mitigation efforts may suffer more pronounced losses. GLOBIOM also does not consider cross-price elasticities or consumption shift towards lower quality products following price increases. Despite these methodological shortcomings, comparisons with other well established agricultural sector models showed reasonable model behaviour (Schmitz *et al* 2014, Valin *et al* 2014, Hertel *et al* 2016). We assume that all AFOLU emissions can be taxed, which may be difficult especially in developing countries given poor monitoring and reporting systems in place, and we assume no redistribution of the income generated by the carbon tax to consumers. The latter is likely to cause only a small bias as AFOLU emissions are anticipated to decrease fast until 2050 in the 1.5 °C scenario, thus offering only limited potential for (net) revenue generation from carbon taxation. Hence, only small impacts on household income can be expected if distributed proportionally. The baseline scenario does not include any climate change impacts while in reality climate change will also impact the agricultural sector without mitigation efforts. For example, Valin *et al* (2014) show average global calorie losses across different agricultural sector models between 50–90 kcal per capita per day for RCP 8.5 compared to a baseline without climate change impacts[12].

While the limitations listed above tend to buffer food security impacts, a number of underlying data uncertainties may however also further increase impacts on calorie availability and undernourishment. The applied bioenergy demand quantities for the mitigation scenarios based on MESSAGE-GLOBIOM can be considered conservative compared to other models. Van Vuuren *et al* (2016) estimate based on the IPCC AR5 report scenario database that total bioenergy use could increase to 75–200 EJ by 2050 in a 2 °C scenario (compared to only 81 EJ in this study). Other studies agree that significant amount of bioenergy and afforestation will be required to stabilize the climate with potentially huge implications for land use and food prices (Creutzig *et al* 2015, Kreidenweis *et al* 2016, Popp *et al* 2017). Thus, if bioenergy demand or AFOLU carbon prices were to increase further i.e. driven by a more pessimistic development in other sectors, this could partly offset or even overcompensate (related to the non-linearity of impacts on food security) the bias introduced by the model limitations listed above. Hence, results from the default set-up and the demand sensitivity analysis seem to offer a plausible range of food security impacts given the large uncertainties surrounding the pathway to achieve the 1.5 °C target.

## 4. Conclusions

Achieving climate stabilization without compromising food security requires smart climate policy design that enables GHG-efficient mitigation in the AFOLU sector, while supporting equitable growth among countries and avoiding increased food production costs. We found that using a uniform carbon price across regions and sectors of the economy has inequitable effects with rising efforts on countries' agricultural competitiveness and food availability without accompanying (social) policies e.g. targeted redistribution of revenues generated by the carbon price (Springmann *et al* 2016). Results indicate an average global food calorie loss between 110 up to 285 kcal per capita per day in 2050 in an ambitious mitigation scenario that limits global warming to 1.5 °C and potential increase of people undernourished by 80 up to 300 million people if mitigation requirements are distributed solely based on cost-efficiency across economic sectors. Given the non-linearity of food security impacts with increasing AFOLU mitigation efforts, scenarios with more moderate AFOLU mitigation targets and global participation can still achieve significant GHG reduction, however at much lower costs in terms of calorie losses.

In the absence of global coordinated efforts, targeting land use GHG mitigation hot spots (i.e. countries with high emissions from land use change) should be given high priority when designing mitigation policies i.e. REDD+ initiatives, local certification and protection schemes etc (Van Dam *et al* 2010, Busch *et al* 2015, McGregor 2015) to minimize impacts on food security and avoid emission leakage. Steering mitigation efforts to countries that are land rich and can mitigate proportionally more from LUC rather than agriculture, while also increasing agricultural production, achieves mitigation and food security more cost-efficiently. However, impacts on other policy objectives besides climate change mitigation in these regions i.e. poverty reduction, economic development etc need to be considered to avoid trade-offs

[12] Results from two global circulation models and crop models for SSP2 in 2050 were used in the agricultural models.

(Hussein *et al* 2013, Tabeau *et al* 2017). Results also show, that regional mitigation schemes perform worse compared to globally coordinated (cost-efficient) mitigation efforts since the same level of GHG abatement is only achieved with higher impact on food security.

Mitigation policies should encourage GHG-efficient agricultural development in emerging regions, while at the same time not penalize highly efficient production systems in the developed regions, as they may be displaced with less efficient systems elsewhere with potential knock-on effects for GHG abatement and food security. Different levels of ambition in GHG reduction targets for the agricultural sector and other emission sources in the land use sector may also ease food security trade-offs. The findings reassure the direction taken in the Paris Agreement that allows countries to propose their mitigation targets considering national circumstances, while at the same time achieving a large buy-in across countries. However, more mitigation than what is currently proposed by the countries and timely delivery on these proposals will be needed to achieve net negative emissions and keep climate change well below 2 °C (den Elzen *et al* 2016, Rogelj *et al* 2016).

Including SOC sequestration on agricultural land in our analysis showed that the same levels of GHG abatement in the AFOLU sector can be reached at considerably lower carbon prices and costs in terms of calorie decrease (−65%, SOC scenario) assuming no redistribution of mitigation efforts across sectors due to the availability of SOC sequestration. Consequently, undernourishment could be reduced significantly by 60–225 million people in a 1.5 °C scenario depending on the price elasticities. Assuming an alternative implementation of the mitigation policy and adjusting AFOLU mitigation efforts in the SOC scenarios to reach the 1.5 °C target by applying the initial carbon price levels, allows enhancing the AFOLU mitigation potential by 3.5 $GtCO_2eq\,yr^{-1}$ through SOC sequestration in 2050 while at the same time still achieving slightly improved food security outcomes of −10% calorie loss and a reduction of around 10–40 million people undernourished (depending on the assumed price elasticities). As SOC sequestration generates production subsidies for carbon-enhancing management practices under a carbon price scheme, production costs increases through the carbon price are buffered and more cropland remains in production consequently benefiting food security. Given the significant potential of SOC sequestration for climate change mitigation and as it is one of the few operational negative emission technology available today, the economic potential should be further explored (Fuss *et al* 2016, Smith 2016). Feedback on non-$CO_2$ emissions, saturation effect, and permanence in the soils has to be considered (Paustian *et al* 2016) to avoid overestimating the potential contribution to climate change mitigation, especially when looking beyond 2050.

Win-win options that reduce the trade-offs between GHG abatement and food security, both on the supply and demand side, i.e. SOC sequestration, sustainable intensification, diet shift towards less GHG intensive products, reducing food waste and post-harvest losses etc., are key to avoid achieving ambitious climate stabilization targets at the expense of food security in the most vulnerable regions of the world. Together with cost-efficient mitigation options e.g. the mitigation of land use change emissions, climate finance, or additional investments (Tavoni *et al* 2015, Schellnhuber *et al* 2016, Wollenberg *et al* 2016) in agriculture, these measures could ensure that not only developed regions can achieve ambitious mitigation targets without compromising food security.

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