Agricultural non-CO_2 emission reduction potential in the context of the 1.5 °C target

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Agricultural methane and nitrous oxide emissions represent around 10-12% of total anthropogenic greenhouse gas emissions and have a key role to play in achieving a 1.5 °C (above pre-industrial) climate stabilization target. Using a multi-model assessment approach, we quantify the potential contribution of agriculture to the 1.5 °C target and decompose the mitigation potential by emission source, region, and mitigation mechanism. Results show that the livestock sector will be vital to achieve emission reductions consistent with the 1.5 °C target mainly through emission-reducing technologies or structural changes. Agriculture may contribute emission reductions of 0.8-1.4 $GtCO_2e$/yr at just 20 USD/tCO_2e in 2050. Combined with dietary changes, emission reductions can be increased to 1.7-1.8 $GtCO_2e$/yr. At carbon prices compatible with the 1.5 °C target, agriculture could even provide on average emission savings of 3.9 GtCO2e/yr in 2050, which represents around 8% of current greenhouse gas emissions.

Agriculture is the biggest source of anthropogenic non-CO_2 emissions, being responsible for around 40% of total methane (CH_4), 60% of nitrous oxide (N_2O), and around 10-12% (including CO_2 up to 20-35%) of total anthropogenic greenhouse gas (GHG) emissions [1-5]. Over the past decades agricultural non-CO_2 emission have increased from 4.3 $GtCO_2e$/yr in 1990 to around 5.7 $GtCO_2e$/yr in 2015 according to FAOSTAT (www.fao.org/faostat/en/#data/GT, applying global warming potentials from the IPCC AR4) [3,6,7]. This growth is mainly related to increased emissions from synthetic fertilizer and manure application and enteric fermentation from ruminants [2,3,6]. However, even though emissions increased by around one third, agricultural production over the same period increased by around 70% according to the FAOSTAT gross production index. Hence agriculture still continues to become more GHG efficient at global scale [6,8].

To achieve the Paris Agreement of limiting the temperature increase to well below 2 °C above pre-industrial levels, possibly to 1.5 °C, the remaining cumulative emissions should not exceed 400-1000 $GtCO_2$ by the end of the century [9,10], which requires a rapid decarbonisation of the energy system at unprecedented speed over the next decades [11-13]. Agriculture and forestry will have to contribute significantly to achieve the climate change goals, on the one hand by increasing biomass supply for fossil fuel substitution and to enable the provision of negative emissions in the second half of the century, and, on the other hand, through direct GHG emission cuts [13-16]. However, stringent mitigation challenges may affect agricultural markets either directly, e.g. through production changes and increased afforestation or dedicated energy plantations [17], or indirectly through increased costs for energy and GHG intensive inputs such as synthetic fertilizers [18,19]. Since the large-scale deployment of bioenergy with carbon capture and storage (BECCS) remains uncertain [20,21], agriculture's role in mitigation efforts is likely to receive much more attention in the future due to its importance as residual source of GHG emissions [22]. As any reduction in agricultural non-CO_2 emissions in the short term will alleviate the burden and need for negative emissions in the second half of the century [15,23], the sound estimation of mitigation potentials and mitigation measures for agriculture is key to inform mitigation policy design at global and regional scale.

Several studies assessed economic mitigation potentials in agriculture using mainly bottom-up [24-28] or top-down approaches [22,29-31] focused on supply side options. Depending on the approach used and the mitigation options included, global estimates for non-CO_2 emission reductions range from around 0.3 $GtCO_2e$ [1,24,25] up to 2.0 $GtCO_2e$ [29,31] at a carbon price of 100 USD/tCO_2e. In general, top-down approaches using equilibrium models tend to project higher mitigation potentials related to more flexible resource allocation across activities in response to a mitigation policy [32]. As the majority of agricultural non-CO_2 emissions is associated with the livestock sector [2,6], demand side options through reduced consumption of livestock products may also significantly contribute to GHG savings with potential co-benefits for health and food security [23,28,33-36]. For example, Springmann, et al. [35] showed that a global carbon tax of 52 USD/tCO_2e resulted in 107,000 avoided deaths globally and reduced agricultural non-CO_2 emissions by 1 $GtCO_2e$ in 2020. By mid-century, non-CO_2 mitigation potential through dietary changes could even be as high as 3.3-4.4 $GtCO_2e$ [23,34,36].

Here we apply four global state-of-the-art economic models (CAPRI, GLOBIOM, IMAGE, and MAGNET) to provide a comprehensive assessment of the potential contribution of the agricultural sector to ambitious mitigation efforts on the supply and demand side. Using a combination of integrated assessment (IMAGE), partial equilibrium (CAPRI, GLOBIOM) and computable general equilibrium (MAGNET) models guarantees a good coverage of uncertainty related to alternative representation of biophysical and economic agricultural features, such as land quality and spatial heterogeneity as well as cross-sectorial linkages through factor markets and substitution effects. We identify the economic mitigation potential for agricultural non-CO_2 emissions by introducing across models a consistent set of carbon prices over time (at the high end compatible with the 1.5 °C target) and assumptions on dietary changes. These globally uniform carbon prices are used to estimate the cost efficient mitigation potential and its distribution across sectors and regions rather than a real world policy. Here we assume that the cost burden of complying with any emission reduction policy will fall on the agricultural producers themselves instead of, for example, the governments. However, the producers will share the cost burden with consumers through increased prices which in turn will lead to reduction in production. This reduction will still be much smaller than if the consumer demand were perfectly elastic and all the cost would need to be carried by producers only. In a nutshell, a carbon price allows us to estimate the cost-efficient mitigation potential as mitigation measures get adopted provided that the carbon price exceeds the costs per tonne CO_2e saving of a mitigation option. We then decompose the total agricultural non-

CO_2 emission mitigation potential to gain insights on the contribution of different mitigation options and identify robust emission reduction strategies both on the supply and demand side. We differentiate between three mitigation mechanisms on the supply side: “technical options” including technologies such as animal feed supplements, nitrification inhibitors, or anaerobic digesters, “structural options” that refer to more fundamental changes in agriculture such as shifts in management systems, crop and livestock production portfolio, and international trade, and “production effects” that are changes in overall production levels across regions. On the demand side, we assess implications for GHG mitigation and food availability by shifting towards less animal product based diets in developed and emerging countries based on United States Department of Agriculture (USDA) recommendations (see method section and supplementary material).

Non-CO_2 emissions without mitigation

Results show a significant increase in agricultural non-CO_2 emissions up to 2070 if no mitigation action is taken in the sector (baseline scenario). Until 2030, emissions continue to follow historical trends (FAOSTAT) in emission growth across models (Figure 1) driven by additional demand for agricultural commodities from a growing and wealthier world population which outpaces GHG efficiency gains through productivity increases. Agricultural non-CO_2 emissions increase from around 5.4 $GtCO_2e$/yr in 2010 to 7.1-8.0 $GtCO_2e$/yr in 2050 and 7.4-9.0 $GtCO_2e$/yr in 2070. Differences across models are mostly related to methane emissions and explained by different trends in activity levels (i.e. mostly ruminant production) and emission factors. For example, the difference between CAPRI and GLOBIOM projections can be traced back to the Sub-Saharan Africa region (Figure 1b). Although both models project ruminant production to more than double by 2050, CAPRI assumes only little improvement in ruminant emission factors (i.e. following historical trends) while GLOBIOM projects a much stronger effect by 2050 driven by more rapid transition in livestock production systems towards more intensive systems with mixed-cereal feeding.

By 2050, all model projections are slightly above the FAOSTAT estimate of around 6.8 $GtCO_2e$/yr for agricultural non-CO_2 emissions and Bennetzen, et al. [37], and below the estimate from other global Integrated Assessment Models (IAMs) not represented in this study (AIM, GCAM, REMIND-MAGPIE), which span for the Shared Socio-economic Pathway 2 (SSP2) from 9.9-11.8 $GtCO_2e$/yr by 2050 [38]. Towards 2070, a slight saturation effect in emission growth is projected by GLOBIOM, IMAGE and MAGNET, especially with respect to N_2O emissions, whereas CAPRI anticipates sustained non-CO_2 emission growth related to more conservative assumptions on emission factor trends. At regional scale, significant emission growth is anticipated for developing and emerging regions in Asia (+37%), Africa (+32%), and Latin America (+21%) by 2050, driven by demand for animal (ruminant) products, particularly milk and beef. In contrast, developed countries in Europe (+3%) and North America (+2%) contribute only marginally to the total increase in agricultural non-CO_2 emissions. The livestock sector accounts for around 75% of total additional non-CO_2 emissions by 2050 compared to 2010, of which around 70% is associated with beef production and around 20% with dairy products.

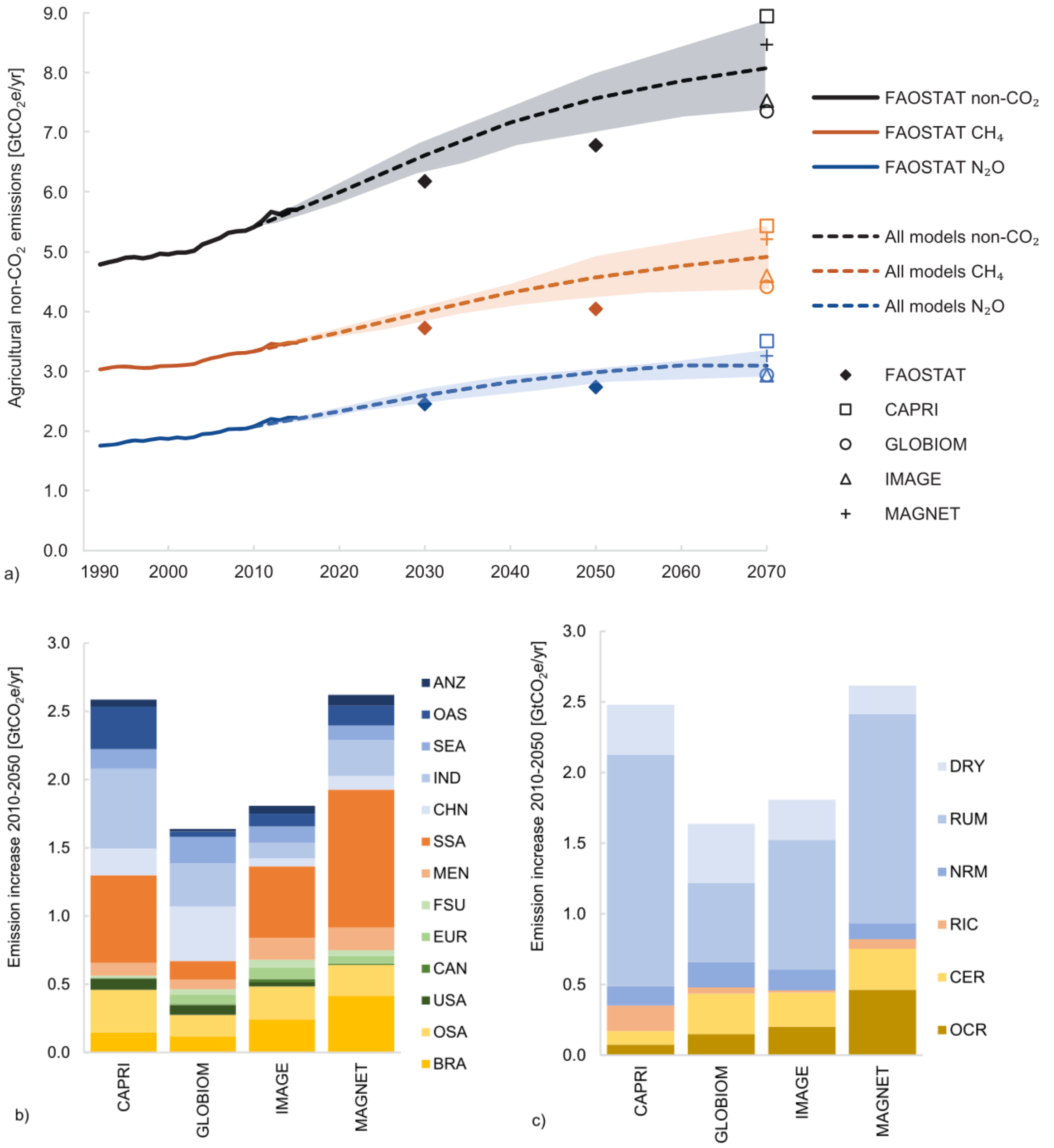

Figure 1. Baseline development of global agricultural CH_4 and N_2O emissions a) across models and absolute changes between 2050/2010, b) by region, and c) by product aggregate. Since models do not represent all crops- and livestock products endogenously, emissions were scaled to historic FAOSTAT data in the graph. The shading in a) displays the range across models. ANZ – Australia & New Zealand, OAS – Other Asia, SEA – South-East Asia, IND – India, CHN – China, SSA – Sub-Saharan Africa, MEN – Middle East, North Africa & Turkey, FSU – Former Soviet Union, EUR – Europe, CAN – Canada, USA – United States of America, OSA – Other South, Central America & Caribbean (incl. Mexico), BRA – Brazil. DRY – milk, RUM – ruminant meats, NRM – non-ruminant meats, RIC – paddy rice, CER – cereals, OCR – other crops.

Supply side mitigation potentials

To calculate the marginal abatement cost curve (MACC) for agricultural CH_4 and N_2O emissions, we implement eight carbon price trajectories on agricultural non-CO_2 emissions in the models and contrast results to the baseline scenario. The highest carbon price trajectory reaches 2500 USD/tCO_2e by 2070 (CP2500 scenario), which is in line with the estimates by the IAMs and consistent with achieving the 1.5 °C target in SSP2 by the end of the century [13]. We differentiate between emission reductions coming from *i)* technical options, *ii)* structural options, and *iii)* change in production levels, critically determined by demand responsiveness. The first two mechanisms relate to changes in emission factors of crop and livestock management activities while the third one relates to a change in activity level (Table 1).

Table 1. Representation of non-CO_2 emissions mitigation options across models.

	CAPRI	**GLOBIOM**	**IMAGE**	**MAGNET**
Non-CO_2 emissions taxed	N_2O: synthetic fertilizer application, manure management, manure applied to soils and dropped on pastures; CH_4: enteric fermentation, manure management, and rice cultivation			
Technical options	Technical options for crops and livestock sector based on MACCs from Lucas, et al. [30]	Technical options for crops and livestock sector based on Beach, et al. [24]	Technical options for crops and livestock sector based on MACCs from Lucas, et al. [30]	Technical options for crops and livestock sector based on MACCs adopted from IMAGE
Structural options	Changes in composition of regional activity or product aggregates; international trade	4 crop production systems; 8 livestock production systems; changes in composition of regional activity or product aggregates; international trade	Changes in composition of regional activity or product aggregates; international trade	Changes in composition of regional activity or product aggregates; international trade
Production level / Demand response	Full elasticity matrix including cross-price elasticities based on Muhammad, et al. [39]	Price elasticities based on Muhammad, et al. [39]	Price elasticities based on MAGNET model	Price elasticities based on GTAP database

Results show already at carbon prices of around 20 USD/tCO_2e a significant potential for emission reductions, ranging from 0.8 to 1.4 GtCO_2e/yr by 2050. At around 100 USD/tCO_2e, mitigation increases to 2.2-2.7 GtCO_2e/yr with IMAGE and MAGNET projecting faster emission reduction at lower carbon prices up to 60 USD/tCO_2e compared with CAPRI and GLOBIOM. The difference is primarily due to technical options where the slope of the MACC is less steep in CAPRI and GLOBIOM. For high carbon price pathways (CP2500, 950 USD/tCO_2e in 2050) compatible with the 1.5 °C target, models anticipate a mitigation potential of 2.9-4.9 GtCO_2e/yr. Despite the range in absolute mitigation potentials across models, which can be associated to a difference in baseline emission trajectories and representation of mitigation mechanisms, looking at relative emission savings compared to the baseline (12-19% at 20 USD/tCO_2e, 31-35% at 100 USD/tCO_2e) gives a more coherent picture. The importance of CH_4 in total non-CO_2 baseline emissions is also reflected in the mitigation potential, and CH_4 provides higher emission reduction potentials across models in both absolute and relative terms.

Figure 2 shows the contributions of mitigation mechanisms across models. Differences in absolute mitigation potentials between CAPRI, GLOBIOM, IMAGE, and MAGNET can be explained through the different representation of structural mitigation options. While in CAPRI, IMAGE and MAGNET, structural options are restricted to changes in product composition, i.e. a switch between ruminant and non-ruminant products, reduced use of fertilizer and international trade, in GLOBIOM, farmers may in addition change to more GHG efficient livestock and crop management systems in response to the carbon price [31]. The relatively small production decreases in CAPRI compared to other models are related to cross price effects. In this model, aggregate food consumption stabilizes even under high food prices due to strong substitution between ruminant and non-ruminant products.

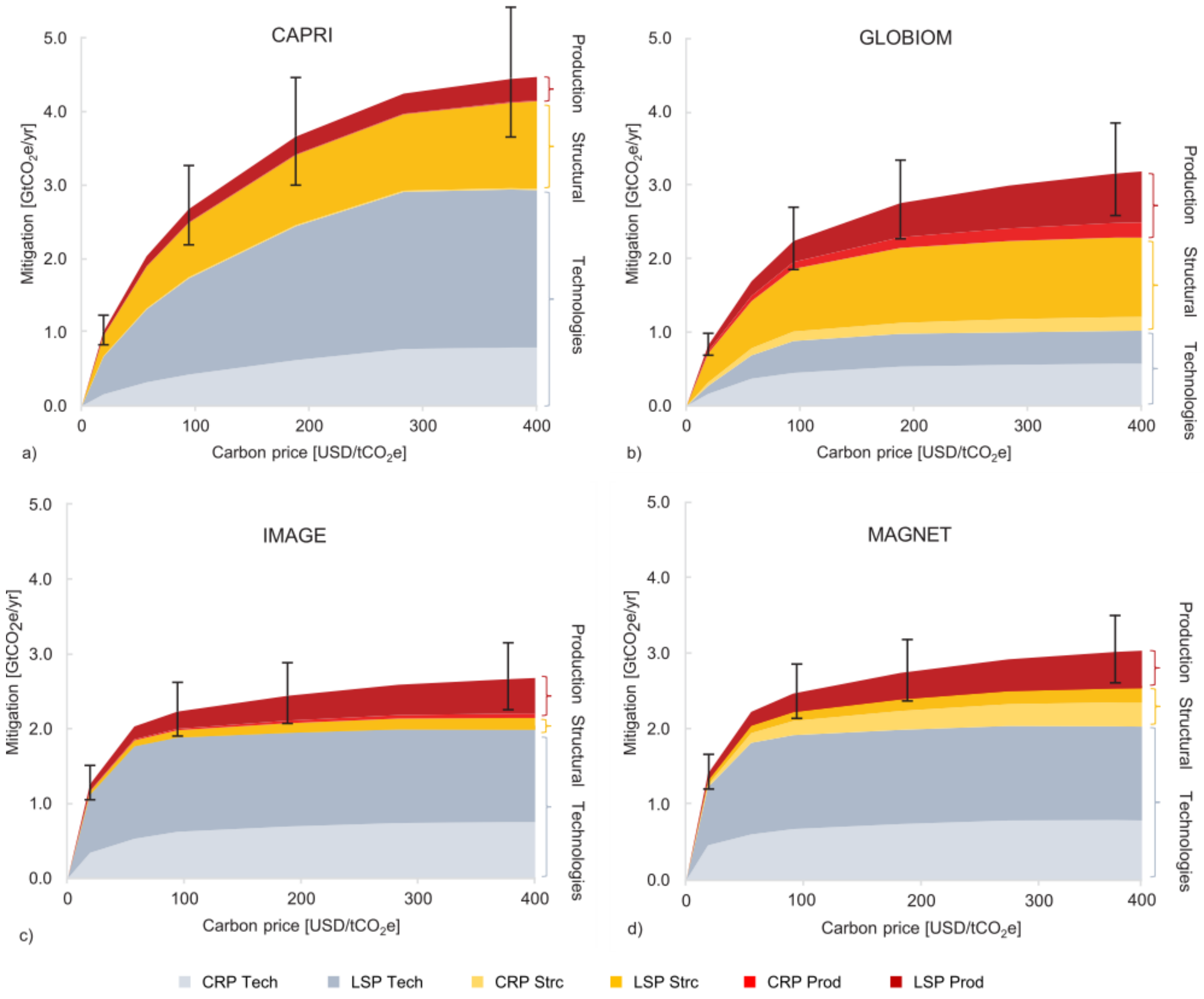

Figure 2. Agricultural non-CO_2 mitigation potentials across models. Decomposition of MACC for crop (CRP) and livestock (LSP) emissions with respect to technical mitigation options (Tech), structural options (Strc), and changes in activity levels (Prod) in 2050. Error bars show the 95% interval for the total mitigation potential when applying the uncertainty ranges calculated by Tubiello et al. (2013) to underlying emission sources at 20, 100, 190, and 380 USD/CO_2e.

Across the three mitigation mechanisms, the contributions of structural and technical mitigation options are the most model sensitive features. At carbon prices of around 20 (100) USD/tCO_2e in 2050 the contribution varies between 0.3-1.2 (0.9-2.0) GtCO_2e/yr for technical and 0.03-0.4 (0.1-1.0) GtCO_2e/yr for structural options, whereas changes in production levels contribute only between 0.05-0.1 (0.2-0.4) GtCO_2e/yr. With increasing carbon prices reducing production becomes more important as technical and structural options get exhausted and may contribute up to 37% in GLOBIOM of total mitigation at 950 USD/tCO_2e in 2050 (Figure 2b). Even though at global scale any decrease in production coincides also with decreased consumption levels, the impact on consumers is different from those on the regional supply side because of international trade.

Figure 3 presents the average mitigation potential across models by region, product aggregate and mitigation mechanism. On average, models project emission savings of around 1.1 (0.8-1.4) and 2.4 (2.2-2.7) GtCO_2e/yr at, respectively, 20 and 100 USD/tCO_2e in 2050 mainly in China, India, Sub-Saharan Africa and Latin America. Regional results are largely consistent across models (see supplementary material). At high carbon prices of around 950 USD/tCO_2e the mitigation potential increases on average up to 3.7 (2.9-4.9) GtCO_2e/yr in 2050. Across commodities, most significant emission reductions are anticipated from ruminant products, i.e. meat and milk, followed by rice and cereals. We find that especially incentivizing the uptake of mitigation (structural and technical) options in ruminant production systems in developing countries is a highly cost-efficient mitigation policy with high impact on GHG emission reduction as also concluded in other studies [28,40].

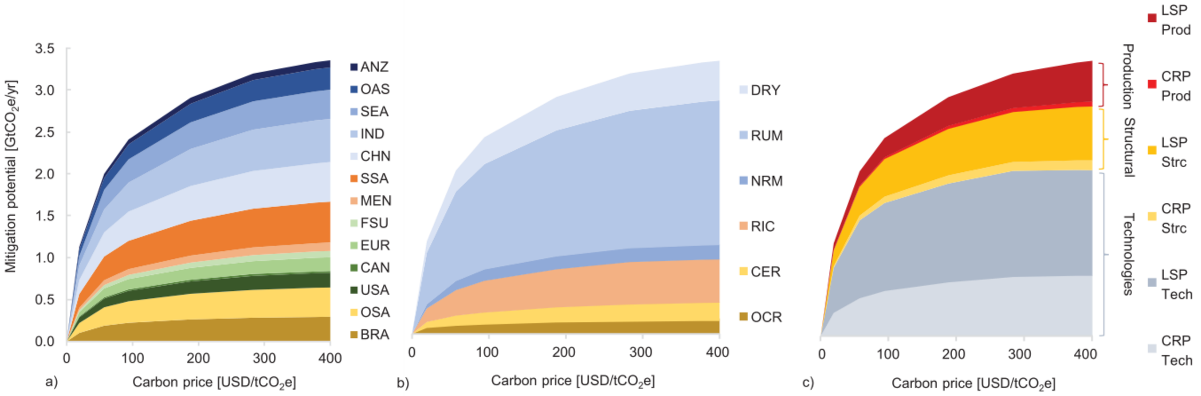

Figure 3. Average mitigation across models in 2050 a) by region, b) by product aggregate, and c) by mitigation mechanism. ANZ – Australia & New Zealand, OAS – Other Asia, SEA – South-East Asia, IND – India, CHN – China, SSA – Sub-Saharan Africa, MEN – Middle East, North Africa & Turkey, FSU – Former Soviet Union, EUR – Europe, CAN – Canada, USA – United States of America, OSA – Other South, Central America & Caribbean (incl. Mexico), BRA – Brazil. DRY – milk, RUM – ruminant meats, NRM – non-ruminant meats, RIC – paddy rice, CER – cereals, OCR – other crops. Technical mitigation options - Tech, structural options - Strc, and changes in activity levels - Prod for crops (CRP) and livestock (LSP).

Non-CO$_2$ emissions mitigation efforts may have additional co-benefits with regard to CO$_2$ emissions and sequestration. Due to the GHG efficient intensification of livestock production and consumption decreases of GHG intensive products, pasture area tends to decline in the mitigation scenarios. At 100 USD/tCO$_2$e, utilized agricultural area decreases on average by around 150 million ha compared to the baseline in 2050, mainly in Sub-Saharan Africa, which is related to the net reduction in rather GHG intensive livestock production systems [41,42]. Hence, land sparing induced by the carbon price policy may yield synergies with CO$_2$ mitigation as abandoned areas could be used for other purposes like afforestation or revegetation, thereby contributing additional mitigation through enhanced carbon sequestration in biomass and soils [8,43-45].

Mitigation potentials under dietary change

We compare the MACC above with mitigation potentials if diet preferences are shifted towards less meat intake. We assume a shift towards less animal based diets (decrease in livestock calorie intake, excluding waste, to 430 kcal/capita/day by 2070) in developed and emerging countries to assess implications of dietary changes on mitigation potentials and food availability. Results show that at carbon prices of up to 100 USD/tCO$_2$e by 2050, the dietary shift enables the realization of significantly higher non-CO$_2$ emission reductions compared to the scenarios with business-as-usual (BAU) food preferences and the same carbon price (Figure 4). At 100 USD/tCO$_2$e, emissions can be on average reduced by additional 0.4 GtCO$_2$e/yr in 2050 across models (total mitigation increases to 2.6-3.3 GtCO$_2$e/yr), which corresponds to an 18% increase in the emission mitigation potential. At 20 USD/tCO$_2$e, even an increase in the abatement potential by 0.6 GtCO$_2$e/yr (+50%) to 1.7-1.8 GtCO$_2$e/yr could be anticipated. However, with increasing levels of mitigation efforts (expressed through higher carbon prices), the additional emission reductions resulting from the dietary changes decline rapidly and in the CP2500_D scenario, the mitigation potential increases on average only by 5% (+0.2 GtCO$_2$e/yr) to 3.9 GtCO$_2$e/yr compared to the CP2500 scenario with carbon price only. Hence, the additional benefit of changing dietary preferences in developed and emerging countries on global agricultural non-CO$_2$ mitigation is likely limited compared to current IPCC climate stabilization scenarios [1] quantified by the IAMs, of which most consider carbon price induced consumption changes when applying a uniform carbon price across sectors and regions [13,46,47].

Notwithstanding, the diet shift enables to achieve the same amount of mitigation at lower carbon prices and a more equal distribution of animal calorie intake across regions (Figure 4b). Hence, even though the effect on the total agricultural non-CO_2 emission profile seems limited, dietary changes may yield economic and socio-economic, i.e. food security, benefits as they reduce the carbon price and hence mitigation costs. Moreover, the distribution of total and animal calorie intake levels is more balanced across developing and developed regions in these scenarios, which enables the developing countries to maintain higher calorie intake levels under stringent mitigation efforts. Given the very price inelastic demand in high-income countries, under BAU diets even a carbon tax of 2500 USD/tCO_2e yields only a 15% decrease in animal product consumption in developed countries compared to baseline levels. In the diet shift scenarios, the additional consumption cut (up to -36%) in overconsuming regions enables developing countries to even slightly improve their animal calorie intake levels also under high carbon prices and overall animal product consumption levels become more homogeneous across regions. For example, animal calorie intake increases by 13% in India and 9% in Sub-Saharan Africa in CP2500_D with diet shift compared to CP2500. Hence, even though a shift towards healthy diets and less livestock calorie intake will likely not contribute significant amounts of extra non-CO_2 emission reduction under stringent mitigation efforts compared to a scenario with high carbon prices only, preference shifts will still allow achieving the same amount of emission reductions with more favourable outcomes in terms of food availability in developing regions.

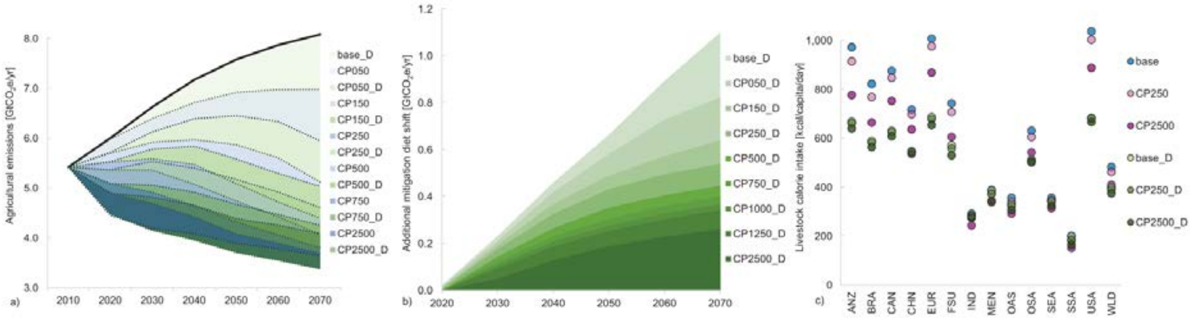

Figure 4. Impact of diet shift and carbon price scenarios on emissions and calorie consumption. Panel a) Development of global agricultural baseline (base) emissions and emission reductions in the carbon price (CP) and diet shift (_D) scenarios. b) Global emission savings in the diet shift scenarios compared to the corresponding carbon price scenario without diet shift. c) Livestock calorie intake across regions for selected scenarios. Displayed results represent an average across models. ANZ – Australia & New Zealand, OAS – Other Asia, SEA – South-East Asia, IND – India, CHN – China, SSA – Sub-Saharan Africa, MEN – Middle East, North Africa & Turkey, FSU – Former Soviet Union, EUR – Europe, CAN – Canada, USA – United States of America, OSA – Other South, Central America & Caribbean (incl. Mexico), BRA – Brazil, WLD - World.

Discussion and conclusions

We find that the agricultural sector may contribute emission reductions of around 0.8-1.4 GtCO_2e/yr already at 20 USD/tCO_2e in 2050, with diet shift even 1.7-1.8 GtCO_2e/yr. With rising carbon prices (> 100 USD/tCO_2e) emission reductions are increasingly achieved through reduction in production levels, which impacts regional food consumption levels especially under business-as-usual diets. However, a shift towards less livestock based diets in developed and emerging countries could alleviate the impacts of mitigation policies on food availability. Under moderate mitigation efforts, a diet shift could contribute significant extra emission reduction (+0.6 GtCO_2e/yr at 20 USD/tCO_2e) while it may yield only little amounts of extra mitigation compared to an ambitious global carbon tax policy which impacts consumers through price increases for high emission intensity products. Still the diet shift would allow balancing livestock calorie intake more equally across world regions and hence benefit food availability in developing countries.

Even though carbon prices are used in economic models to estimate cost-efficient mitigation potentials, they may not represent a likely policy instrument for the agricultural sector, neither in developing nor in developed regions. Given the sector's primary objective of food provision, agricultural policies are currently mainly implemented using regulations and subsidies. While these policies can play substantial role also for mitigation, support to research and development for more GHG efficient production technologies and transfer of existing technologies to developing regions may need particular attentions. It is more likely that also a future mitigation policy will not directly tax emissions, and instead rather focus on other ways of incentivizing emission reductions, where less pronounced impacts on producers and consumers can be expected [40,48]. The presented results should be considered within model and data uncertainties. For example, models differ in their representation and parameterization of mitigation options, adoption rates and costs. Emission factors for agricultural production activities and global warming potentials for non-CO_2 emissions are uncertain [6,7] and models have different anticipation of emission factor developments over time, which further increases uncertainty of results. To quantify these uncertainties and provide a sound range of results we applied four different state-of-the-art economic models focusing on the analysis of global agriculture and quantified a comprehensive set of carbon price and diet shift scenarios.

Results show that the selected models have similar perception of the overall mitigation potential and of the general slope of the agricultural non-CO_2 MACC. Across mitigation mechanisms, models estimate the most significant mitigation potentials coming from technical options such as improved rice management, animal feed supplements, fertilization techniques or anaerobic digesters. Especially ruminants are identified as key sector for climate change mitigation, contributing across models and carbon price scenarios to more than two thirds of the total mitigation potential in agriculture. Steering mitigation action towards a limited number of regions (China, India, Africa, Latin America) and commodities (beef, milk) characterized by relatively high emission intensities per kg produced, would already allow for the realization of substantial emission savings on the supply side. Overall, agriculture could provide on average emission savings of 3.9 $GtCO_2e$/yr at 950 USD/tCO_2e (45% of it already at 20 USD/tCO_2e) in 2050 considering both supply and demand side potentials, including diet shifts. Following Rogelj, et al. [13] this is about 6.5% of the total CO_2 mitigation of around annual 60 $GtCO_2$ required across all sectors by 2050 in SSP2 to achieve the 1.5 °C target cost-efficiently and around 8% of current GHG emissions.

Competing interests

The authors declare no competing interests. The views expressed are solely those of the authors and do not represent an official position of the employers or funders involved in the study.

Authors contributions

SF, PH, ES, HM, PW, and IP designed the research and performed the scenario development. Scenario implementation and simulations were carried out by PW, IPD, TF (CAPRI), SF, PH, HV (GLOBIOM), JD, ES (IMAGE), AT, JK, MD, and HM (MAGNET). SF performed first analysis of the results, produced the figures, and led the writing of the paper. All authors provided feedback and contributed to the discussion and interpretation of the results.

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Methods

We apply four global economic models (CAPRI, GLOBIOM, IMAGE, and MAGNET) to assess the agricultural mitigation potential for CH_4 (enteric fermentation, manure management, rice cultivation) and N_2O emissions (synthetic fertilizer application, manure applied to soils, manure left on pasture, manure management) by implementing a harmonized baseline scenario without mitigation efforts across models and contrasting results to a range of carbon price and diet shift scenarios. The baseline scenario corresponds to the Shared Socio-economic Pathway 2 (SSP2) from the Fifth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC) [49,50] and represents a "business as usual" scenario with continuation of current trends (including dietary preferences) and medium challenges for mitigation and adaptation. Eight exponential carbon price (CP) pathways were implemented on top of the baseline scenario. Carbon prices span from 50 to 2500 USD/tCO_2e by 2070 and cover the full range of anticipated carbon prices for SSP2 consistent with 1.5 °C climate stabilization target by the end of the century as projected by integrated assessment models [13,38]. We quantify the marginal abatement cost curve (MACC) for agricultural non-CO_2 emissions and decompose it by GHG source, region, and mitigation mechanism (i.e. technical, production and structural effects). To assess implications of a change in dietary preferences on GHG mitigation and food availability, we also quantify a set of carbon price scenarios assuming a shift in developed and emerging countries towards lower livestock product based diets.

Models

CAPRI

The Common Agricultural Policy Regionalised Impact (CAPRI) modelling system is a comparative-static partial equilibrium model for the agricultural sector, developed for policy and market impact assessments from global to regional and farm type scale. The core of CAPRI is based on the linkage of a European-focused supply module and a global market module. The regional supply module consists of independent aggregate non-linear programming models combining a Leontief-technology for variable costs of the different production activities with a non-linear cost function which captures the effects of labour and capital on farmers' decisions. Each programming model optimizes income under constraints related to land availability, nutrient balances for cropping and animal activities, and policy restrictions. Prices are exogenous to the supply module and provided by the market module. The global market module is a spatial, non-stochastic global multi-commodity model for about 60 primary and processed agricultural products, covering about 80 countries in 40 trading blocks. It is defined by a system of behavioural equations representing agricultural supply, human and feed consumption, multilateral trade relations, feed energy and land as inputs, and the processing industry; all differentiated by commodity and geographical units. Land is not explicitly allocated to activities when the model is solving. But the land demand elasticities in the system imply certain yield elasticities that may be used to disaggregate the total supply response into contributions from yields and from areas and to estimate the land allocation in scenarios, starting from the baseline land allocation. Bilateral trade and attached prices are modelled based on the Armington approach [51,52]. CAPRI endogenously calculates EU agricultural emissions for nitrous oxide and methane based on the inputs and outputs of production activities, taking specific technological GHG mitigation options into account. GHG emissions for the rest of the world are estimated on a commodity basis in the CAPRI market model [53-56].

GLOBIOM

The Global Biosphere Management Model (GLOBIOM) [31] is a partial equilibrium model that covers the global agricultural and forestry sectors, including the bioenergy sector. Commodity markets and international trade are represented at the level of 35 economic regions in this study. Prices are endogenously determined at the regional level to establish market equilibrium to reconcile demand, domestic supply and international trade. 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 [57]. For crops, livestock, and forest products, spatially explicit Leontief production functions covering alternative production systems are parameterized using biophysical models like EPIC (Environmental Policy Integrated Model) [58], G4M (Global Forest Model) [59,60], or the RUMINANT model [41]. For the present study, the supply side spatial resolution was aggregated to 2 degrees (about 200 x 200 km at the equator). 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. The model includes six land cover types: cropland, grassland, short rotation plantations, managed forests, unmanaged forests, and other natural vegetation land. Depending on the relative profitability of primary, by-, and final products production activities, the model can switch from one land cover type to another. Spatially explicit land conversion over the simulation period is endogenously determined within the available land resources and conversion costs that is taken into account in the producer optimization behavior. Land conversion possibilities are further restricted through biophysical land suitability and production potentials, and through a matrix of potential land cover transitions. GLOBIOM covers major GHG emissions from agricultural production, forestry, and other land use including CO_2 emissions from above- and belowground biomass changes, N_2O from the application of synthetic fertilizer and manure to soils, N_2O from manure dropped on pastures, CH_4 from rice cultivation, N_2O and CH_4 from manure management, and CH_4 from enteric fermentation. For this study, only results for non-CO_2 emissions were reported. The model explicitly covers different mitigation options for the agricultural sector: technical mitigation options such as anaerobic digesters, livestock feed supplements, nitrogen inhibitors etc. are based on Beach, et al. [24], structural adjustments are represented through a comprehensive set of crop- and livestock management systems parameterized using bio-physical models i.e. transition in management systems, reallocation of production within and across regions [31], and consumers' response to market signals [61]. Detailed information on the parameterization of the different mitigation options for the agricultural sector are presented in Frank, et al. [29]. For more information on the general model structure we refer to Havlík, et al. [62] and Havlík, et al. [31].

IMAGE

The Integrated Model to Assess the Global Environment (IMAGE) framework [63] describes various global environmental change issues using a set of linked submodels describing the energy system, the agricultural economy and land use, natural vegetation and the climate system. The socioeconomic models distinguish 26 world regions, while the natural ecosystems mostly work at a 5x5 minutes and 30x30 minutes grids. Agricultural demand, production and trade are modelled via the MAGNET model [64], which is integral part of the IMAGE framework in most scenario studies. Crop production is allocated on the grid-level for 7 crop types using an empirically-based allocation algorithm. Livestock production is modelled on the regional level for 5 animal products determining demand for grass and other feedstuffs as well as GHG emissions. Technical mitigation in the agricultural sector is implemented through MAC curves as implemented in the climate policy submodel [30]. The use of bio-energy plays a role in several components of the IMAGE system. The potential for bio-energy is determined using the land use model, taking into account several sustainability criteria, i.e. the exclusion of forests areas, agricultural areas and nature reserves [65]. In the energy submodel, the demand for bio-energy is assessed by describing the cost-based competition of bio-energy versus other energy carriers (mostly in the transport, electricity production, industry and the residential sectors). The resulting demand for bio-energy crops is combined with the demand for other agricultural products within a region to determine future land use and the effects on the carbon and hydrological cycles. For this purpose, the LPJml model is used, determining yields as a function of land and climate conditions and assumed changes in technology. Based on these spatially explicit attainable yields, and other suitability considerations, land use is allocated on the grid level. Finally, the emissions associated with agriculture, land-use change and the energy system are used in the climate model (MAGICC-6, Model for Assessment of Greenhouse-gas Induced Climate Change) to determine climate change, which then affects all biophysical submodels.

MAGNET

The Modular Applied GeNeral Equilibrium Tool (MAGNET) model is a multi-regional, multi-sectoral, applied general equilibrium model based on neo-classical microeconomic theory [64,66]. It is an extended version of the standard GTAP (Global Trade Analysis Project) model [67]. The core of MAGNET is an input–output model, which links industries in value added chains from primary goods, over continuously higher stages of intermediate processing, to the final assembly of goods and services for consumption. Primary production factors are employed within each economic region, and hence returns to land and capital are endogenously determined at equilibrium, i.e., the aggregate supply of each factor equals its demand. On the consumption side, the regional household is assumed to distribute income across savings and (government and private) consumption expenditures according to fixed budget shares. Private consumption expenditures are allocated across commodities according to a non-homothetic constant difference of elasticity (CDE) expenditure function and the government consumption according to Cobb-Douglas expenditure function.

The MAGNET model, in comparison to GTAP, uses a more general multilevel sector specific nested CES (constant elasticity of substitution) production function, allowing for substitution between primary production factors and (land, labour, capital and natural resources) and intermediate production factors and for substitution between different intermediate input components (e.g. energy sources, and animal feed components). MAGNET includes an improved treatment of agricultural sectors (like various imperfectly substitutable types of land, the land use allocation structure, a land supply function, substitution between various animal feed components [66,68], agricultural policy (like production quotas and different land related payments) and biofuel policy (capital-energy substitution, fossil fuels-biofuels substitution, [69]). On the consumption side, a dynamic CDE expenditure function is implemented which allows for changes in income elasticities when purchasing power parity (PPP)-corrected real gross domestic product (GDP) per capita changes. Segmentation and imperfect mobility between agriculture and non-agriculture labour and capital are introduced in the modelling of factors markets,

MAGNET is linked to IMAGE [63] to account for biophysical constraints and feedbacks. MAGNET uses information from IMAGE on agricultural land availability, crop yield changes, pasture use intensification and changes in livestock production systems. In this way, also environmental feedbacks such as depletion of high-yield land and climate impact on yields are implemented in MAGNET.

Non-CO_2 greenhouse gas emissions and mitigation options

Each model calculates absolute non-CO_2 greenhouse gas emissions resulting from agricultural production. In all models absolute production depends on demand (GDP, population, diet and bioenergy use) as well as productivity. Emission intensities (i.e. emissions per unit of production) are determined through model-specific emission factors. In addition, emission intensities change in the SSP2 baseline scenario due to assumptions on technological improvements which differ between models. In CAPRI emission coefficients are projected to moderately decline in the baseline based on historic data for most products and regions. Typically this decline is by 5-10 % only, implying that any yield increase is mostly driven by increased input use. Any mitigation scenarios starts from the baseline, however, CAPRI assumes that mitigation effectiveness increases over time, but this is less relevant in the baseline (SSP2 without carbon price) than in scenarios with increasing carbon prices. Europe is treated in more detail in CAPRI. In GLOBIOM technological improvements are captured via an exogenous technological change component (crop yield increase and livestock feed conversion efficiency), a fertilizer elasticity (proportional change in nitrogen inputs associated to exogenous technological change), and assumptions on maximum speed of system transition for endogenous reallocation production and system shift. In IMAGE yield increases due to exogenous technological improvements are based on the FAO (Food and Agriculture Organization of the United Nations) agricultural outlook, improved fertilizer use efficiency based on FAO long-term agricultural outlook, and improved livestock system efficiency (i.e. higher feed conversion efficiency) based on FAO long-term agricultural outlook. MAGNET represents technological improvements via nitrogen fertilizer substitution with labour, capital and land, yield increases due to exogenous technological improvements adopted from IMAGE and endogenous improvements due to substitution of land with fertilizer and land-fertilizer bundle with labour and capital, exogenous feed use efficiency by livestock adopted from IMAGE and endogenous substitution between different feed components. Emission intensities for rice and livestock system production are adopted from IMAGE.

Scenarios

We assess the agricultural mitigation potential for methane (CH_4) (enteric fermentation, manure management, rice cultivation) and nitrous oxide (N_2O) emissions (synthetic fertilizer, manure applied to soils, manure left on pasture, manure management, cultivation of organic soils) by implementing a harmonized baseline scenario without mitigation efforts across models and contrast baseline results to a range of carbon price scenarios. The baseline scenario is based on the Shared Socio-economic Pathway 2 (SSP2) from the Fifth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC) [49,50] which represents a “business as usual” scenario with continuation of current trends and medium challenges for mitigation and adaptation. In this scenario, world population is projected to increase to around 9.2 billion until 2050 and GDP per capita is expected to more than double globally to around 25,000 year-2005 USD per capita. More detailed information how the different teams implemented the SSP2 scenario in their respective models is provided in other studies [16,38,49,70].

Eight exponential carbon price pathways starting as off 2020 were implemented in the models. The carbon price trajectories span from 50 to 2500 USD/tCO_2eq (in 2005 prices) by 2070 (scenario CP50, CP150, CP250, CP500, CP750, CP1000, CP1250, CP2500) and hence cover the full range of anticipated carbon prices consistent with a 1.5°C climate stabilization target by the end of the century as projected by integrated assessment models for SSP2 [13,38]. The carbon price was implemented as a carbon tax on agricultural non-CO_2 emissions in the objective function of the models applied in this study. Hence, the carbon price induces the uptake of mitigation options as long as the carbon price exceeds the costs of a mitigation technology.

We quantified two marginal abatement cost curves (MACC) for agricultural non-CO_2 emissions. One MACC assuming business-as-usual SSP2 diet projections and one where we assume a diet shift of total livestock calorie consumption levels to recommended levels. We assume animal product consumption is cut in all countries that consume more animal product calories than 430 kcal/capita/day based on recommendations by the United States Department of Agriculture (USDA) (www.cnpp.usda.gov/USDAFoodPatterns). The calories target (excluding waste) is achieved gradually by 2070 such that calorie consumption will decrease linearly from 2020 level to 430 kcal/capita/day in 2070. For models explaining calories available for consumption including waste, calories per capita per day were corrected for household waste based on FAO [71]. The threshold will be then equal to 430/(1-

waste%/100) where the waste% is 11% for Europe, Russia, North America and Oceania, 8% for Industrialized Asia and North Africa, West and Central Asia, 2% Sub-Saharan Africa, 4% for South and Southeast Asia, and 6% for Latin America.

Decomposition method

We decompose the agricultural CH_4 and N_2O mitigation potential for the crop and livestock sector in model ex-post to three mitigation mechanism:

1. Mitigation from changes in production levels
2. Mitigation from technical options
3. Mitigation from structural adjustments

The total mitigation potential is estimated for different carbon prices as the difference in agricultural CH_4 and N_2O emission between a carbon price scenario and the baseline without carbon price. Total mitigation was decomposed by applying the formulas presented below. Total mitigation was distributed to the change in production levels (i) and change in emission factor (related to technical and structural options, ii and iii). The mitigation potential coming from changes in production levels was calculated by multiplying the difference in production between the baseline and a carbon price scenario with the average emission factor across the two scenarios. The mitigation potential coming from a change in emission factor was calculated vice versa by multiplying the difference in emission factors with an average production level across the two scenarios.

$$Mitigation\ from\ change\ in\ production_{r,t,s} = \left(PROD_{r,p,t,s0} - PROD_{r,p,t,s}\right) * \frac{EF_{r,p,t,s0} + EF_{r,p,t,s}}{2}$$

$$Mitigation\ from\ change\ in\ emission\ factor_{r,p,t,s} = \left(EF_{r,p,t,s0} - EF_{r,p,t,s}\right) * \frac{PROD_{r,p,t,s0} + PROD_{r,p,t,s}}{2}$$

We then decomposed the mitigation potential coming from a change in emission factors further into the part coming from either technical or structural mitigation options. Therefore we calculated the difference in emission factors considering only technical options multiplied with the average production between baseline and carbon price scenarios. In a final step, the mitigation coming from structural options was calculated as a residual by subtracting from the total mitigation potential, the share coming from production changes and changes in emission factor due to technical options.

PROD	Production levels
EF	Emission factor (non-CO_2 emissions / product unit)

r	Region
t	Year
s0	Baseline scenario
s	Carbon price scenarios

Data availability

Scenario data for all scenarios will be made accessible online via a repository at http://data.europa.eu (the exact link will be provided if the paper is accepted)

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