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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 GHG 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. The 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 Gt of CO_2-equivalent (CO_2e) yr^{-1} at just US$20 per t$CO_2$e in 2050. Combined with dietary changes, emission reductions can be increased to 1.7–1.8 GtCO_2e yr^{-1}. At carbon prices compatible with the 1.5 °C target, agriculture could even provide average emission savings of 3.9 GtCO2e yr^{-1} in 2050, which represents around 8% of current GHG 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 GHG emissions[1–5]. Over the past decades, agricultural non-CO_2 emissions have increased from 4.3 GtCO_2e yr^{-1} in 1990 to around 5.7 GtCO_2e yr^{-1} in 2015 according to FAOSTAT (www.fao.org/faostat, applying global warming potentials from the Fourth Assessment Report of the IPCC)[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 the 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 400–1,000 GtCO_2 by the end of the century[9,10], which requires a rapid decarbonization 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 through, for example, 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 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 a 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 the global and regional scales.

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 US$100 per t$CO_2$e. 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]. Springmann et al.[35] showed that a global carbon tax of US$52 per t$CO_2$e 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 sides. 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

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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 a reduction in production. This reduction will still be much smaller than if the consumer demand were perfectly elastic and all of the cost would need to be carried by producers alone. 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 tCO_2e saving of a mitigation option. We then decompose the total agricultural non-CO_2 emission mitigation potential to gain insights into the contribution of different mitigation options and identify robust emission reduction strategies both on the supply and demand sides. 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 the 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 recommendations (see Methods and Supplementary Information).

Non-CO_2 emissions without mitigation

The 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 (Fig. 1) driven by additional demand for agricultural commodities from a growing and wealthier world population that outpaces GHG efficiency gains through productivity increases. Agricultural non-CO_2 emissions increase from around 5.4 $GtCO_2e\,yr^{-1}$ in 2010 to 7.1–8.0 $GtCO_2e\,yr^{-1}$ in 2050 and 7.4–9.0 $GtCO_2e\,yr^{-1}$ in 2070. Differences across models are mostly related to CH_4 emissions and explained by different trends in activity levels (that is, 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 (Fig. 1b). Although both models project ruminant production to more than double by 2050, CAPRI assumes only little improvement in ruminant emission factors (that is, following historical trends) while GLOBIOM projects a much stronger effect by 2050 driven by a more rapid transition in livestock production systems towards more intensive but GHG-efficient systems with mixed-cereal feeding.

By 2050, all model projections are slightly above the FAOSTAT estimate of around 6.8 $GtCO_2e\,yr^{-1}$ 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 and REMIND-MAGPIE), which span for the Shared Socio-economic Pathway 2 (SSP2) from 9.9 to 11.8 $GtCO_2e\,yr^{-1}$ 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 the 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.

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 US$2,500 per 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 technical options, structural options and 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).

The results show already at carbon prices of around US$20 per tCO_2e a significant potential for emission reductions, ranging from 0.8 to 1.4 $GtCO_2e\,yr^{-1}$ by 2050. At around US$100 per tCO_2e, mitigation increases to 2.2–2.7 $GtCO_2e\,yr^{-1}$ with IMAGE and MAGNET projecting faster emission reduction at lower carbon prices up to US$60 per 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, US$950 per tCO_2e in 2050) compatible with the 1.5 °C target, models anticipate a mitigation potential of 2.9–4.9 $GtCO_2e\,yr^{-1}$. Despite the range in absolute mitigation potentials across models, which can be associated with a difference in baseline emission trajectories and representation of mitigation mechanisms, looking at relative emission savings compared to the baseline (12–19% at US$20 per tCO_2e, 31–35% at US$100 per 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 (that is, for example, 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.

Across the three mitigation mechanisms, the contributions of the structural and technical mitigation options are the most model-sensitive features. At carbon prices of around US$20 (100) per tCO_2e in 2050 the contribution varies in the range 0.3–1.2 (0.9–2.0) $GtCO_2e\,yr^{-1}$ for technical and 0.03–0.4 (0.1–1.0) $GtCO_2e\,yr^{-1}$ for structural options, whereas changes in production levels contribute only 0.05–0.1 (0.2–0.4) $GtCO_2e\,yr^{-1}$. With increasing carbon prices, reducing production becomes more important as

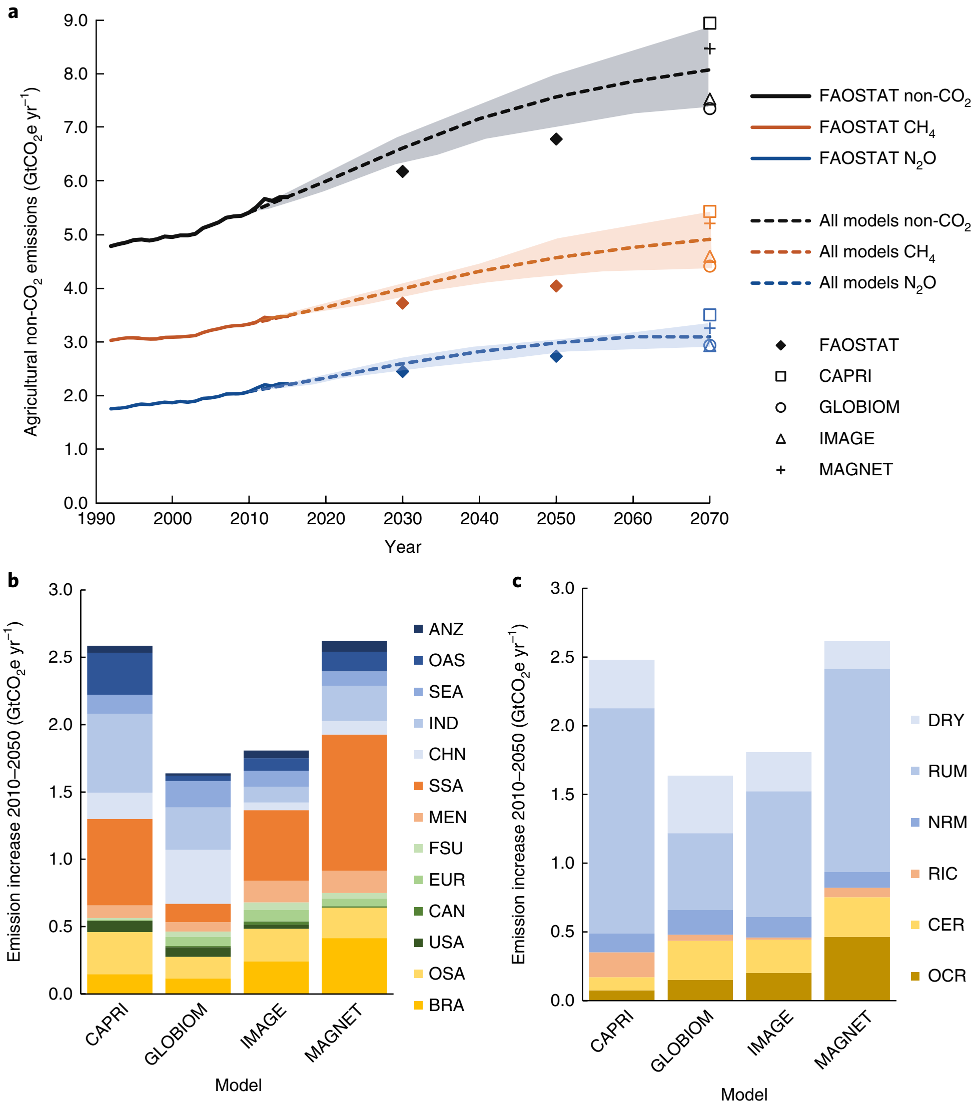

Fig. 1 | Agricultural non-CO$_2$ baseline emissions across models. **a**–**c**, Development of global agricultural CH$_4$ and N$_2$O emissions across models and absolute changes between 2050 and 2010 (**a**), by region (**b**) and by product aggregate (**c**). Since models do not represent all crop and livestock products endogenously, emissions were scaled to historic FAOSTAT data in the graph. The shading in **a** displays the range across models. ANZ, Australia and New Zealand; OAS, other Asia; SEA, Southeast Asia; IND, India; CHN, China; SSA, sub-Saharan Africa; MEN, Middle East, North Africa and Turkey; FSU, former Soviet Union; EUR, Europe; CAN, Canada; USA, United States of America; OSA, other South, Central America and Caribbean (including Mexico); BRA, Brazil. DRY, milk; RUM, ruminant meats; NRM, non-ruminant meats; RIC, paddy rice; CER, cereals; OCR, other crops.

technical and structural options get exhausted and may contribute up to 37% in GLOBIOM of total mitigation at US\$950 per tCO$_2$e in 2050 (Fig. 2b). Even though at the 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$_2$e yr^{-1} at, respectively, US\$20 and US\$100 per tCO$_2$e in 2050 mainly in China, India, sub-Saharan Africa and Latin America. Regional results are largely consistent across models (see Supplementary Information). At high carbon prices of around US\$950 per tCO$_2$e, the mitigation potential increases on average up to 3.7 (2.9–4.9) GtCO$_2$e yr^{-1} in 2050. Across commodities, most significant emission reductions are anticipated from ruminant products (that is 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 a high impact on GHG emission reduction, as also concluded in other studies[28,39].

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 US\$100 per 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[40,41]. 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 such as afforestation or revegetation, thereby contributing additional mitigation through enhanced carbon sequestration in biomass and soils[8,42–44].

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, and 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	Four crop production systems; eight 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.[48]	Price elasticities based on Muhammad et al.[48]	Price elasticities based on MAGNET model	Price elasticities based on GTAP database

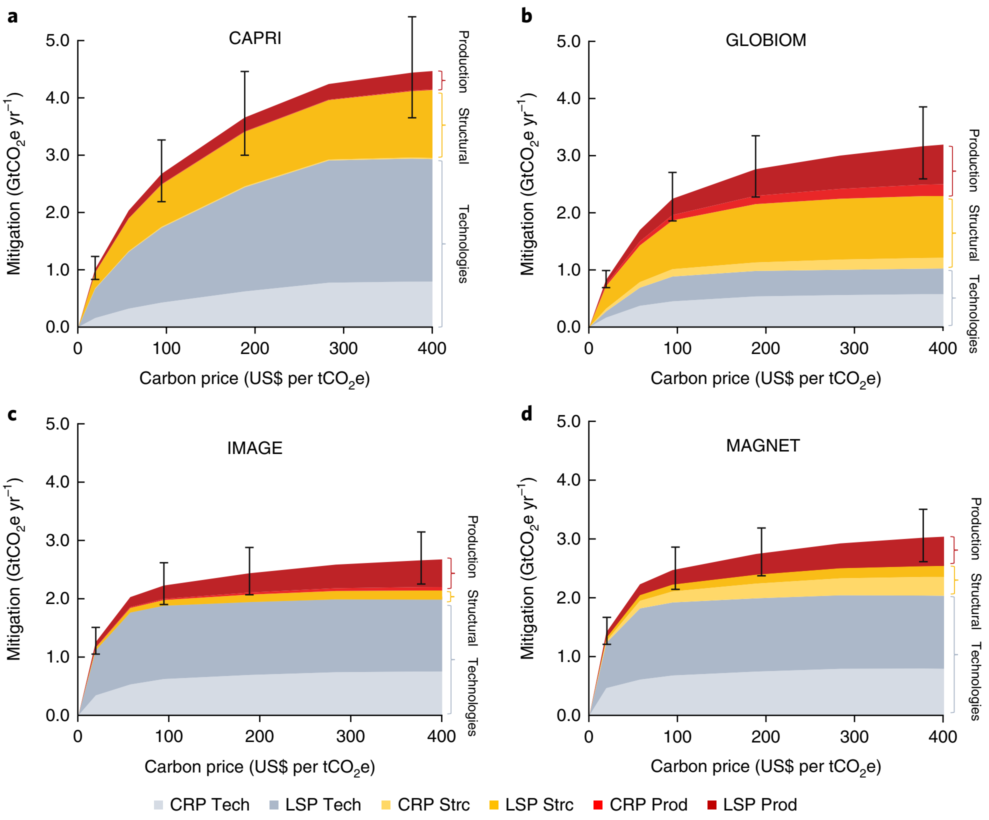

Fig. 2 | Decomposed agricultural non-CO_2 mitigation potentials across models. a–d, Decomposition of MACC for crop (CRP) and livestock (LSP) emissions with respect to technical mitigation options (Tech), structural options (Strc) and changes in activity levels (Prod) in 2050. The error bars show the 95% confidence interval for the total mitigation potential when applying the uncertainty ranges calculated by Tubiello et al.[6] to underlying emission sources at US$20, US$100, US$190 and US$380 per tCO_2e.

Mitigation potentials with dietary changes

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 per capita per day by 2070) in developed and emerging countries to assess implications of dietary changes on mitigation potentials and food availability. The results show that at carbon prices of up to US$100 per tCO_2e by 2050, the dietary shift enables the realization of significantly higher non-CO_2 emission reductions compared to the scenarios with business-as-usual food preferences and the same carbon price (Fig. 4). At US$100 per tCO_2e, emissions can be on average reduced by an additional 0.4 $GtCO_2e\,yr^{-1}$ in 2050 across models (total mitigation increases to 2.6–3.3 $GtCO_2e\,yr^{-1}$), which corresponds to an 18% increase in the emission mitigation potential. At US$20 per tCO_2e, even an increase in the abatement potential by 0.6 $GtCO_2e\,yr^{-1}$ (+50%) to 1.7–1.8 $GtCO_2e\,yr^{-1}$ could be anticipated. However, with increasing levels of mitigation efforts (expressed through higher carbon prices),

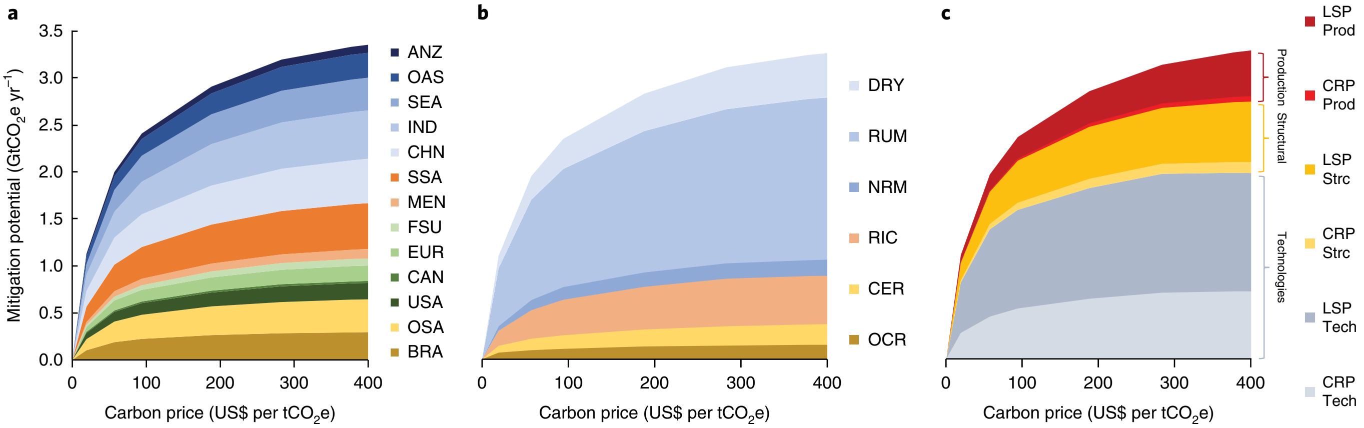

Fig. 3 | Average agricultural non-CO$_2$ mitigation potentials across models. a–c, Average mitigation across models in 2050 by region (**a**), by product aggregate (**b**) and by mitigation mechanism (**c**). ANZ, Australia and New Zealand; OAS, other Asia; SEA, Southeast Asia; IND, India; CHN, China; SSA, sub-Saharan Africa; MEN, Middle East, North Africa and Turkey; FSU, former Soviet Union; EUR, Europe; CAN, Canada; USA, United States of America; OSA, other South, Central America and Caribbean (including 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).

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^{-1}) to 3.9 GtCO$_2$e yr^{-1} compared to the CP2500 scenario with carbon price alone. Hence, the additional benefit of changing dietary preferences in developed and emerging countries on global agricultural non-CO$_2$ mitigation is probably 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[13,45,46].

Notwithstanding, the diet shift enables the achievement of the same amount of mitigation at lower carbon prices and a more equal distribution of animal calorie intake across regions (Fig. 4b). Hence, even though the effect on the total agricultural non-CO$_2$ emission profile seems limited at high carbon prices, dietary changes may yield economic and socio-economic (that is, 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 business-as-usual diets even a carbon tax of US$2,500 per tCO$_2$e yields only a 15% decrease in animal product consumption in developed countries compared to baseline levels. In the diet shift scenarios, the additional consumption cut (up to −36%) in overconsuming regions enables developing countries to even slightly improve their animal calorie intake levels also under high carbon prices and overall animal product consumption levels become more homogeneous across regions. For example, animal calorie intake increases by 13% in India and 9% in sub-Saharan Africa in CP2500_D with diet shift compared to CP2500. Hence, even though a shift towards healthy diets and less livestock calorie intake will probably not contribute significant amounts of extra non-CO$_2$ emission reduction under stringent mitigation efforts compared to a scenario with high carbon prices alone, preference shifts will still allow the achievement of the same amount of emission reductions with more favourable outcomes in terms of food availability in developing regions.

Discussion and conclusions

We find that the agricultural sector may contribute emission reductions of around 0.8–1.4 GtCO$_2$e yr^{-1} already at US$20 per tCO$_2$e in 2050, and with diet shift even 1.7–1.8 GtCO$_2$e yr^{-1}. With rising carbon prices (>US$100 per tCO$_2$e), emission reductions are increasingly achieved through reduction in production levels, which impacts regional food consumption levels especially under business-as-usual diets. However, a shift towards less livestock-based diets in developed and emerging countries could alleviate the impacts of mitigation policies on food availability. Under moderate mitigation efforts, a diet shift could contribute significant extra emission reduction (+0.6 GtCO$_2$e yr^{-1} at US$20 per tCO$_2$e) while it may yield only small amounts of extra mitigation compared to an ambitious global carbon tax policy that impacts consumers through price increases for high-emission-intensity products. Still the diet shift would allow the balancing of 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 also play a substantial role for mitigation, support for research and development of more GHG-efficient production technologies and transfer of existing technologies to developing regions may need particular attention. It is also more likely that 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[39,47]. 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 a different anticipation of emission factor developments over time, which further increases the uncertainty of the 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.

The results show that the selected models have a 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

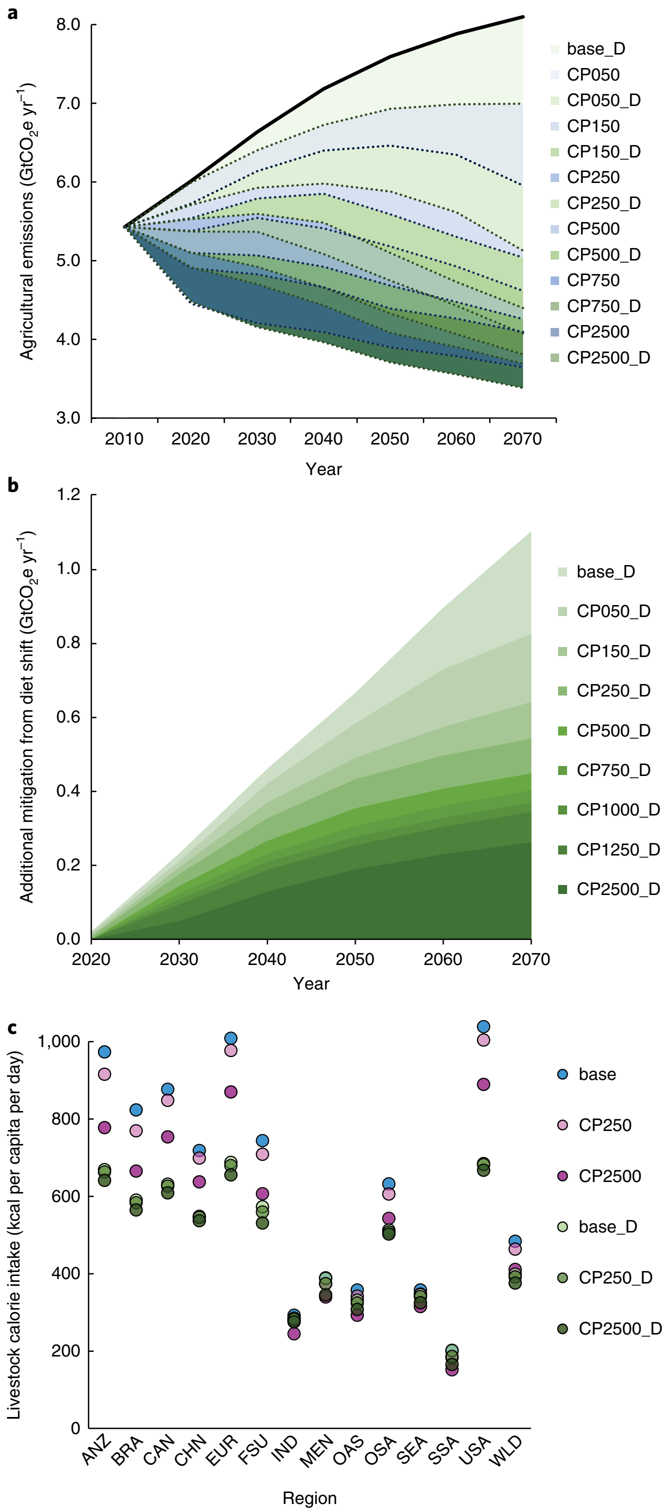

Fig. 4 | Impact of diet shift and carbon price scenarios on emissions and calorie consumption. **a**, Development of global agricultural baseline (base) emissions and emission reductions in the carbon price (CP) and diet shift (_D) scenarios. **b**, Global emission savings in the diet shift scenarios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

from technical options such as improved rice management, animal feed supplements, fertilization techniques or anaerobic digesters, followed by structural changes. Ruminants in particular are identified as a 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 and Latin America) and commodities (beef and milk) characterized by relatively high emission intensities per kilogram 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$_2$e yr^{-1} at US\$950 per tCO$_2$e (45% of it already at US\$20 per tCO$_2$e) 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 annual CO$_2$ mitigation of around 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.

Online content

Any methods, additional references, Nature Research reporting summaries, source data, statements of data availability and associated accession codes are available at https://doi.org/10.1038/s41558-018-0358-8.

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Author contributions

S.F., P.H., E.S., H.v.M., P.W. and I.P.-D. designed the research and performed the scenario development. Scenario implementation and simulations were carried out by P.W., I.P.-D., T.F. (CAPRI), S.F., P.H., H.V. (GLOBIOM), J.C.D., E.S. (IMAGE), A.T., J.F.L.K., M.v.D. and H.v.M. (MAGNET). S.F. performed the 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.

Competing interests

The authors declare no competing interests.

Additional information

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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 and rice cultivation) and N_2O (synthetic fertilizer application, manure applied to soils, manure left on pasture and manure management) emissions 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 SSP2 from the Fifth Assessment Report of the 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 pathways were implemented on top of the baseline scenario. Carbon prices span from US\$50 to US\$2,500 per tCO_2e by 2070 and cover the full range of anticipated carbon prices for SSP2 consistent with the 1.5 °C climate stabilization target by the end of the century as projected by IAMs[13,38]. We quantify the MACC for agricultural non-CO_2 emissions and decompose it by GHG source, region and mitigation mechanism (that is, technical, production and structural effects). To assess the 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 the 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 nonlinear programming models combining a Leontief technology for variable costs of the different production activities with a nonlinear cost function that 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. However, 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 on the basis of the Armington approach[51,52]. CAPRI endogenously calculates EU agricultural emissions for N_2O and CH_4 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 such as EPIC (Environmental Policy Integrated Model)[58], G4M (Global Forest Model)[59,60] or the RUMINANT model[40]. For the present study, the supply-side spatial resolution was aggregated to 2° (about 200 × 200 km at the equator). Land and other resources are allocated to the different production and processing activities to maximize a social welfare function that 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 product production activities, the model can switch from one land cover type to another. Spatially explicit land conversions over the simulation period are endogenously determined within the available land resources and considering conversion costs. 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 below-ground 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 and so on 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 (that is, 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 is presented in Frank et al.[29]. For more information on the general model structure, see Havlík et al.[31,62].

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 socio-economic models distinguish 26 world regions, while the natural ecosystems mostly work at 5 × 5 min and 30 × 30 min grids. Agricultural demand, production and trade are modelled via the MAGNET model[64], which is an integral part of the IMAGE framework in most scenario studies. Crop production is allocated on the grid level for seven crop types using an empirically based allocation algorithm. Livestock production is modelled on the regional level for five 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 bioenergy plays a role in several components of the IMAGE system. The potential for bioenergy is determined using the land-use model, taking into account several sustainability criteria (that is, the exclusion of forests areas, agricultural areas and nature reserves[65]). In the energy submodel, the demand for bioenergy is assessed by describing the cost-based competition of bioenergy versus other energy carriers (mostly in the transport, electricity production, industry and residential sectors). The resulting demand for bioenergy 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. On the basis of 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; that is, 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 expenditure function and the government consumption according to the Cobb–Douglas expenditure function.

The MAGNET model, in comparison to GTAP, uses a more general multilevel sector-specific nested constant elasticity of substitution production function, allowing for substitution between primary production factors (land, labour, capital and natural resources) and intermediate production factors and for substitution between different intermediate input components (for example, energy sources and animal feed components). MAGNET includes an improved treatment of agricultural sectors (such as various imperfectly substitutable types of land, the land use allocation structure, a land supply function and substitution between various animal feed components[66,68]), agricultural policy (such as production quotas and different land-related payments) and biofuel policy (capital–energy substitution and fossil fuels–biofuels substitution[69]). On the consumption side, a dynamic constant difference of elasticity expenditure function is implemented that allows for changes in income elasticities when purchasing power parity-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 GHG emissions and mitigation options. Each model calculates absolute non-CO_2 GHG 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 (that is, 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 that 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 only 5–10%, implying that any yield increase is mostly driven by increased input use. Any mitigation scenario 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 with exogenous technological change) and assumptions on the 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 Food and Agriculture Organization of the United Nations (FAO) agricultural outlook, improved fertilizer use efficiency based on the FAO long-term agricultural outlook and improved livestock system efficiency (that is higher feed conversion efficiency) based on the FAO long-term agricultural outlook. MAGNET represents technological improvements in agriculture via nitrogen fertilizer substitution with labour, capital and land. Yield increases are driven by exogenous technological improvements based on IMAGE and endogenous improvements due to substitution of land with fertilizer and land–fertilizer bundle with labour and capital. Exogenous livestock feed conversion efficiency is based on IMAGE while substitution between different feed components is modeled endogenously. Emission intensities for rice and livestock system production are adopted from IMAGE.

Scenarios. We assess the agricultural mitigation potential for CH_4 (enteric fermentation, manure management and rice cultivation) and N_2O emissions (synthetic fertilizer, manure applied to soils, manure left on pasture, manure management and cultivation of organic soils) by implementing a harmonized baseline scenario without mitigation efforts across models and contrast baseline results with a range of carbon price scenarios. The baseline scenario is based on the SSP2 from the Fifth Assessment Report of the 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, the 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 2005US$25,000 per capita. More detailed information on 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 of 2020 were implemented in the models. The carbon price trajectories span from US$50 to US$2,500 per tCO_2e (in 2005 prices) by 2070 (scenarios CP50, CP150, CP250, CP500, CP750, CP1000, CP1250 and 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 IAMs 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 MACCs 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 that animal product consumption is cut in all countries that consume more animal product calories than 430 kcal per capita per day based on recommendations by the United States Department of Agriculture (www.cnpp.usda.gov/USDAFoodPatterns). The calories target (excluding waste) is achieved gradually by 2070, such that calorie consumption will decrease linearly from the 2020 level to 430 kcal per capita per day in 2070. For models explaining calories available for consumption including waste, calories per capita per day were corrected for household waste based on the FAO[71]. The threshold will then be 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% for 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 the model ex post to three mitigation mechanisms: mitigation from changes in production levels; mitigation from technical options; and 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 equations presented below. Total mitigation was distributed to the change in production levels and to the change in the emission factor (related to technical and structural options). 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 by 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 by an average production level across the two scenarios.

$$\text{Mitigation from change in production}_{r,t,s} = (\text{PROD}_{r,p,t,s0} - \text{PROD}_{r,p,t,s}) \times \frac{\text{EF}_{r,p,t,s0} + \text{EF}_{r,p,t,s}}{2}$$

$$\text{Mitigation from change in emission factor}_{r,p,t,s} = (\text{EF}_{r,p,t,s0} - \text{EF}_{r,p,t,s}) \times \frac{\text{PROD}_{r,p,t,s0} + \text{PROD}_{r,p,t,s}}{2}$$

where PROD represents the production level, EF represents the emission factor (non-CO_2 emissions per product unit), r represents the region, p represents the product aggregate, t represents the year, $s0$ represents the baseline scenario and s represents the carbon price scenario.

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 by the average production between the 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.

Data availability

Scenario data for all scenarios will be made accessible online via a repository at: http://data.europa.eu/89h/5a06cad1-6c12-4d17-b008-4b58956ec3d8.

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