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OPINION

Reducing emissions from agriculture to meet the 2 °C target

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Abstract

More than 100 countries pledged to reduce agricultural greenhouse gas (GHG) emissions in the 2015 Paris Agreement of the United Nations Framework Convention on Climate Change. Yet technical information about how much mitigation is needed in the sector vs. how much is feasible remains poor. We identify a preliminary global target for reducing emissions from agriculture of ~1 $GtCO_2e\ yr^{-1}$ by 2030 to limit warming in 2100 to 2 °C above pre-industrial levels. Yet plausible agricultural development pathways with mitigation cobenefits deliver only 21–40% of needed mitigation. The target indicates that more transformative technical and policy options will be needed, such as methane inhibitors and finance for new practices. A more comprehensive target for the 2 °C limit should be developed to include soil carbon and agriculture-related mitigation options. Excluding agricultural emissions from mitigation targets and plans will increase the cost of mitigation in other sectors or reduce the feasibility of meeting the 2 °C limit.

Keywords: agriculture, climate change, integrated assessment modeling, mitigation, policy, target, United Nations Framework Convention on Climate Change

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Introduction

The 2015 Paris Agreement of the United Nations Framework Convention on Climate Change (UNFCCC) aims to hold the rise in global average temperatures by

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2100 to 'well below 2 °C above pre-industrial levels and to pursue efforts to limit the temperature increase to 1.5 °C above pre-industrial levels'. A surprisingly large number of countries – at least 119 – voluntarily pledged to reduce their agricultural greenhouse gas (GHG) emissions for the agreement in their statements of Intended Nationally Determined Contributions to the UNFCCC (Richards *et al.*, 2016). Yet how much mitigation is needed in agriculture to meet a global target vs. how much is feasible remains poorly understood (Del Grosso & Cavigelli, 2012; Cafaro, 2013). Current pledges reflect countries' interests and capacities and are limited to available technical options. Meanwhile, scenarios indicate that agricultural and agriculture-related emissions, including non-CO_2 emissions, will constitute the largest sector of surplus emissions in the future, as other sectors are projected to reduce their emissions to the maximal extent by 2030, so agriculture is critical to meeting global climate targets (Bajželj *et al.*, 2014; Gernaat *et al.*, 2015). Excluding agricultural emissions from mitigation targets will increase the cost of mitigation in other sectors (Reisinger *et al.*, 2013) or reduce the feasibility of meeting the 2 °C limit.

A global target for reduced emissions from agriculture based on meeting the 2 °C limit would show the shared effort required and in turn guide countries' ambitions, drive the development of new low emissions options, and assess the global relevance of mitigation contributions. We identify here a preliminary target to guide this process. We also examine its implications by comparing the target with plausible future mitigation pathways, showing that vastly more effort is needed.

Agriculture contributes ~5.0–5.8 $GtCO_2e\ yr^{-1}$ or ~11% of total anthropogenic GHG emissions, not including land-use change (Smith *et al.*, 2014). Developing countries collectively produce the majority of agriculture-related emissions globally and are where emissions are expected to rise the fastest (Smith *et al.*, 2014). Agricultural emissions are also significant at national levels, contributing an average of 35% of emissions in developing countries and 12% in developed countries according to countries' GHG emissions inventory reports to the UNFCCC (Richards *et al.*, 2015).

We define agricultural net emissions as the methane (CH_4) and nitrous oxide (N_2O) emissions, and carbon sequestration resulting from the production of crops, livestock, and agroforestry on farms. Agriculture-related emissions and opportunities for mitigation also occur in the supply chain (transport, processing fertilizer production, postharvest loss) and due to land-use change and consumption patterns (diet and food waste). One of the challenges of developing a sectoral mitigation target linked to the 2 °C goal is defining the boundaries of the sector. The tools and data available currently shape how global emissions reductions are allocated to the sector. Most models use 2 °C climate scenarios that focus only on non-CO_2 emissions in agriculture, as soil carbon is highly variable and involves assumptions related to organic matter inputs, carbon–nitrogen ratios, depth and bulk density, and timing of saturation (Powlson *et al.*, 2011). In addition, global data on carbon in biomass, such as agroforestry, are comparatively weak. Carbon sequestration is also reversible. As a result, the target presented here is for only non-CO_2 emissions. We acknowledge the importance of other sources and sinks, however, and provide aspirational targets for the other components as preliminary guidance.

Scenarios that limit warming by 2 °C

To determine the emissions budget necessary to limit warming in 2100 to no more than 2 °C above pre-industrial levels, we used a scenario prepared for the Intergovernmental Panel on Climate Change (IPCC) known as Representative Concentration Pathway (RCP) 2.6 (van Vuuren *et al.*, 2011). The RCP 2.6 scenario represents 2.6 W m^{-2} radiative forcing in 2100, or ~450 ppm of CO_2e in 2100, which results in a 66% or 'likely' chance of staying below the 2 °C warming limit (van Vuuren *et al.*, 2011). The RCP 2.6 is one of four reference scenarios used to model concentration pathways for the IPCC.

We then compared the emissions in this desirable scenario against the business-as-usual emissions in agriculture from three integrated assessment models (IAM): Integrated Assessment of Global Environmental Change (IMAGE) (van Vuuren *et al.*, 2011), Global Change Assessment Model (GCAM) (Wise *et al.*, 2014), and Model for Energy Supply Strategy Alternatives and their General Environmental Impact (MESSAGE) (Reisinger *et al.*, 2013). Using this approach differs from previous estimates of agriculture's contribution that identify the wedges of mitigation possible (Pacala & Socolow, 2004), allocate mitigation proportional to current emissions (Del Grosso & Cavigelli, 2012), or examine contributions to the total emissions budget in 2030 necessary for 2 °C (Hedenus *et al.*, 2014). By using the sectoral emissions in the RCP 2.6 scenario as the target, we generated a goal consistent with a 2 °C pathway and based on a coherent least-cost approach across sectors.

The three IAMs used to compare the desirable 2 °C degree and business-as-usual worlds produce slightly different scenarios, but use similar assumptions to achieve the RCP 2.6 pathway, including significantly increased carbon prices relative to current prices, for example, IMAGE used 80 USD per tCO_2e in 2030 and

160 USD per tCO_2e in 2050; increased food production to meet the needs of a larger population and shifts in consumer demand; and maintaining current rates of food insecurity in the population, not eliminating it entirely. As noted previously, the models only account for non-CO_2 gases in agriculture, not soil carbon sequestration. They do, however, include bioenergy with carbon capture and storage to achieve the negative emissions needed to offset increases driven by an increasing population and consumption, as well as carbon sequestration associated with land-use change. More details on data and methods are provided in the Appendices S1–S3.

A 2030 goal

The resulting scenarios indicate that a preliminary goal for agricultural non-CO_2 emissions mitigation by 2030 to stay within the 2 °C limit is 0.92–1.37 $GtCO_2e\ yr^{-1}$ or about 1 $GtCO_2e\ yr^{-1}$. This is an annualized, not cumulative, goal. The target assumes an allowable emissions budget of 6.15–7.78 $GtCO_2e\ yr^{-1}$ for agriculture in 2030 (Table 1). The goal represents an 11–18% reduction relative to the scenarios' respective 2030 business-as-usual baselines. Our estimate falls in the range of 0.3–2.0 $GtCO_2e\ yr^{-1}$ for land-based CH_4 and N_2O emissions reductions reported by Smith *et al.* (2014) in the idealized implementation of the 2 °C scenario for 2010–2050. The goal would contribute ~4–5% of the 26 $GtCO_2e\ yr^{-1}$ in mitigation needed across all sectors in 2030 to achieve the 2 °C limit; business-as-usual emissions for all sectors in the same year are ~68 $GtCO_2e$ (New Climate Economy, 2014).

As a target for 2030, this is a near-term goal only. The scenarios show that the contribution of agriculture would need to increase in 2050 to 2.51 $GtCO_2e\ yr^{-1}$ (IMAGE) and 2.63 $GtCO_2e\ yr^{-1}$ (GCAM), reaching a maximum of 2.91 $GtCO_2e\ yr^{-1}$ in 2070–2080 using IMAGE and 4.30 $GtCO_2e\ yr^{-1}$ in 2100 using GCAM. Despite the models' different trajectories, all scenarios indicate the ongoing importance of agricultural emissions for decades to come.

Is the goal achievable?

Assuming that 1 $GtCO_2e\ yr^{-1}$ in 2030 is a reasonable order of magnitude for reducing non-CO_2 emissions in the agriculture sector, is it feasible? We examined this question using the best comprehensive scientific evidence available and tested two plausible development pathways: one that reflects widespread dissemination of technical agronomic practices at prices of up to 20 USD per tCO_2e; and one based on intensified production of crops and livestock with increases in efficiency, also at prices of up to 20 USD per tCO_2e. Both pathways rely on existing practices that improve, or at least do not compromise, food production.

The pathway for widespread dissemination was tested by summing the mitigation achieved across agricultural technologies demonstrated to reduce non-CO_2 emissions and shows that agricultural non-CO_2 GHG emissions could be reduced by up to 0.40 $GtCO_2e\ yr^{-1}$ in 2030 globally (Smith *et al.*, 2008, 2013). This technology-by-technology estimate includes livestock management, cropland management, and paddy rice management practices used by the IPCC, but excludes practices related to soil carbon due to the need for consistency with the 2 °C scenarios. This pathway would require implementing improved technologies with nearly universal adoption globally.

The second pathway of intensifying livestock and crop production and increasing economic efficiency was tested using the Global Biosphere Management Model. This pathway reduced agricultural non-CO_2 emissions by up to 0.21 $GtCO_2e\ yr^{-1}$ in 2030 (Havlík *et al.*, 2014). The estimate reflects five broad crop and livestock sector-related structural transformations, such as transitioning from extensive rangeland systems to more efficient and productive livestock production,

Table 1 Greenhouse gas emissions and mitigation needed in the agriculture sector in 2030 to avoid exceeding 2 °C

Model	Model category	Basis for non-CO_2 mitigation	Baseline 2030 emissions $GtCO_2e\ yr^{-1}$	450 ppm scenario emissions $GtCO_2e\ yr^{-1}$	Mitigation modeled
IMAGE RCP 2.6 (van Vuuren *et al.*, 2011)	Recursive dynamic partial equilibrium model	US-EPA MAC curves based on Lucas *et al.* (2007)	7.52	6.15	1.37
GCAM (Wise *et al.*, 2014)	Recursive dynamic partial equilibrium model	US-EPA MAC curves based on DeAngelo *et al.* (2006)	8.97	7.78	1.19
MESSAGE (Reisinger *et al.*, 2013)	Intertemporal optimization general equilibrium model	US-EPA MAC curves based on Beach *et al.* (2008)	8.58	7.66	0.92

with accompanying improvements in livestock feed quality, breeding, reproductive efficiency, health and grassland management, and re-allocation of production to GHG-efficient regions. Soil carbon was also not included in this analysis.

Comparing the two pathways against the idealized RCP 2.6 scenarios (Fig. 1) indicates that current agronomic and policy interventions compatible with food production would achieve only 21–40% of the needed mitigation. Neither technological dissemination as considered in Smith *et al.* (2008, 2013) nor large-scale transformation of crop and livestock production systems as analyzed by Havlík *et al.* (2014) contributes the required emission reduction at low costs. Even if implemented jointly, the results would fall short of the necessary mitigation, and the interventions are unlikely to be additive. Examining the mitigation possible in specific agricultural subsectors also shows that only a fraction of the mitigation needed would be achievable with current technologies (Table S3).

How to reduce emissions further?

The large gap between desired and plausible mitigation outcomes indicates that more transformative technical and policy options will be needed to reduce non-CO_2 emissions or that mitigation from other sources will be needed to offset them. New low emissions technologies are in the pipeline for agriculture, but vastly more effort and urgency is necessary to make options operational (Herrero *et al.*, 2016). Many are high-tech solutions not likely to be widely available soon, especially in the developing world. Promising options include recently developed methane inhibitors that reduce dairy cow emissions by 30% while increasing body weight without affecting milk yields or composition (Hristov *et al.*, 2015). Work is in progress to identify cattle breeds that produce less methane (Herd *et al.*, 2013) and wheat and maize varieties that inhibit the production of nitrous oxide (Subbarao *et al.*, 2015). Evidence suggests it may be possible to manage soil–plant microbial processes to increase the stability of soil organic matter and thereby retain carbon in the soil longer (Cotrufo *et al.*, 2013; Paustian *et al.*, 2016). These are each potentially transformative options, but they are not yet enough to create the menus of options needed for diverse agroecological systems and farmers to meet a mitigation target for 2 °C. Coordinated research and investment among countries toward high-impact, quickly implementable technical options, especially for new breeds and varieties that can be easily accessed and do not require completely new management practices or inputs, is key.

More ambitious policy mechanisms also will be needed to create incentives for improved information systems and for farmers to use new practices at large scales. Policies supporting more productive agricultural practices, finance of low emissions agricultural development, innovative means for valuing carbon reductions, and use of government or supply chain incentives to meet sustainability standards for reduced

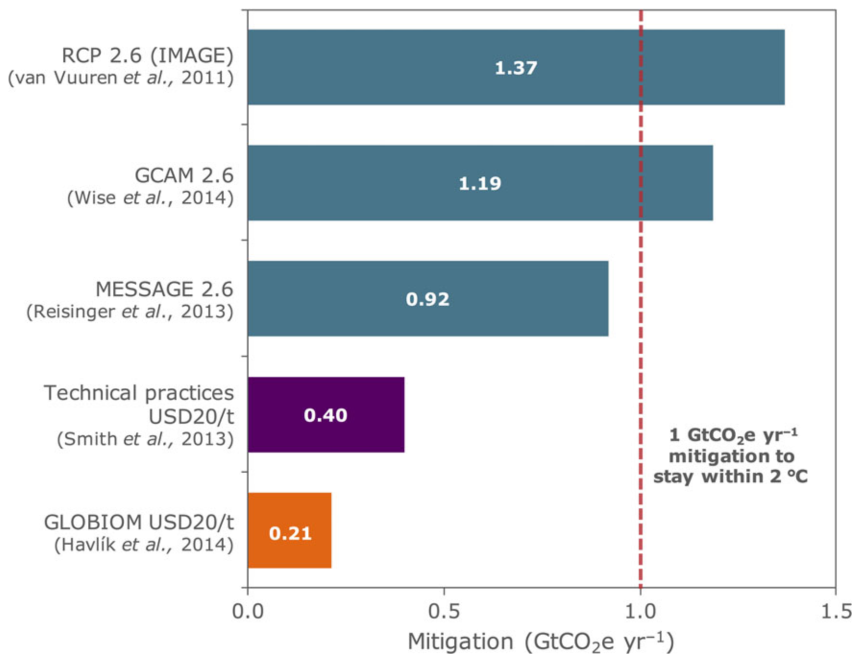

Fig. 1 Contributions of mitigation scenarios compared to the 2 °C mitigation goal for agriculture.

emissions will all likely be needed. The finance and technology mechanisms in the 2015 Paris Agreement are a good start, but complementary effort will be needed at national and subnational levels, especially to engage farmers and producer organizations. Strong technical assistance for farmers, including farmer innovation hubs, two-way technical support via cell phones, web-based information portals, and farmer-to-farmer exchange, will be essential to foster changes in behavior and locally relevant options. As rapidly implementing new farming practices at large scales is risky, especially given climate uncertainties, monitoring and iterative improvement of mechanisms will be vital to provide feedback for further improvements.

The need for increased global food production by 2050 presents an opportunity to introduce mitigation measures as cobenefits of agricultural development and support farmers to leapfrog to more sustainable low emissions practices. Investments in mitigation could thereby hasten agricultural development. Special effort will be needed to ensure that new technologies are relevant, affordable, and accessible to farmers in the developing world.

Other targets for agriculture

Targets linked to the 2 °C limit are also needed for carbon sequestration and agriculture-related mitigation options, which can have equal or larger impacts on mitigation than practices to reduce non-CO_2 and may help offset non-CO_2 emissions. Improving models to produce these additional targets is a priority.

In the absence of models that enable calculations of these targets, we estimated aspirational targets for agriculture-related emissions sources based on what is achievable globally at low costs. Where available, we used economic potentials. Soil carbon sequestration is the largest potential sink compatible with food production, mitigating ~1.2 $GtCO_2e\ yr^{-1}$ in 2030 at USD 20/tCO_2e (Smith *et al.*, 2014; Williamson, 2016), although its effects are easily reversed with tillage or soil disturbance. Reducing land-use change due to clearing for agriculture would mitigate by 1.71–4.31 $GtCO_2e\ yr^{-1}$ in 2030 at USD 20/tCO_2e (Carter *et al.*, 2015).

Decreasing food loss and waste by 15% (of the total global loss and waste; current loss and waste is 30% to 50% of global food production) would reduce emissions by 0.79–2.00 $GtCO_2e\ yr^{-1}$ (Stehfest *et al.*, 2013). Shifting dietary patterns, to the diet recommended by the World Health Organization (Stehfest *et al.*, 2013) or in response to increases in carbon prices (Havlík *et al.*, 2014), would mitigate 0.31–1.37 $GtCO_2e\ yr^{-1}$ in 2030. See Appendices S1–S3 for details on methods. Based on these proxy estimates, a more comprehensive goal for agriculture-related emissions would be on the order of ~5–9 $GtCO_2e\ yr^{-1}$, or about 27% of the mitigation needed across all sectors. This estimate is consistent with Del Grosso & Cavigelli's (2012) estimate for a similar set of options.

Targets also can be organized by supply chains to mobilize action for specific subsectors or products. In the livestock supply chain, a major source of emissions globally, emissions could be reduced by about 1.77 $GtCO_2e\ yr^{-1}$ (Gerber *et al.*, 2013). Since food production will need to increase in the coming decades, a target based on the GHG efficiency of agricultural products, (emissions intensity, or GHG per unit product), is a useful secondary indicator to guide ambition and mark progress.

Conclusion

We propose that the global institutions concerned with agriculture and food security set a sectoral target to guide more ambitious mitigation and track progress toward goals. To be policy relevant, a target for mitigation in agriculture must help achieve the 2 °C warming limit while also assuring food security. Using the RCP 2.6 scenario, we identified ~1 $GtCO_2e\ yr^{-1}$ by 2030 as a preliminary 2 °C-based target for reducing agricultural non-CO_2 emissions. Plausible development pathways fall far short of this goal. Coordination of high-impact technical and policy interventions will be needed, including options that meet the needs of farmers in the developing world.

The proposed target is based on the best available scientific evidence, but can be improved. A more comprehensive 2 °C-based target is needed that includes the full menu of options for mitigation related to agriculture. For more transformative impacts, the potential of emerging technical and policy options also should be tested using the RCP 2.6 or similar scenarios. Better understanding of the sensitivity of a target to different carbon prices, alternative mitigation pathways, and varied levels of food security – including full food security globally – would support more robust quantification and understanding of impacts. Better estimates of uncertainties are also needed. Aligning scenarios with a consistent emissions baseline, such as FAOSTAT's projections for agricultural emissions (Tubiello *et al.*, 2013), or countries' reported emissions, would enable verification and more harmonized analysis. Scenarios for limiting warming to 1.5 °C also will be needed, as even 2 °C is expected to result in extensive damage and the Paris Agreement mandates to pursue 1.5 °C. Downscaling the target to the country level is needed to inform countries' revised submissions of Nationally Determined Contributions to the UNFCCC (Höhne *et al.*, 2014).

As more countries seek to address climate change in the agriculture sector, linking national targets to the global 2 °C threshold can guide research agendas, agricultural development, and national farm policy. Analysis of the investment needed in agriculture to reach the 2 °C goal will inform what is economically desirable and where trade-offs might occur with other sectors. Without the guidance of a 2 °C-based goal in agriculture, much effort will be driven by what is technically or politically feasible, rather than by what is necessary. Better understanding of the gaps will show where further investment and accelerated action are really needed.

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Supporting Information

Additional Supporting Information may be found in the online version of this article:

Appendix S1. Overview of methods, including Tables S1–S4.
Appendix S2. Data sources and methods, including Figure S1 and Tables S5–S10.
Appendix S3. 2030 reference levels.
Appendix S4. References.