LETTER

The role of non-CO2 mitigation options within the dairy industry for pursuing climate change targets

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Abstract

Mitigation of non-CO2 climate forcing agents must complement the mitigation of CO2 to achieve long-term temperature and climate policy goals. A large share of global non-CO2 greenhouse gas emissions is attributed to agriculture, with a significant contribution related to dairy production. As demonstrated by the results of a recent USDA coordinated project, Dairy-CAP, dairy farmers can significantly reduce their greenhouse gas emissions by implementing beneficial management practices (BMPs). This study assesses the potential mitigation of projected climate change if greenhouse gases associated with the dairy subsector were reduced. To compare the performance of several mitigation measures under future climate change, we employ a fully coupled Earth system model of intermediate complexity, the MIT Earth System Model. With an interactive carbon-cycle, the model is capable of addressing important feedbacks between the climate and terrestrial biosphere impacting greenhouse gas concentrations. We illustrate the importance of ongoing mitigation efforts in the agricultural sector to reduce non-CO2 greenhouse gas emissions towards established climate goals. If BMPs are implemented globally within the next three decades, projected warming by the end of the century can be reduced by 0.21 °C on average or 6% of total warming, with dairy farm mitigation contributing to 0.03 °C of the temperature reduction.

1. Introduction

Substantial reductions in anthropogenic greenhouse gas emissions are needed to limit the rise in global temperatures to 2 °C above the preindustrial level [1–4]. While anthropogenic emissions of carbon dioxide (CO2) are the largest contributors, non-CO2 emissions collectively contribute to a quarter of the total current greenhouse gas emissions based on equivalent emissions using the 100 year global warming potential (GWP) [5]. To meet climate stabilization goals, efforts to reduce CO2 would benefit from complementary efforts in reducing non-CO2 emissions [6, 7]. Mitigation of short-lived climate pollutants such as methane (CH4) can lead to a rapid decline in radiative forcing, and will significantly impact the magnitude of the peak temperature response and CO2 budget set for a policy-relevant temperature limit [8]. Following strict CH4 mitigation, a CO2 emissions budget could extend to 25% higher than a budget that does not limit CH4 [2]. Long-lived non-CO2 emission reductions can also provide additional benefits. Mitigation of nitrous oxide (N2O) will offer the combined benefit of limiting dangerous climate change and sustaining stratospheric ozone. With soils producing the most N2O emissions, the greatest mitigation potential lies in the agricultural sector [9].

The agricultural sector is the principal contributor to anthropogenic non-CO2 greenhouse gas emissions, accounting for 45% of global CH4 emissions and 82% of global N2O emissions in 2005 [10]. Between 1961 and 2010, on average, agricultural emissions increased at 1.6% per year with the greatest growth in Africa, Asia, and the Americas [11]. During this same period,
some emission growth was offset by sustainable farming practices in Europe and Oceania. As the demand for food increases with population growth, agricultural emissions are projected to further increase by 20% before 2030 [10]. As a whole, the sector must reduce emissions and increase resilience to changes in future climate, while simultaneously increasing productivity and achieving sustainable food security [12].

To address food security challenges and support agricultural development, the US Department of Agriculture launched the Sustainable Dairy Coordinated Agricultural Project (hereafter, Dairy-CAP) (sustainabledairy.org). Dairy-CAP brought together multi-disciplinary teams of researchers to understand how US dairy agroecosystems are connected to the global environment and how improved farm management practices can reduce greenhouse gas emissions. The coordinated Dairy-CAP project developed multiple agricultural beneficial management practices (BMPs) to reduce greenhouse gas emissions, while ensuring continued productivity and economic profitability of the US dairy industry [13]. BMPs identified by the collaboration included changes to animal feed, manure management systems, and field systems [14, 15]. The Dairy-CAP project differs from other agricultural investigations by considering combinations of practices on the whole-farm rather than assessing implementation of a single BMP at a time [12, 16]. Whole-farm solutions are necessary because introducing a BMP for one farm component can impact total farm emissions by counteracting emission reductions in another farm component [17]. If considered as whole-farm strategies, BMPs in dairy production systems have the potential to reduce 41% of carbon and reactive nitrogen footprints, while increasing net monetary return and milk production [13].

As a component of the Dairy-CAP project, we evaluate the global impact and effectiveness of the management practices that were developed for US dairy farms. We seek to understand how implementation of whole-farm BMPs can contribute to the reduction in atmospheric non-CO2 greenhouse gases in an effort to reach policy-relevant temperature targets in a warming world.

To our knowledge, no studies exist that estimate the dairy contribution to warming or calculate how mitigation efforts in the dairy subsector can limit future warming. However, several modeling studies look at net livestock emissions, in which emissions from beef production and dairy production are aggregated together [18, 19]. Using a simple carbon-climate model, a recent study determined that global livestock emissions caused about 23% of the total warming in 2010 and could potentially lead to an additional 0.23 °C of warming by 2100 [20].

Our work extends beyond previous livestock studies by using whole-farm BMP strategies to inform plausible emission reductions within an Earth system model of intermediate complexity. The model we employ contains a more sophisticated representation of the carbon-cycle with interactive atmospheric chemistry to capture the time-evolving chemical feedbacks that extend the lifetime of atmospheric species like CH4 and ozone.

Dairy-CAP research results guide the development of future emission scenarios for this Earth system modeling study. We design two plausible emission scenarios based on the whole-farm BMP strategies for two farm sizes; a representative 150-cow and 1500-cow US dairy farm as defined in Veltman et al (2018). The scenarios assume whole-farm BMPs begin to be globally implemented in 2020 and are fully employed within 30 years. Because it is unlikely all farms would abruptly implement BMPs, we use a linear trend in emissions reductions to broadly represent a wide range of pathways for economies to adjust to new farming technologies and practices. With this study, we demonstrate the global impact agricultural mitigation options can have on the global mean temperature. By demonstrating how non-CO2 reductions from globally implemented BMPs will limit future warming, our study could help motivate the dairy and agricultural policy makers to begin transitioning to better farm practices.

2. Methods

2.1. Whole-farm BMPs

Here, we briefly summarize the Dairy-CAP work of Veltman et al (2018), which developed whole-farm BMPs for two distinct but representative US dairy farms. Simulated farms portray present-day dairy farming practices of a small 150 herd-size Wisconsin farm and a 1500 herd-size New York farm. As a comparison, a control farm with no BMPs was simulated for each farm size. BMPs were applied to three farm components; animal feed, manure management, and field cultivation. The individual BMPs for each component were then combined to provide whole-farm mitigation strategies. Implementation of the combined BMP strategies was simulated on a whole-farm process-based model, The Integrated Farm System Model (IFSM4.3) [21]. In the IFSM4.3 simulations, total cultivated area and herd size were fixed, milk production was allowed to increase, and purchases of crops and proteins were minimized.

Three types of BMPs were considered; cow feed, manure processing, and field cultivation. A description for each BMP is in table 1. Both the 150-cow and 1500-cow mitigation strategies assumed the same feed BMPs. This included providing lactating cows feed with low forage rations at 50% dry matter intake, increased (2%) neutral detergent fiber, decreased diet protein (14%), and increased cow feed efficiency (1.65 kg milk per kg feed of dry matter intake). The mitigation strategies varied in their prescribed manure management and field cultivation practices. The
Table 1. Emission scenarios including whole-farm BMP scenario descriptions, prescribed emission reductions, and global mean temperature change relative to pre-industrial levels using a 20 year running mean centered on 2090.

| Scenario        | Description                                                                 | Emission reduction | GMSAT (relative to 1861–1880) |
|-----------------|-----------------------------------------------------------------------------|--------------------|--------------------------------|
| No Mitigation   | Business as usual projection. No climate policies after 2015. No BMPs included. | 0%                 | 0%                             | 0%                             | 3.14                           |
| Dairy–low Mitigation | Resembles a 1500-cow farm. Non-CO₂ emission reductions applied to the global dairy subsector. Feed BMPs: 50% forage rations, high NDF, high feed efficiency, decreased diet protein. Manure BMPs: anaerobic digester, manure solids separated. Field BMPs: cover crop, no-till system, subsurface injection of manure, summer application of manure. | 43%               | 4%                             | 10%                            | 3.12                           |
| Dairy–high Mitigation | Resembles a 150-cow farm. Non-CO₂ emission reductions applied to the global dairy subsector. Feed BMPs: 50% forage rations, high NDF, high feed efficiency, decreased diet protein. Manure BMPs: sealed flare storage, free-stall barn for heifers. Field BMPs: no-till system, subsurface injection of manure, summer application of manure. | 53%               | 56%                            | 20%                            | 3.10                           |
| Agr–low Mitigation | Same percent emission reductions as the Dairy–Low Mitigation scenario but emission reductions applied to the whole agricultural sector. | 43%               | 4%                             | 10%                            | 2.95                           |
| Agr–high Mitigation | Same percent emission reductions as the Dairy–High mitigation scenario but emission reductions applied to the whole agricultural sector. | 53%               | 56%                            | 20%                            | 2.92                           |

* BMP descriptions and raw data provided by Veltman et al (2018) [13].
150-cow farm applied a flare to burn trapped biogas in a sealed manure storage system and shelters the heifers in a separate free-stall barn. In comparison, the larger 1500-cow farm used a separator to remove the manure-solids and ran an anaerobic digester on the liquid manure. The two farm strategies were similar in the way fields were managed. Both used a no-till crop establishment with subsurface injection of manure and summer manure application on the fields. The larger farm also applied an additional grass cover-crop following corn harvest. Further details about each BMP studied by the Dairy-CAP project can be found in Veltman et al (2018).

For both the large and small herd-size farms, there is an overall potential to reduce greenhouse gas emissions by implementing whole-farm BMP strategies (table 1). Smaller farms have greater mitigation potential than large farms due to the scale of the infrastructure, applied practices, and herd size. For this reason, we describe the 150-cow farm as the Dairy-High Mitigation scenario and the 1500-cow farm the Dairy-Low Mitigation scenario. Compared to a controlled no-BMP farm scenario, a small 150-cow farm can reduce CH₄ emissions by 53% per hectare, and reduce N₂O and CO₂ emissions by 56% and 20%, respectively per hectare. A large 1500-cow farm can reduce CH₄ emissions by 43% per hectare, N₂O emissions by 4%, and CO₂ emissions by 10% per hectare.

2.2. Estimation of regional and global dairy emissions

Because emission projections that drive Earth system models rarely separate agricultural emissions into subsectors, it is necessary to estimate dairy emissions from an external dataset. We infer percentage contributions of non-CO₂ emissions attributable to the global dairy subsector using the FAOSTAT database [22]. The FAOSTAT classifies agricultural emissions into commodity and activity categories for nearly 200 countries without relying on any equivalence metric like the GWP [23]. Direct and indirect emissions of CH₄ and N₂O are documented for dairy activities related to manure management, manure application to soils and pasture, and enteric fermentation. However, the FAOSTAT omits CO₂ emissions from dairy and treats them as carbon neutral. We take a 10 year average for the non-CO₂ emissions over the 2007–2016 period to reflect recent emission trends in dairy activities. To account for localized differences in dairy production and practices, we partition country-level dairy emissions into 16 economic regions.

Non-CO₂ dairy emissions are then compared to emissions from the whole agricultural sector to calculate fractional contributions for each region (figure 1). In every region, CH₄ emissions, originating primarily from enteric fermentation, predominate all dairy emissions. Methane emissions also vary significantly across regions, from 1% in high income countries of East Asia to 41% in Russia, reflecting the diversity in farm practices and production sizes. Unlike the variability in dairy CH₄ emissions, N₂O emissions remain fairly homogeneous across nations. Nitrous oxide emissions coming from manure management and field application tend to stay less than 13% of total N₂O agricultural emissions.

We assert that our approach is likely to underestimate dairy emissions and thus potential warming mitigation attributed to milk production because the FAOSTAT data does not constitute a full life-cycle assessment (LCA). Methodologies for LCA are designed to assess the environmental impact at all stages of dairy production from the development of feed to the processing of milk. Only a select number of studies have conducted LCA approaches for dairy systems on a country-by-country basis [24–26]. But, LCA quantification of global dairy emissions remains a challenge as measurements, particularly those in developing nations, are limited and often highly uncertain. In addition, the data products from LCA use aggregated CO₂-equivalencies to compare emissions of greenhouse gases, making it difficult to extract separate emissions. Using different life cycle assessment models, two studies have estimated global dairy emissions make up around 2.7% of total anthropogenic emissions [27, 28]. This figure agrees with our estimate of 1.2% based on CH₄ and N₂O dairy activities within the FAOSTAT.

2.3. Emission scenarios

We develop five emission scenarios (table 1) to demonstrate the influence agricultural mitigation strategies have on future global climate change. We include a business as usual scenario to represent the future in anthropogenic emissions without any climate policies. And, we develop emission reduction strategies designed to reflect the mitigation potential of the two US dairy farms considered by the Dairy-CAP project [13].

To design our emission scenarios, we use emissions output of the Economic Projection and Policy Analysis model Version 5.0 (EPPA), a computable general equilibrium model of the world economy and human system [29, 30]. EPPA projects global economic development at multi-regional and multi-sectoral levels by solving for the prices of consumer goods, as well as, domestic and international trade of energy and non-energy markets. It allows for simulation of changes in land-use, technological advancements, and greenhouse gas emissions. Using population mapping, the scenarios spatially distribute anthropogenic emissions as either agricultural or non-agricultural and interpolate to yield yearly latitudinal emissions. More importantly, emissions from agricultural subsectors are aggregated within EPPA. Modeling detailed changes in individual farm practices,
food demand, and production by country is not structurally possible in EPPA’s current configuration.

For our No Mitigation scenario, we use a projection that assumes no climate policies restrict greenhouse gas emissions or pollutants after 2015 [31]. Starting from about 330 million tons (Mt) in 2005, CH₄ emissions grow to nearly 700 Mt in 2100 (figure 2), primarily driven by agricultural growth in East Asia and Africa. In the No Mitigation scenario, N₂O emissions initially increase from 10 Mt in 2005 to 17.8 Mt in 2060, but are then followed by a slight decrease in emissions to 17 Mt in 2100. Increases in CO₂ emissions are largely attributed to the fossil fuel industry during the twenty-first century, with some land-use changes offsetting the increase. Agricultural emissions of CO₂ are minuscule compared to the energy and industrial sectors. By 2100, total CO₂ emissions are about 60 Gigatons (Gt) per year, nearly doubling from 2005.

The No Mitigation scenario is comparable to the range in emission trajectories of the IPCC shared socioeconomic pathways (SSPs) [32–36]. For emissions through the twenty-first century, the No Mitigation scenario considers CH₄ and N₂O emissions on the higher end of the SSP range, while CO₂ emissions fall between the mid-to-low end of the SSP range (figure 2). The differences lie within the assumptions of technological growth and regional economic development.

We evaluate four plausible emission reduction scenarios to assess the potential mitigation of future climate change with the implementation of best management practices on dairy farms. The mitigation scenarios are developed as an extension of the results from the Dairy-CAP project [13]. The Dairy-CAP project analyzed emissions from two farm sizes, a 150-cow farm and 1500-cow farm, and concluded that they are able to reduce emissions of CH₄, N₂O, and CO₂ by implementing whole-farm BMP strategies.

Because the EPPA model output aggregates agricultural emissions, we estimate dairy emissions for CH₄ and N₂O by applying fractional contributions of dairy to total agricultural emissions for each region in EPPA (see figure 1). Without specific details of future dairy systems (e.g. regional effects or improved mitigation strategies), this makes the assumption that the fraction of dairy emissions for all agricultural emissions remains constant over time. However, the
method does allow for fluctuations in future dairy emissions as the projection in total agricultural emissions fluctuates.

Using the No Mitigation scenario, we apply percent reductions of CH₄, N₂O, and CO₂ (table 1) to the estimated dairy emissions from 2020 to 2050, with linear interpolation. Whole-farm BMPs are assumed to be fully implemented on a global scale by 2050 and continue to be implemented at their full reduction potential through 2100. For CO₂, emission reductions are applied to the whole agricultural sector. All other non-dairy agricultural and non-agricultural emissions of greenhouse gases and pollutants follow the No Mitigation scenario emissions. We call the two dairy farm mitigation scenarios Dairy-Low Mitigation (Dairy-Low) and Dairy-High Mitigation (DairyHigh) for the large and small farm strategies, respectively. Designing the two farm emission scenarios recognizes the existing heterogeneity in dairy farms across the globe, where it is presumed the average farm would most likely fall somewhere between the two scenarios.

Because we are interested in the potential impact of emission reductions within the whole agricultural sector, we design an additional two scenarios based on the same percent emission reduction estimates as the farm strategies. The Agri-Low Mitigation (AgLow) scenario applies percent emission reductions to the whole agricultural sector as described by the DairyLow scenario, while the Agri-High Mitigation (AgHigh) applies DairyHigh reductions to the whole agricultural sector. Emission pathways and non-agricultural emissions remain the same as the farm mitigation scenarios. With these assumptions, it is important to note that agricultural and dairy emissions constitute a decreasing share of total anthropogenic emissions as CO₂ emissions from fossil fuels increase unabated in the emission scenarios.

2.4. Earth system modeling

We use the MIT Earth System Model (MESM) to simulate future climate from the emissions projections. The MESM couples submodels of the atmosphere, ocean, thermodynamic sea-ice, and terrestrial biosphere, and thus simulates critical feedbacks within the Earth system [37]. The model is advantageous in its ability to simulate the Earth system response to imposed climate policy and emission abatement measures, as well as, providing a tool to analyze uncertainties intrinsic to the climate system and emission scenarios [38, 39].

The MESM includes a two-dimensional zonally-averaged atmospheric dynamics and chemistry submodel with a statistical dynamical description of the atmosphere [40]. The detail in carbon cycle dynamics and atmospheric chemistry makes the model ideal for the application of testing reductions in anthropogenic emissions. Atmospheric composition is determined by solving the continuity equations in mass conservative flux form for 33 chemical species, along with 41 gas-phase and 12 heterogeneous reactions [41, 42]. For long-lived species, concentrations are affected by transport, surface deposition, and production and loss by chemical reactions. As a result, the MESM accounts for time-evolving and temperature dependent chemical feedbacks that extend the lifetime and loss rate of atmospheric species. One example is the inclusion of the impacts of CH₄ and N₂O on both the production of tropospheric water vapor and the depletion of tropospheric ozone. However, atmospheric chemistry is turned off in the stratosphere and stratospheric ozone is prescribed beyond the 150 mb level.

The terrestrial submodel consists of a full representation of the carbon cycle, with the inclusion of natural CH₄ and N₂O fluxes [43]. A mixed layer anomaly diffusing ocean model completes the carbon cycle through explicit parameterization of mixed layer biogeochemistry and simulation of carbon and heat uptake.

Climate model parameters that set the equilibrium climate sensitivity (3.30 °C), square root of the average diffusion coefficient of heat anomalies into the ocean below the mixed-layer (4.41 cm² s⁻¹), and net anthropogenic aerosol forcing (−0.25 W m⁻²) account for the uncertainty in future climate system behavior. We select values for the three model parameters based on the greatest likelihood probabilistic estimation that yields model output that best match with observational records of surface warming and ocean heat content [44]. The combination of equilibrium climate sensitivity and rate of ocean heat uptake sets the transient climate sensitivity of the model run (1.75 °C).

Each MESM simulation has two distinct stages. In the first stage, the model is driven with historical concentrations of relevant greenhouse gases and aerosols from 1861 to 2005. The climate model parameters remain the same when the model transitions from being concentration-driven to emission-driven [37]. The second stage uses derived latitudinally distributed emissions from EPPA to convert greenhouse gases and pollutants into atmospheric concentrations.

3. Results

Following global implementation in 2020, atmospheric concentrations of mitigated greenhouse gases decline when compared to the No Mitigation scenario (figure 3). The AgHigh demonstrates the greatest mitigation potential, having an atmospheric CH₄ reduction of over 27% compared to the No Mitigation scenario in 2100. The AgLow strategy shows a similar drop in concentration by 34% for a AgHigh mitigation strategy when compared with No Mitigation in 2100. In comparison, the AgLow strategy provides about a 3% decline in mean N₂O concentration. Although not as extensive, dairy emission reductions provide a notable impact on non-CO₂ concentrations. Both the DairyLow
and DairyHigh simulations reduce CH$_4$ concentrations by more than 100 ppb in 2100. And, the dairy simulations reduce N$_2$O concentrations by 1.3–3.3 ppb.

However, there are no substantial decreases in CO$_2$ concentration for the mitigation scenarios despite a 10%–20% reduction in agricultural emissions. This is because agricultural CO$_2$ emissions are minuscule, less than 1%, compared to net anthropogenic CO$_2$ emissions by the end of the century. As a result, the temperature impact is primarily influenced by non-CO$_2$ emission reductions.

The reduction in greenhouse gas concentrations generates a change in the projected response for the global mean temperature relative to the 1861–1880 average for the five emission scenarios (figure 4). The chaotic nature of the global temperature curves reflects the uncertainty in internal processes of the climate system and decadal to multi-decadal regional

![Projected Atmospheric Concentrations](image1)

![Global Average Surface Temperature Change](image2)
weather fluctuations. By 2100, the No Mitigation scenario increases to 3.5 °C, well above the 2 °C temperature target of the Paris Agreement [3].

The mitigation scenarios begin to show a deviation in global mean temperature from the No Mitigation scenario immediately following BMP implementation (figure 4). If the global agricultural industry could reduce emissions to the level seen by the simulated small and large farms, global temperature may be reduced by 0.21 °C on average by the end of the century. Although global emission cuts would be small, dairy farms have the potential to make an impact on mitigating future warming. We determine that the average 0.03 °C decrease in global mean temperature results from a 43%–53% reduction in CH4 emissions, 4%–54% reduction in N2O emissions, and 10%–20% reduction in CO2 emissions of the global dairy subsector, in which reductions are guided by findings from BMP implementation in US dairy farms.

To understand the mitigation potential of each greenhouse gas reduced, we simulate the AgHigh strategy with individual reductions of CH4, CO2, and N2O, and reduction combinations of the three gases (figure 5). In this case study, only agricultural emissions are reduced. Non-agricultural emissions follow the No Mitigation scenario. Reducing all three greenhouse gases has the potential to limit warming by 0.25 °C in the year 2100. However, no significant change in the global temperature occurs when only CO2 emissions are reduced. As fossil fuel emissions increase unabated, the proportion of CO2 agricultural emissions to total anthropogenic CO2 emissions becomes minuscule, making the impact of a 20% reduction less apparent. This suggests that the emission reductions of non-CO2 gases in the agricultural sector have a significant impact in mitigating projected temperature change.

Simulations of N2O and CH4 agricultural emission reductions show greater promise in limiting future warming (figure 5). Reductions in N2O and more notably reductions in CH4 decrease the projected temperature rise by 0.07 °C and 0.22 °C, respectively, in 2100. The substantial difference results from the larger mitigation in CH4, where early reductions in CH4 result in a larger decrease in radiative forcing and leads to decreased warming rates. The combined agricultural reductions in N2O and CH4 are able to reduce the 2100 temperature projection by 0.23 °C, because they contribute 6% of the instantaneous radiative forcing in 2100. We note that the temperature projections are influenced by internal variability and therefore are not additive for each combination of greenhouse gas mitigation.

4. Discussion and conclusions

In this study, we focus on how global implementation of BMPs in the agricultural sector can further reduce non-CO2 greenhouse gas emissions and assist in reaching temperature goals set by international policy. We have two main advantages in this work. First, we use a coupled Earth system model containing full chemistry and interactive carbon cycle components to project changes in future greenhouse gas concentrations. Second, the idealized emission reductions are guided by the results of the coordinated Dairy-CAP project, in which whole-farm emission reductions were estimated for representative 150-cow and 1500-cow US dairy farms [13]. Using Dairy-CAP results, we apply emission reductions of CH4, N2O, and CO2 across the global dairy subsector.

Based on our simulations, we find that if BMP implementation for the dairy industry is fully realized by 2050 and sustained, warming in the late century can be reduced on average by 0.03 °C or 1% of total warming when compared to a business as usual emission
scenario. We emphasize that our result could be an underestimate since dairy emissions from the FAO-STAT lack full life cycle assessment, and only account for a selection of CH₄ and N₂O dairy practices. While this may be the case, our results agree with a recent analysis looking at the contribution of livestock (combined beef, dairy, poultry, etc) to past and future warming [20]. Under a low emissions scenario (RCP2.6) with an additional 50% reduction in CH₄ and N₂O from livestock, 0.08°C is reduced by 2100. However, if emissions continue unabated under a high emissions scenario (RCP8.5), the study found direct livestock non-CO₂ emissions alone could lead to 0.23°C or 5% of total warming in 2100.

Our results also suggest that immediate action taken across the whole agricultural sector could potentially reduce future warming 0.21°C on average or 6% of projected total warming by the end of the century. We find that reductions in agricultural non-CO₂ gases provide the greatest mitigation impact because their high emission rates and their stronger radiative effect per molecule is diminished. However, abatement of non-CO₂ agricultural greenhouse gases alone could not reach a 2°C target. To reach such a temperature target would require supplemental reductions in CO₂ from the fossil fuel sector. Any delay in the onset of implementation or falling short of full emission reductions would result in higher non-CO₂ atmospheric concentrations and limit the temperature mitigation potential [45]. Our study therefore demonstrates the importance for immediate action across the globe to begin curtailing agricultural emissions with new management practices.

Through changes in farm techniques, infrastructure, scale, and efficiency, there are countless possible ways in which agricultural emissions can be reduced across the globe. We apply distinct linear emission reductions to the global dairy subsector and aggregated agricultural sector to address the uncertainty in the future emission pathway. By doing so, this method accounts for possible technological advances and newly developed BMPs that have yet to be implemented on the farm scale. It also accounts for potential trade-offs across the globe, where some industrialized nations may reduce emissions while others increase their emissions.

We acknowledge and account for the fact that not all farms resemble the representative highly-efficient US dairy farms used to calculate the BMP emission reductions. Using both a small farm and large farm scenario allows for the true distribution of all farm sizes to fall somewhere in between the two scenarios. It is well known that the mitigation potential varies around the globe depending on production volume and emission intensities [46]. High production areas, usually in industrialized countries, have a high mitigation potential and can begin to reduce emissions from the largest sources of emissions; feed production, manure, and enteric fermentation [47]. Low production regions, such as Sub-Saharan Africa, are generally characterized by high emission intensities and low mitigation potential. Albeit, areas such as these are often remote and have financial difficulties adopting new practices. But if adopted, sustainable agricultural practices could yield substantial improvements in emission intensities and food security [48].

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References

[1] Sanderson B M, O’Neill B C and Tebaldi C 2016 Geophys. Res. Lett. 43 7133–42
[2] Rogelj J, Meinshausen M, Schaeffer M, Knutti R and Riahi K 2015 Environ. Res. Lett. 10 075001
[3] Meinshausen M, Meinshausen N, Hare W, Raper S C, Frieler K, Knutti R, Frame D J and Allen M R 2009 Nature 458 1158–62
[4] Matthews H D and Caldeira K 2008 Geophys. Res. Lett. 35 1–5
[5] van Vuuren D P, Weyant J and de la Chesnaye F 2006 Energy Econ. 28 102–20
[6] Gambhir A, Napp T, Hawkes A, Høglund-Isaksson L, Wininwarter W, Purohit P, Wagner F, Bernie D and Lowe J 2017 Energies 10 602
[7] Hansen J, Sato M, Ruedy R, Lacis A and Oinas V 2000 Proc. Natl. Acad. Sci. 97 9875–80
[8] Monttaka S A, Dlugokencky E J and Butler J H 2011 Nature 476 43–50
[9] Reay D, Davidson E, Smith K, Smith P, Melillo J, Dentener F and Crutzen P 2012 Nat. Clim. Change 2 410–6
[10] EPA 2012 Summary report: global anthropogenic non-CO₂ greenhouse gas emissions: 1990–2030 Technical Report 430-S-12-002 (Washington, DC: EPA)
[11] Tubiello F, Salvatore M, Cóndor Golec R, Ferrara A, Rossi S, Biancalani R, Federici S, Jacobs H and Flammerini A 2014 Agriculture, forestry and other land use emissions by sources and removals by sinks Technical Report ESS Work. Pap. No. 2 (Rome, Italy: FAO)
[12] Wollenberg E et al 2016 Glob. Change Biol. 22 3859–64
