Info Note

Global Warming Potential* (GWP*): Understanding the implications for mitigating methane emissions in agriculture

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Key messages

- GWP* (global warming potential) complements conventional climate metrics such as GWP_{100} because GWP* better describes the actual warming caused by methane (CH_4) emissions. For example, using GWP_{100}, a constant annual rate of CH_4 emissions may be misinterpreted as having a 3-4 times higher impact on warming than observed. The use of GWP* can correct this misestimation.
- GWP* was used here to evaluate the impact of agricultural CH_4 emissions scenarios from 2020-2040, finding that:
  - A sustained ~0.35% annual decline is sufficient to stop further increases in global temperatures due to agricultural CH_4 emissions. This is analogous to the impact of net-zero CO_2 emissions.
  - A ~5% annual decline could neutralize the additional warming caused by agricultural CH_4 since the 1980s.
  - Faster reductions of CH_4 emissions have an analogous impact to removing CO_2 from the atmosphere.
  - However, a 1.5% annual increase in CH_4 emissions would lead to climate impacts about 40% greater than indicated by GWP_{100}.
- The application of GWP* to CH_4 emissions accounting suggests that avoiding further warming due to CH_4 emissions in agriculture is more attainable than previously understood. CH_4 reductions can have a rapid and highly substantial impact, which underscores the importance of making significant cuts in CH_4 emissions immediately.

Climate change is caused by warming due to the increasing concentration of climate pollutants such as methane (CH_4) and carbon dioxide (CO_2) in the atmosphere. Each climate pollutant is distinct in terms of its lifecycle and effects on warming. Hence, metrics have been developed to make it easier to understand and compare the relative effects of each pollutant, aggregate them, and facilitate the development and implementation of climate policy. The most widespread climate metric in use today is the 100-year global warming potential (GWP), or GWP_{100}.

However, the choice of which climate metric to use can have important implications for how we understand the relative impact of different greenhouse gases (GHGs). For example, GWP_{100} has been criticized for misrepresenting the climate effects of short-lived climate pollutants (SLCPs) such as CH_4 and black carbon relative to other proposed metrics – for example, Fuglestvedt et al. (2003) and Lauder et al. (2013).

Allen et al. (2018) developed GWP* to better approximate the climate impacts of SLCPs by capturing both the short- and long-term effects of changing SLCP emission rates. The difference between the two metrics can be profound, with GWP_{100} potentially over- and underestimating the warming effects of SLCPs under different scenarios and timescales. This has important implications for measuring and managing agricultural GHG emissions, dominated by SLCPs.

Agricultural GHG emissions are predominately in the form of CH_4, nitrous oxide (N_2O), CO_2, and black carbon. Methane and black carbon are both SLCPs. Black carbon emissions can be caused by the burning of biomass

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(such as crop residues) and from incomplete combustion of fossil fuels. Cold-chain logistics – part of the broader food system's footprint – may also result in refrigerant leakage, some of which are SLCPs. Most importantly, agriculture is the major anthropogenic CH_4 emission source, especially from the enteric fermentation of ruminant animals (e.g., beef cattle). For the purposes of this Info Note, we focus exclusively on CH_4 to illustrate the importance and relevance of GWP* to agricultural GHG accounting and mitigation.

Global sources and rates of methane emissions

Anthropogenic methane emissions come from both fossil fuel extraction and biogenic sources such as wetlands (including rice paddies), livestock (enteric fermentation, manure management), and waste management (landfills, wastewater treatment). From 2008-2017, global annual CH_4 emissions were estimated to be approximately 576 $MtCH_4$, of which 359 $MtCH_4$, or ~60%, were attributed to anthropogenic sources.

The agriculture sector was the largest source of anthropogenic CH_4 emissions (~40%), followed by fossil fuels (~30%), waste (~20%) and biomass and biofuel burning (~10%) (Saunois et al. 2020). Anthropogenic CH_4 emissions are commonly understood to make up 20% of total annual anthropogenic GHG emissions, using the GWP_{100} metric to enable the comparison of multiple GHGs in units of CO_2 equivalents (CO_2-e).

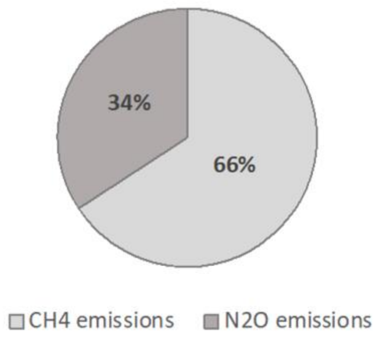
In 2019, the agriculture sector emitted approximately 140 $MtCH_4$ (Figure 1). This accounts for 66% of the direct emissions footprint of global agriculture when estimated using GWP_{100} (IPCC-AR5) in units of CO_2-e (5.9 $GtCO_2$-e; FAO-STAT 2021). N_2O represents the remaining 34% (Figure 1). Indirect emissions from land conversion, fertilizer production, tractor fuel use, and more are excluded from this figure and are conventionally included in separate IPCC reporting categories. Enteric fermentation from livestock is by far the greatest contributor to the sector's CH_4 emissions (Figure 1). The predominance of CH_4 in agriculture's direct GHG emissions footprint underscores the importance of correctly accounting for the effect of SLCPs like CH_4 on warming.

Understanding the impact of SLCPs

SLCPs are powerful climate pollutants that, as their name suggests, remain in the atmosphere for a much shorter period than long-lived climate pollutants (LLCPs). SLCPs include black carbon, CH_4, tropospheric ozone (O_3), and some hydrofluorocarbons (HFCs), commonly associated with diesel combustion, solid-fuel cooking fires, fugitive leaks from fossil fuel infrastructure, waste and wastewater infrastructure, agricultural activities, and refrigeration.

Methane, of particular relevance to agriculture, has an average atmospheric lifetime of 9.8 (between 7.6-14) years (SPARC 2013).

By comparison, LLCPs associated with agriculture include CO_2 and N_2O, both of which have much longer atmospheric lifetimes. It is estimated that N_2O has an average lifetime of 123 years (between 91-192), whereas CO_2 emissions are expected to continue to demonstrate warming effects even after 10,000 years (SPARC 2013), due to ongoing cycles of absorption and re-emission. Although SLCPs have relatively short atmospheric lifespans, it has been estimated that SLCPs are responsible for approximately one-third to half of the current radiative forcing (IPCC 2014; UNEP, CCAC 2021). These impacts are largely attributed to the sustained high rates of emissions that maintain elevated atmospheric concentrations and the relatively greater efficiency with which many SLCPs contribute to warming compared to the most important GHG, CO_2.



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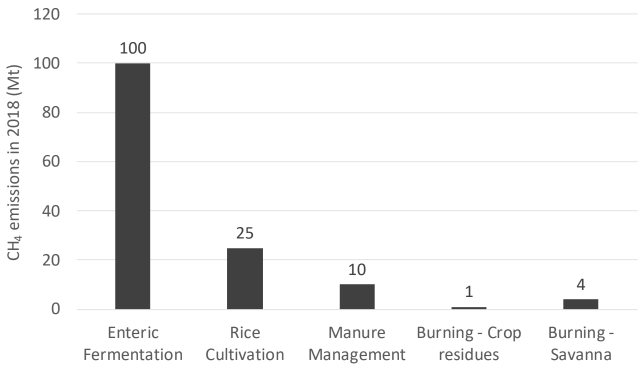

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Figure 1. Global emissions from agriculture in 2018 (5.9 $GtCO_2e$/GWP100; IPCC-AR5) by gas (1a) and global methane (CH_4) emissions from agriculture in 2018 (140 $MtCH_4$) by source (1b) (Source: FAO-STAT)

These fundamental differences between SLCPs and LLCPs have important implications for how emissions of individual GHGs will affect the earth's climate. Gases with long atmospheric lifespans that are emitted today will cumulatively add to atmospheric concentrations and continue to cause warming for multiple generations. Hence, for LLCPs like CO_2, and to a lesser extent N_2O, the total quantity emitted since the rise of industrialization is the primary determinant of impacts on climate change.

Whereas the effects of SLCPs persist for shorter durations and do not act cumulatively, with only recent emissions exerting a major impact on observed warming at a given point in time. Furthermore, if SLCP emissions are sustained at fixed rates, then new emissions will be balanced by "removals" due to oxidation into CO_2 (Box 1) and the gas will achieve a stable concentration in the atmosphere. This contrasts with LLCPs, where even fixed emission rates will still result in accumulating concentrations over centuries.

Box 1. Biogenic versus fossil fuel methane emissions

Methane is a short-lived greenhouse gas, with an average atmospheric lifetime of around a decade, after which it is largely oxidized into CO_2. Each methane molecule in the atmosphere, from biogenic or fossil sources, has the same climate impact. However, the source of methane emissions determines whether the resulting CO_2 molecule makes a net contribution to global warming.

Unlike emissions from biogenic sources, emissions from fossil fuel activities – including leakage from wells, drilling sites, and pipelines – represent new transfers of carbon from long-term geological stocks or sinks to the atmosphere. This is effectively a transfer of carbon from the geological carbon cycle (the slow cycle) to the biological carbon cycle (the fast cycle). Emissions from biogenic sources are part of the biological cycling of carbon between the atmosphere and the biosphere and do not contribute to increased CO_2 concentrations. Over time, some of this carbon will re-enter geological carbon stocks, for example, as ocean sediment incorporated via plate tectonics, but this is an extremely slow process.

The distinction between these two sources of CH_4 emissions is important because the transfer of carbon from the geological to the biological carbon cycle is the principal cause of climate change.

Metrics for Comparing SLCPs and LLCPs

Most GHG inventories report individual gases separately to account for the critical differences in their climate impacts. However, to support prioritization of mitigation activities and international and national climate policies, many metrics have been proposed that enable comparison of different GHGs, going back to the Intergovernmental Panel on Climate Change (IPCC) 1st Assessment Report (IPCC 1990). One such metric is the GWP, which was developed to enable an expression of how much an emission of a given GHG (expressed on a per unit mass basis) will affect the atmospheric energy balance (warming) over a given time relative to an equal mass of a reference gas (e.g., CO_2).

For example, GWP_{100} compares the climate effects of an emission pulse of one ton of a given gas over a 100-year period to that of CO_2, expressed in terms of units of CO_2-equivalents (e). CO_2, by definition, has a GWP_{100} value of one. As science has evolved, different GWP_{100} values have been adopted (Table 1). Currently, N_2O and CH_4 have GWP_{100} values of 265 and 28, respectively (IPCC 2014), which is intended to represent the greater climate effect of emitting these gases compared to a similar quantity of CO_2.

Table 1. Global warming potential values for 100-year and 20-year time horizons (GWP_{100} and GWP_{20}).

GHG	GWP values (100-y, 20-y)		
	IPCC 2nd Assessment Report (SAR)	IPCC 4th Assessment Report (AR4)	IPCC 5th Assessment Report (AR5)
CO_2	1	1	1
CH_4	21, 56	25, 72	28, 84
N_2O	310, 280	298, 289	265, 264

*Source: SAR and AR4 and AR5

GWP_{100} has been adopted by many international climate policies and action frameworks as the preferred GHG accounting metric, including the United Nations Framework Convention on Climate Change (UNFCCC 2014). The same approach has been taken in the GHG Protocol Corporate Accounting and Reporting Standard, the *de facto* standard for the development of corporate emissions inventories (WRI & WBCSD 2004). Despite the widespread adoption of GWP_{100}, shortcomings of the metric have been noted and discussed since its inception in the IPCC 1st Assessment Report. The primary criticism of GWP_{100} is that it does not sufficiently capture how different gases have different dynamic impacts.

For example, most of the climate impact resulting from methane emissions are experienced within a few decades, so comparing gases across a 100-year period can be misleading. This has led some to adopt GWP_{20}, which uses a 20-year for comparison, and so emphasizes gases with shorter lifetimes. Yet this revision still fails to adequately capture the distinct climate effects of SLCPs and LLCPs. In recognition of these important shortcoming, a *Methodology Report on Short-Lived Climate Forcers* has been commissioned and is forthcoming as part of the IPCC 6th Assessment Report.

An alternative metric, GWP* or GWP-star, has been developed to address the criticisms of GWP_{100} and GWP_{20} and enable an accurate representation of the climate effects of SLCPs and LLCPs in a single metric. In the following sections, we outline the basics of calculating the GWP* metric and its application and implications within the agricultural sector.

Basics of GWP*

How it works

Originally defined in Allen et al. (2018), and subsequently updated in Cain et al. (2019) and Smith et al. (2021), GWP* allows a more consistent expression of how emissions of SLCPs and LLCPs contribute to overall temperature change (warming) by equating a change in the rate of SLCP emissions to a single emission quantity (pulse) of an LLCP. The result is a single metric of carbon dioxide "warming equivalents" or CO_2-we.

Under GWP*, emissions of LLCPs, defined here as those having an atmospheric lifetime longer than around 100 years are still represented as a cumulative pollutant within this time-horizon, and therefore equivalent emissions for LLCPs are derived simply by multiplying those emissions by GWP_{100} in the conventional manner.

For SLCPs, Smith et al. (2021) provide the most up-to-date and simple means of applying GWP*, using the following formula that can be adapted for all SLCPs:

$$E_{CO_2we} = 4.53 \times E_{100}(t) - 4.25 \times E_{100}(t-20)$$

In this equation, E_{100} corresponds to CO_2-equivalent emissions calculated using GWP_{100}.This value is required for current emission rates, $E_{100}(t)$, and the emission rate from 20 years ago, $E_{100}(t-20)$. When there is a large difference between these two emission rates, a large E_{CO_2}-we value is returned, emphasizing the significant, rapid impact of changing methane emission rates. However, for constant sustained emission rates, GWP* estimates a much smaller climate effect, (4.53 − 4.25) = 0.28 × GWP_{100}, better capturing the constant removal of past methane emissions from the atmosphere. This straightforward GWP* formulation therefore has the potential to overcome the problems inherent to GWP_{100} (or any pulse-based metric) in distinguishing the largely non-cumulative behavior of SLCPs.

Using GWP* to understand the net impacts of CH_4 on climate change

Net effect of global agriculture CH4 emissions on climate change: comparing GWP100 and GWP*

The science of how different GHG emissions contribute to overall climate change is well-understood and is independent of emission metrics. However, as the use of emission metrics is so widespread, they are often viewed in practice as a direct reflection of the impact of GHG emissions on the climate, rather than as a simple approximation intended for policy use. In this context, any distortion introduced by any given metric risks misleading practitioners and policymakers. GWP* is explicitly intended to correct distortions inherent to the widely used GWP_{100} metric and, in turn, better reflect the impact of SLCPs on climate change. To better understand the implications for policy and practice, we compare various emissions scenarios using both GWP_{100} and GWP*.

Figure 2a shows how using the GWP* metric alters our understanding of the relative contribution of agricultural CH_4 emissions in global GHG accounting. When applying GWP*, the relative climate impact of agricultural CH_4 emissions in 2019 is 33% lower than suggested by GWP_{100} (Figure 2a). The cumulative warming effect of CH_4 emissions from 1981 to 2019 is similarly 35% lower (Figure 2b). These differences are a result of the relatively slow rate of increase in CH_4 emissions during this period (<1% y^{-1} on average) (Figure 2a).

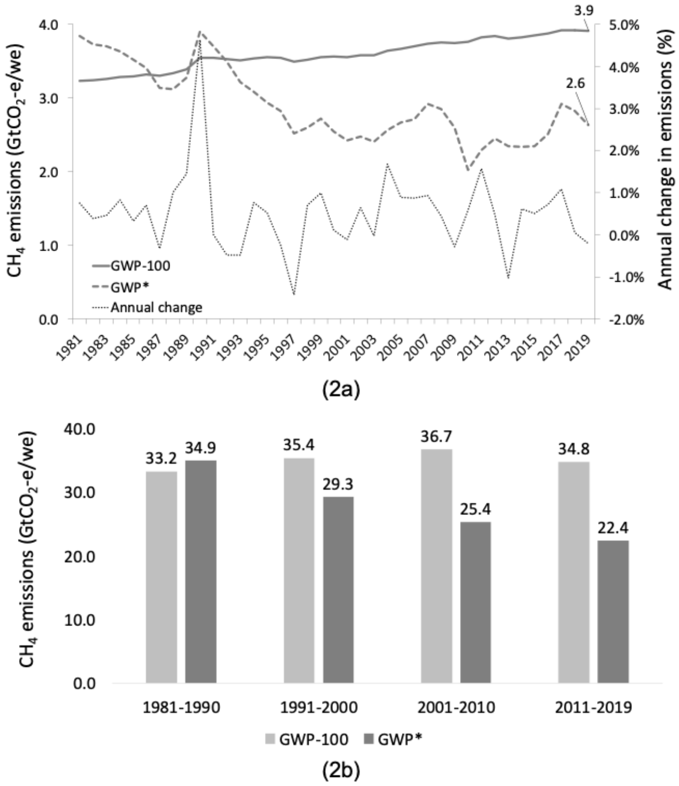


Figure 2. Methane (CH_4) emissions from agriculture estimated using GWP_{100} ($MtCO_2$-e; IPCC-AR5) and GWP ($MtCO_2$-we) metrics.*

When applying GWP* to future emissions scenarios, we estimate that the agriculture sector could achieve "neutral" CH_4 emissions (i.e., no additional temperature increases due to CH_4, by reducing emissions ~7% (9.37 $MtCH_4$) by 2040). Thus, assuming no changes in other emission sources (e.g., N_2O and black carbon) and excluding land conversion and other indirect emissions, the agriculture sector could reduce its direct contribution to ongoing temperature increases by 60% by 2040 (Figure 1) solely by cutting CH_4 emissions by ~0.35% per year by 2040 (Figure 3a).

Furthermore, sustained cuts in CH_4 emissions of 5.00% per annum (p.a.) (2020-2040) could neutralize the additional warming caused since 1981, bringing the contribution of agricultural CH_4 to global warming back to this level (Figure 3b). By comparison, the GWP_{100} accounting method suggests the same reductions in CH_4 emissions (0.35% p.a. and 5.00% p.a.) would result in a much smaller reduction of ~0.3 and 2.6 $GtCO_2$-e by 2040, respectively (Figure 3b).

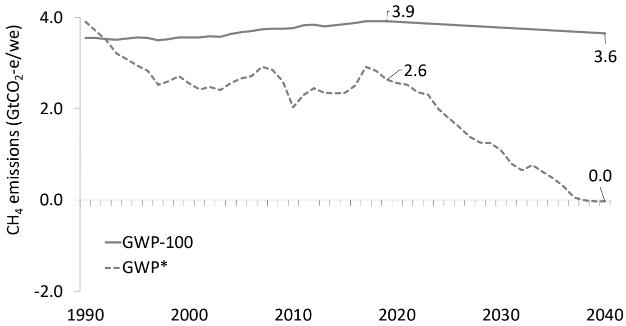
There are also notable differences between the two accounting methods when considering future scenarios in which agricultural CH_4 emissions remain stable or increase. Under a constant emissions scenario, GWP_{100} overestimates the impact of CH_4 emissions by a factor of three to four (Figure 3c); GWP_{20} overestimates the impact by a factor of ten (an order of magnitude). Both GWP* and GWP_{100} predict that an increase in CH_4 emissions of 1.00% per year from 2019 emissions would result in moderate warming potentials in 2040 (Figure 3d). However, GWP* indicates that the agricultural sector's contribution to climate change would be about three times higher in 2040 than in 2019 if CH_4 emissions increase by 1.5% per year, 2.6 $GtCO_2$-we to 7.4 $GtCO_2$-we (Figure 3e). The traditional metric, GWP_{100}, suggests an increase in warming potential of only ~1.4 times the 2019 level (from 3.9 to 5.3 $GtCO_2$-e) under the same emissions scenario (Figure 3e). In this way, we highlight the consequences of representing and addressing the distinct behaviors of SLCPs in GHG accounting and climate action in the agriculture sector using GWP*.

Implications

CH_4 management is urgent in all sectors: progress may be easier to achieve than previously understood

The use of GWP* highlights the enormous climate benefits of reducing CH_4 emissions immediately. Even modest sustained annual reductions in SLCPs can deliver major benefits for the climate, helping delay the warming effects caused by the emission of LLCPs. Reducing SLCPs can reverse up to 0.3° C of warming by the 2040s (UNEP, CCAC 2021). While the effect of modest reductions (e.g., using current technology and practices, Table 2) may appear marginal from the perspective of climate change when evaluated using GWP_{100}, GWP* underscores the disproportionate effect CH_4 mitigation can have in the near term. Furthermore, as a precursor to ozone, CH_4 mitigation can have air quality benefits in addition to climate benefits. A recent UNEP and CCAC report (2021) estimates that economically and technically feasible CH_4 mitigation practices could reduce emissions by 30% in the next decade, simultaneously avoiding more than 250,000 premature deaths p.a. due to reductions in ground-level ozone levels.

Of primary importance is mitigating CH_4 emissions from fossil sources, as these represent new carbon fluxes from the geological to the biological cycles. Fossil CO_2 emissions must be reduced to net-zero to stop continued temperature increases.



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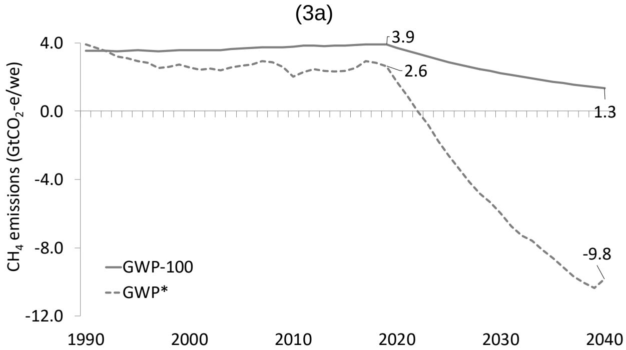

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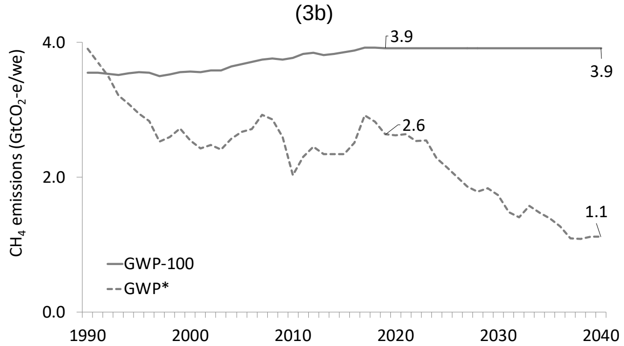

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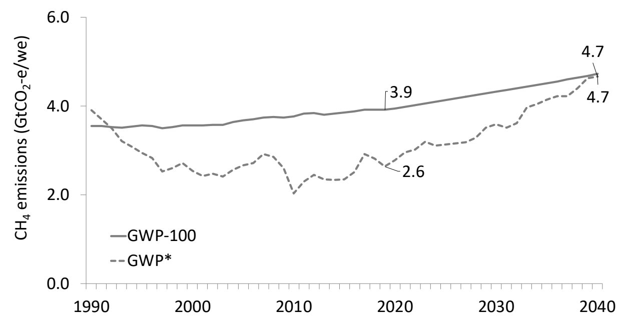

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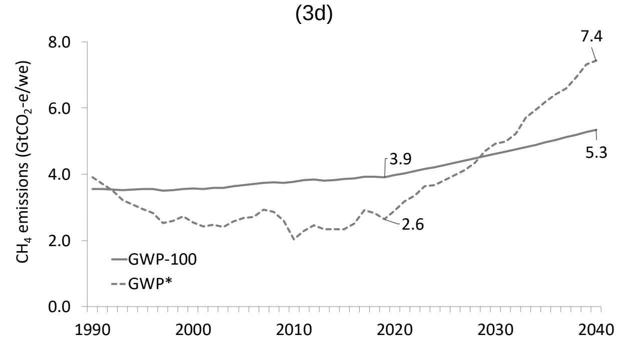

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Figure 3. Global agriculture methane (CH_4) emissions from 2020 to 2050 using GWP_{100} (IPCC-AR5) and GWP accounting methods. Emissions scenarios include CH_4 emissions at a constant rate (0% increase/decrease) (a), reduction of 0.35% p.a. (b) and 5.00% p.a. (c) and an increase of about 1.00% p.a. (d) and 1.50% p.a. (e).*

Agriculture – as the largest source of anthropogenic CH_4 emissions (40%) – has a critical role to play, similar to that of fossil fuels (30%) (Saunois et al., 2020). Agricultural CH_4 emissions have generally increased in recent years, albeit slowly (Figure 1). Current rates of increase in agricultural methane emissions must be reversed to achieve effective climate neutrality (Figure 3). Fortunately, there are multiple practices and technologies that can contribute to the necessary mitigation, many of which deliver significant co-benefits (Table 2). Mitigation can be achieved by adopting improved animal feeding and manure management, more efficient water management in rice paddies, and through other technologies. For example, by adopting Alternate Wetting and Drying (AWD), CH_4 emissions in rice production can be reduced by 30-70% (IRRI). Improved animal feeding and manure management can reduce CH_4 emissions by 27% and 60-90% in some systems, respectively (Ericksen, Crane 2018). These mitigation potentials clearly show that reversing the effect of agricultural CH_4 on climate change is feasible.

Table 2. Major methane mitigation practices and adaptation co-benefits in the agriculture sector.

Production system	Core interventions	Examples of practices	Adaptation benefits
Paddy rice	Water and residue management	Safe AWD, midseason drainage, short duration varieties, direct seeding, laser leveling; removal of rice residues in flooded and upland rice production lands	Water saving (reduces water demand and consumption), reduces energy costs and fossil emissions where water is pumped
Livestock	Animal management*	Improving feeding, breeding and animal health; feed additives; methane mitigation devices	Improved production efficiency; carbon sequestration in rangelands through improved grazing management
	Manure management*	Bio-digesters and anaerobic digestion	Reduces reliance on and associated emissions from inorganic fertilizer use. Application of livestock manure to soil can increase soil C content
		Active composting of solid manure	

*Cross-cutting interventions may have additive GHG mitigation potential.

However, CH_4 emissions are only part of the climate story in agriculture. Agriculture is also a major driver of land-use change, biodiversity loss, and water and soil pollution (Poore, Nemecek 2018). Therefore, focusing on reducing emissions of CH_4 should not come at the expense of mitigating these other impacts. There are considerable opportunities to drive win-wins for climate and society. For example, through the adoption of agroforestry systems, reducing food waste and loss, improving nutrient management, avoiding land conversion, and integrating semi-natural habitat into agricultural landscapes.

Climate Policy

The implications of GWP* are significant for our understanding of the relative role of CH_4 and other SLCPs in the climate arena. Yet the implications for policy may be more modest. First, most national communications account for each GHG source separately, even if metrics such as GWP_{100} are subsequently calculated to enable comparison. GWP* allows assessment of how emission pathways contribute to overall temperature change, which cannot be derived from pulse emission metrics such as the GWP_{100}. However, GWP* may also face some difficulties to implementation at national and project-levels because it requires CH_4 emissions data from the past 20 years to accurately estimate the warming effects.

Second, rather than undermine the attention and importance given to CH_4 up until now, GWP* underscores the importance of making meaningful reductions in CH_4 emissions as soon as possible to meet climate targets.

Like other climate metrics, GWP* emphasizes that action to address CH_4 emissions can only contribute meaningfully to limiting overall climate change if LLCP emissions are also reduced to net-zero. While GWP* demonstrates that other potentially less daunting targets may be justified for methane, climate action in agriculture and beyond is no less urgent to meet climate objectives. Given steady growth in CH_4 emissions over the past two decades and across all sectors, the challenge is still considerable.

Final thoughts

Agricultural GHG emissions are dominated by SLCPs. The development of GWP* has provided an important tool for better understanding the comparative effects of SLCPs and LLCPs. The application of GWP* to CH_4 emissions accounting suggests that avoiding further warming due to CH_4 emissions in agriculture is more attainable than previously understood. CH_4 reductions can have a rapid and highly substantial impact, which underscores the importance of making significant cuts in CH_4 emissions immediately.

Further reading

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This info note focuses on assessing the implications of recent research on climate change metrics for efforts to mitigate GHG emissions from agriculture.

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