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Agricultural Methane Emissions and the Potential for Mitigation

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Summary

Agriculture is the largest anthropogenic source of methane (CH_4), emitting 145 Tg CH_4 y^{-1} to the atmosphere in 2017. The main sources are enteric fermentation, manure management, rice cultivation and residue burning. There is significant potential to reduce CH_4 from these sources, with bottom-up mitigation potentials of ~10.6, 10, 2 and 1 Tg CH_4 y^{-1} from rice management, enteric fermentation, manure management and residue burning. Other system-wide studies have assumed even higher potentials of 4.8 to 47.2 Tg CH_4 y^{-1} from reduced enteric fermentation, and 4 to 36 Tg CH_4 y^{-1} from improved rice management. Biogas (a methane-rich gas mixture generated from anaerobic decomposition of organic matter and used for energy) also has potential to reduce unabated CH_4 emissions from animal manures and human waste. In addition to these supply-side measures, interventions on the demand-side (shift to a plant-based diet and a reduction in total food loss and waste by 2050) would also significantly reduce methane emissions, perhaps in the order of >50 Tg CH_4 y^{-1}. While there is an pressing need to reduce emissions of long-lived greenhouse gases (CO_2 and N_2O) due to their persistence in the atmosphere, despite CH_4 being a short-lived greenhouse gas, the urgency of reducing warming means we must reduce any GHG emissions we can as soon as possible. Because of this, mitigation actions should focus on reducing emissions of all the three main anthropogenic greenhouse gases, including CH_4.

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1 Emissions of methane from agriculture

The main sources of methane (CH_4) emissions from agriculture are enteric fermentation, manure management, rice cultivation and residue burning, with FAOSTAT being the main source of statistics on agricultural emissions [1].

Enteric CH_4 is produced under anaerobic conditions by a diverse community of methanogenic archaea, using mainly hydrogen and CO_2 as substrates, although smaller amounts are produced using formate and methyl compounds as alternatives to hydrogen [2]. The quantity of feed consumed by a ruminant largely determines the quantity of CH_4 emitted, though the type and quality of the animal feed also influence emissions [3,4]. The species of ruminant, an individual's digestive physiology and the makeup of the resident microbial population can also influence the quantity of CH_4 it produces [5,6,7].

Methane production from animal wastes is also an anaerobic microbial process and occurs mostly when animal wastes are stored (manure management). Smaller quantities are produced from wastes deposited directly onto the ground. Manure type (e.g. wet versus dry), storage method, storage duration, manure chemical composition and temperature all influence the quantity of manure produced per unit of substrate [8].

Methane emissions from paddy rice occur when soils are flooded, which creates anaerobic conditions suitable for methanogenic microorganisms to produce CH_4. While methanotrophs are able to oxidise some of the CH_4 produced, there is still a large net emission from paddy rice fields [9]. Global cropland CH_4 emissions are dominated by rice production, with 90% of emissions from tropical Asia, more than half from China and India combined [10], and a small contribution to the global CH_4 soil sink from other croplands (see section 1.2).

Residue burning releases CH_4 through incomplete combustion of biomass, though the quantity is small compared to enteric fermentation, manure management and rice cultivation [1].

1.1 The global methane budget and the contribution of agriculture

Global CH_4 emissions were 596 (572-614) Tg y^{-1}, partly offset by a CH_4 sink of 571 (540-585) Tg y^{-1} in 2017 (see section 1.2) [11]. Of total CH_4 emissions, bottom-up and top-down estimates of the anthropogenic component were 380 (359–407) and 364 (340–381) Tg y^{-1}, respectively in 2017 [11]. Of total anthropogenic CH_4 emissions, the majority were attributable to the agriculture and waste sector, with bottom-up and top-down estimates of 213 (198–232) and 227 (205–246) Tg y^{-1}, respectively in 2017 [11], with bottom-up estimates of emissions suggesting that 68% of these are from agriculture (Figure 1).

[Figure 1 here]

Within the agricultural sector, enteric fermentation and manure management together contributed 115 (110–121) Tg CH_4 y^{-1}, rice cultivation contributed 30 (24–40) Tg CH_4 y^{-1}, with the remainder from landfills and waste (68 [64–71] Tg CH_4 y^{-1}) in 2017 [11]. Enteric fermentation represents about 30-32% of total anthropogenic CH_4 emissions. Enteric fermentation is responsible for about 90% of all livestock derived CH_4 emissions, with cattle (77%) being the dominant source [12]. Manure management emissions are dominated by pigs (~42%) and cattle (~41%) [12].

Additional managed land-based emission sources in 2017, though not accounted for in the agriculture sector, were 16 (11–24) and 13 (10–14) Tg CH_4 y^{-1}, for biomass burning and biofuel burning, respectively [11]. Agricultural CH_4 emissions in 2017 have increased since the early 2000s (2000-2006) by 12.7% for enteric fermentation and manure management, and 7.1% for rice cultivation [11]. Changes in agricultural CH_4 emissions for 1961 to 2017 are shown in figure 2.

[Figure 2 here]

Regionally, for enteric fermentation emissions, largest emissions are found in Asia followed by Latin America, OECD-90, Africa and the Middle East and Economies in transition [10, 13]. For manure management, largest emissions are seen in OECD-90 and Asia, and for rice emissions, Asia has larger emissions than all other world regions together [10]. The increase in agricultural CH_4 emissions from the early 2000s and 2017 was largely seen in South America, Africa (7-9 Tg y^{-1}) - largely from enteric fermentation and manure, and South

Asia/Oceania (of 9-10 Tg y^{-1}) – from paddy rice, enteric fermentation and manure. Estimates of agricultural emissions of CH_4 in Europe fell by −1.4 to −2.8 Tg y^{-1}, for top-down and bottom-up methods, respectively [11].

1.2 Sinks of methane in agriculture

As noted in Section 1.1 above, there are large natural sinks for CH_4. Most of the CH_4 sink is in the atmosphere, which includes reaction with tropospheric hydroxy (OH) radicals to produce carbon dioxide (CO_2) and water, and chlorine (Cl) radicals in the troposphere and the stratosphere. The other significant sink, estimated to be responsible for uptake of 30 (11-49) or 40 (37-47) Tg CH_4 y^{-1} in 2017 from bottom-up and top-down measurements, respectively, is the soil [11].

Cultivation of land for agriculture can significantly reduce the sink capacity of soils to oxidize CH_4 [14]. Mineral soils under forests and other natural vegetation act as the strongest CH_4 sink, followed by grasslands, with the sink strength weakest in cultivated soils and those receiving nitrogen fertilizer [7,14,15]; as such, as cropland has expanded, the CH_4 sink strength of soils globally will have declined [14]. When mineral soils become anaerobic, the net flux to the atmosphere can be positive, with waterlogged soils becoming a CH_4 source, often with large emission rates [16]. When soils are deliberately flooded, e.g. for paddy rice cultivation, they can become very large global sources of CH_4 as described in section 1.1 [7].

1.3 Metrics of the climate warming effect of methane

For comparability with other greenhouse gases, the radiative forcing of CH_4 is often expressed in terms of CO_2 equivalents, calculated using a global warming potential (GWP) over a 100-year time horizon (GWP_{100}). National greenhouse gas inventories, to date, have used a GWP_{100} value of 25 from the IPCC Fourth Assessment Report (1 kg of CH_4 is equivalent to 25 kg of CO_2). The GWP_{100} of CH_4 has frequently been updated as scientific understanding has improved and was quoted as 21, 25 and 28 in the IPCC 2nd, 4th and 5th Assessment Reports, respectively. When feedbacks are included, the GWP_{100} value for CH_4 was estimated to be 34 in the IPCC 5th Assessment Report.

Given the relatively short atmospheric lifetime of CH_4 – 12.4 years compared to 121 for nitrous oxide and 300->1000 years for CO_2 – some have argued that GWP_{100} is not a useful metric for assessing the contribution of

CH_4 to climate warming [17]. Instead, they propose a metric that reports equivalent emissions, based on whether sustained changes in the emission rates of short-lived gases (like CH_4) would result in a similar warming contribution to an individual, one-off CO_2 emission [18, 19]. This metric is known as GWP* [17,18,19].

The consequences of using the GWP_{100} and GWP* metrics for assessing the climate warming caused by CH_4 are very different. Instead of providing a snapshot of CH_4 emissions at a single point in time, the calculation underpinning GWP* expresses the warming impacts of changes in the *rate of emissions of* CH_4 as equivalent to a large pulse emission of CO_2 [20]. Using GWP* as the metric for CH_4, if CH_4 emissions remain constant there is no additional warming, unlike for CO_2 (or other long-lived gases) where each additional tonne of CO_2 added to the atmosphere causes additional warming. This has led some sectors of the agricultural industry, particularly in the livestock sector, to make statements such as: "This means that the CH_4 emissions of a herd of 100 cows today are simply replacing the emissions that were first produced when that herd was established by a previous generation of farmers. There was an initial pulse of warming when the herd was established, but there is no ongoing warming from that herd" [21]. These statements are used to support arguments that grazed livestock are part of the climate solution [21]. The assertion has been challenged [22] and the authors of the GWP* themselves note, "while some ongoing CH_4 emissions may be able to give no further temperature increases from those emissions, maintaining these emissions into the future means they will continue to contribute to our elevated temperatures, and the resulting climate damages we will experience" [20]. It is a fundamental, metric-independent reality that emitting less methane will mean having a smaller impact on the climate.

2 Reducing methane emissions from agriculture

As outlined in section 1.1, the main sources of CH_4 emissions from agriculture of from rice production, enteric fermentation, manure management and residue burning. The technical options for reducing emissions from these sources are described below, along with their estimated global mitigation potential, summarised in Figure 3.

2.1 Mitigation opportunities in rice production

Changes in rice management have the potential to significantly decrease paddy rice soil CH_4 emissions [10,23]. Mid-season drainage is the main mitigation option with other mitigation measures including changed fertilizer practices and tillage/residue management [10].

Emissions during the growing season can be reduced by many practices [24,25,26]. Mid-season drainage effectively reduces CH_4 emissions [27,28], although this benefit may be partly offset by higher nitrous oxide emissions, and the practice may be constrained by water supply. Mid-season drainage is now becoming prevalent in many rice-growing areas [7]. Rice cultivars with low exudation rates could offer an important CH_4 mitigation option [26]. In the off-rice season, CH_4 emissions can be reduced by improved water management, especially by keeping the soil as dry as possible and avoiding waterlogging [29,30,31,32]. Methane emissions can also be reduced by adjusting the timing of organic residue additions (e.g. incorporating organic materials in the dry period rather than in flooded periods [33,34]) and composting the residues before incorporation.

The estimated global mitigation potential for rice management has been estimated to be ~8, 9 and 10 Tg CH_4 y^{-1} at carbon prices of 20, 50 and 100 US\$ tCO_2e, respectively [10,23].

2.2 Mitigation opportunities for enteric fermentation

Practices for reducing enteric CH_4 emissions fall into three general categories: a) improved feeding practices, b) use of specific agents or dietary additives, and c) longer term management changes and animal breeding. Additional options to reduce emissions arise from reducing ruminant livestock numbers, enabled by demand-side changes (dietary change and reduced food loss/waste; discussed further in section 3.1).

For improved feeding practices, CH_4 emissions can be reduced by feeding livestock more concentrates which normally replace forage [35,36,37,38]. Although concentrates may increase daily CH_4 emissions, emissions per unit of feed intake and per unit product (emission intensity) are almost always reduced. The net benefit, however, depends on reduced animal numbers or younger age at slaughter for beef animals and on how the practice affects emissions when producing and transporting the concentrates [39,40]. Other practices that can reduce enteric CH_4 emissions include adding oils to the diet [41,42] and improving pasture quality, especially in less developed regions, because it improves animal productivity and reduces the proportion of energy lost as CH_4 [43,44,45].

A wide range of specific agents and dietary additives have been tested, mostly aimed at suppressing methanogenesis. These include ionophores, which are antibiotics that can reduce CH_4 emissions [46,47,48], but their effect may be transitory [49] and they have been banned in some jurisdictions, such as the European Union. Halogenated compounds which inhibit methanogenic bacteria [50,51] have also been tested, but their effects, too, are often transitory and they can have side effects such as reduced calorie intake. Probiotics, such as yeast culture, have shown only small, insignificant effects [48], but selecting strains specifically for CH_4 reducing ability could improve results [52]. Propionate precursors, such as fumarate or malate, reduce CH_4 formation by acting as alternative hydrogen acceptors [53], but are effective only at high doses and are therefore expensive [54]. Vaccines against methanogenic bacteria have been developed but are not yet commercially available [55]. Bovine somatotrophin (bST) and hormonal growth implants do not specifically suppress CH_4 formation, but by improving animal performance [56,57] they can reduce the emission intensity (emissions per unit of product) of meat/dairy [58,59], but like ionophores, are banned in some jurisdictions, such as the European Union. Some natural feed additives, such as seaweed, have been tried [60]

Longer term management changes and animal breeding includes increasing productivity through breeding and better management practices, which spreads the energy cost of maintenance across a greater feed intake, often reducing CH_4 output per unit of animal product [61]. With improved efficiency, meat-producing animals reach slaughter weight at a younger age, with reduced lifetime emissions [62]. The whole system effects of such practices are not clear, however; for example, selecting for higher yield might reduce fertility, requiring more replacement animals [40].

Mitigation potential from reducing enteric fermentation from livestock has been estimated to be ~6.4, 8.5 and 10.6 Tg CH_4 y^{-1} at carbon prices of 20, 50 and 100 US\$ tCO_2e, respectively [10,23].

2.3 Mitigation opportunities in manure management

Animal manures can release significant amounts of CH_4 during storage, but the magnitude of these emissions varies. Methane emissions from manure stored in lagoons or tanks can be reduced by cooling or covering the sources, or by capturing the CH_4 emitted [63,64,65,66]. The manures can also be digested anaerobically to maximize retrieval of CH_4 as an energy source [63,67]; see section 2.5).

Storing and handling the manures in solid, rather than liquid form, can suppress CH_4 emissions but may increase nitrous oxide formation [66]. For most livestock production systems globally, there is limited opportunity for manure management, as treatment or storage - excretion happens in the field and handling for fuel or fertility amendment occurs when it is dry and CH_4 emissions are negligible [66]. Emissions from manure might be curtailed somewhat by altering feeding practices [69] or by composting the manure [70], but these mechanisms and the system-wide impacts have not been widely explored.

Mitigation potential from improved manure management has been estimated to be ~0.4, 1 and 2 Tg CH_4 y^{-1} at carbon prices of 20, 50 and 100 US$ tCO_2e, respectively [10,23].

2.4 Mitigation opportunities for residue burning

Strategies to reduce residue burning are often promoted to improve air quality and address a mix of long- and short-lived climate pollutants [7]. Since residue burning is responsible for just over 1 Tg CH_4 y^{-1} (Figure 2, [1]), the total cessation of crop residue burning would have a maximum mitigation potential of ~1 Tg CH_4 y^{-1}. Figure 3 summarises the mitigation potentials described in this section.

2.5 Potential for biogas

Biogas is a methane-rich gas mixture, generated from anaerobic decomposition of organic matter that can be burnt to release energy. Use of organic wastes in production of biogas has potential to change net CH_4 emissions in two ways. Collection of organic wastes for use as a feedstock for biogas production may reduce CH_4 emissions by removing wastes from the environment where uncontrolled anaerobic decomposition can result in significant emissions of CH_4 [8]. However, emissions of CH_4 may also be increased by CH_4 leakage from the biogas digesters [71], piping [2] and appliances [73,4]. The net effect on CH_4 emissions is a balance between these different processes. While we focus here only on the impact of biogas on CH_4 emissions, it should be noted that using organic wastes in biogas production has further impacts on total greenhouse gas emissions by potentially replacing fossil fuels [75], reducing deforestation associated with use of wood as a fuel [77,77] and increasing soil carbon sequestration associated with application of bioslurry as an organic fertilizer [78]. These latter impacts are not discussed further here.

Reduced emissions of methane from organic wastes – The global emissions of CH_4 from deposited and stored manures is estimated to be 9.9 Tg y^{-1} (Figure 2; [1]). The maximum potential reduction in CH_4 emissions associated with prevention of uncontrolled anaerobic decomposition of manures is 9.9 Tg y^{-1}, but since only stored manures can be used for biogas production, this maximum potential is likely to be substantially lower. In practice, anaerobic digestion can only be implemented in locations with sufficient access to water [79]. Consistency of supply of water is also important, with seasonal breaks in supply likely to increase the proportion of digesters that are abandoned [80]. Therefore, the actual potential for reduction in CH_4 emissions using anaerobic digestion is likely to be significantly less than this maximum potential.

The proportion of the CH_4 produced that leaks from the digester, pipes and biogas appliances is dependent on the scale of the system and the sophistication of the technology used; large-scale, state-of-the-art plants are likely to leak a much lower proportion of CH_4 produced than simple, small-scale systems. Net emissions also depend on the counterfactual emissions from the energy that is replaced by biogas; for example, for household cookstoves, emissions of CH_4 during combustion are 57 mg per MJ energy delivered for biogas, compared to 8.9 mg MJ^{-1} for LPG, 600 mg MJ^{-1} for wood, 1300 mg MJ^{-1} for coal and 7100 mg MJ^{-1} for dung. Therefore, combustion losses of CH_4 from cookstoves are increased only compared to LPG, whereas by comparison to wood, coal and dung, combustion losses are very much reduced [71].

Leaks of CH_4 from biogas digesters can occur from any openings in the digester tank; for example, in fixed dome digesters, the inlet and outlet are open to the atmosphere, so any CH_4 produced in these locations can be lost, while in floating drum digesters, any CH_4 produced from the small volume of manure on the outside of the upper drum can be lost. These losses from well-maintained small-scale digesters in India have been estimated to be 14 – 17% of the CH_4 produced in fixed dome digesters [81], and 5 – 8% in floating drum digesters [82]. Cracks in the digester body or gas tubing due to poor maintenance can result in further unintentional losses of CH_4. Even in well-maintained large-scale agricultural digesters in Canada, these losses were estimated to average 3.1% of the CH_4 produced [83], whereas in less well-maintained systems in China, fugitive losses due to poor maintenance were estimated to be as high as 10% [71]. However, the largest source of CH_4 emissions from biogas digesters may be due to the intentional venting (without flaring) of excess biogas; these losses were estimated in a study of small scale digesters in Thailand to be 15% of the CH_4 produced [84], and in southern Vietnam to be as high as 36.6% [72]. In larger scale systems, alternative uses are usually found for excess biogas, and any further excess is usually converted to CO_2 by flaring. Bruun et al. [71] estimated that typical total CH_4 losses due to leaks and venting from small-scale biogas digesters is in the region of 40% of the CH_4 produced, and estimated that in 2014, this amounted to a global total of ~4.5 Tg y^{-1}.

Therefore, while anaerobic digestion has potential to reduce CH_4 emissions from uncontrolled anaerobic decomposition of manures by up to 9.9 Tg y^{-1}, losses due to leaks from digesters, pipes and appliances are likely to be in the region of ~4.5 Tg y^{-1}. Therefore, the net potential impact of anaerobic digestion on CH_4 emissions could be to increase CH_4 emissions by up 4.5 Tg y^{-1} if no reduction in uncontrolled decomposition is achieved, or to reduce CH_4 emissions by up to 4.4 Tg y^{-1}. Future initiatives to increase implementation of anaerobic digestion must therefore be combined with improvements in maintenance of digesters in order to achieve maximum benefits in CH_4 emission reduction and avoid increased emissions.

[Figure 3 here]

3 Reducing methane emissions from the food system

3.1 Dietary change

Food supply chain and demand-side interventions that save CH_4 emissions at the production phase, such as reduced supply chain loss and waste, also have an important role to play in this sector [85]. Since enteric fermentation dominates agricultural CH_4 emissions, any transition away from ruminant livestock will reduce CH_4 emissions [86].

On an emissions intensity basis (greenhouse gas emissions per unit mass, protein or energy), numerous studies have shown the climate impact of ruminant meat to be 10-100 times greater than plant-based foods [86, 87,88,89 ,90], so a shift away from ruminant meat and dairy, toward plant-based products in the diet, greatly reduces the climate footprint of food, largely by reducing CH_4 emissions [,89,90,91,92,93,94,94].

A shift toward meat from monogastrics (e.g. pig and poultry) also lowers CH_4 emissions, since they produce no enteric CH_4, although emissions from manure management remain. In a meta-analysis, Aleksandrowicz et al. [94] showed that a vegan diet reduced emissions by 45% (>20->70%) relative to current average diets, vegetarian diet reduced emissions by ~30% (15%-~60%) while transition to meat from monogastrics reduced emissions by ~20% (~5%-~35%). It is worth noting that dietary transitions for individuals do not have to be absolute; any reduction in ruminant product consumption will reduce CH_4 emissions associated with diets. A dietary transition to one in which every person on the planet eats according to healthy dietary guidelines would deliver significant CH_4 emission reductions [93].

Since CH_4 from enteric fermentation are around 100 Tg CH_4 y^{-1} in 2017 (see Figure 2; [1]), the maximum technical emission reduction potential (with no ruminant meat or dairy consumption) would be 100 Tg CH_4 y^{-1}, but Roe et al. [95] model an equivalent of 50% of the human population, which would halve CH_4 emissions from enteric fermentation, ceasing eating meat and dairy to deliver a land / food system that is compliant with a 1.5°C world (see section 4.2).

3.2 Waste reduction

Food supply chain and demand-side interventions that save CH_4 emissions at the production phase, such as reduced supply chain loss and waste, also have an important role to play in this sector. An estimated 26% of food produced globally is lost or wasted each year, equivalent to 6% of global anthropogenic greenhouse gas emissions [89]. Methane-intensive foods, such as ruminant meat and dairy, play a disproportionately large role in these food wastage emissions and one that has continued to expand over the past half century [85].

In developed nations, the bulk of these losses occur in the consumer phase, with avoidable wastage of milk in UK households, for example, being estimated at 290 thousand tonnes each year [96]. Applying a simplistic global average CH_4 emission factor (48kg CH_4 per tonne of milk [based on [97] and assuming CH_4 comprises

50% of global average footprint of 2.4kg CO_2e per kg fat and protein-corrected milk and GWP_{100} of 25]) to these consumer-phase milk losses equates to around 14 thousand tonnes of CH_4 emission per year for the UK alone.

Similarly, for dairy milk in the US, the huge volumes wasted represent a very large CH_4 emissions penalty, but by reducing losses in both the retail and consumer phases, Thoma et al. [98] estimate that emissions from US milk could be reduced by 23%. As such, reducing food loss and waste represents a potentially powerful, albeit indirect, CH_4 mitigation strategy for global agriculture.

4 Future prospects

4.1 Climate change impacts on future agricultural methane fluxes

Climate change itself may alter future CH_4 fluxes from agriculture, and so the efficacy of mitigation measures. For the livestock sector, changes in feed quantity and quality, increased animal heat stress and manure fermentation rates, and increased pest and disease impacts, may all serve to enhance emissions [8]. The net effect globally remains highly uncertain, with wide variation in impacts likely between different regions and production systems. Adaptation will play a central role here in terms of buffering the impacts of climate change at local scales, such as through use of shading, ventilation and livestock management strategies in the case of extreme heat events [99].

For cropland systems the projected impacts of climate change on CH_4 fluxes are relatively minor and largely stem from changes in soil moisture, such as drying of waterlogged mineral soils reducing methanogenesis. More important will be the effects on CH_4 emissions from rice agriculture. Here, reduced soil moisture may substantially reduce emissions in some rain-fed systems [100], while in irrigated systems higher temperatures combined with enhanced atmospheric CO_2 concentrations can greatly increase emissions [101]. As with the livestock sector, variation across locations and production systems will be large.

Overall, the greatest impacts of climate change on CH_4 emissions from agriculture are likely to arise indirectly through effects on production efficiency. While this includes heat stress, drought, disease and other 'on-farm' impacts, it is also relevant right along the food supply chain, for instance, higher temperatures increasing food spoilage rates. As discussed earlier, given the current magnitude of loss and wastage of CH_4-intensive foods, such as milk, any climate change impacts that exacerbate these losses risk an upstream ripple effect of increased on-farm emissions.

The net impact of such climate change- CH_4 feedbacks on emissions from agriculture at a global scale is likely to be dwarfed by future changes in food demand, land use, and food system management practices (including those focussed on mitigation). Nevertheless, CH_4 mitigation strategies in agriculture must be cognisant of these feedbacks, make the most of any synergies with climate adaptation and avoid any undermining of food system resilience.

4.2 Methane reduction in climate stabilization pathways

While some studies have suggested that future temperature targets could be achieved without major reductions in ruminant/agricultural methane emissions (102,103,104), Roe et al. [95], synthesising previous top-down and bottom-up estimates of mitigation in agriculture propose a 25% reduction in agricultural non-CO_2 emissions by 2050, compared to business as usual, in their implementation roadmap for the land sector. Priority regions for reducing CH_4 emissions from enteric fermentation and manure management are China, India, Brazil, EU, US, Australia, Russia and Latin America (Brazil, Argentina, Mexico, Colombia, Paraguay, Bolivia). Priority regions for reducing CH_4 emissions by improving water and residue management of rice fields, and manure management are in Asia, namely India, China, Indonesia, Thailand, Bangladesh, Vietnam, Philippines. Globally, this translates to mitigation from reduced enteric fermentation from better feed and animal management of 4.8 to 47.2 Tg CH_4 y^{-1}, and 4 to 36 Tg CH_4 y^{-1} from improved rice management. Note that the higher numbers in the range are somewhat higher than the potentials reported in section 2.

In their implementation roadmap for the land sector, Roe et al. [95] propose 50% of the global population shift to a plant-based diet by 2050 and a 50% reduction in total food loss and waste by 2050 compared to BAU. The priority regions for a shift to plant-based diets are developed and emerging countries, i.e. US, EU, China, Brazil, Argentina, Russia and Australia), while the priority regions for reduced food waste are China, Europe, North America and Latin America, and for reduced food loss are Southeast Asia and Sub-Saharan Africa. The estimated mitigation potential of these measures, excluding land-use change benefits, is 0.9 Gt CO_2e y^{-1} for 50% shift to plant-based diets by 2050 and 0.9 Gt CO_2e y^{-1} for a 50% reduction in food loss and waste by 2050 [95]. Not all of this, however, is through CH_4 reduction, and the figures include reduction in nitrous oxide emissions [105]. If 50% of the global population shift to a plant-based diet by 2050 and a 50% reduction in total food loss and waste led to a halving of enteric fermentation and manure production, the mitigation potential could be in the order of >50 Tg CH_4 y^{-1}.

Methane abatement is clearly an important component of a land sector that helps to deliver a 1.5 °C world, with interventions both on the supply side (reduction in emissions from enteric fermentation, rice and manure) and the demand side (dietary shifts toward plant-based diets and reduction in food loss and waste) necessary to achieve a land sector that is compliant with the Paris Climate Agreement [95], with the IPCC in the Special Report on 1.5°C target suggesting that agricultural methane emissions need to be 24-47% below 2010 emissions in 2050 [106].

5 Concluding remarks

Agriculture is the largest anthropogenic source of methane, emitting 145 Tg CH_4 y^{-1} to the atmosphere in 2017. The main sources are enteric fermentation, manure management, rice cultivation and residue burning. There is significant potential to reduce CH_4 from these sources, with mitigation potentials of ~10.6, 10, 2 and 1 Tg CH_4 y^{-1} from rice management, enteric fermentation, manure management and residue burning, respectively (Figure 3). Other studies assume even higher potentials of 4.8 to 47.2 Tg CH_4 y^{-1} from reduced enteric fermentation, and 4 to 36 Tg CH_4 y^{-1} from improved rice management [95]. Biogas also has potential to reduce unabated CH_4 emissions from animal manures and human waste. In addition to these supply-side measures, interventions on the demand-side (50% of the global population shift to a plant-based diet by 2050 and a 50% reduction in total food loss and waste) would also significantly reduce methane emissions, perhaps on the order of >50 Tg CH_4 y^{-1}.

While there is an pressing need to reduce emissions of long-lived greenhouse gases (CO_2 and N_2O) due to their persistence in the atmosphere, despite CH_4 being a short-lived greenhouse gas, the urgency of reducing warming means we must reduce any GHG emissions we can as soon as possible. Mitigation actions should focus on reducing emissions of all the three main anthropogenic greenhouse gases, including CH_4.

Additional Information

Ethics
There are no ethical considerations in the paper.

Data Accessibility
This paper does not report primary data. All publicly available data sources are given. There are no Supplementary Materials.

Authors' Contributions
PS wrote the first draft of the manuscript. **PS**, **DR** and **JS** drafted individual sections and edited / revised the manuscript drafts. All authors read and approved the manuscript.

Competing Interests
The authors declare that they have no competing interests.

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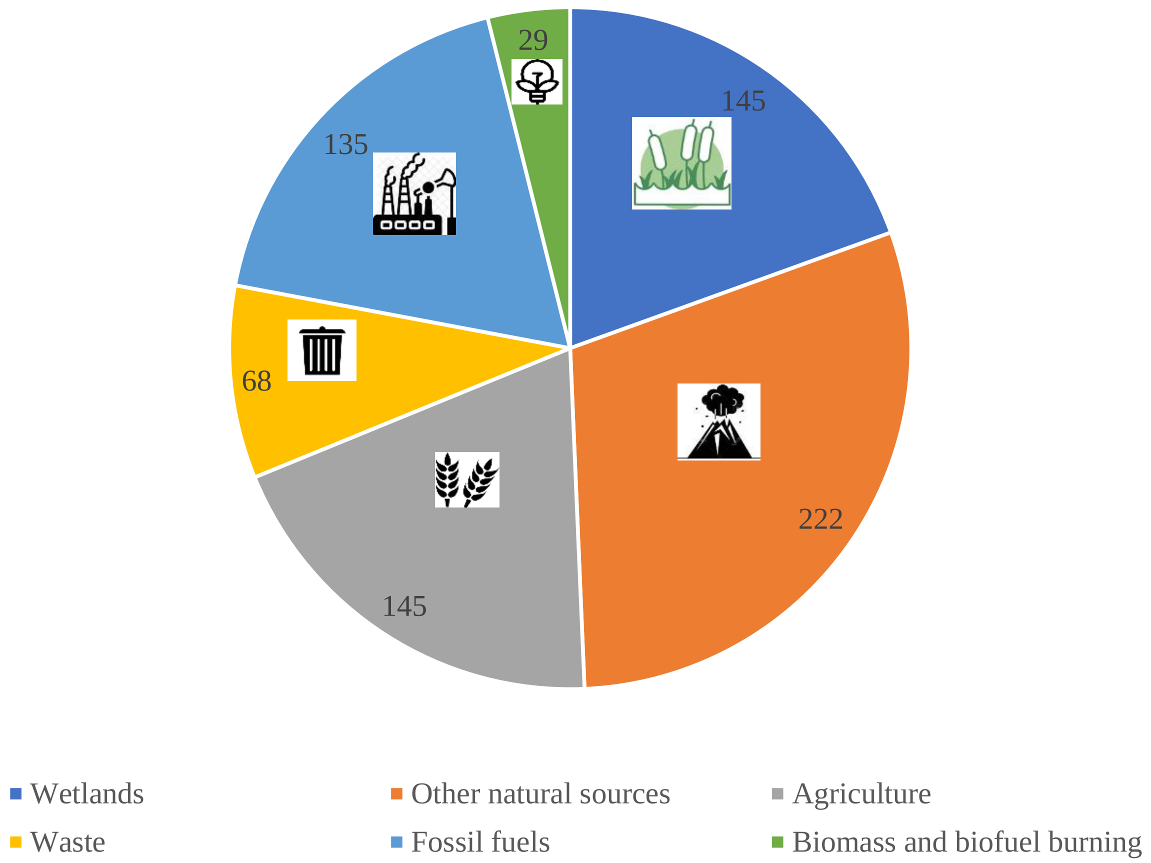
Figure captions

Figure 1. Global methane emissions (Tg y^{-1}) from global emissions sectors in 2017. Bottom up best estimates from [11].

Figure 2. Agricultural methane emissions 1961-2017 by source. Data from [1]. Note: Though savannas are used to varying extents for grazing domestic livestock, savanna burning emissions are not included.

Figure 3. Estimated maximum mitigation potential (for carbon price of 100 US$ tCO_2e^{-1}) for methane emissions from agriculture [10,23]. Note: Biogas mitigation potential not shown as emission reductions are accounted for in the energy sector.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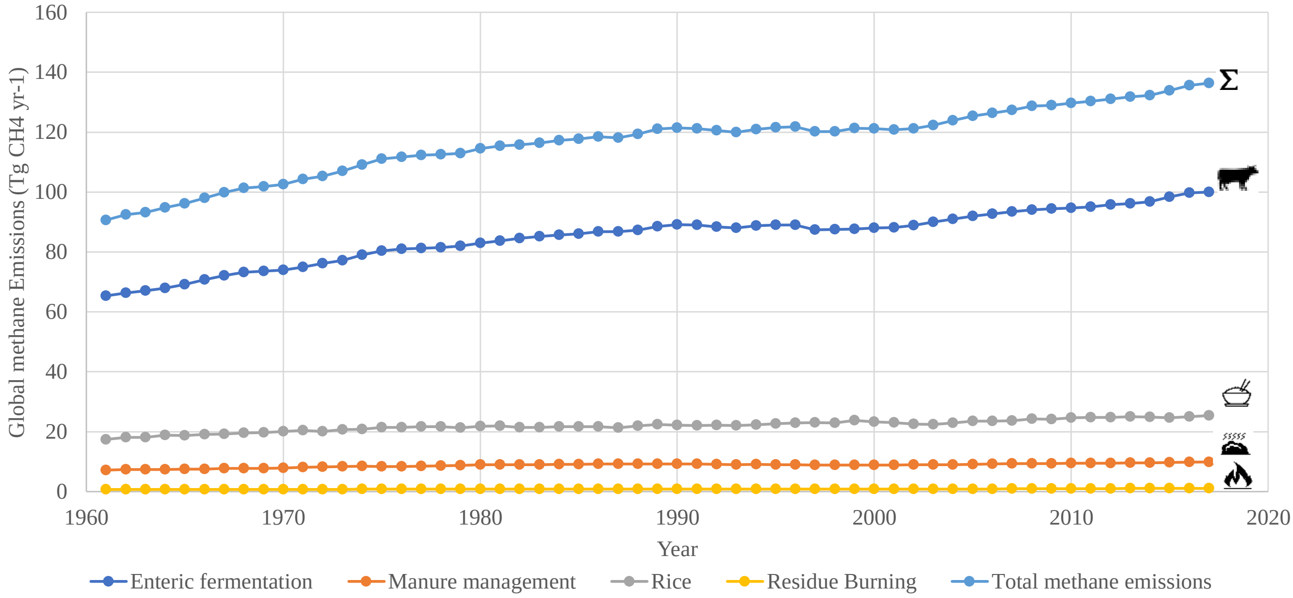
Wetlands
Other natural sources
Agriculture
Waste
Fossil fuels
Biomass and biofuel burning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1960
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Global methane Emissions (Tg CH4 yr-1)
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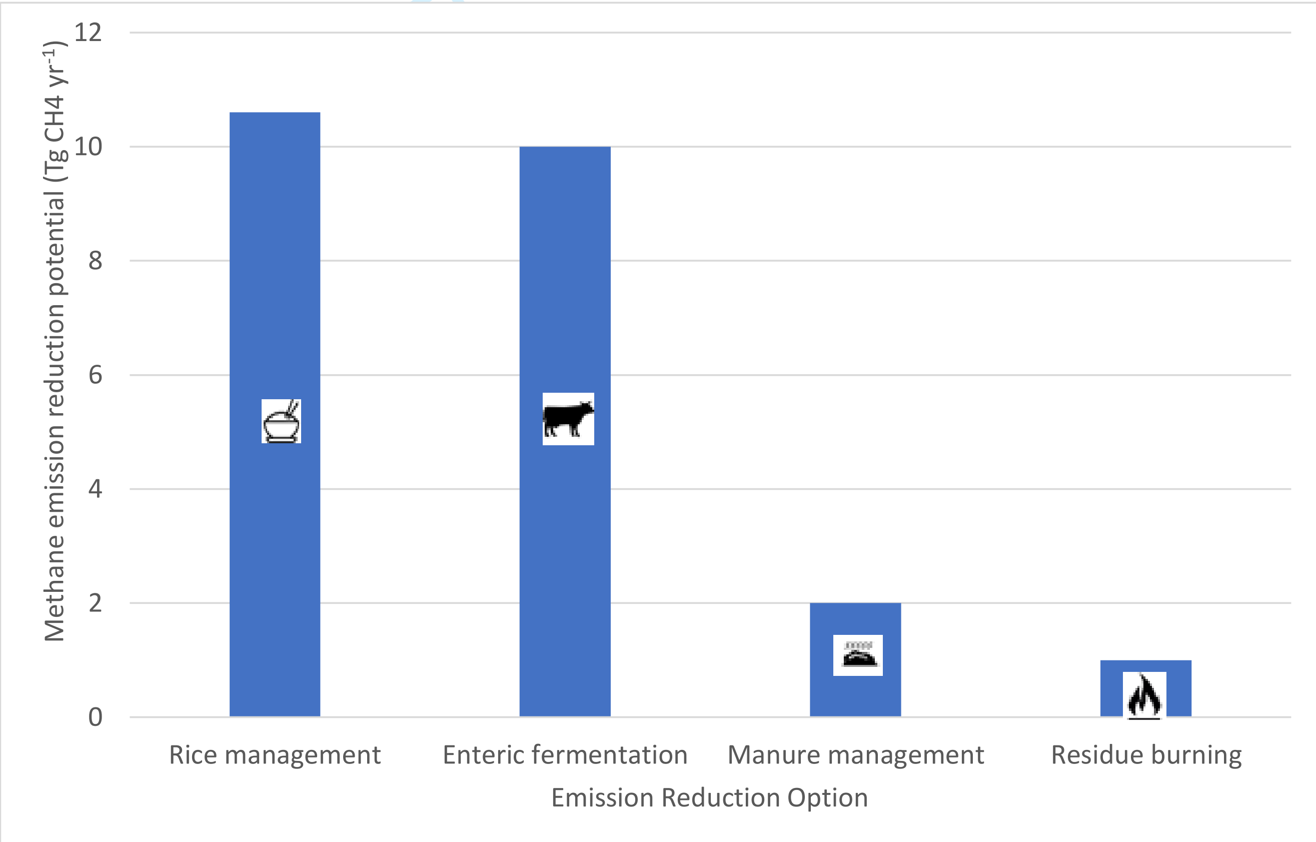
Enteric fermentation
Manure management
Rice
Residue Burning
Total methane emissions



Methane emission reduction potential (Tg CH4 yr-1)
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Rice management
Enteric fermentation
Manure management
Residue burning
Emission Reduction Option