Opportunities to Reduce Methane Emissions from Global Agriculture

Discussion Paper
November 2021

Authors:

Tim Searchinger, School of Public & International Affairs, Princeton University (tsearchi@princeton.edu)
Mario Herrero, College of Agriculture and Life Sciences, Cornell Atkinson Center for Sustainability, Cornell University (mh2258@cornell.edu)
Xiaoyuan Yan, Institute of Soil Science, Chinese Academy of Sciences
Jinyang Wang, College of Resources & Environmental Science, Nanjing Agricultural University
Patrice Dumas, CIRAD, UMR CIRED
Karen Beauchemin, Agriculture and Agri-Food Canada
Ermias Kebreab, College of Agricultural and Environmental Sciences, University of California, Davis

PRINCETON UNIVERSITY

Cornell University

Contents

This report was prepared with the financial support of the Bezos Earth Fund.

Abstract

Quickly reducing methane emissions is an important strategy for meeting 2050 climate targets because of the powerful radiative forcing of methane and its relatively short lifetime, but this strategy is undermined by rapidly rising emissions. Agriculture contributes around 40-46% of global methane emissions, and because of rising food production, these emissions are on a path to increase roughly 40% by 2050. Of these emissions, two-thirds are from enteric methane from ruminant livestock, roughly 20% are from rice, and 7% are from managed manure.

Although mitigation efforts for agriculture have received less attention, we set forth a credible scenario to decrease these emissions by 54% relative to otherwise likely emissions in 2050 and by 36% compared to present emission levels. Mitigation opportunities include:

(1) increasing the feed efficiency of ruminant livestock;
(2) rapid development and deployment of promising enteric methane inhibitors;
(3) realizing an "Optimistic Trend Projection" for consumption of ruminant meat, which relies more heavily on alternative sources of animal protein;
(4) deployment of at least one basic water level drawdown in flooded rice fields plus better offseason management of residues;
(5) broad use of at least one method of reducing methane emissions from manure managed in wet form; and
(6) reductions in global food loss and waste.

Other innovative ideas are also promising. To achieve this mitigation, we suggest in the near-term an internationally coordinated effort to develop "shovel-ready" projects using known mitigation options but structured to encourage innovation and to improve our understanding of how to reduce emissions further. We also suggest a series of internationally coordinated R&D projects and demonstration projects of promising technologies. One key need is a $100 million initiative to have multi-year tests of promising enteric methane inhibitors in at least 20 world locations, and related technical work to bring them to market.

1. The Challenge

Rapidly reducing global emissions of methane, on the order of 45% by 2040, is critical to any climate strategy that aims to hold global warming to 1.5 degrees Celsius (UNEP 2021). Since 2010, however, methane emissions have been increasing at a rapid rate, and these methane increases also undermine any reasonable path to stabilize the climate at 2 degrees Celsius of warming. Because a kilogram of methane's radiative forcing is presently more than 300 times more powerful than a kilogram of carbon dioxide, methane emissions can have a powerful effect on warming. And because methane's average persistence in the atmosphere is only around 10 years, increasing emissions quickly increases warming while reducing methane emissions quickly reduces warming. For this reason, modeling has estimated that reducing methane emissions by 45%, or 180 million tons per year by 2030, would avoid nearly 0.3 degrees of warming by the 2040s. Because methane also contributes to smog (ground level ozone), this level of reductions would also prevent 255,000 premature deaths, three quarters of a million hospital visits, and avoid 26 million tons of crop losses (UNEP 2021).

Annual human-caused emissions of methane are likely between 350 and 380 million tons (MT) per year (UNEP 2021). Of these emissions, roughly 35% comes from leaks of methane from fossil fuels, mainly through extraction and transport, 20% from wastes, such as landfills, but roughly 40-46% comes from agriculture. According to FAO estimates reported in FAOSTAT, which use simple emission factors and ignore agriculture's energy use, agriculture generated 147 million tons of methane in 2018. Using a new analysis of emissions from rice presented in this paper, overall agricultural methane emissions are somewhat higher at 156 million tons.

In agriculture, there are a few major sources of emissions. Two-thirds of the emissions result from "enteric methane," which is methane generated in the digestive tracts of livestock, and overwhelmingly from "ruminants" (primarily cattle, buffalo, sheep and goats) (Table 1). According to FAO estimates, rice generates 17% of emissions (although our estimate is a little higher). The management of manure in confined settings contributes another 7%. The FAO also lists various burnings associated with agriculture, which contribute another 8% of methane emissions, including 1% from burning crop residues and 4% from various forms of land use change such as forest clearing and fires in drained peatlands.

Rising demand for food will increase methane emissions under "business as usual." Using the Globagri model developed primarily at CIRAD, the World Resources Institute estimated that these sources of agricultural methane emissions would rise 38% between 2010 and 2050 (Searchinger et al. 2019). Applied to FAO estimates of agricultural methane emissions, this increase implies agricultural methane emissions of roughly 200 million tons by 2050. Given the scope of agricultural emissions today and these likely increases without concentrated effort, reducing agricultural methane emissions becomes critical to stabilizing the climate at acceptable temperatures.

Most estimates of the potential to reduce methane from agriculture have been modest and often expensive in the hundreds of dollars per ton of carbon dioxide equivalent (see summary in UNEP 2021) (Wollenberg et al. 2016) (Henderson et al. 2017). The modesty and expense of these estimates may discourage country efforts. Here we set forth some more optimistic, but we believe, credible scenarios for achieving significant reductions in methane from the three principal agricultural sources. Although there are costs to moving these practices forward, most mitigation options discussed would increase productivity and overall food output. Investments are needed to help farmers adopt these practices and to further develop technologies, but we believe each of the options presented here has the potential to be profitable or at a minimum a highly cost-effective form of climate mitigation. As in the energy sector, these scenarios rely in part on existing technologies and in part on technologies that have already showed promise but that require some further research and development. The level of investment in this kind of R&D, however, has been minimal. To advance mitigation, the final section of this paper provides some suggestions for moving forward.

This paper does not directly address methane emissions from burning or methane emissions associated with agricultural energy use. There are good, often profitable methods for reducing crop residue burning, such as use of a form of no-till seeding machine for planting wheat after rice in the Punjab (Shyamsundar et al. 2019). Restoring drained peatlands and reducing agricultural expansion would reduce the 4% of methane emissions attributed to forest and peatland fires, and such efforts are even more critical to reduce the roughly 10% of all human emissions, primarily from carbon dioxide, attributable to land use change. Other reports, such as the WRI/World Bank/UN report, *Creating a Sustainable Food Future*, set forth comprehensive strategies for addressing these emissions (Searchinger et al. 2019). Yet many of the methane mitigation measures discussed here would simultaneously help meet rising food demands without expanding agricultural land and therefore contribute even more broadly to addressing climate change.

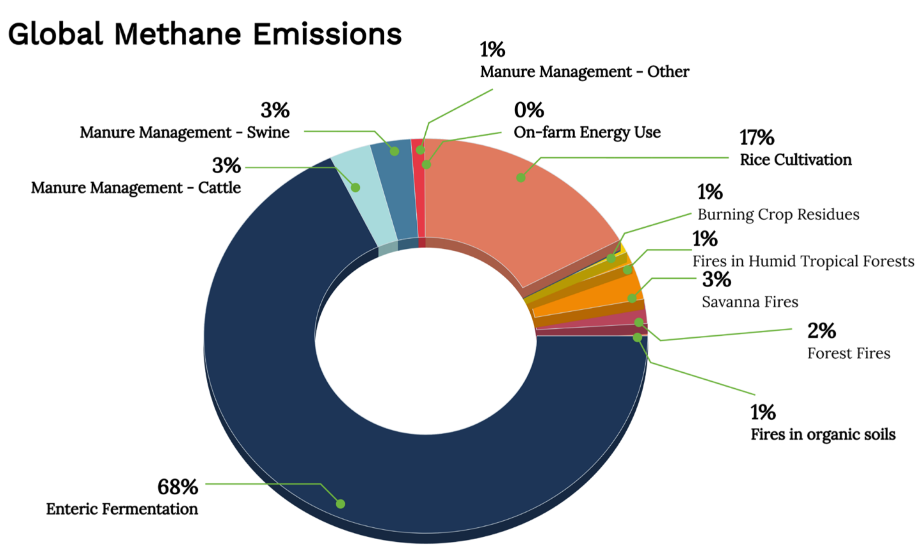

Figure 1: FAO estimates of methane from agriculture

2. Enteric Methane

The world's farmers annually raise 1.7 billion cattle and buffalo and 2.2 billion sheep and goats, all of which are ruminants (Searchinger et al. 2019). Ruminants contain a portion of the stomach, known as the rumen, which supports the microbial populations able to break down cellulose. This ability allows these animals to survive on diets of grasses, leaves, high-fiber byproducts and other "fodders." Microorganisms known as archaea, which are ultimately the source of all methane on earth, use the hydrogen that is released by other microorganisms in the rumen to produce methane. Overall, this "enteric" methane from global agriculture, including a very modest contribution from pigs, equaled 100 million tons in 2018 according to the FAO. Without change, these emissions could grow substantially due to rising demand for and production of meat and milk. Using FAO projected diets in 2050 and UN projections of population growth, we estimate using the Globagri model that enteric methane would rise by roughly 50% from 2010 levels by 2050.

Unlike many other sources of emissions (including not only energy but also rice and manure management), ruminants are broadly distributed around the world, which means a broad distribution of enteric methane. Figures 2 and 3 show the global distribution of cattle and sheep and goats as estimated by FAO. Globally, almost 85% of emissions are from cattle and buffalo, with another 12% from sheep and goats. Despite this broad distribution, eight countries generate more than half of the enteric methane according to FAO estimates: India, Brazil, China, the U.S., Pakistan, Argentina, Ethiopia, and Mexico (Europe collectively is also a large source collective). Among cattle, one quarter of enteric methane emissions is from dairy and three quarters of emissions are from meat or other cattle uses.

Three basic methods exist for reducing enteric methane: one, producing more meat and milk per animal and per kilogram of feed to generate comparable output while reducing animal numbers; two, manipulation of the microbial processes in the rumen, particularly through feed additives; three, reduced reliance on ruminant products. The most promising alternative is reducing reliance on ruminant meat because it is far less efficient than dairy, other sources of meat, and plant-based proteins.

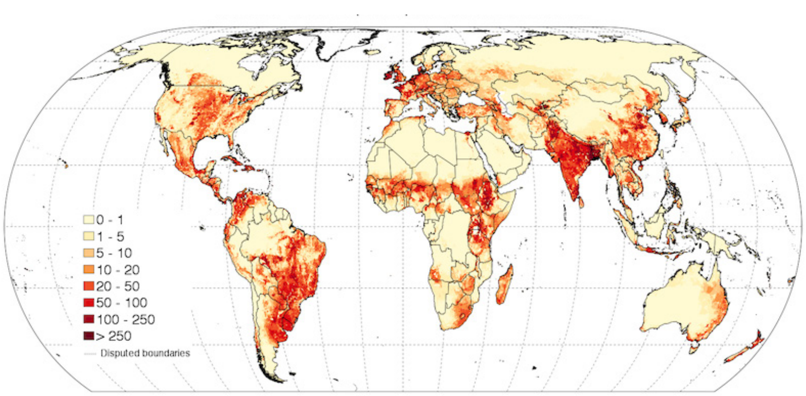

Figure 2: Global distribution of cattle (source FAO); excludes buffalo, which are heavily concentrated in South Asia and China

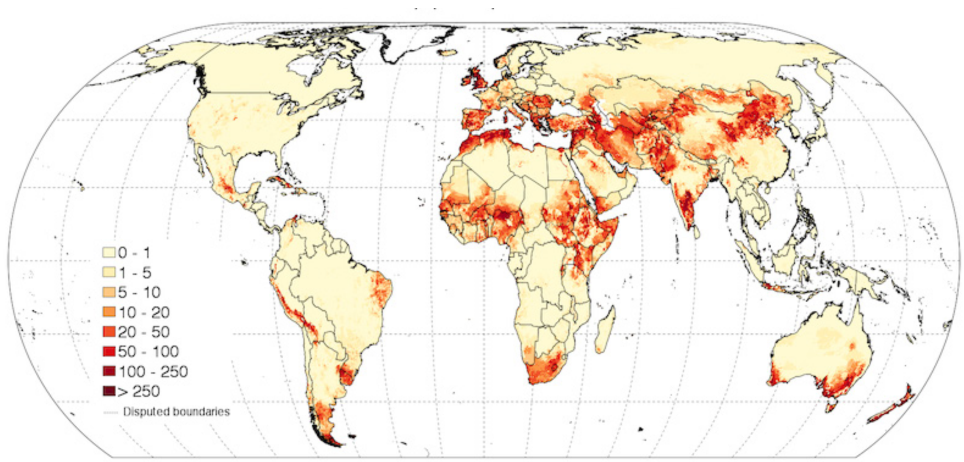

Figure 3: Global distribution of sheep (source FAO)

Improved efficiency

Although other factors influence enteric methane emissions, the dominant factor is the quantity of feed, measured by its gross energy content (Blaxter & Clapperton 1965) (Moraes et al. 2013). For this reason, one reasonable estimate of methane emissions still allowed by the IPCC is that methane (measured by its energy content) equals 6.5% of the gross energy of the feed (IPCC 2006). More recent IPCC recommendations still estimate emissions based on quantity of feed, but also factor in quality. Poor quality feed generates even more emissions while better quality feeds generate less (IPCC 2019) because the rumen works more efficiently. Other formulas for methane emissions introduce additional factors and can be more accurate, but the quantity of feed remains the dominant factor that determines enteric methane emissions (Moraes et al. 2014). As a result, increasing the milk or meat produced for each kilogram of feed can dramatically reduce the methane emissions per kilogram of milk or meat produced.

Better feed quality primarily means more digestible feed – feed ruminants can more thoroughly digest and use for energy – and feed with balanced nutrients, including sufficient protein. Although ruminants can break down the cellulosic material that makes up much of the hard cell walls of grasses, leaves and other forages, some fibrous material is easier to digest than other material. As a result, more digestible feeds provide more energy for cattle and less that is lost to methane, other gases, or manure. Because cattle also cannot digest lignin, which increases with the age of the grass, consuming fresher grasses and reducing reliance on most crop residues also helps to reduce methane and improve growth.

As importantly, the quantity of feed that ruminants can eat is limited by the speed with which the material is digested. Because cattle cannot digest lignin at all, and digest carbohydrates more rapidly than cellulose, they can eat more overall feed when it is more digestible. That has an important effect because the first use of feed by an animal is to support its own maintenance: the energy an animal needs to live. It is the surplus of energy in feed over maintenance requirements that can contribute to milk production, or to weight gain, which means the addition of meat. Although cattle need a balance of different types of feed, in general, cattle fed more digestible feeds can eat more, produce more milk and grow faster than cattle fed less digestible feeds. Although they produce more methane per animal, the methane per kilogram of milk or meat decreases.

The result is that there is a strong relationship between the methane produced per kilogram of milk or meat and both the digestibility of animal feed and the output of milk and meat per animal. For beef, for example, Herrero et al. (2013) estimated that increasing the digestible energy of feed overall from 8.5 to 10 mega joules per kilogram of feed reduces emissions per kilogram of meat or milk by roughly 80%. Figure 1 shows estimates using the same model of reduced emission as milk yield or daily weight gain increase per animal. Similarly, increasing milk production from an average of roughly 1 liter per day per animal to 5.5 liters per day cuts the greenhouse gas emissions per liter of milk by more than two thirds (Gerber et al. 2010) (Herrero et al. 2013). Productivity gains have been responsible for large reductions in the intensity of methane emissions in cattle in Western countries. For example, emissions per kilogram of milk have declined by 45% in California in the last few decades (Naranjo et al. 2020).

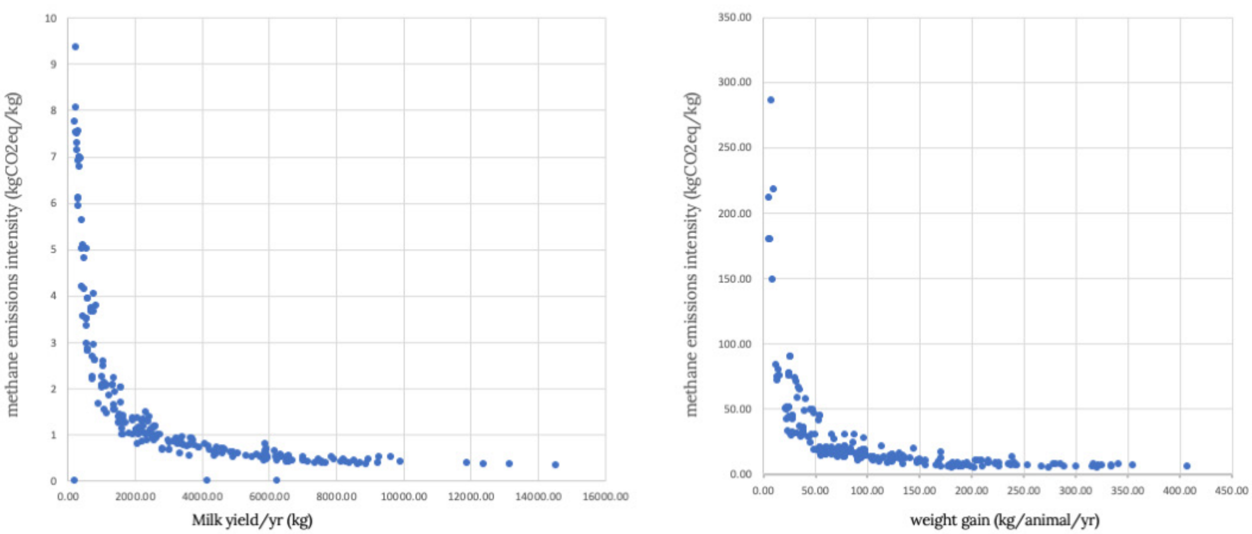

Figure 4: Relationship between emissions intensity per kg of product and a) milk yield and b) weight gain of cattle (Herrero et al 2013)

The important role for output per animal also creates other opportunities to reduce methane. Sick animals produce less milk and meat. Dead animals waste the resources (and methane emissions) used to produce them. Heat stress can reduce animal output (Gisbert-Queral et al. 2021) and is likely to become an increasing challenge (P. Thornton et al. 2021). For these reasons, increasing livestock health also reduces greenhouse gas emissions intensity. Management systems that increase the portion of the year dairy cows are lactating or their overall productive lifespans also reduce emissions intensity. In most of the world, there are also dry seasons in which both the quantity and quality of feed declines, which can result in sharp declines in milk production and weight loss by beef animals. Providing supplemental, quality feeds in dry seasons therefore often has disproportionate benefits on overall production and emissions intensity.

High quality feed and care can also make it possible to use breeds, particularly European breeds, that are more efficient at converting feed and produce more milk per animal and higher daily weight gains. The use of these breeds can be inefficient in warmer countries where these breeds can suffer from heat stress and are less resistant to local diseases or ticks. These breeds are also less efficient where feed has poor quality. Improvements in feed and health care, however, can often allow greater use of western breeds or, quite commonly, productive crossbreeds of western breeds and indigenous cattle breeds.

Global analyses show a high potential for increased efficiency to reduce methane emissions per kilogram of milk or meat. Figure 5, recreated from Herrero et al. (2013), found that beef production in many countries has 10 to 30 times the emissions rate of beef production in Europe, the United States, Canada and Japan. The FAO similarly estimates that dairy production in India releases twice the emissions per liter of milk as in Europe, and in Africa five times European emissions (Gerber et al. 2010).

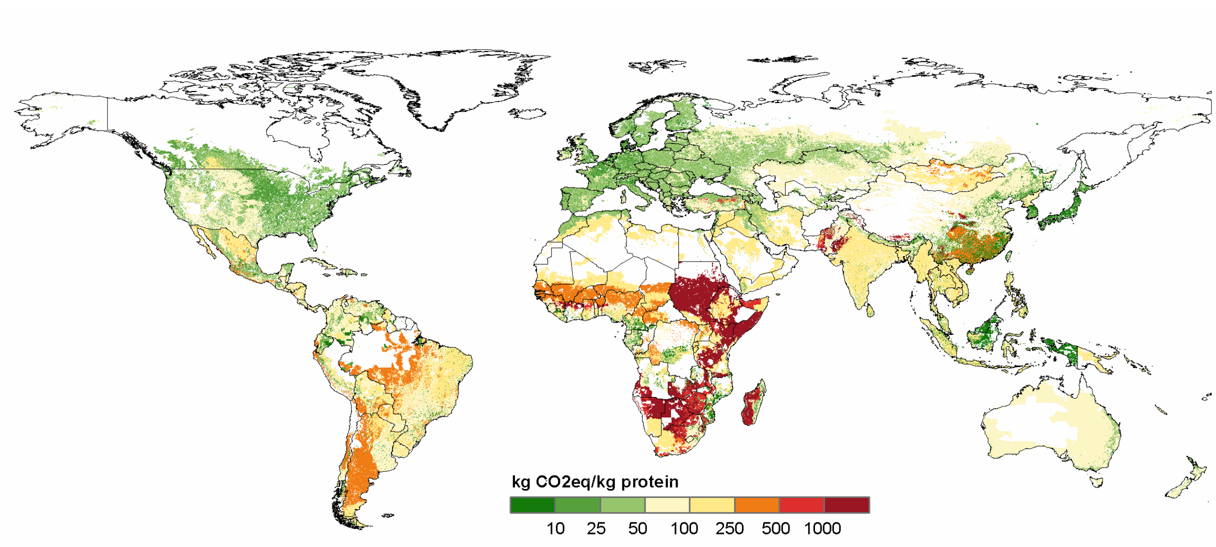

Figure 5: Methane emissions per kilogram of protein from beef around the world (Source Herrero et al. 2013)

Reducing methane emissions is possible without shifting to U.S. levels of dairy and beef intensification that rely primarily or exclusively on confined feeding. Grasses and other forages, crop residues, and by-products of other agriculture and food production provide the vast majority of feed for ruminants globally (Herrero et al.

2013). Improving the quality of forages can have dramatic effects. That can be done through better management of grasses in pastures and by cultivating better forages in the "cut and carry" systems that predominate in much of Asia and much of Africa. Other improvements that both increase production and reduce methane emissions intensity include providing better healthcare, providing mineral supplements, using supplemental feeding during the dry-season, and management changes such as producing calves at the beginning of wet seasons when they will have better access to feed.

As the Herrero et al. (2013) and FAO analyses have found, the most dramatic reductions occur in shifting from the least digestible feeds to moderately more digestible feeds. For example, according to one study, improvements from the least efficient to a medium-efficient grazing system in Brazil, which still relies entirely on pasture, reduces methane emissions per kilogram of meat by more than half (Cardoso et al. 2016). In another study of actual Brazilian farms, methane emissions per kilogram of meat ranged by a factor of more than 5 and was strongly associated with cattle growth rates (D'Aurea et al. 2021).

Use of crops for supplemental feeding even at moderate levels also has high promise. One study estimated that modest increases in use of high protein leaves from nitrogen-fixing shrubs and use of grains at a level of 0.5 kg/day would reduce emissions intensity of both dairy and beef production in sub-Saharan Africa and South Asia by more than 55% (Thornton & Herrero 2010). That would therefore reduce total emissions by allowing fewer animals to produce the same quantity of milk and meat. As shown in Figure 5, the global technical improvement would be vast from closing gaps between efficiencies in different countries.

India has been rapidly expanding dairy production and has done an excellent job of integrating small dairy farms into national production systems, but its productivity per animal is still much lower and emissions intensity is still much higher than Western systems. Overall India produces 40% more milk than the United States but has 900% of the animals (Landes et al. 2017). Buffalo and crosses of cattle between indigenous and western varieties provide higher yields than indigenous varieties and create an opportunity for improvements. Improved feed is also a major opportunity. Roughly two thirds of dairy feeds in India come from crop residues. Purpose-grown fodders or grazing provide only one third of feed and crop concentrates only 6%. The sector is dominated by small farms with more than two thirds of cattle and buffalo on farms less than two hectares. Women perform the primary labor, and dairy production is mostly a secondary farming goal. Opportunities exist both to replace residues with other, higher quality feeds, and to improve the digestibility of residues (Blümmel et al. 2009). Table 1 provides examples of potential mitigation calculated using the Ruminant model for some major livestock systems in different countries.

Region	System	% increase in output per animal	% reduction in emissions per kg of output	Improvements
Brazil	humid grazing beef	65	19	Improved pastures with higher digestibility and N content
Brazil	humid grazing dairy	287	57	Improved pastures with higher digestibility and N content
India	mixed arid dairy	87	31	High digestibility crop residues from dual purpose crops
India	mixed humid dairy	43	15	Higher quality crop residues from dual purpose crops, crop by-products and quality grasses
China	mixed humid beef	118	16	Higher quality crop residues from dual purpose crops, crop by-products and quality grasses
China	mixed humid dairy	124	15	Higher quality crop residues from dual purpose crops, crop by-products and quality grasses
Ethiopia	mixed temperate dairy	130	104	Higher quality crop residues from dual purpose crops, crop by-products and quality grasses

Table 1: Potential reduction in emissions to produce the same quantity of food through feed quality improvements (Source: Author calculations).

To provide one estimate of global potential, we used the Globagri model to estimate changes in emissions from global improvements in feed use efficiency of 35% for both beef and milk production. Such improvements allow fewer animals to produce the same quantity and types of milk and meat. Such a change would reduce expected 2050 global enteric methane emissions by 40%. This change alone would change a 52% increase in enteric methane from 2010 levels to an 8% decrease.

Enteric methane inhibition

In addition to improving livestock productivity, scientists have been pursuing three approaches to reduce methane by influencing the dominant microbiological communities in the rumen: using vaccines, selectively breeding animals to generate less methane, and various feed additives and supplements. Vaccines have so far proved frustrating and only temporarily effective but merit continued research. Breeding is another option. Variation in methane production among different individual animals (Wallace et al. 2019), which appears to be heritable, suggests that breeding can over time reduce methane levels. One study estimated methane reductions might approach 15% (González-Recio et al. 2020). These efforts merit serious work but will only show results over several decades.

The most promising methods in the shorter term now appear to be some feed additives, which are well summarized in a recent paper (Honan et al. 2021). Feed additives fall into two broad categories: those that change the "rumen environment" in ways that discourage growth of methane-producing archaea, and those that directly interfere with some step in the process of generating methane. The latter do so either by competing with archaea for the hydrogen that goes into methane or by interfering directly with an enzymatic step in methane generation used by archaea.

Including lipids (fats) up to 4-6% in feed rations is a safe and promising method of reducing methane emissions by influencing the rumen environment (Honan et al. 2021). A broader range of lipids, at inclusion rates up to 6%, have achieved reductions up to 40%. Some oils, such as coconut oils, have shown even greater promise. But inclusion of oils just for methane control is expensive (Henderson et al. 2017). Some level of oils, typically at 6-7%, is already included in feed rations in intensive systems in the U.S. because the oils pay for themselves through productivity gains. Matching this level of lipid use in parts of the Global South and in Asia has promise for achieving reductions from 5-20% in methane. Unfortunately, lipid use has been little studied in these less-intensive systems. Quick analysis to study its effects in different countries around the world and to identify low-cost lipid sources should be a priority.

A variety of other compounds, summarized in Table 2 (placed as an appendix below) and discussed in (Honan et al. 2021), also offer promise for reducing methane but to date have limited or uneven test results or face significant challenges.

Fortunately, two feed additives have shown exciting results in the last few years, both for methane reduction and for productivity gains.

One is a small molecule known as 3-NOP (3-nitroxypropanol), trademarked as "Bovaer" in the EU. It works by binding to the enzyme that archaea use in the last of several steps for producing methane. More than 40 studies have now reported the effects of 3-NOP on methane production in either dairy or beef systems using different, always small, inclusion rates (from 0.004% to 0.02%). Reductions in methane have ranged from as low as 20% in one study to more than 80% in others with typical reductions around 35-40%. Higher dosage rates resulted in greater reductions but may reach a maximum of around 40% in general.

Results on production have been mixed but generally positive. Most studies of 3-NOP in dairy cows have not found increased production of dairy milk or greater weight gain in beef cattle (Hristov et al. 2015) (Melgar et al. 2021) (Jayanegara et al. 2018). But at least one paper has found higher milk fat, which is valuable (Melgar et al. 2020). Most beef studies and one dairy study also report small improvements in feed conversion efficiency, which means they achieve the same production but with less feed (Schilde et al. 2021) (Honan et al. 2021).

The second promising feed additive is red algae, particularly using the species *Asparagopsis taxiformis.* For more than a decade, use of such algae has shown promise in test tube studies, but only in recent years have three studies emerged of testing in actual animals. Depending on inclusion rates, studies have found methane reductions of 60% to nearly 100% (Roque et al. 2019) (Roque et al. 2020) (Kinley et al. 2020).

Significantly, these studies have also found increases in productivity in cattle. The dairy study found a 5% increase in milk yield with 25% less feed (Roque et al. 2019), while the beef studies found increases in feed conversion efficiency from 7 to 35%. The gains in feed conversion efficiency found have been sufficiently large that they exceed the energy savings from the reduction in methane. They may occur because algae shifts the production of fatty acids by cattle to those that are more efficiently produced (from acetate to propionate). Yet the gains remain uncertain as the number of animals in the experiments was not large, and there was high variability in the results of individual animals.

Various kinds of safety studies of these two additives are also promising. There was original concern that reducing methane production in the rumen could lead to problems with excess hydrogen, but no evidence of such problems has emerged.

Despite these very promising signs, important issues remain to be resolved. Although studies have promising results so far, the world is unlikely to undertake a massive investment to incorporate these feed additives globally on the basis of a limited number of studies that have lasted each for only a few months for 3-NOP and three studies with live animals for algae. We believe a few steps are critical to widespread adoption although they could be undertaken with enough commitment in the next three years.

Multi-year studies: The first need is for studies that last at least two years for each of these products. Studies to date have at most lasted four months. That is a significant time for a conventional research project and constrained by typical research budgets as all of the milk must be discarded. Sustained effects over these months is very promising, but for broad use, proof is required of longer lasting effects. Measuring methane every day in these studies is not important. But regular measurements, e.g., weekly, over a two-year period is necessary.

Evaluating yield and feed efficiencies: Longer-term studies also provide the opportunity to evaluate effects on yields and feed conversion efficiency. Those effects have the potential to make use of these supplements profitable or to offset much or all the costs. These effects are therefore important to achieving broad application.

Safety tests: Although uses of 3-NOP have raised no safety issues in published literature, multiple longer-term studies are probably still necessary for broad acceptance.

Use of algae raises important safety issues that require careful study to prove algae's safety conclusively (Vijn et al. 2020). The active ingredient in red algae is bromoform. In synthetic form, bromoform is toxic, and it also harms the ozone layer. In most studies so far, bromoform was not detected in meat or milk and there was no evidence of damage to the animals. One likely reason is that bromoform is destroyed in the oxygen-less environments such as the rumen. However, one study detected bromoform in several milk samples on some experimental days when cows were fed *Asparagops*is, so safety aspects need further evaluation (Muizelaar et al. 2021). Assuring public confidence in safety will require multiple, thorough studies of seaweed provided through different methods (such as dried or wet) with different quantities and potencies.

Production: Because 3-NOP is a proprietary product, its costs of production are not known, but it uses ingredients that are low cost. In the long run, we believe its costs of production will be low. However, 3-NOP was developed by a private company, which has invested substantial sums in its development and holds a patent. For many years, its cost will therefore be subject to negotiation.

Obtaining red algae in sufficient quantity and providing it in a suitable form to farmers presents a technical and environmental challenge. Growing sufficient algae in the ocean for broad use is not feasible and threatens to release enough bromoform to be at least an issue for harmful effects on the ozone layer (Searchinger et al. 2021). Fortunately, algae could also be grown in factories where air filters could be used to capture and destroy the bromoform released (at least one commercial algae factory is already producing fish oil for aquaculture). Recent identification of algae with a much higher concentration of the active ingredient suggests that volumes required can be dramatically reduced compared to some earlier estimates. However, production of algae needs to be demonstrated, and additional progress also needs to be made in drying the algae. Tests must also demonstrate the stability, persistent benefits and safety of the product when transported and stored in multiple conditions and then used.

Although this work seems challenging, it is only challenging in the context of the small research budgets that have been devoted to this problem. It took more than a decade after discovery of the potential benefits of algae in test tube research before just two research groups could obtain the funds for three trials in actual animals. What is needed is a coordinated effort of at least 20 to 30 trials in different countries, each lasting two years or two lactations, with different types of animals and feeds and using 3-NOP, algae and some other feed additives. Methane emissions do not need to be measured every day but on a regular basis. Feed intake, daily weight gain and milk production should be monitored continuously as well as whether bromoform can be detected in milk or urine. Animal health should be monitored throughout and at the end of the tests along with milk and meat output.

Relative to other climate challenges, the cost is not great. Along with additional work to closely examine production processes, we estimate that a budget of $100 million over three years could make great progress if the research were carefully coordinated across countries.

Another issue with these products is the challenge of obtaining regulatory approval. Brazil has approved 3-NOP, which should quickly lead to improvements in understanding of how it works. Europe is considering approval. Approval in the U.S. is more burdensome because it must be approved as a drug. Costs of regulatory approvals are high. For algae and many other additives, it is unclear whether any entity would undertake the costs and burdens for obtaining regulatory approval. One idea would then be to create a non-profit organization with the funding and responsibility of seeking the approvals.

Emphasizing alternatives to ruminant meat and reducing food loss and waste

Nearly all enteric methane emissions come from ruminants, and the methane reductions described above could be overwhelmed if ruminant consumption grows too much. The methane intensity of beef is generally estimated at roughly 6 times higher than producing milk (per kilocalorie) because cattle can produce far more milk for the same quantity of feed as they do meat (Searchinger et al. 2018) (Springmann et al. 2018). Ruminant meat also uses far more land and generates at least similar nitrous oxide as the production of other livestock products. As a result, focusing increases in livestock production on other animal products has both environmental and food security benefits because these alternatives generate far more food per hectare.

How much ruminant meat is consumed in the future may reflect the level of government and private investment in ruminant meat versus alternative livestock products or even plant-based alternative "meats." Native grazing lands will continue, and should continue, to be used to produce ruminants (often prioritizing milk as many pastoralists and grazing farmers do today). The question is which form of animal product will meet rising demand, or whether some of the growth in demand for proteins of that kind will be supplied by plant-based alternatives.

Already many regions have reduced their consumption of ruminant meats. Based on FAO statistics, consumption in Australia and New Zealand has declined from a peak of 432 kcal per person per day in 1972 to 152 kcal in 2018. Consumption of ruminant meat in North America declined between 1976 and 2018 from 175 to 105 kcal per person per day. In Western Europe, this consumption went from 97 kcal in 1991 to 66 kcal in 2018. A few regions have not yet decreased their consumption, including South America, where consumption is at 148 and Central Asia where consumption is at 194. Many other regions, such as most of sub-Saharan Africa, South Asia and East Asia have always had low levels of ruminant meat consumption.

We constructed an "Optimistic Trend Projection" scenario. Many regions have had declining per capita ruminant meat consumption, and we assume those declines continue to occur and cause modest additional declines by 2050. We also assume that per capita consumption in the highest-consuming regions comes down by 2050 to the levels of North America today. In regions below 60 kcal per person per day, we assume that per capita consumption remains at present levels. In each scenario, the 2050 consumption of animal products does not decline. In this scenario, milk production continues to increase rapidly, by more than 50% between 2010 and 2050. Animal production also has large increases, including substantial per capita increases in poorer countries. Reductions in ruminant meat are replaced by poultry and pork. Overall, this analysis assumes that ruminant meat consumption in the highest-consuming regions will follow more recent trend lines in North America and Europe while agricultural development in poorer countries will focus on strategies that generate far more meat per hectare.

We also built into this scenario a 25% reduction in food loss and waste. Overall, global food loss and waste of animal products in general, and ruminant meat in particular, are estimated at roughly 30% (Porter et al. 2016). A sustainable development goal includes reducing food loss and waste by 50% by 2030. Companies and some countries have made steps forward in the last few years although the world is not yet on course to achieve these goals (Champions 12.3 2021). Many strategies exist for achieving these reductions, with particular progress in the United Kingdom (Searchinger et al. 2019).

With these two assumptions regarding demand, enteric methane emissions decline by one-third from likely 2050 levels and stay roughly constant with 2010 levels.

Potential combined effects

We estimated the potential reductions in enteric methane from these three mechanisms combined: increased feed efficiency, enteric methane inhibition, and our "optimistic trend line" for consumption. The combined effect would be a 59% reduction from otherwise likely 2050 levels and a 37% reduction from 2010 emissions.

3. Rice

Rice is the staple food for half of the world's population, and 90% of rice is produced in Asia (Searchinger et al. 2019). To meet the increasing demand for food, rice cultivation area has increased over the last several decades although only modestly in the last few years.

Rice is primarily grown flooded, which creates the conditions without oxygen that allow the archaea that produce methane to thrive. Global methane emissions have a significant level of uncertainty for many reasons, one of which is that they depend on the persistence of this flooding. The precise ways in which farmers manage water levels in different regions and on different farms is not certain. The FAO, which uses a relatively simple "Tier 1" method of estimating methane rice emissions, estimates global rice methane emissions at 25 million tons. That number is similar to an estimate published in 2009 by one of the authors of this paper using more complicated methods (Yan et al. 2009).

Because more detailed information has become available about rice farming systems and methane emissions (Ogle et al., 2019) (Saunois et al. 2020), we here produce a new estimate of annual, global rice methane emissions of 34 million tons. This estimate is roughly 35% more than FAO estimate and other prior estimates. About 85% of the global total is emitted from the major rice cultivation countries in monsoon Asian region (Table 3). China and India account for approximately half of the world total.

Region/Country	**Irrigated rice**	**Rain-fed and deepwater rice**	**Total**
China	9.57	0	9.57
India	4.61	2.86	7.47
Vietnam	1.64	0.65	2.29
Indonesia	1.52	0.59	2.11
Bangladesh	0.51	1.51	2.02
Myanmar	1.08	0.54	1.62
Thailand	0.22	1.33	1.55
Philippines	0.89	0.32	1.21
Cambodia	0.12	0.48	0.61
Pakistan	0.51	0	0.51
Rest of the world	3.9	1.32	5.21
Total	24.57	9.6	34.17

Table 3: Estimated CH4 emissions from global rice fields in 2019 (Tg CH4 yr-1)

Yield gains

One way to mitigate methane emissions from rice cultivation is simply to increase yields. Rice emissions are based on the number of hectares planted and harvested each year, and higher yields reduce the area planted for the same total production. Higher yielding crop varieties also appear to generate less methane per hectare (Jiang et al. 2017).

Global rice yields today are roughly 4.7 tons per hectare. In 2012, the FAO projected that global rice yields in 2050 would be 5.3 tons per hectare per year, increasing from 2006 to 2050 at only half the rate of increases from 1962 to 2006. That level of yield gain would probably require that rice area expand. However, one expert review found sufficient "yield gaps" that could be closed by more careful management to raise global rise yields to 7.4 tons per hectare per year (Fischer, Byerlee, and Edmeades 2014). Other studies also reveal significant gaps between the yields farmers achieve and those they could achieve with improved management (Deng et al. 2019) (Senthilkumar et al. 2020) (Agus et al. 2019). Moreover, in addition to management, rice yield potential has continued to rise steadily through improved crop breeding (Kumar et al. 2021), and breeders for rice, as for other crops, have many ideas for potentially larger increases in yield potential (Qian et al. 2016).

Each 1% increase in rice yields roughly reduces rice methane emissions by 1%. If global rise yields rise only to 5.3 tons per hectare by 2050, the Globagri model estimates that rice methane emissions would rise 13% from 2010 levels (T. Searchinger et al. 2019). But achieving a global average yield of 6.4 tons per hectare per year in 2050 would result in a 4% drop in emissions.

Optimizing water management

Irrigated and flooded rice fields account for a large proportion of global rice cultivation. In general, the longer fields are continuously flooded, the greater the emissions from methane. As a result, any technique that reduces continuous flooding tends to reduce methane emissions (Adhya et al. 2014). A single drawdown of water levels during the growing season can reduce methane emissions by 40-50% (Adhya et al. 2014) (Wang et al. 2018; Cai et al. 2003) (Ogle et al. 2019). That means bringing water levels low enough to allow some oxygen into the top few centimeters of soil. Repeated drawdowns, known as alternative wet and dry, can reduce methane emissions by up to 90%. Shortening flooding by seeding rice on a dry field instead of transplanting a rice seedling into a flooded field can also substantially reduce emissions (Adhya et al. 2014).

Using full alternative wet and drying techniques, i.e., repeated drawdowns, faces practical challenges for many farms (Adhya et al. 2014). Farmers need to have sufficiently reliable water supply that they can reflood their farms after each drawdown. Some fields receive too much rainfall to be drained. Some rice fields are sufficiently large or uneven that the right level of reduced water for some of the field requires too much of a drawdown in other parts of the field and affects yield. Some of these challenges probably also apply to single drawdowns, but the potential for such drawdowns is probably significantly more than the potential for repeated drawdowns.

We estimated the potential to reduce emissions by assuming one drainage during the rice-growing season on those rice fields that are otherwise continuously flooded. We estimate that this drawdown would result in methane reduction of 4.72 million tons per year (Table 4), which accounts for approximately 14% of the global methane emissions. Due to differences in current water management regimes applied in different countries, there are geographical differences in the emission reduction potential of this approach, and the greatest potential is concentrated in South and Southeast Asia.

Country	**Draining rice field**	**Rice straw applied off-season**	**Both options**
Bangladesh	3.6	25.0	27.8
Brazil	15.8	37.1	47.0
Cambodia	5.3	29.0	33.4
China	12.0	14.6	26.8
Colombia	17.8	18.3	32.9
Egypt	20.0	39.9	51.9
India	11.2	23.9	32.5
Indonesia	18.3	9.8	26.7
Japan	14.2	36.1	45.2
Myanmar	17.8	17.8	33.1
Nepal	15.5	21.5	33.7
Nigeria	13.5	23.0	33.4
North Korea	21.6	38.3	51.6
Pakistan	26.6	27.6	46.9
Philippines	19.6	10.8	28.7
South Korea	11.1	26.6	34.7
Sri Lanka	22.1	22.5	40.1
Thailand	3.7	23.4	26.4
United States	20.0	39.2	51.3
Vietnam	32.5	6.4	37.3
Globe	13.8	19.5	31.5

Table 4: Mitigation potential of CH_4 emission from rice cultivation in major rice producing countries by draining all continuously flooded rice fields, applying rice straw off-season where possible, and adopting both options simultaneously. Values are given in percent.

Adjusting the time of straw returning to the field

Mounting experimental evidence demonstrates the significant effect on methane emissions of the time when rice straw is returned to rice fields. When rice straw is returned, i.e., plowed in, during the off-season, a global dataset and associated modeling suggest that methane emissions are approximately half those of when rice straw is returned or plowed in during the rice-growing season (Wang et al. 2018). The reason is likely that earlier returns of rice straw reduce availability of biomass in a form methane-producing archaea can use.

At the global scale, if applying rice straw off-season were adopted in all single rice areas, and for early rice in double rice areas, we estimate that global methane emissions would be reduced by 6.65 million tons per year (Figure 1). The adoption of rice straw applied off-season would reduce emissions by 6.4% to 40% in different major rice-producing countries (Table 4). The global reduction in methane from rice would be 19.5%.

Biochar

As a negative emission technology, biochar has been widely recommended as a potential mitigation measure in the agricultural sector (Smith 2016). Biochar consists of biomass that has been turned into a form of charcoal by burning it in a very low-oxygen environment. Scientists have recorded a wide range of benefits from the use of biochar, including added soil carbon sequestration, often yield gains, and sometimes reductions in nitrous oxide emissions (Kammann et al. 2017). Key challenges in using biochar are the expense and finding sufficient and large sources of biomass because diverting biomass from other uses, or harvesting additional wood, raises its own problems. But opportunities to address these challenges exist if crop residues can supply a sufficient quantity of biomass, and if biochar increases yields enough to offset much or all of the costs of its use.

Results of biochar in rice fields are promising for methane reduction, yields gains and other benefits. Many experiments have now been done, and global meta-analyses suggest that biochar amendment in rice fields can reduce methane emissions by 6-13% compared to not using biochar (Awad et al. 2018) (Liao et al. 2021). In theory, if all rice straws were charred and returned to the fields, the estimated global methane emission reductions along with our estimated changes in water management would increase to 12.55 million tons (Figure 6). In addition, accumulating evidence suggests that biochar amendment in rice fields can boost rice yield by about 9% (Liao et al. 2021). This level of yield benefits could significantly help defray the costs of using biochar. In rice production, biochar appears neither to decrease nor increase nitrous oxide emissions (Liao et al. 2021), but it likely will also contribute to soil carbon gains (Wang, Xiong, & Kuzyakov 2016).

Combined effects

Figure 6 summarizes the technical mitigation of our water and residue management scenarios. If these two mitigation options described above in Table 4 were adopted simultaneously, the net reduction in methane emissions relative to likely 2050 emissions would be 31.5%. If yields only grow to an average of 5.3 tons per hectare, this reduction in emissions relative to 2010 would be 18%. If yields grow to 6.3 tons per hectare per year, we estimate a further 4% reduction from present levels, so 2010 emissions would decline by 35%. Combined with 25% reductions in food loss and waste, the overall reductions would be roughly 40%.

Figure 6 shows also the possible effect of biochar. Its widespread use would increase the savings significantly more.

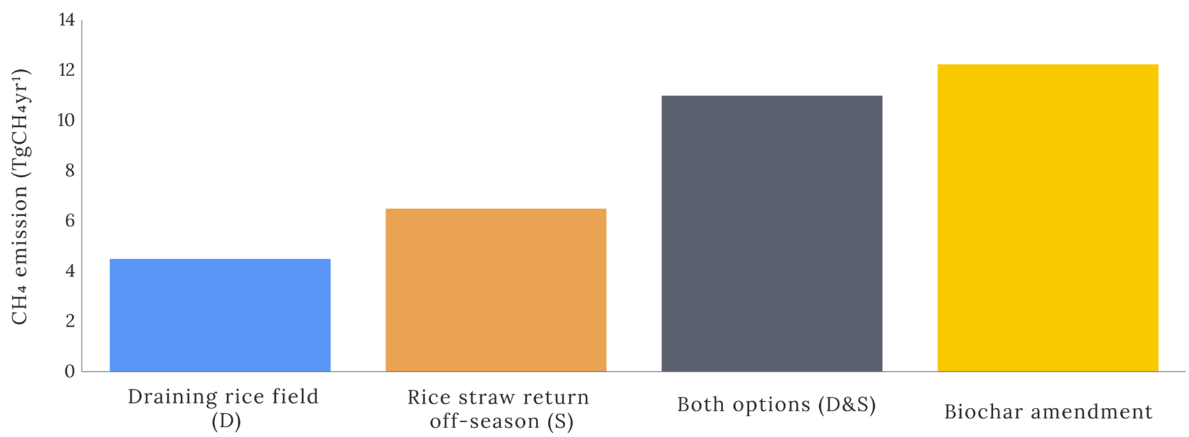

Figure 6: Mitigation potential of CH_4 emissions from global rice fields following adoption of proposed management practices

Innovative case studies

Although the estimates above discuss mitigation opportunities that can be globally estimated, there are multiple additional, innovative methods that may be applied to mitigate rice emissions in particular locations. We describe two promising examples in China below that could be applied both more broadly there and likely in other countries.

Water saving and drought-resistant rice

The change of precipitation patterns caused by climate change has a profound impact on agricultural production. Because water shortages and frequent drought in agricultural ecosystems may threaten rice production worldwide, tools to decrease water use or vulnerability to drought are needed. Although conventional irrigation requires maintaining a certain depth of surface water layer, water-saving irrigation can also meet the essential water requirement of rice growth by instead keeping the soil moist or covered by a thin layer of water (Islam et al. 2020).

Current rice varieties may not be suitable for this water-saving irrigation system, which can have a negative impact on rice yield. To achieve the dual goals of water-saving and stable yield, researchers developed a new rice variety, named water-saving and drought-resistant rice (Luo 2010) (Figure 7). Researchers have found that relative to conventional irrigation (i.e., flooding-midseason, drainage-flooding), applying water-saving irrigation can significantly reduce methane emissions up to 77% (Sun et al. 2016) (Xu et al. 2015). In recent years, this approach has expanded over large areas in Anhui, Hunan and other provinces in China, but it has far greater potential for expansion.

Figure 7: Cultivation of drought-resistance rice (Hanyou 73) in China (photo provided by Sheng Zhou)

Ratoon rice

Ratoon rice is a rice cultivation model suitable for planting in areas with insufficient sunlight and heat to grow two-season rice (Figure 8). Since it is grown again on the original root system, it is called ratoon rice which saves the time between the harvest of the first-season rice and the second season. In southwestern China, researchers have conducted many years of field observations and find that compared with conventional single-season rice, there were small increases in methane and nitrous oxide emissions in the ratoon season. But because of a 19% gain in yield, ratoon rice had a reduction of 12% in the emissions per ton of rice produced (Song et al. 2021). The adoption of ratoon rice cultivation also improved the net economic benefits of farmers (Song et al. 2021).

Ratoon rice cultivation in three Chinese provinces has increased to 0.67 million hectares, and we estimate it could be used on 3.3 million hectares in China. The National Planting Structural Adjustment Plan (2016-2020), issued by the Ministry of Agriculture and Rural Affairs of China, proposes to develop ratoon rice in the more middle and lower reaches of the Yangtze River, and in southern and southwest China.

Figure 8: Cultivation of ratoon rice in Hefei City, Anhui province, eastern China (photo provided by Guangbin Zhang)

4. Manure

Manure management emissions occur when animals are kept in confinement. In those conditions, the manure must be gathered, usually stored, and ultimately distributed back to fields sometime later. “Manure management” emissions are those that occur prior to redistribution to fields. Methane can be released in large quantities when wet manure accumulates because the wet conditions prevent oxygen from getting into the manure, leading to the conditions in which methane-producing archaea thrive.

According to estimates provided in FAOSTAT, manure management globally emits 10 million tons of methane. Although these estimates use very rough, tier one emission factors, a more sophisticated FAO analysis using the GLEAM model estimates methane emissions at 11 million tons. Roughly half of these emissions are from pork systems, roughly a third from dairy and the remainder mostly from beef. As shown in Figure 9, these emissions are highly concentrated in those countries that produce high levels of pork and dairy. According to GLEAM estimates, methane emissions in 21 countries contribute almost 90% of these emissions. China, the United States, India and Brazil alone contribute two-thirds of these emissions. The major agricultural countries in Europe also contribute large methane emissions, and Russia, Pakistan and Vietnam are the remaining countries in this top 21.

There are dramatic differences in methane emissions based on whether manure is managed in wet or dry form. The overwhelming majority of methane and 60% of overall greenhouse gas emissions from manure management occur in wet systems, which means feces and urine are stored in tanks or pits of some type (Searchinger et al. 2019). Most manure by volume is managed in dry systems, in which manure is allowed to dry, sometimes with the help of mixing with straw or other bedding material. These systems generate more nitrous oxide and therefore can still cause climate problems, but the overall greenhouse gas emissions are still substantially lower in dry systems.

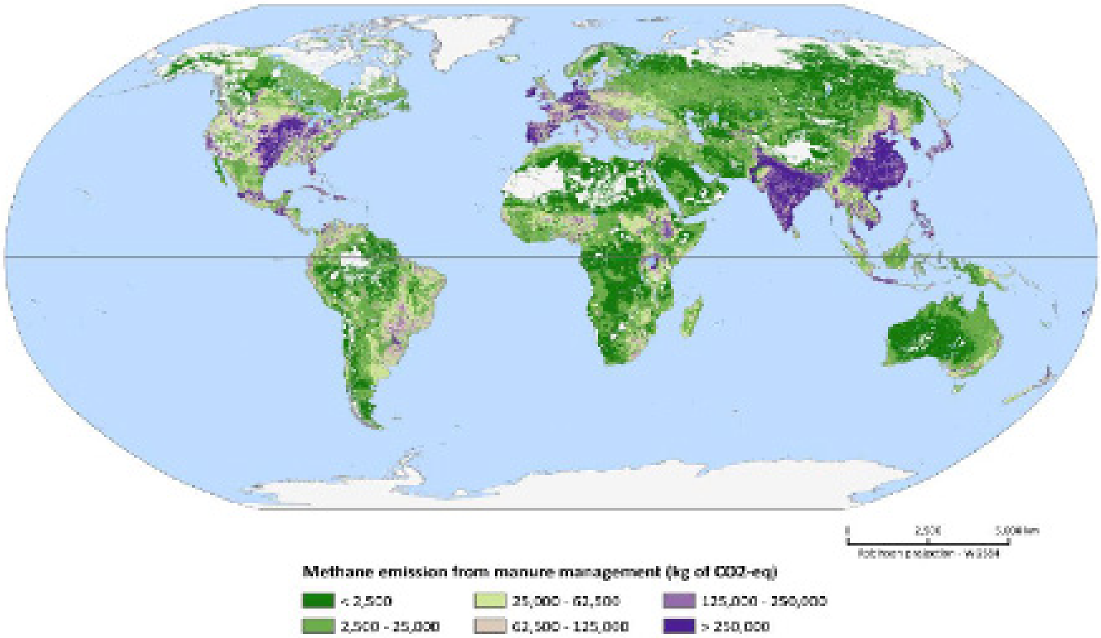

Figure 9: Global distribution of manure management emissions (source: FAO)

Mitigation methods

Opportunities to reduce manure methane emissions depend on the precise manure management in use already.

Much of the focus on manure management has been to encourage the use of digesters. Digesters turn even more of the many into methane into biogas, but in a way that can be captured and burned for energy. Millions of small, low-technology digesters are in use in Asia for household energy use, and larger, modern digesters have also received significant investments in Western countries. For farms that now produce large quantities of methane – for example, that use large lagoons to store manure in warm parts of the world – digesters can be a cost-effective mechanism for reducing methane as well as overall greenhouse gas emissions (Searchinger et al. 2019).

In other contexts, however, the climate benefits for methane are uncertain and probably unable to justify the expense. The purpose of a digester is to turn as much of the biomass in manure into methane as possible. As a result, digesters create more methane than normal storage systems. Although the intent is to capture and burn this methane for energy, if the digester has significant leakage rates the amount of methane released can exceed the methane released by present management, depending on the system in use. That seems particularly likely in informal, household systems studied so far (Bruun et al. 2014), although the leakage rates around the world have been little studied. Leakage can also nullify other benefits where manure is combined with food waste or some other waste, which is common to increase overall biogas production

(Searchinger et al. 2019). Some analyses have also found that biogas digesters can have limited methane benefits and be very expensive per kilogram of methane mitigated in cooler parts of the world. In these areas methane emission rates from traditional manure storage are relative low (Searchinger et al. 2021).

These findings suggest that biogas should focus on manure management systems where methane emissions are otherwise high, such as lagoons in warm environments, and where methane leaks can be and are carefully controlled. These findings also suggest there could be substantial benefits from programs to reduce leaks in existing biogas systems, including household systems.

Several alternative manure management options exist. One starts with more quickly removing manure from barns because barn temperatures tend to be high, and higher temperatures increase methane formation (Montes et al. 2013). Barn storage can lead to high methane losses even in a few days, particularly in pig barns where temperatures are often higher than outside (Petersen et al. 2016). In many systems, it is common for manure to remain in pig or dairy barns for a few weeks – and some for much longer -- but it is possible to construct systems and sometimes to operate existing barns to remove manure each day. One analysis of different studies found average reduction rates for methane at the level of 50%, although that will obviously depend on climate and alternative management systems (Mohankumar, et al. 2018).

A second set of options focuses on separating the solid portion of manure from the liquid portion. Even without adding water for barn cleaning, manure in pork and cattle systems tends to be wet enough to create the oxygenless conditions that create methane. A variety of techniques with increasing sophistication can separate solids from liquids. The simplest systems use gravity and grates or ponds to settle solids out. Mechanical systems use presses or centrifuges and achieve much higher separation (Searchinger et al. 2019). Addition of flocculants (chemicals that help solids bind together) can achieve separation levels with 75% of the solid material separated from the liquid fraction, including nearly all the phosphorus. Benefits of these systems include reducing the costs of hauling manure into far-away fields. By making it cheaper to transport the solids with most of the phosphorus farther away, these systems also help farmers avoid putting too much phosphorus on fields near the animals.

New systems of barn design are also being developed that effectively encourage cattle and pigs to deposit urine and feces in different places. These systems were primarily designed to reduce emissions of ammonia, for which the mixing of urine and feces is a critical step. But this level of separation also makes it easier to manage manure solids in dry form and avoid methane losses.

The benefits for methane largely depend on managing the solid fraction of the manure in a dry form. It is common for studies to report emissions reductions of roughly 30% (Holly et al. 2017) (Montes et al. 2013). If the solid portion of the manure is then properly composted, almost all of the methane can be eliminated from this solid portion

(Vanotti, Szogi & Vives 2008). There is evidence that reducing methane emissions in biomass requires proper windrowing or other composting (Vergara & Silver 2019). But there is also evidence that holding material in piles without active turning of compost can sometimes achieve even greater methane reductions if the manure has sufficient bedding material added to keep it dry (Owens et al. 2020). Composting can also increase losses of nitrogen and greenhouse gas emissions from nitrous oxide but can be controlled through a variety of other methods (Montes et al. 2013) (Searchinger et al. 2019).

Another emerging option involves adding acid to manure stored in wet form, which can almost eliminate methane emissions. Some experiments with acidification have occurred for many years (Fangueiro, Hjorth, and Gioelli 2015) (Søren O. Petersen, Andersen, and Eriksen 2012), but experimental work has been increasing (Rodhe et al. 2019). Acidification can be done at different stages of manure management: in the barn, in storage tanks, prior to field application. Methane reductions require a regular, but modest, insertion of acid into storage tanks. Acidifying manure also reduces ammonia losses when methane is applied, and in some experiments increases yields (Loide 2019). Yield gains probably occur if farmers either do not apply or are not allowed to apply more nitrogen fertilizer to replace the nitrogen lost with the releases of ammonia. The amount of acid required for sufficient acidification to greatly reduce methane is still unclear.

Experiments with acidification have largely focused on their benefits for reducing ammonia. The quantity of acid required to reduce methane alone is less (Olesen et al. 2018) (Petersen, Andersen & Eriksen 2012). If ammonia emissions do not need control or are controlled by covering tanks, the costs for controlling methane alone should be economical relative to other forms of climate mitigation (Searchinger et al 2021).

There are also a variety of promising innovative methods to reduce methane. There is experimental evidence, for example, that some additives, such as sulfate, can be added in modest quantities and still reduce two-thirds of the methane emissions from storage even without significantly reducing pH (Petersen, Andersen & Eriksen 2012) (Petersen et al. 2014) (Sokolov et al. 2020). There are ways of storing manure with gentle mixing to keep enough oxygen to avoid methane (Tooley 2013). There are also far more ambitious strategies to make more valuable uses of manure for purposes, such as producing feed through insects or microorganisms (Hussein et al. 2017) (Patthawaro & Saejung 2019).

There are challenges with some of these technologies. If acidification is required at high levels, it could still be expensive (although still probably less than $100 per ton of CO2e) (Searchinger et al. 2021). It is unclear where or if those costs would be offset by increased yields. In Denmark acidification also helps farmers to comply with restriction on their losses of nitrogen. Because of that benefit, WRI determined that acidification was likely to be a cost-effective form of mitigation even without yield gains (Searchinger et al. 2021). Acidification might also add too much sulfur to some soils, which has raised concerns about potential water quality problems.

More generally, some technologies require a period of more extensive demonstration projects before full-scale implementation. And there remains a great deal of uncertainty about the real methane emission rates from different farms and in different conditions. Better information about these emission rates would greatly assist in targeting mitigation funding. A large-scale, coordinated execution of pilot projects in multiple countries could dramatically improve knowledge of where and how to implement different manure management systems.

Estimated reduction potential

Despite these uncertainties, we believe there is a realistic potential with reasonable efforts to mitigate 40% of the methane that is emitted from manure stored in wet form. Doing so would reduce overall manure management methane emissions by 38% relative to present manure management. These kinds of controls are generally important for reducing other environmental problems from manure, including water and air pollution and simply noxious odors. Combined with demand-side strategies discussed in this report, that would reduce overall methane from livestock by 50% from estimated 2050 emissions using FAO projections of 2050 diets, and 30% from present emission levels.

5. Combined Mitigation Scenario

Combining all our mitigation scenarios would result in a 54% reduction from otherwise likely 2050 levels of methane emissions from enteric sources, rice and manure management. They would also achieve a 36% reduction compared to present emission levels.

6. Suggestions for Progress

Overall, there are many promising measures and strategies to reduce methane emissions in agriculture. Many efforts to increase livestock productivity and rice yields, important for food security, have the additional benefit of reducing methane emissions. In addition, many explicit mitigation strategies, such as enteric methane inhibitors or improved water or residue management in rice, have the additional benefit of boosting productivity and yields. Yet the efforts made to mitigate methane emissions in agriculture lag even those of mitigation efforts in energy and other sectors. Under the umbrella of the Global Research Alliance on Agricultural Greenhouse Gases and through the IPCC, many researchers from around the world have had the opportunity to meet and learn from each other. But without large-scale additional funding, the opportunities for coordinated research and development at the scale required have not existed.

We offer three suggestions for moving rapidly forward.

1. Develop "shovel-ready" projects

The world's growing attention to climate change suggests a willingness to fund improvements, but the agricultural projects to do so are not ready. That is true even for well documented technologies that have potential to pay for themselves through higher productivity, such as improvements in livestock efficiencies and the methods we describe for water and residue management in rice. To take advantage of this possible funding, projects that are "shovel-ready," i.e., ready to move forward, need to exist.

Developing these projects requires technical analysis, planning and coordination at local levels. For example, for rice farmers to drawdown water levels, they must be able to drain their fields at least once during the growing season, fields must be level enough, and water management systems must be able to resupply water. Where these criteria can be met through reasonable improvements, they need to be identified. Where this approach will work, incentives need to be developed, which should recognize the potential for water savings. In other words, these kinds of efforts require analyzing the potential to implement drawdowns irrigation district by irrigation district or otherwise at local levels. The same principles apply to changing residue management, including use of biochar, or using any of the other innovative strategies, such as those described in this paper.

Similarly, improved feeding strategies for livestock require coordinated activity. That includes different production and use of feeds, health care systems, and marketing opportunities. Coordinated efforts are also required to combine improved feeding strategies for ruminants meat with strategies to produce as much of increased protein output as possible from alternatives, ranging from dairy to poultry or pork or to plant-based "meats."

One way to move these efforts forward is for governments, the private sector, including NGOs and foundations, to develop local projects at the level of detail appropriate for increased funding. For example, in the rice sector, such projects would undertake at least initial analysis of the technical issues we have raised. In support, funders could create and fund international technical teams to assist and facilitate knowledge development and transfer as projects proceed.

2. Structure projects to advance innovation

To support technical advancement and innovation, such projects should wherever possible have a monitoring and assessment component to generate improved understanding. Coordinated assessment protocols and informal opportunities for information sharing would be desirable. Projects should also seek to be testing grounds for special innovations, such as new rice varieties, or new livestock feeds. Dedicated funding for this kind of technical support and innovations would be desirable.

3. Implement targeted, internationally coordinated R&D projects.

Some technologies are promising but not yet ready for full-scale implementation. Examples include the enteric methane inhibitors this paper has described, broad use of biochar in rice, and probably even manure acidification. Other basic technologies are known, such as solid separation and improved management of the solid fraction, but even they would greatly benefit from systematic technical refinement. The quantities of funding required should be achievable. We recommend the development of targeted, coordinated international research efforts to explore these ideas. Funders could galvanize these efforts by inviting proposals. For these kinds of projects, they could select projects in two rounds and provide funding for developing plans to the most promising first-round proposals. One priority is funding multi-year coordinated evaluation of enteric methane inhibitors in 20 or 30 countries. Creating international panels of experts for each major source of emissions – separate panels for enteric, rice and manure emissions - would be one way to move these efforts forward.

Strategy	Efficacy (expected CH_4 decrease range) and level of confidence	Co-benefits	Safety and risk management and licensing challenges	Production system applicability	Market readiness	Barriers to adoption on-farm, cost effectiveness and development needs
Supplementation of lipids Adding oils, oilseeds or other high-fat feeds to the diet. The lipids decrease methane and the additional digestible energy can increase animal production.	5-20% decrease in methane depending on level of fat supplementation and diet. High confidence. A number of meta-analysis already published. Some differences between lipid sources and oils vs oilseeds, but these differences are relatively small.	May improve milk/meat production as well as their fatty acid profiles. Many lipid feed sources are byproducts and waste from human food industry. Can increase animal production if dry matter intake is not decreased.	Safe, but need to limit total lipid content of diet to 4-6% of dry matter to limit negative effects on intake and digestibility, especially for high forage diets. Milk fat depression and "soft" butter can occur if diets are not formulated properly. No licensing issues.	Applicable to all systems, except extensive low-input grazing systems. Can be incorporated into total mixed rations or offered as supplements to grazing cattle.	Market ready	Can be costly – lipids are already included in many dairy diets in North America and the EU as a source of energy. Also in feedlot diets, depending on cost. Opportunities for lipid inclusion higher in less developed production systems. Need to identify low-cost local feeds and byproducts with high lipid contents and their effects on animals in Global South (total cost $2-5 million). This requires feed analysis and incorporation into feed formulation software. Need more info on effects on meat and milk quality. Substantial research already published for intensive systems, but not a lot of research done in low-moderate income counties.
Chemical inhibitor 3-Nitrooxypropanol (3-NOP)	Average efficacy of 30% (range: 20 to 80%), but dose dependent and inversely affected by fiber content of the diet. At the same dose, responses greater for dairy vs. beef cattle. High confidence with over 50 published papers.	None expected. Minimal effects on animal production or manure.	Needs to be dosed correctly. Needs regulatory approval (3-NOP approved in Brazil and Chile). No carry-over in meat and milk. Low safety risks for animals and humans. 3-NOP is manufactured and sold by DSM as Bovaer®.	In current form, needs to be incorporated into total mixed rations. Not applicable to grazing cattle.	3-NOP approved in Brazil and Chile. Dossiers submitted to various countries by DSM. Regulatory approval in most jurisdictions requires an extensive efficacy and safety dossier as inhibitors are considered "drugs" because they change animal metabolism.	Cost at the farm level unknown, and without co-benefits 3-NOP will increase the cost of feeding. Need to develop a slow-release formulation to extend use to grazing animals and for non-total mixed ration farms (total cost ($5-10 million). Need more information on long-term effects over multiple lactations (methane and animal production/health) and potential adaptation of the rumen ($2-5 million). Need more information on effects in Global South ($5-10 million). Research is controlled and mainly funded or co-funded by DSM, as they control the supply of product.

Strategy	Efficacy (expected CH_4 decrease range) and level of confidence	Co-benefits	Safety and risk management and licensing challenges	Production system applicability	Market readiness	Barriers to adoption on-farm, cost effectiveness and development needs
Bromoform-containing seaweeds (Asparagopsis sp.). About 5-8 experiments have been conducted so far all showing consistent results in high potential to reduce emissions.	Efficacy depends on basal diet and dose but in general it ranges from 40 to 98%. There is high level of confidence in the efficacy shown. We need information on net emission reduction considering production and transport to farm so life cycle assessments are needed.	A couple of small experiments have shown that there is an improvement in feed conversion efficiency, i.e., animals consume less feed but gain same weight compared those in control.	Safety risks need to be established, bromoforms are ozone depleting and potential human carcinogens. May need processing as there could be high levels of inorganic compounds transferred to products. Subject to USDA approval to feed seaweed (currently approved for trials) and FDA approval for methane mitigation and efficacy.	Needs to be incorporated into total mixed rations. We don't know how long the efficacy lasts so more work is needed in this area. If it lasts up to a week, it will broaden its range of applicability.	Early-stage research with a few start-ups working on scaling up and commercialization.	Need information on safety, bromoform content and stability, product production, and effects on animal productivity. Unknown cost effectiveness but potentially it can be produced in aquaculture setting and distributed as feed additive. There needs to be at least a dozen experiments including long term studies of either one or two lactations and a clinical trial. More research is needed for selection of seaweed with greater bromoform concentration and lower inorganic compounds. Research is needed to determine stability of seaweed over time and optimal storage conditions (stored room temp, refrigerated or frozen). Freeze drying is expensive so more research to figure out alternative drying and processing methods. Developing a product and getting it to commercial setting requires further investment, which start-ups are taking control of. Currently, research is underfunded so commercialization is over 5 years away. Long term plan would be to try to incorporate bromoform in small quantities through bioengineering of crops and slow-release forms for grazing cattle.

Strategy	Efficacy (expected CH_4 decrease range) and level of confidence	Co-benefits	Safety and risk management and licensing challenges	Production system applicability	Market readiness	Barriers to adoption on-farm, cost effectiveness and development needs
Other seaweeds Seaweeds other than Aspargopsis that inhibit methanogenesis due to the presence of specific bioactive components.	Decrease in methane of 5 to 20% but life cycle assessments needed. High uncertainty as there are few published papers so far, but this area is expanding in coastal countries.	Unknown, but many of these seaweed are highly digestible and may increase animal productivity.	Some may contain high levels of inorganic compounds (e.g., iodine). Will need to determine safety including residues and off-flavors. Many are already approved by government agencies for feed, so regulatory issues may be less than for Aspargopsis.	Applicable to all systems, except extensive low-input grazing systems	Early-stage research conducted mainly in high income coastal countries. At least 5 years from product delivery.	Need research on bioactive and inorganic compounds, product production, and effects on animal productivity. May need to purify or extract the bioactive components to minimize shipping costs and inorganic contaminants. Adoption will depend on cost:benefit analysis and regional availability. Currently, research is underfunded so commercialization is over 5 years away.
Essential oils. These are naturally occurring compounds extracted from plants or synthesized chemically. Products are usually essential oil blends e.g. Agolin. Mootral is made from natural products (such as garlic- and flavonoid-containing citrus extract) with demonstrated anti-methanogenic properties. Tropical grown lemongrass has also been shown to reduce emissions	0 to 25%; low to medium confidence due to the lack of published animal studies so far. However, this area is expanding.	Potential to increase animal productivity. There is evidence for at least Agolin to improve milk production.	Low risks. Many already approved as feed palatability enhancers. Essential oil products can be unstable and require encapsulation and proper storage. Odor might be a problem in some case (Mootral has heavy garlic smell to it).	Needs to be incorporated into total mixed rations; not applicable to extensive grazing systems.	Some products are market ready for methane reduction (Mootral, Agolin), but based on very limited research. Agolin is already being sold to increase milk production but methane mitigation is less than 10% based on few studies. Mootral shows up to 23% reduction in one study, but needs substantiation in science-based publications.	Research to date has focused on animal productivity although some products are developed for methane abatement specifically. Need research on optimum product formulation for methane mitigation. This will show whether this is something worth pursuing. Early indication is yes but we don't know the cost effectiveness (except Agolin that would increase milk production). Most are natural based products so it is easier for them to be approved as feed additives by USDA but still require FDA approval if methane reduction is to be claimed. Long term plan is to include some of the anti-methanogenic essential oils into common feeds through bioengineering technology.

Strategy	Efficacy (expected CH_4 decrease range) and level of confidence	Co-benefits	Safety and risk management and licensing challenges	Production system applicability	Market readiness	Barriers to adoption on-farm, cost effectiveness and development needs
Tannins Condensed and hydrolysable tannins contained in some plants (forages, shrubs, leaves and bark of trees). Can also be prepared as extracts.	5 to 20%. Moderate certainty with reduction being dose dependent.	Can improve nitrogen use efficiency and decrease nitrogen excretion. Can prevent bloat, control intestinal parasites, and improve the fatty acid composition and oxidative stability and sensory qualities of meat and milk.	High levels (> 3% of dietary dry matter) can decrease digestibility. Therefore, some of the methane reduction at higher levels can be due to decreased digestibility.	Applicable to all systems. Tannin containing forages mainly for pastoral systems, extracts for total mixed ration systems.	Some tannin forages are market ready. New extracts in 3-5 years.	A lot of the research has been done in vitro, with very positive results. Need more animal research using regionally available high-tannin sources Potential to develop supplements and extracts based on using local shrubs/trees. Need more work to characterize the types of tannins and levels in relation to methane mitigation and animal performance.
Immunization against methanogens. Growth and methane production of a pure culture of a methanogen were inhibited by a vaccine but ruminants contain numerous different species of methanogens	10 to 15%. High uncertainty, as the research is developmental.	None	Safety concerns unknown, it is low risk, as antibodies naturally exist in animal tissues. Vaccines are veterinary drugs so would need to go through appropriate regulatory approval processes.	Expected to have broad applicability globally. This is especially attractive for extensive systems if the requirement is one or two doses of the vaccine.	It is still at the experimental stage and may take over 5 years to be on the market.	Not yet demonstrated in live animals and still at a proof-of-concept stage. The biggest issue it that vaccines may lack a broad-spectrum effect on rumen methanogenic community. Research is needed to select appropriate antigens present across diverse rumen methanogens and assess their efficacy against cultivable rumen methanogens. Needs to assess the persistence of immune responses across ruminant populations. It may be cost effective as production of vaccines (if given one or two shots) could potentially be covered through incentives. Mainly driven by New Zealand. Long-term plan depends on in vivo experiment results.

Table 2: Summary of current and near-market ready enteric methane inhibition strategies

References

Adhya, T. K., B. Linquist, T. D. Searchinger, R. Wassmann, and X. Yan. 2014. "Wetting and Drying: Reducing Greenhouse Gas Emissions and Saving Water from Rice Production." Working Paper, Installment 8 of Creating a Sustainable Food Future. World Resources Institute Washington, DC.

Agus, Fahmuddin, José F. Andrade, Juan I. Rattalino Edreira, Nanyan Deng, Dwi K. G. Purwantomo, Nurwulan Agustiani, Vina E. Aristya, et al. 2019. "Yield Gaps in Intensive Rice-Maize Cropping Sequences in the Humid Tropics of Indonesia." Field Crops Research 237 (May): 12–22. https://doi.org/10.1016/j.fcr.2019.04.006.

Awad, Yasser M., Jinyang Wang, Avanthi D. Igalavithana, Daniel C.W. Tsang, Ki-Hyun Kim, Sang S. Lee, and Yong Sik Ok. 2018. "Biochar Effects on Rice Paddy: Meta-Analysis." In Advances in Agronomy, 1–32. https://doi.org/10.1016/bs.agron.2017.11.005.

Blaxter, K. L., and J. L. Clapperton. 1965. "Prediction of the Amount of Methane Produced by Ruminants." British Journal of Nutrition 19 (1): 511–22. https://doi.org/10.1079/BJN19650046.

Blümmel, M., M. Samad, O. P. Singh, T. Amede, M. Blümmel, M. Samad, O. P. Singh, and T. Amede. 2009. "Opportunities and Limitations of Food–Feed Crops for Livestock Feeding and Implications for Livestock–Water Productivity." The Rangeland Journal 31 (2): 207–12. https://doi.org/10.1071/RJ09005.

Bruun, Sander, Lars Stoumann Jensen, Van Thi Khanh Vu, and Sven Sommer. 2014. "Small-Scale Household Biogas Digesters: An Option for Global Warming Mitigation or a Potential Climate Bomb?" Renewable and Sustainable Energy Reviews 33 (May): 736–41. https://doi.org/10.1016/j.rser.2014.02.033.

Cai, Zucong, Haruo Tsuruta, Ming Gao, Hua Xu, and Chaofu Wei. 2003. "Options for Mitigating Methane Emission from a Permanently Flooded Rice Field." Global Change Biology 9 (1): 37–45. https://doi.org/10.1046/j.1365-2486.2003.00562.x.

Cardoso, Abmael S., Alexandre Berndt, April Leytem, Bruno J.R. Alves, Isabel das N.O. de Carvalho, Luis Henrique de Barros Soares, Segundo Urquiaga, and Robert M. Boddey. 2016. "Impact of the Intensification of Beef Production in Brazil on Greenhouse Gas Emissions and Land Use." Agricultural Systems 143 (March): 86–96. https://doi.org/10.1016/j.agsy.2015.12.007.

Champions 12.3. 2021. "SDG TARGET 12.3 ON FOOD LOSS AND WASTE: 2021 PROGRESS REPOR." https://champions123.org/sites/default/files/2021-09/21_WP_Champions_Progress%20Report_v5.pdf.

D'Aurea, André Pastori, Abmael da Silva Cardoso, Yuri Santa Rosa Guimarães, Lauriston Bertelli Fernandes, Luis Eduardo Ferreira, and Ricardo Andrade Reis. 2021. "Mitigating Greenhouse Gas Emissions from Beef Cattle Production in Brazil through Animal Management." Sustainability 13 (13): 7207. https://doi.org/10.3390/su13137207.

Deng, Nanyan, Patricio Grassini, Haishun Yang, Jianliang Huang, Kenneth G. Cassman, and Shaobing Peng. 2019. "Closing Yield Gaps for Rice Self-Sufficiency in China." Nature Communications 10 (1): 1725. https://doi.org/10.1038/s41467-019-09447-9.

Fangueiro, David, Maibritt Hjorth, and Fabrizio Gioelli. 2015. “Acidification of Animal Slurry– a Review.” Journal of Environmental Management 149 (February): 46–56. https://doi.org/10.1016/j.jenvman.2014.10.001.
Fischer, R. A., D. Byerlee, and G. O. Edmeades. 2014. Crop Yields and Global Food Security: Will Yield Increase Continue to Feed the World? ACIAR Monograph No. 158. Canberra: Australian Centre for International Agricultural Research.
Gerber, P., T. Vellinga, C. Opio, B. Henderson, and H. Steinfeld. 2010. “Greenhouse Gas Emissions from the Dairy Sector: A Life Cycle Assessment.” Rome, Italy: FAO. http://www.fao.org/docrep/012/k7930e/k7930e00.pdf.
González-Recio, O., J. López-Paredes, L. Ouatahar, N. Charfeddine, E. Ugarte, R. Alenda, and J. A. Jiménez-Montero. 2020. “Mitigation of Greenhouse Gases in Dairy Cattle via Genetic Selection: 2. Incorporating Methane Emissions into the Breeding Goal.” Journal of Dairy Science 103 (8): 7210–21. https://doi.org/10.3168/jds.2019-17598.
Henderson, B., A. Falcucci, A. Mottet, L. Early, B. Werner, H. Steinfeld, and P. Gerber. 2017. “Marginal Costs of Abating Greenhouse Gases in the Global Ruminant Livestock Sector.” Mitigation and Adaptation Strategies for Global Change 22 (1): 199–224. https://doi.org/10.1007/s11027-015-9673-9.
Herrero, M., P. Havlik, H. Valin, A. Notenbaert, M. C. Rufino, P. K. Thornton, M. Blummel, F. Weiss, D. Grace, and M. Obersteiner. 2013. “Biomass Use, Production, Feed Efficiencies, and Greenhouse Gas Emissions from Global Livestock Systems.” Proceedings of the National Academy of Sciences 110 (52): 20888–93. https://doi.org/10.1073/pnas.1308149110.
Holly, Michael A., Rebecca A. Larson, J. Mark Powell, Matthew D. Ruark, and Horacio Aguirre-Villegas. 2017. “Greenhouse Gas and Ammonia Emissions from Digested and Separated Dairy Manure during Storage and after Land Application.” Agriculture, Ecosystems & Environment 239 (February): 410–19. https://doi.org/10.1016/j.agee.2017.02.007.
Honan, M., X. Feng, J. M. Tricarico, E. Kebreab, M. Honan, X. Feng, J. M. Tricarico, and E. Kebreab. 2021. “Feed Additives as a Strategic Approach to Reduce EntericMethane Production in Cattle: Modes of Action, Effectiveness and Safety.” Animal Production Science, February. https://doi.org/10.1071/AN20295.
Hussein, Mahmoud, Viju V. Pillai, Joshua M. Goddard, Hui G. Park, Kumar S. Kothapalli, Deborah A. Ross, Quirine M. Ketterings, et al. 2017. “Sustainable Production of Housefly (Musca Domestica) Larvae as a Protein-Rich Feed Ingredient by Utilizing Cattle Manure.” PLOS ONE 12 (2): e0171708. https://doi.org/10.1371/journal.pone.0171708.
IPCC. 2006. IPCC Guidelines for National Greenhouse Gas Inventories. Prepared by the National Greenhouse Gas Inventories Programme. Published: IGES.
———. 2019. “2019 Reinfement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories.” Switzerland: Intergovernmental Panel on Cliamte Change.
Islam, Syed Faiz ul, Bjoern Ole Sander, James R. Quilty, Andreas de Neergaard, Jan Willem van Groenigen, and Lars Stoumann Jensen. 2020. “Mitigation of Greenhouse Gas Emissions and Reduced Irrigation Water Use in Rice Production

through Water-Saving Irrigation Scheduling, Reduced Tillage and Fertiliser Application Strategies." Science of the Total Environment 739: 140215. https://doi.org/10.1016/j.scitotenv.2020.140215.
Kammann, Claudia, Jim Ippolito, Nikolas Hagemann, Nils Borchard, Maria Luz Cayuela, José M. Estavillo, Teresa Fuertes-Mendizabal, et al. 2017. "Biochar as a Tool to Reduce the Agricultural Greenhouse-Gas Burden – Knowns, Unknowns and Future Research Needs." Journal of Environmental Engineering and Landscape Management 25 (2): 114–39. https://doi.org/10.3846/16486897.2017.1319375.
Kinley, Robert D., Gonzalo Martinez-Fernandez, Melissa K. Matthews, Rocky de Nys, Marie Magnusson, and Nigel W. Tomkins. 2020. "Mitigating the Carbon Footprint and Improving Productivity of Ruminant Livestock Agriculture Using a Red Seaweed." Journal of Cleaner Production 259 (June): 120836. https://doi.org/10.1016/j.jclepro.2020.120836.
Kumar, Arvind, Anitha Raman, Shailesh Yadav, S. B. Verulkar, N. P. Mandal, O. N. Singh, P. Swain, et al. 2021. "Genetic Gain for Rice Yield in Rainfed Environments in India." Field Crops Research 260 (January): 107977. https://doi.org/10.1016/j.fcr.2020.107977.
Landes, Maurice. n.d. "India's Dairy Sector: Structure, Performance, and Prospects," 49.
Liao, Ping, Yanni Sun, Xiangcheng Zhu, Haiyuan Wang, Yong Wang, Jin Chen, Jun Zhang, Yanhua Zeng, Yongjun Zeng, and Shan Huang. 2021. "Identifying Agronomic Practices with Higher Yield and Lower Global Warming Potential in Rice Paddies: A Global Meta-Analysis." Agriculture, Ecosystems & Environment 322 (September): 107663. https://doi.org/10.1016/j.agee.2021.107663.
Loide, Valli. 2019. "The Effect of Acidified Slurry on Soil Based on Leaching Test Data (2017–2018)," 27.
Luo, L. J. 2010. "Breeding for Water-Saving and Drought-Resistance Rice (WDR) in China." Journal of Experimental Botany 61 (13): 3509–17. https://doi.org/10.1093/jxb/erq185.
Melgar, A., K.C. Welter, K. Nedelkov, C.M.M.R. Martins, M.T. Harper, J. Oh, S.E. Raisanen, et al. 2020b. "Dose-Response Effect of 3-Nitrooxypropanol on Enteric Methane Emissions in Dairy Cows." Journal of Dairy Science 103 (7): 6145–56. https://doi.org/10.3168/jds.2019-17840.
Mohankumar Sajeev, Erangu Purath, Wilfried Winiwarter, and Barbara Amon. 2018. "Greenhouse Gas and Ammonia Emissions from Different Stages of Liquid Manure Management Chains: Abatement Options and Emission Interactions." Journal of Environmental Quality 47 (1): 30–41. https://doi.org/10.2134/jeq2017.05.0199.
Montes, F., R. Meinen, C. Dell, A. Rotz, A. N. Hristov, J. Oh, G. Waghorn, et al. 2013. "SPECIAL TOPICS — Mitigation of Methane and Nitrous Oxide Emissions from Animal Operations: II. A Review of Manure Management Mitigation Options1." Journal of Animal Science 91 (11): 5070–94. https://doi.org/10.2527/jas.2013-6584.
Moraes, Luis E., Anders B. Strathe, James G. Fadel, David P. Casper, and Ermias Kebreab. 2014. "Prediction of Enteric Methane Emissions from Cattle." Global

Change Biology 20 (7): 2140–48. https://doi.org/10.1111/gcb.12471.
Muizelaar, Wouter, Maria Groot, Gert van Duinkerken, Ruud Peters, and Jan Dijkstra. 2021. "Safety and Transfer Study: Transfer of Bromoform Present in Asparagopsis Taxiformis to Milk and Urine of Lactating Dairy Cows." Foods 10 (3): 584. https://doi.org/10.3390/foods10030584.
Naranjo, A., A. Johnson, H. Rossow, and E. Kebreab. 2020. "Greenhouse Gas, Water, and Land Footprint per Unit of Production of the California Dairy Industry over 50 Years." Journal of Dairy Science 103 (4): 3760–73. https://doi.org/10.3168jds.2019-16576.
Ogle, Stephen Michael, Stephen John Wakelin, Leandro Buendia, Brian McConkey, Jeffrey Baldock, Hiroko Akiyama, Ayaka W Mo Kishimoto, Ngonidzashe Chirinda, M A R Goheer, and K Hergoualc'h. 2019. "Cropland."
Olesen, Jorgen, Soren Petersen, Peter Lund, Uffe Jorgensen, Troels Kristensen, Lars Elsgaard, Peter Sorensen, and Jan Lassen. 2018. "VIRKEMIDLER TIL REDUKTION AF KLIMAGASSER I LANDBRUGET." DCA 130. Aarhus, Denmark: Aarhus Universitet.
Owens, Jennifer L., Ben W. Thomas, Jessica L. Stoeckli, Karen A. Beauchemin, Tim A. McAllister, Francis J. Larney, and Xiying Hao. 2020. "Greenhouse Gas and Ammonia Emissions from Stored Manure from Beef Cattle Supplemented 3-Nitrooxypropanol and Monensin to Reduce Enteric Methane Emissions." Scientific Reports 10 (1): 19310. https://doi.org/10.1038/s41598-020-75236-w.
Patthawaro, Sirada, and Chewapat Saejung. 2019. "Production of Single Cell Protein from Manure as Animal Feed by Using Photosynthetic Bacteria." MicrobiologyOpen 8 (12): e913. https://doi.org/10.1002/mbo3.913.
Petersen, S. O., O. Højberg, M. Poulsen, C. Schwab, and J. Eriksen. 2014. "Methanogenic Community Changes, and Emissions of Methane and Other Gases, during Storage of Acidified and Untreated Pig Slurry." Journal of Applied Microbiology 117 (1): 160–72. https://doi.org/10.1111/jam.12498.
Petersen, Søren O., Astrid J. Andersen, and Jørgen Eriksen. 2012. "Effects of Cattle Slurry Acidification on Ammonia and Methane Evolution during Storage." Journal of Environmental Quality 41 (1): 88–94. https://doi.org/10.2134/jeq2011.0184.
Petersen, Søren O., Anne B. Olsen, Lars Elsgaard, Jin Mi Triolo, and Sven G. Sommer. 2016. "Estimation of Methane Emissions from Slurry Pits below Pig and Cattle Confinements." PLOS ONE 11 (8): e0160968. https://doi.org/10.1371/journal.pone.0160968.
Porter, Stephen D., David S. Reay, Peter Higgins, and Elizabeth Bomberg. 2016. "A Half-Century of Production-Phase Greenhouse Gas Emissions from Food Loss & Waste in the Global Food Supply Chain." Science of The Total Environment 571 (November): 721–29. https://doi.org/10.1016/j.scitotenv.2016.07.041.
Qian, Qian, Longbiao Guo, Steven M. Smith, and Jiayang Li. 2016. "Breeding High-Yield Superior Quality Hybrid Super Rice by Rational Design." National Science Review 3 (3): 283–94. https://doi.org/10.1093/nsr/nww006.
Rodhe, Lena, Johny Ascue, Marianne Termeden, and Leticia Pizzul. 2019. "Ammonia Emissions from Storge: Non-Digested and Digested Cattle Slurry with and

without Acid." Interreg Baltic Sea Region, European Union.
Roque, B. M., M. Venegas, R. Kinley, R. deNys, T. L. Neoh, T. L. Duarte, X. Yang, J. K. Salwen, and E. Kebreab. 2020. "Red Seaweed (Asparagopsis Taxiformis) `` Supplementation Reduces Enteric Methane by over 80 Percent in Beef Steers." BioRxiv, July, 2020.07.15.204958. https://doi.org/10.1101/2020.07.15.204958.
Roque, Breanna M., Joan K. Salwen, Rob Kinley, and Ermias Kebreab. 2019. "Inclusion of Asparagopsis Armata in Lactating Dairy Cows' Diet Reduces Enteric Methane Emission by over 50 Percent." Journal of Cleaner Production 234 (October): 132–38. https://doi.org/10.1016/j.jclepro.2019.06.193.
Saunois, Marielle, Ann R. Stavert, Ben Poulter, Philippe Bousquet, Josep G. Canadell, Robert B. Jackson, Peter A. Raymond, et al. 2020. "The Global Methane Budget 2000-2017." Earth System Science Data 12 (3): 1561–1623. https://doi.org/10.5194/essd-12-1561-2020.
Searchinger, Timothy D., Stefan Wirsenius, Tim Beringer, and Patrice Dumas. 2018. "Assessing the Efficiency of Changes in Land Use for Mitigating Climate Change." Nature 564 (7735): 249. https://doi.org/10.1038/s41586-018-0757-z.
Searchinger, Timothy, Richard Waite, Craig Hanson, and Janet Ranganathan. 2019. Creating a Sustainable Food Future: A Menu of Solutions to Feed Nearly 10 Billion People by 2050. World Resources Institute, World Bank, UNDP, UNEP. sustainablefoodfuture.org.
Searchinger, Timothy, Jessica Zionts, Stephan Wirsenius, Liqing Peng, Tim Beringer, and Patrice Dumas. 2021. "A Pathway to Carbon Neutral Agriculture in Denmark." Washington D.C.: World Resources Institute.
Senthilkumar, Kalimuthu, Jonne Rodenburg, Ibnou Dieng, Elke Vandamme, Fitta Silas Sillo, Jean-Martial Johnson, Arisoa Rajaona, et al. 2020. "Quantifying Rice Yield Gaps and Their Causes in Eastern and Southern Africa." Journal of Agronomy and Crop Science 206 (4): 478–90. https://doi.org/10.1111/jac.12417.
Shyamsundar, P., N. P. Springer, H. Tallis, S. Polasky, M. L. Jat, H. S. Sidhu, P. P. Krishnapriya, et al. 2019. "Fields on Fire: Alternatives to Crop Residue Burning in India." Science 365 (6453): 536–38. https://doi.org/10.1126/science.aaw4085.
Smith, Pete. 2016. "Soil Carbon Sequestration and Biochar as Negative Emission Technologies." Global Change Biology 22 (3): 1315–24. https://doi.org/10.1111/gcb.13178.
Sokolov, Vera K., Andrew VanderZaag, Jemaneh Habtewold, Kari Dunfield, Claudia Wagner-Riddle, Jason J. Venkiteswaran, Anna Crolla, and Robert Gordon. 2020. "Dairy Manure Acidification Reduces CH4 Emissions over Short and Long-Term." Environmental Technology 0 (0): 1–8. https://doi.org/10.1080/09593330.2020.1714744.
Song, Kaifu, Guangbin Zhang, Haiyang Yu, Qiong Huang, Xiaoli Zhu, Tianyu Wang, Hua Xu, Shihua Lv, and Jing Ma. 2021. "Evaluation of Methane and Nitrous Oxide Emissions in a Three-Year Case Study on Single Rice and Ratoon Rice Paddy Fields." Journal of Cleaner Production 297: 126650. https://doi.org/10.1016/j.jclepro.2021.126650.
Springmann, Marco, Michael Clark, Daniel Mason-D'Croz, Keith Wiebe, Benjamin Leon Bodirsky, Luis Lassaletta, Wim de Vries, et al. 2018. "Options for Keeping

the Food System within Environmental Limits.” Nature 562 (7728): 519–25. https://doi.org/10.1038/s41586-018-0594-0.
Sun, Huifeng, Sheng Zhou, Xiangfu Song, Zishi Fu, Guifa Chen, and Jining Zhang. 2016. “CH4 Emission in Response to Water-Saving and Drought-Resistance Rice (WDR) and Common Rice Varieties under Different Irrigation Managements.” Water, Air, and Soil Pollution 227 (2). https://doi.org/10.1007/s11270-015-2741-7.
Thornton, Philip K., and Mario Herrero. 2010. “Potential for Reduced Methane and Carbon Dioxide Emissions from Livestock and Pasture Management in the Tropics.” Proceedings of the National Academy of Sciences 107 (46): 19667–72. https://doi.org/10.1073/pnas.0912890107.
Thornton, Philip, Gerald Nelson, Dianne Mayberry, and Mario Herrero. 2021. “Increases in Extreme Heat Stress in Domesticated Livestock Species during the Twenty-First Century.” Global Change Biology 27 (22): 5762–72. https://doi.org/10.1111/gcb.15825.
Tooley, William. 2013. “Aerobic Treatment of Manure Lagoons Showing Environmental and Economic Benefits with Eco-System Service Paybacks.” NRCS 69-3A75-0-123. Natural Resources Conservation Service.
Vanotti, M. B., A. A. Szogi, and C. A. Vives. 2008. “Greenhouse Gas Emission Reduction and Environmental Quality Improvement from Implementation of Aerobic Waste Treatment Systems in Swine Farms.” Waste Management, OECD Workshop - Soils and Waste Management: A Challenge to Climate Change, 28 (4): 759–66. https://doi.org/10.1016/j.wasman.2007.09.034.
Vergara, Sintana E, and Whendee L Silver. 2019. “Greenhouse Gas Emissions from Windrow Composting of Organic Wastes: Patterns and Emissions Factors.” Environmental Research Letters 14 (12): 124027. https://doi.org/10.1088/1748-9326/ab5262.
Vijn, Sandra, Devan Paulus Compart, Nikki Dutta, Athanasios Foukis, Matthias Hess, Alexander N. Hristov, Kenneth F. Kalscheur, et al. 2020. “Key Considerations for the Use of Seaweed to Reduce Enteric Methane Emissions From Cattle.” Frontiers in Veterinary Science 7 (December): 597430. https://doi.org/10.3389/fvets.2020.597430.
Wallace, R. John, Goor Sasson, Philip C. Garnsworthy, Ilma Tapio, Emma Gregson, Paolo Bani, Pekka Huhtanen, et al. 2019. “A Heritable Subset of the Core Rumen Microbiome Dictates Dairy Cow Productivity and Emissions.” Science Advances 5 (7): eaav8391. https://doi.org/10.1126/sciadv.aav8391.
Wang, Jinyang, Hiroko Akiyama, Kazuyuki Yagi, and Xiaoyuan Yan. 2018. “Controlling Variables and Emission Factors of Methane from Global Rice Fields.” Atmospheric Chemistry and Physics 18 (14): 10419–31. https://doi.org/10.5194/acp-18-10419-2018.
Wang, Jinyang, Zhengqin Xiong, and Yakov Kuzyakov. 2016. “Biochar Stability in Soil: Meta=analysis of Decomposition and Priming Effects.” GCB Bioenergy 8 (3): 512–23.
Wollenberg, E., M. Richards, P. Smith, P. Havlík, M. Obersteiner, F.n. Tubiello, M. Herold, et al. 2016. “Reducing Emissions from Agriculture to Meet the 2°C Target.” Global Change Biology, May, n/a-n/a.

https://doi.org/10.1111/gcb.13340.
Xu, Ying, Junzhu Ge, Shaoyang Tian, Shuya Li, Anthony L. Nguy-Robertson, Ming Zhan, and Cougui Cao. 2015. “Effects of Water-Saving Irrigation Practices and Drought Resistant Rice Variety on Greenhouse Gas Emissions from a No-till Paddy in the Central Lowlands of China.” Science of the Total Environment 505: 1043–52. https://doi.org/10.1016/j.scitotenv.2014.10.073.
Yan, Xiaoyuan, Hiroko Akiyama, Kazuyuki Yagi, and Hajime Akimoto. 2009. “Global Estimations of the Inventory and Mitigation Potential of Methane Emissions from Rice Cultivation Conducted Using the 2006 Intergovernmental Panel on Climate Change Guidelines.” Global Biogeochemical Cycles 23 (2). https://doi.org/10.1029/2008GB003299.