COURSE 5

Reduce Greenhouse Gas Emissions from Agricultural Production

Agricultural production is responsible for more greenhouse gas (GHG) emissions each year than land-use change but production-related emissions are traditionally regarded as harder to control. In general, our estimates of mitigation potential are more optimistic than the estimates of other researchers, partly because many analyses have not fully captured the opportunities for productivity gains and partly because we factor in promising potential for technological innovations.

TABLE OF CONTENTS

Chapter 24. Menu Item: Reduce Enteric Fermentation through New Technologies 315

Chapter 25. Menu Item: Reduce Emissions through Improved Manure Management...................... 321

Chapter 26. Menu Item: Reduce Emissions from Manure Left on Pasture...................................333

Chapter 27. Menu Item: Reduce Emissions from Fertilizers by Increasing Nitrogen Use Efficiency 339

Chapter 28. Menu Item: Adopt Emissions-Reducing Rice Management and Varieties 355

Chapter 29. Menu Item: Increase Agricultural Energy Efficiency and Shift to Nonfossil Energy Sources.......... 369

Chapter 30. Menu Item: Focus on Realistic Options to Sequester Carbon in Agricultural Soils 375

Chapter 31. The Need for Flexible Regulations 387

Introduction

GHG emissions from agricultural production processes alone (i.e., excluding emissions from converting land to agricultural use) reach 9 gigatons (Gt) by 2050 in our baseline scenario, an increase from 6.8 Gt in 2010 (Figure C5-1). These production emissions arise mainly from six sources:

- "Enteric" methane emitted from the stomachs of cattle, buffalo, goats, and sheep (ruminants)
- Manure produced by some ruminants, pigs, and chickens kept in confined animal facilities (large and small)
- Unmanaged manure left on pasture and paddocks
- Crop and pasture fertilization, particularly with nitrogen
- Rice production
- Energy use in on-farm activities and in the production of agricultural inputs such as fertilizer

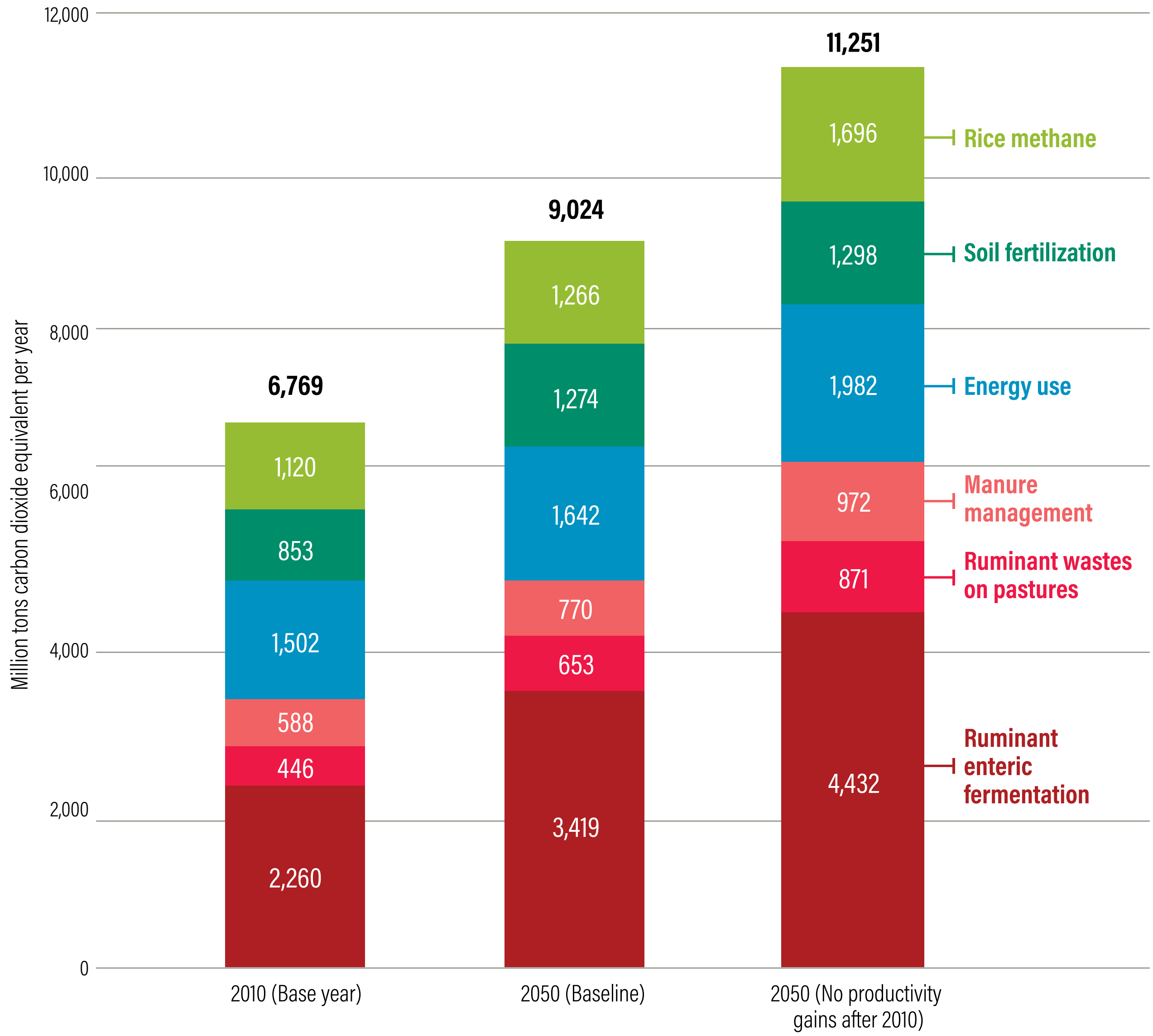
A baseline emissions level of 9 Gt results in a GHG mitigation gap of 5 Gt relative to our target of 4 Gt of total emissions from agriculture, even if we assume that all net emissions from land-use change, including peatland degradation, are eliminated or offset (as we contemplate in some scenarios).

Our 2050 baseline already builds in many productivity gains, without which agricultural production emissions in 2050 would rise even further (Figure C5-1). Even with highly optimistic estimates of changes in demand discussed in Course 1 (e.g., reducing food loss and waste, shifting diets to less ruminant-based foods), annual production emissions would still reach 7.2 Gt in 2050. Additional increases in livestock productivity analyzed in Chapter 11 would reduce production emissions to only about 7 Gt.

To reach our target of total agricultural emissions of 4 Gt by 2050 (see Figure 2-6 in "Scope of the Challenge and Menu of Possible Solutions"), efforts to reduce agricultural production emissions will be essential. Many possible approaches would also reduce other environmental impacts of agriculture, including air and water pollution caused by manure and fertilizer.

The following chapters explore menu items that could reduce agricultural production emissions by changing production processes. We find that meaningful potential exists today and that innovation offers the possibility of much greater mitigation in the future. Achieving these innovations will require both public support for research and development and flexible regulations that provide incentives for farmers and the private sector to pursue cost-effective solutions.

Figure C5-1 | **Annual agricultural production emissions could reach 9 gigatons or more by 2050**



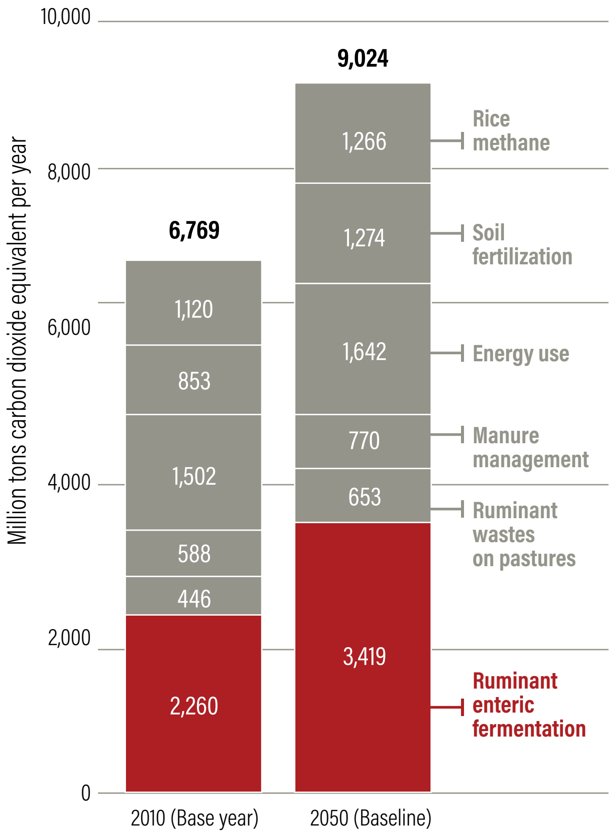
Source: GlobAgri-WRR model.

CHAPTER 24

MENU ITEM: REDUCE ENTERIC FERMENTATION THROUGH NEW TECHNOLOGIES

Methane produced by digestive processes in the stomachs of ruminants—mainly cattle, sheep, and goats—is the largest source of GHG emissions from livestock. Productivity improvements will reduce methane emissions, mainly because more milk and meat is produced per kilogram of feed, but additional measures will be needed to help offset growth in demand for ruminant meat. This chapter explores technological approaches to reducing enteric methane emissions.

Figure 24-1 | Greenhouse gas emissions from agricultural production, 2010 and 2050



The Challenge

Livestock generate roughly half of agricultural production GHG emissions today (Figure 24-1), even when excluding the emissions resulting from feed production. In 2050, two-thirds of livestock emissions, and more than one-third of total agricultural production emissions, will be methane generated by "enteric fermentation." This methane, which exits mainly from the animal's mouth, is produced by the natural breakdown of forages and other feed by anaerobic microorganisms (technically archaea) in the stomachs of ruminants—cattle, goats, sheep, and buffalo.

Strategies to reduce enteric methane emissions, in addition to improving livestock productivity, rely on four approaches to manipulate the dominant microbiological communities in the rumen: using vaccines, selectively breeding animals that naturally produce fewer emissions, incorporating special feeds or supplements into diets, and using compounds that can be thought of as drugs.

Governments have supported more research on this issue than on other sources of agricultural GHGs. Some dedicated scientific facilities are evaluating mitigation options. For example, at one New Zealand facility, scientists for years have systematically tested thousands of possible drugs or feed supplements. They start by adding compounds in small glass containers filled with rumen fluids. The most promising compounds are fed directly to animals temporarily housed in clear, tightly sealed glass chambers, which permit researchers to carefully measure the methane they release. The same chambers allow researchers to test different food additives, vaccines, and breeds to minimize methane emissions.

Unfortunately, the vast majority of results have been disappointing, mainly because the archaea that produce methane have found ways to overcome whatever initially suppresses them.[1] Although testing of animals has shown that different individual animals at different times produce very different levels of methane,[2] breeding has not yet produced animals that systematically generate below-average methane levels.[3] Vaccines also have proven only modestly and temporarily effective.[4] Although many feed compounds at first reduced methane emissions, most quickly lost their effectiveness. The digestion of cellulose results in a hydrogen gas that provides an energy source for microorganisms that can use it. As one paper summarized the problem, "The rumen microorganisms have the ability to adapt to foreign agents or changes in the feeding regimen and, therefore, short-term responses are not representative of the effect of a given mitigation compound or practice in real farm conditions."[5]

A few chemical compounds have provided persistent benefits so far, such as bromoform and chloroform.[6] These compounds are found in the red algae that make up some kinds of seaweed and explain why feeding experiments using small quantities of such seaweeds in feed, around 0.5 percent, have achieved greater than 50 percent reductions in methane emissions.[7] Unfortunately, these compounds are associated with important animal health or environmental concerns.[8] As a result, scientists are divided on whether to continue investigating

seaweed, with researchers in New Zealand discontinuing work while some researchers in Australia and the United States continue their studies. Separately, New Zealand researchers announced the identification of five promising compounds in 2015,[9] but peer-reviewed publications with results have yet to emerge.

As alternatives to chemical or drug compounds, some feed supplements—including vegetable oils and nitrate—have shown limited effectiveness at reducing methane emissions without health or productivity concerns.[10] But the financial costs of these supplements are high relative to emissions avoided. One analysis estimated that the potential costs of mitigation using these supplements start at $100 per ton of carbon dioxide equivalent (CO_2e) and rise with higher levels of mitigation. The analysis further estimated that even at a marginal cost of $300 per ton, the potential mitigation from these feed supplements amounted to only a few percent of enteric emissions.[11] We consider these approaches too expensive and their emissions-reduction benefits too small to be worthy of inclusion in our menu for a sustainable food future.

The Opportunity

Fortunately, since about 2015, at least one promising chemical feed additive has emerged. Multiple studies of cattle have shown that a small molecule, called 3-nitrooxypropan (3-NOP), generates sustained methane reductions of 30 percent or more in both cattle and sheep over at least several weeks.[12] This additive appears to have a persistent effect because the compound interferes with part of the fundamental chemical reaction that produces methane in *all* archaea.[13] The fundamental nature of this pathway may also reduce the rate at which archaea can mutate around it. On the basis of existing research, the chemical appears to have no adverse effects on animal health.

There is also good evidence from 3-NOP and other studies so far that reducing methane harms neither animals nor their productivity. This testing alleviates concerns that cows might be harmed by a build-up of hydrogen in the rumen when it no longer binds with carbon to form methane.[14]

3-NOP may also increase meat productivity, although the results to date have not demonstrated such gains clearly. Because ruminants lose up to 12 percent of the gross energy in feed as a result of the rumen's methane production,[15] reduced methane production in theory has the potential to increase productivity or reduce the quantity of feed needed. Yet studies of 3-NOP in dairy cows have not found increased production of milk, and only some have found increases in daily weight gain (and only in dairy cows, not beef cows). Research is still ongoing, and DSM, the company that makes 3-NOP, is exploring the alternative route of maintaining output while reducing feed input.

Steps remain before 3-NOP can be broadly adopted. Researchers are still conducting experiments to obtain approval.[16] DSM hopes to have 3-NOP available on the market by 2020, though problems could still emerge. Yet overall, the progress made so far increases confidence that researchers will ultimately identify a cost-effective, safe, and effective compound.

Mitigation Potential

Although the novelty of effective compounds makes any projections uncertain, our mitigation options are based on assumptions about using 3-NOP or a comparable compound. The principal limitation of 3-NOP now is that it requires daily ingestion, and preferably frequently. In the leading study, it was mixed with feed in stall-fed dairy animals, which therefore ingest it throughout the day.

In our modeling, we assume that a feed compound will reduce emissions by 30 percent, which is the claim now being made by the producers of 3-NOP. We apply it in our first (Coordinated Effort) scenario to half of animals that receive more than a small amount of concentrated feed, which would facilitate their ingestion of a compound. In our Highly Ambitious scenario, we apply these reductions to all animals receiving concentrated feed. Under our Breakthrough Technologies scenario,

Table 24-1 | Global effects of enteric fermentation reduction scenarios on greenhouse gas emissions from agricultural production

SCENARIO	ENTERIC FERMENTATION EMISSIONS (MT CO_2E)	TOTAL PRODUCTION EMISSIONS (MT CO_2E)	PRODUCTION EMISSIONS GHG MITIGATION GAP (GT CO_2E)
2010	**2,260**	**6,769**	**—**
No productivity gains after 2010	4,432	11,251	7.3 (2.3)
2050 BASELINE	**3,419**	**9,023**	**5.0**
30% methane emissions reduction (animals receiving half of concentrated feeds) *(Coordinated Effort)*	3,126	8,730	4.7 (-0.3)
30% methane emissions reduction (all animals receiving concentrated feeds) *(Highly Ambitious)*	2,807	8,411	4.4 (-0.6)
30% methane emissions reduction (all ruminants) *(Breakthrough Technologies)*	2,393	7,997	4.0 (-1.0)

Notes: Numbers not summed correctly are due to rounding. Numbers shown in parentheses are changes relative to 2050 baseline.
Source: GlobAgri-WRR model.

the feed compound and associated 30 percent emissions reduction is assumed to apply to all ruminants including those permanently grazed. We make this assumption only in that scenario because such an achievement would likely require additional technological innovation to develop ways of delivering 3-NOP or alternative compounds, such as long-lasting, slow-release additives (Table 24-1).

The three mitigation scenarios lead to a reduction of enteric fermentation emissions of between 9 percent and 30 percent relative to our 2050 baseline. They would close between 6 percent and 20 percent of the production emissions GHG mitigation gap.

Recommended Strategies

Governments first need to continue their support for developing compounds to reduce methane from enteric fermentation. Without such support, the opportunities are less likely to be realized.

Researchers and corporations also need to know that if they develop a measure that provides cost-effective mitigation, it will be used. It is possible that compounds like 3-NOP will eventually pay for themselves through reduced need for feed or increased productivity, but they also might not, and cost-effective mitigation benefits should be considered sufficient justification to require their use.

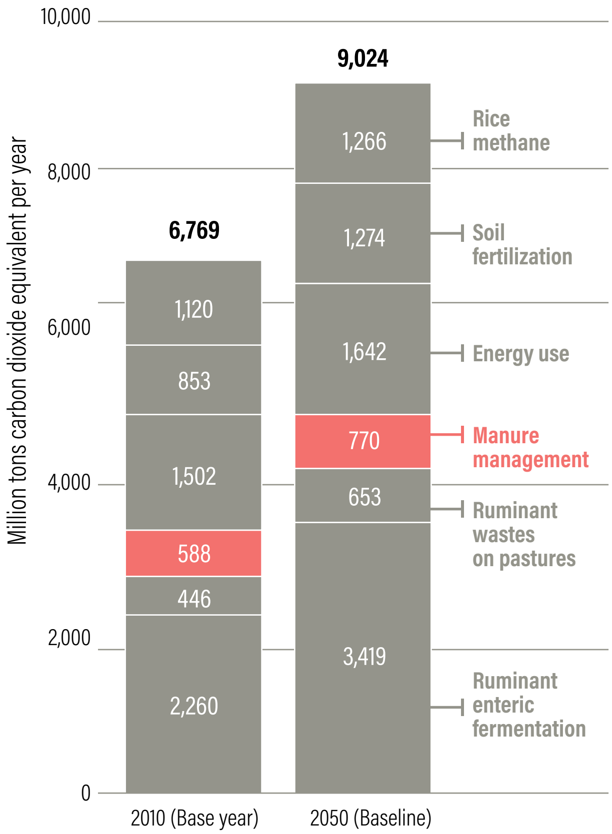
We therefore recommend that governments provide incentives to the private sector by promising to require use of compounds if and when they prove to mitigate emissions at a reasonable cost. A first step could require use of such compounds as a condition of receiving farm subsidies. Because this recommendation applies to several mitigation strategies, we elaborate more on it in the final chapter of this course.

CHAPTER 25

MENU ITEM: REDUCE EMISSIONS THROUGH IMPROVED MANURE MANAGEMENT

The breakdown of manure by microorganisms under waterlogged conditions generates both methane and nitrous oxide emissions, which are powerful GHGs. Concentrated manure presents many other environmental challenges: it compromises water quality, contributes to local and regional air pollution, harbors pathogens, and generates noxious odors. This menu item focuses on ways to reduce GHG emissions from managed manure—but the same measures that reduce GHGs also tend to mitigate other environmental problems.

Figure 25-1 | Greenhouse gas emissions from agricultural production, 2010 and 2050



The Challenge

Livestock produce vast quantities of manure. Manure is "managed" when ruminants, pigs, or poultry are raised in confined settings and farmers remove manure and dispose of it in some way. (The manure that cattle, sheep, and goats deposit on grasslands and paddocks is considered unmanaged, and we address emissions from this source in the next menu item.) Manure begins to emit GHGs immediately after it is deposited in the barn where animals are kept,[17] but the majority of emissions occur in the manure storage system.

Dry and wet manure management systems

Some manure is managed in "dry systems," in which farms allow the urine to partially dry where it falls before scraping and piling the manure. Dry systems are found in virtually all poultry facilities because low volumes of urine leave poultry manure naturally dry. In the case of cattle and pigs, partial saturation of pockets of manure by urine creates the kinds of low-oxygen, high-carbon conditions that, when present for a day or more, are ideal for the microorganisms that produce nitrous oxide. More permanently saturated pockets tend to generate methane. Although the majority of the world's managed manure is managed dry, dry manure produces roughly 40 percent of global manure management GHG emissions (using estimates generated by the Global Land Evaporation Amsterdam Model [GLEAM] developed by the Food and Agriculture Organization of the United Nations [FAO]),[18] mostly in the form of nitrous oxide. Dry systems also result in high losses of nitrogen in a variety of forms, which reduces the nutrient value of the manure and typically generates abundant ammonia, an air pollutant.

Roughly 60 percent of managed manure emissions occur in "wet systems," in which farmers collect both feces and urine and sometimes add some water to flush manure into storage areas. These storage systems can take a variety of forms. When farmers use relatively small pits dug out of the earth, which they must empty several times a year, they are often called pits or slurries. When farmers use much larger dug-out pits, they are called "lagoons." These storage systems provide ideal conditions for archaea to generate methane. Per ton of manure, wet systems generate on the order of 20 times more methane than dry-managed manure, according to guidance from the Intergovernmental Panel on Climate Change (IPCC) and more recent studies.[19] Dry systems produce far more nitrous oxide although they have lower total emissions. When and if farmers ultimately apply wet manure to cropland and pasture, the manure also generates emissions, but we count and discuss those emissions as part of "soil fertilization," which we address in Chapter 27.

Managed manure volumes and emissions

We estimate GHG emissions from managed manure at nearly 590 million tons (Mt) of CO_2e in 2010. We project that these emissions will rise to 770 Mt CO_2e in our 2050 baseline (Figure 25-1). Of this total, we estimate that roughly one-third is in the form of nitrous oxide and two-thirds is in the form of methane.

Our estimates and projections are similar to those of other researchers. Perhaps because all global managed manure estimates use some form of guidance from the IPCC, seven of eight estimates recently summarized ranged only from 470 to 590 Mt CO_2e for recent years.[20] In all studies, the estimated emissions from methane are very similar.[21] Differences arise primarily in estimates of nitrous oxide emissions. There is also evidence from a meta-analysis of available field data that IPCC emission factors are too low, at least for dairy cows in developed countries, which would suggest higher total global emissions.[22]

Although estimates are rough, estimates by FAO using the GLEAM model indicate that manure from pigs is responsible for half of all managed manure emissions, primarily through methane generated in wet systems. Dairy cows generate around one-third of all emissions, roughly evenly divided between methane and nitrous oxide. Beef operations produce roughly one-sixth of all GHGs, primarily through nitrous oxide, because their predominant manure management systems are dry. Poultry produce relatively low GHG emissions (although they tend to generate abundant ammonia) because their wastes are dry enough to inhibit production of nitrous oxide or methane.

The critical question is what farmers can do to mitigate emissions from managed manure. More efficient production has only modest effects on managed manure emissions, unlike most other sources of agricultural emissions. To date, global estimates of technical—let alone economic—mitigation potential tend to be modest. For example, one review estimated the potential at 100 Mt CO_2e per year.[23] Such a level would mitigate only around one-sixth to one-eighth of present estimates of emissions from managed manure. Although we are ultimately more hopeful, we too consider mitigating managed manure emissions to be challenging for three reasons:

First, because most manure managed under dry systems generates relatively low emissions per kilogram of manure,[24] any control technology must be fairly inexpensive if it is to be cost-effective.[25]

Second, one-third of managed manure emissions today take the form of nitrous oxide, which is harder to control than methane—and this share is likely to rise by 2050.[26] Nitrous oxide emissions occur when manure is moist but not in liquid form and starts to occur as soon as wastes are deposited by the animal.[27] We discuss below opportunities to use solid separation on pig and dairy farms, but, in dry beef operations and many smaller farms, the main strategy suggested in the literature is to reduce overfeeding of protein (and therefore nitrogen) to livestock. In some countries, farmers feed excess protein, so reductions are practicable. In advanced systems, feed can more closely match the specific amino acid needs of livestock.[28] But in large parts of the developing world, livestock underconsume protein. Even where cows consume more nitrogen than they need, reducing protein in feed may result in more methane emissions from manure management through a complex and poorly understood microbial interaction.[29] In addition, efficiency gains in consumption of nitrogen by animals are mostly tied to the overall efficiency of feeding, and our baseline analysis already assumes substantial increases in overall feeding efficiency.

Third, farmers cannot practically influence many of the factors that influence emissions. For example, emissions from stored manure can be much higher in warmer climates than cool climates.[30] But strong economic factors influence where farmers raise animals, so it generally would be expensive, and socially and politically challenging, to shift livestock production to cooler areas just to reduce GHG emissions. Managed manure emissions also increase the longer farmers store manure before spreading it on farm fields. But spreading manure more frequently would often mean fertilizing crops when they cannot use the nutrients and thus increasing water pollution and nitrous oxide emissions in the field.

The Opportunity

Despite these challenges, we see greater potential for mitigation if countries take reasonable steps to advance manure-management technologies. There appears to be abundant opportunity for innovation. Even existing technologies appear capable of reducing emissions at a cost equal to only a small percentage of the price of meat and milk and at an acceptable cost per ton of emissions.

In this section, we discuss the opportunities for controlling managed manure emissions with a simple technology, solid separation, that can mitigate emissions from wet and dry manure alike and can grow in complexity and levels of mitigation as required. We then consider some lessons from research into manure management at a North Carolina pig farm, which offer insight into the potential to develop truly sophisticated manure management systems. Finally, we discuss digesters, which have received much of the manure management focus. They have potential to improve manure management but also present risks if not properly managed.

Separating solids, liquids, and nutrients

Separating liquids from solids is a relatively simple measure to reduce emissions and improve manure management generally. Since the solid portions of manure are drier after separation, they are likely to emit somewhat less methane. The liquid portion also causes fewer emissions because its lower carbon content gives microorganisms less to feed on and turn into methane.

Even without government incentives, a wide variety of systems already exist that can separate solids and, in the process, improve potential use of manure's nutrients. The simplest systems use gravity and a series of grates or ponds to let solids settle out. Many dairy farms in the United States use these systems. But mechanical systems can include screw presses or centrifuges that squeeze or whisk water out of solids and greatly increase the extent of the separation. Use of chemical "flocculents," which cause small particles to bind together, can increase removal rates of solids to 75–90 percent or higher, and can remove nearly all the phosphorus. More advanced systems use a variety of techniques to strip out nitrogen and phosphorus.

Separating liquids from solids also helps segregate nutrients; more nitrogen tends to remain with the liquid and more phosphorus stays with the solids. Two waste streams make it possible to better direct nitrogen and phosphorus to fields that need them. The phosphorus content of manure tends to be particularly high relative to local field needs, so concentrating and drying out phosphorus in solids makes it cheaper to transport the manure to fields that can benefit from it.[31]

The degree of GHG mitigation that separation can achieve will probably vary according to the type of farm and the extent of the solid separation. Studies to date use modeling assumptions rather than real field data. One study of pig farms in China found that solid separation would reduce emissions by more than half compared to even a basic dry management system (which mixes manure with straw), mostly by reducing nitrous oxide emissions. If compared to storage of manure in a deep pit, solid separation systems would reduce emissions by two-thirds.[32]

Achieving large reductions requires more than a low level of solid separation achieved by simple gravity-fed, grated systems. For example, a study of manure management changes on large dairy farms conducted for the California state government estimated only an 11 percent reduction in methane using solid separation.[33] But this study assumed that only 15 percent more solids would be separated, which would require only simple systems of solid separation.

One analysis of dairy farms in the United States estimated the cost of simple separation systems at only about $5–$6 per cow per year, with more advanced systems costing $50–$75 per cow per year.[34] A cost of $75 per cow in the United States is roughly equivalent to only 1 cent per liter of milk,[35] and these systems can still potentially pay for themselves because they save other costs of manure management, including hauling costs, and because they enable more valuable use of nutrients.[36] One analysis of dairy farms in Iowa found that farms using advanced solid separation actually had the lowest manure management costs.[37] To indicate the potential, some dairy farms in Michigan and New York have installed a system that uses reverse osmosis to clean up effluent almost to drinking water standards for reuse. Although the system is expensive, the farm owners believe it will ultimately save them money, mainly by lowering hauling costs and making more valuable use of nutrients.[38]

With good, daily solid separation, perhaps half or more of remaining emissions will result from the storage of solids, perhaps in equal parts methane and nitrous oxide.[39] These emissions can be reduced by the use of chemical additives to inhibit nitrous oxide emissions, some of which have proven effective at least during composting.[40] Other approaches that may improve performance and reduce costs include integrating systems into initial barn design and construction that help separate urine, which is high in nitrogen, from feces, which are high in phosphorus.[41]

Although solid separation receives relatively little attention in the mitigation literature, it represents both a good technology for initial implementation and one that farmers are likely to improve over time. It has many characteristics that make it promising across multiple farms:

- Because even simple separation can help to reduce emissions, solid separation is not an all-or-nothing strategy. Opportunities exist for incremental improvements, which in turn create opportunities for the kinds of small-scale innovations that tend to push down costs.
- Unlike some technologies, small farms should be able to employ solid separation because the technology should scale up or down according to the size of the farm and the costs will depend mainly on the quantity of manure.
- Solid separation is a pretreatment technology for almost all other likely advanced manure management techniques, whether designed to reduce emissions or other air and water pollution problems.
- Once systems are installed, farmers will have incentives to make them work well to reduce hauling costs and to increase the value of the use of nutrients.

Mitigating manure managed as a liquid

Manure that is currently stored as a liquid in lagoons or smaller storage facilities presents the largest opportunities for mitigation because the manure provides a concentrated source of emissions. Based on GLEAM data, wet manure generates 90 percent of pig farm emissions globally. Studies and experience with manure management systems for pig farms in the U.S. state of North Carolina illustrate the potential, given some financial encouragement (Box 25-1). In that state, roughly $15 million of research and development funding, distributed competitively, resulted in development of a sophisticated wastewater system that would virtually eliminate not just GHGs but all other forms of air and water pollution, odor, and disease risk. The system should add only around 2 percent to the retail price of pork.[42] These technologies emerged without the advantages of "learning by doing" or economies-of-scale production. They suggest that with more incentives, broader application, and without the need to meet such stringent standards for other pollutants, variations in liquid manure technology would likely emerge at even lower costs.

Digesters and covered storage

Advanced manure management has focused much of its attention on systems that "digest" manure, so these systems merit special attention here. One lesson from substantial work to date is that digesters have promise for manure already managed in wet systems but are unlikely to reduce overall emissions from manure otherwise managed in dry systems. A second lesson is the critical importance of controlling leaks wherever digesters are used, whether low-technology digesters in poorer countries or higher-technology digesters in rich ones.

Digesters typically confine liquid manure without oxygen to generate and capture methane, which is then often burned to provide heat or to make electricity. Digesters can be large and simple (e.g., lagoons covered with plastic tarps), large and more sophisticated (e.g., various forms of metal tanks), or small and simple (e.g., small clay or brick structures). In developed countries, where digesters are mostly large, the gas is typically used to run an electric turbine or cleaned of its many impurities and fed into a natural gas grid. These steps greatly raise the cost despite the energy they generate. For a 700-cow dairy operation in the United States, the overall costs of installation including the electricity-generating turbine may be $4 million. Operating costs can be high—as much as the annualized cost of the installation.[43] By contrast, household-level digesters in developing countries typically feed the gas back for use by the households, which is inexpensive and provides a cheaper, easier, and cleaner source of energy than wood or charcoal—even if the gas contains impurities that would fail the standards of most grid systems. The vast majority of the world's digesters are in developing countries, with 7 million in just five large Asian countries.[44]

Digesters were generally developed not to reduce GHG emissions but to provide energy and to reduce odor and organisms that cause disease. Whether they reduce emissions depends on how much they leak and whether farmers would otherwise manage their manure wet or dry. With no leaks in either the digester or in transport and use of the gas, a digester and its ultimate use should eliminate all the methane and convert it to carbon dioxide, a much less potent GHG. But leaks raise concerns. The IPCC accounting guidance establishes a high, default emission factor for digesters of 10 percent of the methane-producing potential of the manure. In addition, the liquid "digestate" that comes out of the digester is itself stored in a covered form and continues to generate methane. Unless this digestate is itself captured and its methane recovered, it can add leakage of an additional 10 percent or more of the total methane produced by the digester.[45]

In contrast to the IPCC standard leakage rates of 10–20 percent from digesters, the IPCC estimate of methane emissions from manure stored in dry form is 4 percent. As a result, switching from dry storage to a leaky digester would increase methane emissions (and the reduction in nitrous oxide emissions would typically not make up the difference).[46] At typical leakage rates, even factoring in use of the energy to displace fossil fuels, switching from dry manure to wet manure managed by a digester is likely to increase emissions.[47]

By contrast, the IPCC default emission factors for wet manure systems are much higher. The standard emission rate for a lagoon, typically a large earthen pond, is around 70 percent of the methane-producing potential of the manure in the lagoon. The

BOX 25-1 | The opportunities for improved manure management on North Carolina pig farms

Eastern North Carolina experienced massive growth in large-scale pork production in the 1980s and 1990s. The management of manure in large, open lagoons contributed to a wide array of local problems including obnoxious odors, air pollution, nitrogen enrichment, pathogens, and dangerous algal blooms in North Carolina's principal estuary. Large fish kills occasionally occurred when lagoons broke or were flooded.[a]

After legal action from the state government, the principal pork producer and pig purchaser in the state agreed to provide $15 million to fund research into "environmentally superior" manure management technologies under the supervision of North Carolina State University. It also agreed to implement any such technologies found to be economically feasible by the university. Reflecting the many other concerns about manure, the criteria for "environmentally superior" were stringent but unrelated to climate change: technologies must substantially eliminate all pathogens, threat of nutrient pollution, odor, and air pollution.

The project's conclusions in 2006 were in one sense a disappointment because the university found that no technologies qualified as economically feasible. Yet the economic analysis for the study assumed that pork facilities in North Carolina alone would implement these technologies, so anything more than trivial costs would put them at a competitive disadvantage with farms in other states. The study did not analyze whether requiring all pork producers in the United States to control their pollution would be economically advantageous.

Review of the findings of that study indicates that even an extraordinarily sophisticated, tank-based manure management system would cost-effectively reduce GHG emissions without even factoring in the other pollution-reduction benefits. This system employed a series of tanks to separate pollutants, flocculent chemicals helped to achieve high levels of solid separation, and alternating tanks with and without oxygen drove out the nitrogen.[b] Although the system in effect employed the most advanced technologies of sewage waste management, we estimate from the project's documents that the system would mitigate emissions at a cost of only $22 per ton of CO_2e, while eliminating 99 percent of the methane emissions.[c] Costs for other manure management systems studied, ranging from simple covering of lagoons to more complex digesters, ranged from $12 to $55 per ton of CO_2e, excluding any GHG savings from fossil fuel use and any economic value of the solid material left over after digestion.[d] If judged in relation to the mitigation costs that will be involved in meeting global GHG emissions targets, these costs are not high. In fact, the GHG reduction could be considered free from a social perspective, although not to the pork producers, because of the large cobenefits from reduced water and air pollution, odor, and risk of disease.

If all pork producers were required to implement these manure management measures, they would add most of the additional cost to the product price. However, the cost of the tank system for an average farm would represent 1.4 to 2.5 percent of the average retail price of pork over the past six years in the United States. That cost is much smaller than the fluctuations in pork prices during this time.[e]

Notes:

a. National Geographic (2014).

b. Oxygen tanks turn other forms of nitrogen into nitrate, and tanks without oxygen break down the nitrate into nitrogen gas.

c. Costs for the treatment technology are from Vanotti et al. (2013) and are provided per pig in the form of SSLW/year (steady state live weight per year). Griffing et al. (2004) Table 50, estimated methane emissions at 21,353 kg/1,000 pigs of 45 kg weight average. At the most recent 100-year global warming potential (GWP) of 34, that translates into 726 tons CO_2e. Zering et al. (2013) estimate costs of the "tank system" on a large pig farm in North Carolina at $158 per SSLW/year and costs for more typically sized farms ranging from $202 to $280 per SSLW/year. The unit dollars per 1,000 SSLW translates into dollars per 10 pigs of this weight. As a result, manure management systems capable of handling 100,000 SSLW are needed to address these emissions of 726 tons, which equals 100 x $158 or $15,800 per year. Assuming 99 percent abatement of methane, this calculation results in a cost estimate of $22 per ton and even assuming abatement of only 95 percent only increases that cost to $23 per ton.

d. This figure uses the same method as above except it uses digester costs based on Zering et al. (2006) and updated by communication with Kelly Zering, November 3, 2016.

e. USDA/ERS (2015b) averages annual prices from 2010–15.

emission rate for a smaller “slurry tank” is around 35 percent. As a result, switching from wet manure systems to digesters should reduce emissions, even if digesters have 10–20 percent leakage rates.

Even so, the benefits are not certain. Digesters produce energy more efficiently if they combine manure with food waste, so this is a common practice. Because this food waste typically would generate less methane if left alone in a landfill—the combination of digesting manure and food waste will likely lead to higher overall methane emissions from even a moderately leaky digester.[48] Fortunately, studies show that leakage rates from sophisticated digesters can be kept to a few percent.[49] If those low leakage rates are achieved, digesters can achieve large mitigation benefits.[50]

In developing countries, where the vast majority of the world’s digesters are located, the GHG benefits are especially contingent on controlling leaks. In typical, simple digesters, methane is likely to leak from the input and output components and from cracks in systems that are not well maintained.[51] Because the biogas is typically used directly by households, biogas production sometimes exceeds household needs and is deliberately vented to avoid harm to the digester. Studies in the south of Vietnam estimated these intentional releases at 34 percent of the biogas (and therefore of the methane), while a study in the north of the country estimated intentional releases at only 7 percent. Because the alternative manure management system is likely to be dry storage, the potential for savings from the use of digesters in manure management alone is doubtful.

Yet even in these systems, the potential for overall GHG savings exists if the biogas replaces coal or wood harvests as a source of energy or enables more efficient use of the manure as fertilizer. Factoring in these nonmanure benefits, one study estimated that even quite leaky digesters could reduce overall emissions on small farms in Asia.[52] Digesters also provide important cobenefits, including reduced disease-bearing organisms, improved water quality, and replacement of inefficient indoor stoves—which reduces unhealthy indoor smoke and wood cutting. One Chinese study used scanning devices to detect household-based digesters and observed lower leakage rates than those generally found in other Asian studies (although the study probably did not capture intentional venting).[53] This finding suggests that inspection systems may be feasible and could help identify and reduce leakages.

Overall, the lesson is that digesters could provide a viable means of controlling manure management emissions—particularly using more sophisticated digesters to control wet manure—but only if they are properly managed to control leaks both from the digester itself and from the storage of the digestate liquid that comes out of the digester.

In addition to the leakage challenge, the large up-front costs of installing sophisticated digester systems tend to inhibit their use. The main costs relate either to the turbine and related components if the biogas is used to generate electricity, or to cleaning the biogas so that it can be used as natural gas in developed countries. A simpler alternative is to cover a lagoon or storage pit with an impermeable plastic cover and to capture the gas and burn it. Doing so converts methane to carbon dioxide, which has a much smaller warming potency. The cost is more modest in part because a cover helps reduce hauling costs by reducing the addition of rainwater. Cost-effectiveness also increases with larger operations.[54]

Model Results: Mitigation Potential

Any effort to properly evaluate the costs of mitigating GHG emissions from manure must start with the enormous environmental and social problems presented by badly managed manure. Leaking storage systems contribute to groundwater pollution and drinking water problems.[55] In China, the world's largest producer of pork, some 30–70 percent of manure is discharged directly into water bodies without any treatment, creating the primary source of pollution that causes algal blooms and dead zones in the South China Sea.[56] The southeastern United States experienced massive flooding during Hurricane Florence in September 2018, when at least 60 hog farm lagoons overflowed, releasing contaminated water into surrounding communities.[57] Ammonia also contributes to serious air pollution problems.[58] Manure carries disease-bearing organisms that pose health risks, and ammonia emissions often contribute substantially to small-particle air pollution, a major source of ill health in humans and animals. And large feedlots often cause major odor problems for surrounding communities, which can even be unhealthy.

These concerns, not GHG emissions, have to date driven most efforts to improve manure management. Health concerns and the need to mitigate the impacts of climate change together justify more vigorous action to manage manure effectively.

We used GlobAgri-WRR to test three GHG emissions mitigation scenarios for managed manure (Table 25-1). Although the mix of farm systems changes between 2010 and 2050, our 2050 baseline projection assumes that the share of each type of manure management system for each type of farm remains unchanged. Based on our analysis above, we believe that 90 percent reductions in methane are possible from wet manure systems. For dry manure pork production systems, the study of pig farms in China described earlier suggests that 60 percent reductions in nitrous oxide emissions (but no change in methane emissions) are achievable with good solid separation.[59]

Less research has been conducted into dry beef and dairy systems, so the evidence is not clear. However, dry systems tend to leave manure uncollected for long periods in feedlots, and there is evidence that collecting and distributing the manure more frequently can reduce nitrogen losses by 20–30 percent.[60] Although we do not expect large gains from animal dietary changes, we believe that 10 percent reductions in nitrous oxide from feed changes are plausible. Based on these considerations, we develop the following scenarios:

- In our first scenario, we assume mitigation of 40 percent of the methane from manure that is managed in wet form.
- In a second scenario, we assume that all farms, including both wet and dry manure farms, reduce their total manure management emissions by 20 percent. We include this scenario for perspective but consider it less realistic.
- In our most optimistic scenario, we assume 80 percent reduction of emissions of methane from wet manure, 20 percent mitigation of methane emissions from dry manure, and 20 percent mitigation of nitrous oxide emissions from all manure.

These scenarios reduce emissions from managed manure (relative to 2050 baseline) by 13 to 37 percent.

Table 25-1 | Global effects of manure management scenarios on agricultural greenhouse gas emissions

SCENARIO	MANURE MANAGEMENT EMISSIONS (MT CO_2E)	TOTAL PRODUCTION EMISSIONS (MT CO_2E)	PRODUCTION EMISSIONS GHG MITIGATION GAP (GT CO_2E)
2010	**588**	**6,769**	**–**
No productivity gains after 2010	972	11,251	7.3 (2.2)
2050 BASELINE	**770**	**9,023**	**5.0**
40% reduction in methane emissions from wet manure *(Coordinated Effort)*	673 (–13%)	8,925	4.9 (-0.1)
20% reduction in manure management emissions across all farms *(Illustrative, not included in any combined scenario)*	617 (–20%)	8,869	4.9 (-0.2)
80% reduction in wet manure emissions, plus 20% reduction of all other manure management emissions *(Highly Ambitious, Breakthrough Technologies)*	489 (–37%)	8,742	4.7 (-0.3)

Notes: Numbers not summed correctly are due to rounding. Numbers shown in parentheses are changes relative to 2050 baseline.
Source: GlobAgri-WRR model.

Recommended Strategies

We make a number of specific recommendations:

Build spatial databases of large concentrated livestock facilities. Information about manure management is remarkably rough because in most of the world there has been no effort to map and identify the types and levels of manure management systems used, even on large livestock operations. That not only frustrates analysis but also inhibits action. By contrast, Denmark not only tracks information on every substantial pig and dairy farm but tracks each animal as well. As a first step, governments need to develop reasonable data on each sizable livestock operation and its manure management system.

Adopt regulations immediately to require improved manure management on all new farms, as well as on all medium and large concentrated livestock farms that currently use wet manure management systems. New livestock farms can more easily incorporate at least basic solid separation into their design. Even in parts of developing countries without power, farms can use gravity systems to help separate solids and liquids. Standards should be extended to increasing numbers of existing farms over time. In this way, sounder manure management by 2050 should be feasible.

Many of the farms that manage manure in wet form are relatively large, commercial operations,[61] particularly pig farms. In the U.S. pork industry in 2012, for example, just 13 percent of pig farms held 2,000 or more pigs, but these farms held 87 percent of all pigs nationally.[62] These farms should also be required to meet the standards for new operations. Based on the technology analysis in North Carolina, governments of wealthier countries should require that farms emit methane and other pollutants at no more than 10 percent of the rate of today's standard facilities. To avoid placing facilities at a competitive disadvantage, regulations should be adopted at the national or regional level. Large food companies should also adopt standards to require proper manure management by their suppliers.

Phase in regulation of all existing livestock operations with managed manure systems, focusing on livestock purchasers. One goal of any regulatory system should be to find the cheapest options for mitigation first, which allows technology to improve and become cheaper before addressing more expensive challenges. For manure management, this would likely entail imposing regulations on larger wholesale operations and requiring increasingly large percentages of their product over time to come from farms certified as meeting higher manure management standards. For example, in the United States in 2012, five large firms controlled 62 percent of the nation's pig slaughtering capacity.[63] To facilitate this ratcheting up of standards, the government could issue certificates to farms that meet different standards of emissions per kilogram of meat or milk or, if easier, per animal. Wholesalers would then be required to hold certificates sufficient to demonstrate that they meet increasingly stringent targets of emissions per kilogram of meat or milk. Wholesalers would pass on the bulk of these costs to consumers and reimburse the costs borne by producers who meet manure management standards by purchasing certificates. Such a system would encourage improved management by those farms that could do so at the least cost. If such a system assigned more credit to farms that meet higher standards of performance, it could also create powerful incentives for innovation and improvement wherever cost-effective.

Adopt competitive programs to encourage new technology. The challenge in manure management is often just to refine mechanical and chemical engineering approaches for handling manure. These are engineering challenges well suited to the capabilities of the private sector, which can build upon waste-treatment technologies already developed for industrial wastes and municipal sewage. Governments can play a role by establishing competitive grants programs for private companies, based on criteria such as cost, environmental performance, and promise of technological improvement.

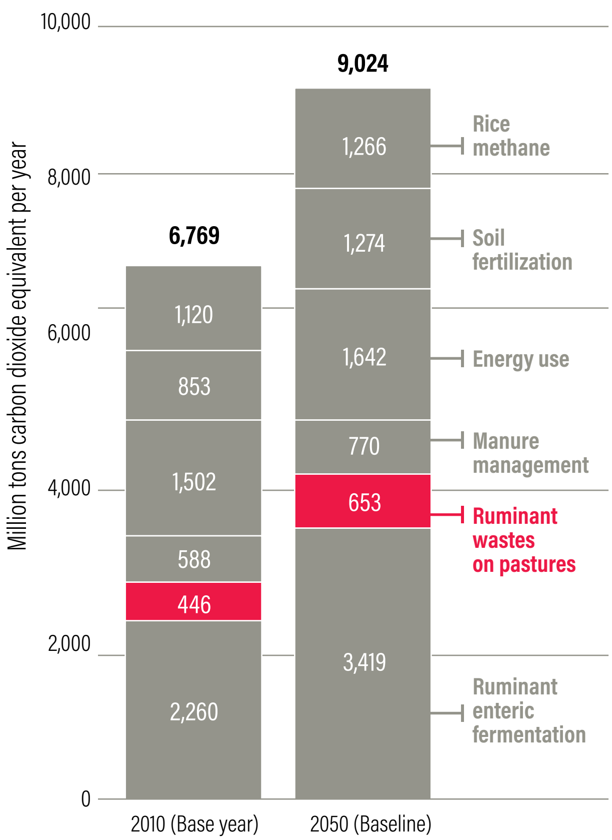
Adopt inspection systems to monitor digester leaks. For manure management systems using digesters, particularly in developing countries, governments should require future use of digester technologies with lower leakage potential. In addition, governments should adopt inspection systems that use methane detectors to monitor leaks.

CHAPTER 26

MENU ITEM: REDUCE EMISSIONS FROM MANURE LEFT ON PASTURE

Manure deposited by cattle, sheep, and goats on grazing lands or in paddocks can concentrate nitrogen in carbon-rich, saturated conditions that encourage the production of nitrous oxide by microorganisms. Manure consists of both feces and urine, and, in general, urine contains most of the nitrogen and generates nitrous oxide at a greater rate than feces. Reducing emissions from pasture manure is challenging because sources are diffuse; biological and chemical nitrification inhibitors hold the most promise.

Figure 26-1 | Greenhouse gas emissions from agricultural production, 2010 and 2050



The Challenge

According to standard emission factors used by the IPCC, nitrogen deposited in feces and urine turns into nitrous oxide roughly twice as fast as nitrogen in fertilizer. According to FAO (reported in FAOSTAT), these deposits, all from ruminants, are rising rapidly, contributing 800 Mt CO_2e emissions in 2010 and 846 Mt CO_2e in 2014. Our estimate, using GlobAgri-WRR, is substantially lower at 446 Mt CO_2e in 2010, and we project emissions of 653 Mt CO_2e by 2050 (Figure 26-1). FAO bases its estimates on the number of animals, assuming the same emissions per animal, whereas GlobAgri-WRR uses a method based on estimated nitrogen in excretions from different animals based on what they eat. Regardless of which source is used, these emissions are on a course to be substantial in 2050, and even our lower projection would contribute 16 percent of the total allowable emissions from agriculture (4 Gt target) in 2050.

As with enteric methane, one way to reduce emissions from unmanaged manure is to improve efficiency; that is, to improve the output of product per animal and per kilogram of feed. Under our "no productivity gains after 2010" scenario, emissions from unmanaged manure would reach 871 Mt CO_2e in 2050 (Figure C5-1), but our baseline estimates 25 percent fewer emissions due to the efficiency gains built into our baseline. Our Course 2 scenario that involves a higher efficiency target for livestock (discussed in Chapter 11) could reduce these emissions only modestly to 630 Mt in 2050. Even our 30 percent reduction in ruminant meat consumption scenario (Chapter 6) would only reduce these emissions to 524 Mt in 2050. Finding additional ways to reduce these emissions is therefore necessary.

The Opportunity

Other studies typically estimate little to no global potential to mitigate this source of diffuse emissions.[64] We are more optimistic, but our optimism rests on further development of some technologies that have shown good potential but are not yet ready for deployment. They focus on "inhibiting" the formation of nitrate.

Livestock deposit nitrogen primarily in the form of urea (CH_4N_2O). Through biochemical processes mediated by bacteria and archaea in soils, urea is typically converted into ammonia (NH_3), ammonium (NH_4+), and then nitrate (NO_3-). Nitrous oxide (N_2O) is primarily released by the bacteria that break down nitrate in waterlogged conditions, and, although the quantity is small, the warming effect is great because of the potent warming effect of nitrous oxide. Because nitrate is soluble in water and does not adhere to soils, it is also the primary form of nitrogen that runs off of fields or leaches into groundwater, causing water pollution. Inhibiting the formation of nitrate in soils reduces both losses of nitrogen through water runoff and leaching and emissions of nitrous oxide.

Spreading nitrification inhibitors

One way to reduce these emissions involves spreading chemicals that inhibit nitrification directly on pastureland. Most experiments have used dicyandiamide (DCD), the most commonly used inhibitor. A summary of six experiments using DCD on grazing land found reductions in nitrous oxide ranging from 17 percent to 88 percent.[65]

Inhibitors do not persist in their effects, however, particularly under higher temperatures, so a one-time application is not sufficient. In New Zealand, the practice has been to spread the inhibitor twice per year, each time shortly after animals are moved away from a field, when grass is grazed down and farmers can directly apply the inhibitors to the urine patches, which typically cover 20 percent of a field.[66] One study in the warmer parts of New Zealand suggested that three applications per year would be needed to achieve high effectiveness there because of a higher breakdown rate. Although bacteria might be able to develop resistance to inhibitors, no studies have yet shown this effect.[67]

The practicality of using inhibitors in this way also depends on the size of fields and on the effects of inhibitors on grass yields. Inhibitors are most likely to be practical and economical on farms such as dairy farms in New Zealand, where intensive, rotational grazing is practiced on generally well-watered, highly managed fields, and where grazing is concentrated in relatively small areas. Research studies in New Zealand have typically found positive effects of inhibitors on grass yields from 15 to 36 percent, although these studies are not necessarily representative of real, commercial operations.[68] Other studies in both New Zealand and the United Kingdom have found no beneficial effect on pasture yield, which suggests variability in inhibitor performance.[69] Use of inhibitors is likely to be less practical on more extensively managed grazing lands, although these lands will receive less manure and therefore produce fewer emissions per hectare.

Feeding nitrification inhibitors

An alternative approach to inhibiting nitrification involves feeding inhibitors directly to animals. A few studies have found that adding inhibitors to water or livestock feed provides effective reduction of both nitrous oxide emissions and nitrogen leaching, and that most of the inhibitor passes through the animal in the urine.[70] This method would be easier than pasture application and would probably require less inhibitor to be effective.[71] However, the inhibitor would probably need to be ingested frequently, even daily, by the animals.

Feeding inhibitors through water or feed does raise health issues. Although toxicological studies of DCD have found very low toxicity,[72] the lack of an agreed international safety standard caused New Zealand to suspend use of DCD in 2013 after trace levels were found in milk.[73] One New Zealand study also found that DCD washed off into freshwater ecosystems, where it might affect natural nitrification rates.[74] These concerns need to be thoroughly researched for any nitrification inhibitor, although the low toxicity ratings of DCD so far suggest that it could satisfy these health and environmental concerns.

Breeding biological nitrification inhibition

A third opportunity involves breeding and selecting grasses that inhibit the conversion of ammonium to nitrate, which is the first step in the process of generating nitrous oxide. Many studies have now found extremely low rates of nitrous oxide formation in fields of *Brachiaria humidicola*, which is one variant of the African *brachiaria* grass family used extensively in Brazil.[75] This "biological nitrification inhibition" appears to be due in small part to stronger root uptake of nitrogen but in larger part to a chemical exuded by the roots of the grass (brachialactone), which blocks a key enzymatic pathway in the formation of nitrate. The production and exudation of this chemical varies widely among plants, but it has been found at significant levels in another *brachiaria* species (*Brachiaria decumbrens*).[76] It is also plausible, although not yet tested, that cattle consuming one of these grass species will excrete some of the chemical in their manure, which would also help to inhibit nitrous oxide production.

The results suggest in part that more widespread use of *Brachiaria humidicola* could reduce emissions. But this species is useful only in tropical and subtropical areas. It constitutes only a small percentage of total *brachiaria* use in Latin America, and its preferential use compared to other species depends on many agronomic factors. For grazing purposes, the alternative is to breed this inhibitory effect into other grass species.

Mitigation Potential

An important question for estimating mitigation potential is whether the present emission factors used by the IPCC are too high. The IPCC Tier 1 sets an emission factor of 2 percent of nitrogen in manure turning into nitrous oxide, which is double the rate assumed for fertilizer and is based on older measurements in temperate countries. A variety of recent evidence suggests lower rates. Because emissions require a high level of soil saturation, emissions factors in hotter and drier climates, where urine patches dry out quickly, should be substantially lower, which is the finding of several recent studies.[77] Even in wetter, temperate countries, some studies are finding lower emission factors, for example in New Zealand and the United Kingdom.[78]

Despite this evidence, there is a growing discrepancy between field-level estimates of nitrous oxide emission rates, studies that use flux towers, and studies that use modeling based on patterns of nitrous oxide sensed in the atmosphere by satellites.[79] It is already difficult to reconcile IPCC emission factors with measured global nitrous oxide levels, and estimated emissions rates that are lower than IPCC figures—whether from pasture or cropland—would create larger inconsistencies. One likely explanation is that the rates vary greatly depending on a range of soil and temperature conditions. There are also likely hotspots—areas that are more frequently saturated or that have the right acidity, which result in large releases of nitrous oxide.[80]

These differences could present an opportunity. Identifying hotspots would allow mitigation to focus on them. Mitigating nitrous oxide emissions from manure deposited on extensive grazing lands in arid regions would be difficult because urine patches will be spread over large areas, farmers do not provide daily feed supplements, and farmers do not use planted grasses. If evidence continues to confirm low emission rates from extensive grazing in more arid areas,[81] mitigation in these areas could be ignored. Mitigation efforts could then focus on more intensive grazing systems in wetter areas.

Overall, although promising technological approaches exist to mitigate nitrous oxide emissions from grazing operations, they all are too little developed to allow refined estimates of mitigation potential. We exclude additional mitigation in our Coordinated Effort scenario because all progress relies on some degree of technological improvement. We also assume that mitigation on arid grazing land will be economically or practically unfeasible because the emissions are too low to justify the expense of addressing them. We assume mitigation improvements on wetter grazing lands of 20 percent and 40 percent in our Highly Ambitious and Breakthrough Technologies scenarios, respectively. Finally, for illustrative purposes, we show one scenario with 60 percent mitigation on wetter grazing lands (Table 26-1).

Recommended Strategies

Because solutions for this source of emissions are underdeveloped, research and regulatory incentives have to focus on ways to develop them.

Increase research funding

The most obvious recommendation is that governments and research agencies should substantially increase research funding into methods for reducing nitrification of nitrogen on pasturelands. Three initiatives are appropriate:

Table 26-1 | Global effects of scenarios of emissions reductions from manure left on pasture on agricultural greenhouse gas emissions

SCENARIO	NITROUS OXIDE EMISSIONS FROM PASTURE, RANGE, AND PADDOCK (MT CO_2E)	TOTAL PRODUCTION EMISSIONS (MT CO_2E)	PRODUCTION EMISSIONS GHG MITIGATION GAP (GT CO_2E)
2010	**446**	**6,769**	**–**
No productivity gains after 2010	871	11,251	7.3 (2.2)
2050 BASELINE and Coordinated Effort	**653**	**9,023**	**5.0**
20% reduction of nitrogen left on wetter pastures *(Highly Ambitious)*	584	8,954	5.0 (-0.1)
40% reduction of nitrogen left on wetter pastures *(Breakthrough Technologies)*	515	8,884	4.9 (-0.1)
60% reduction of nitrogen left on wetter pastures *(illustrative, not included in any combined scenario)*	445	8,814	4.8 (-0.2)

Notes: Numbers not summed correctly are due to rounding. Numbers shown in parentheses are changes relative to 2050 baseline. Coordinated Effort scenario assumes no reduction in nitrous oxide emissions relative to levels projected in the 2050 baseline.
Source: GlobAgri-WRR model.

- **Research into development and uses of nitrification inhibitors.** Virtually all published research on their use in pastures comes from a few small research groups in New Zealand. Other countries need to expand these efforts.

- **Research into biological nitrification inhibition.** Analysis of biological nitrification inhibition is currently being undertaken by a small cooperative effort of four research institutions coordinated by the Japan International Research Center for Agricultural Scientists and the International Maize and Wheat Improvement Center. Not counting the salaries of participating researchers, the budget for their research is roughly $1 million per year.[82] A budget of tens of millions of dollars would be the minimum appropriate for this research given its level of importance and the many ways additional research could be performed.

- **Research on agricultural emissions rates**. As the discussion above indicates, it is likely that emissions rates of nitrous oxide vary greatly from one area to another and are concentrated in certain hotspots. Although some research shows these effects, it is not systematic. Field analyses have become cheaper, however, and can be combined with measures from tall towers and satellites. The world needs a comprehensive, international initiative to identify these hotspots and emissions rates.

Create private regulatory incentives

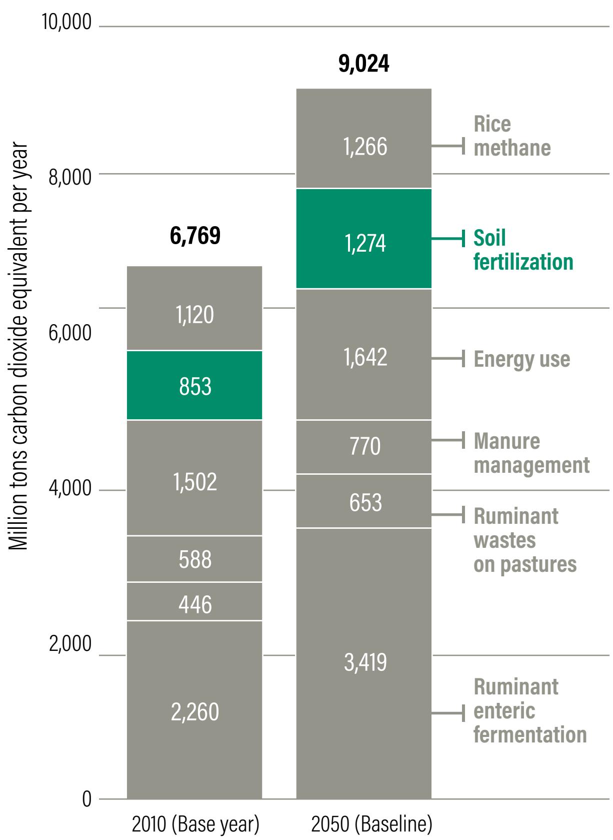
Opportunities also exist to craft regulations that give incentives to industry to develop workable new technologies by guaranteeing them a market. For example, governments could promise to require use of nitrification inhibitors on an increasing percentage of farms if industry could demonstrate products or technologies that achieve a specified level of nitrous oxide reduction at a specified cost per ton of nitrous oxide saved. We elaborate on these regulatory opportunities at the end of this course.

CHAPTER 27

MENU ITEM: REDUCE EMISSIONS FROM FERTILIZERS BY INCREASING NITROGEN USE EFFICIENCY

Less than half of the nitrogen added to crop fields is absorbed by crops and the remainder contributes to emissions and other forms of nitrogen pollution. This menu item involves increasing the efficiency of nitrogen use, in significant part by focusing on the composition of fertilizers themselves, to reduce both the quantity of fertilizer required and associated emissions.

Figure 27-1 | Greenhouse gas emissions from agricultural production, 2010 and 2050

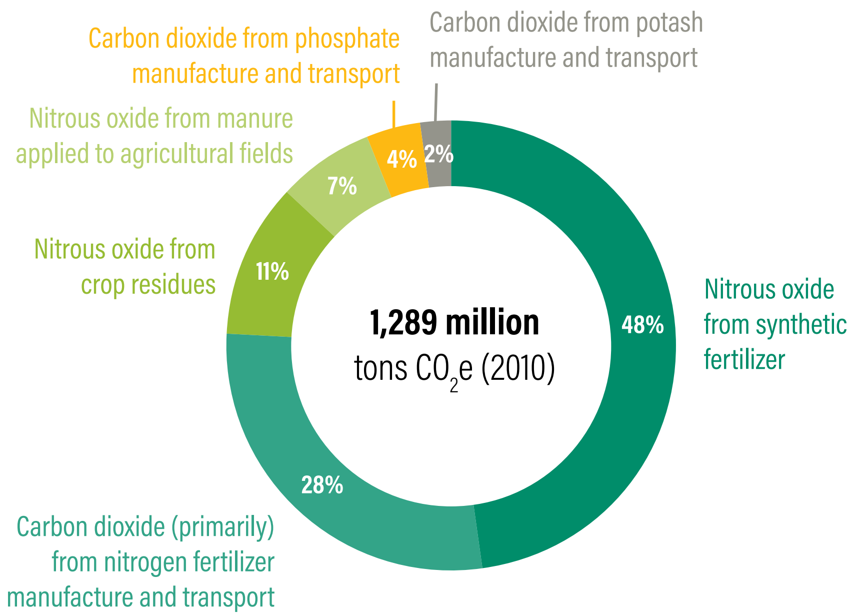


The Challenge

Although fertilizing crops with nitrogen, phosphorus, and potassium—the major nutrients—is vital to achieving high crop and pasture yields, it also contributes substantially to GHG emissions. Using GlobAgri-WRR, we estimate fertilizer emissions in 2010 at 1,289 Mt CO_2e, of which 94 percent resulted from nitrogen use (Figure 27-1). Two-thirds of these nitrogen emissions were in the form of nitrous oxide emitted in crop fields from all forms of applied nitrogen; the other one-third came from the energy used in the manufacture and transportation of nitrogen fertilizer (Figure 27-2).[83] (Because fertilizer production is so energy-intensive, and because more efficient nitrogen use would substantially reduce these emissions, we discuss emissions from fertilizer manufacture both in this menu item and in our menu item focused on ways of reducing fossil energy use.) Synthetic fertilizer accounts for roughly half of all nitrogen fertilization,[84] the other half comes from manure applied to crops (excluded from manure management calculations), the residues of nitrogen-fixing crops such as soybeans, nitrogen in rain, irrigation water and air dust; and even nitrogen fixed by freely associated microorganisms in soil.

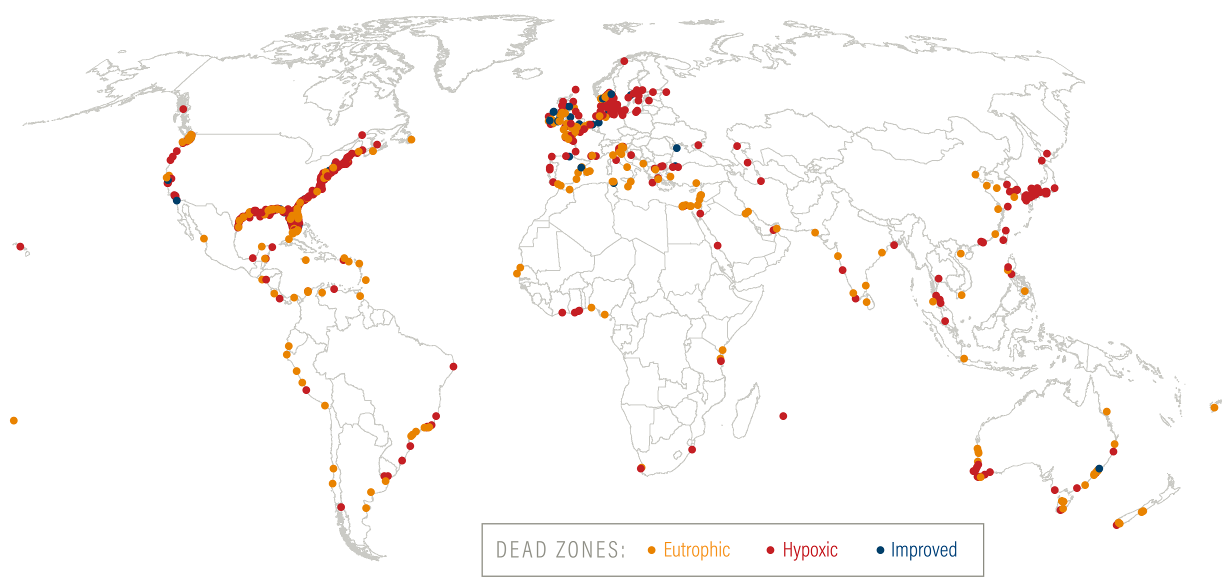
Fertilizer (mineral and organic) also contributes to a variety of other environmental challenges. These include small particulate smoke and smog (technically ground-level ozone), which are the leading air pollution problems for human health.[85] Agricultural runoff is the principal cause of unsafe levels of nitrate in drinking water from wells or rivers in many areas in the world. When nitrogen runoff or leachate into rivers reaches coastal waters, it can contribute to algal blooms, some of which are toxic to fish and other sea life. Other algal blooms lead to hypoxia—a condition where coastal waters have little or no oxygen—also called “dead zones.” Both types of blooms have been increasing in size and frequency and now contaminate large portions of major water bodies such as the Gulf of Mexico, the Chesapeake Bay, and the China Sea during certain seasons. Figure 27-3 maps 762 overfertilized coastal waters around the globe.[86] Phosphorus runoff also contributes to algal blooms and dead zones in lakes and rivers and in brackish coastal waters, which mix fresh and saltwater.[87] One estimate suggested that alleviating the nitrogen contribution to environmental problems would require reductions in nitrogen losses to the environment of roughly one-half.[88]

Figure 27-2 | Approximately 94 percent of emissions from fertilizing soils are the result of nitrogen application



Note: This chart excludes emissions from manure left on paddocks and pasture, discussed above, and differs from FAOSTAT estimates in part because GlobAgri-WRR is based on nitrogen estimates underlying Zhang et al. (2015b) and nitrogen availability in manure from a livestock management component based on Herrero et al. (2013).
Source: GlobAgri-WRR model.

Figure 27-3 | More than 700 "dead zones" exist in the world's coastal waters



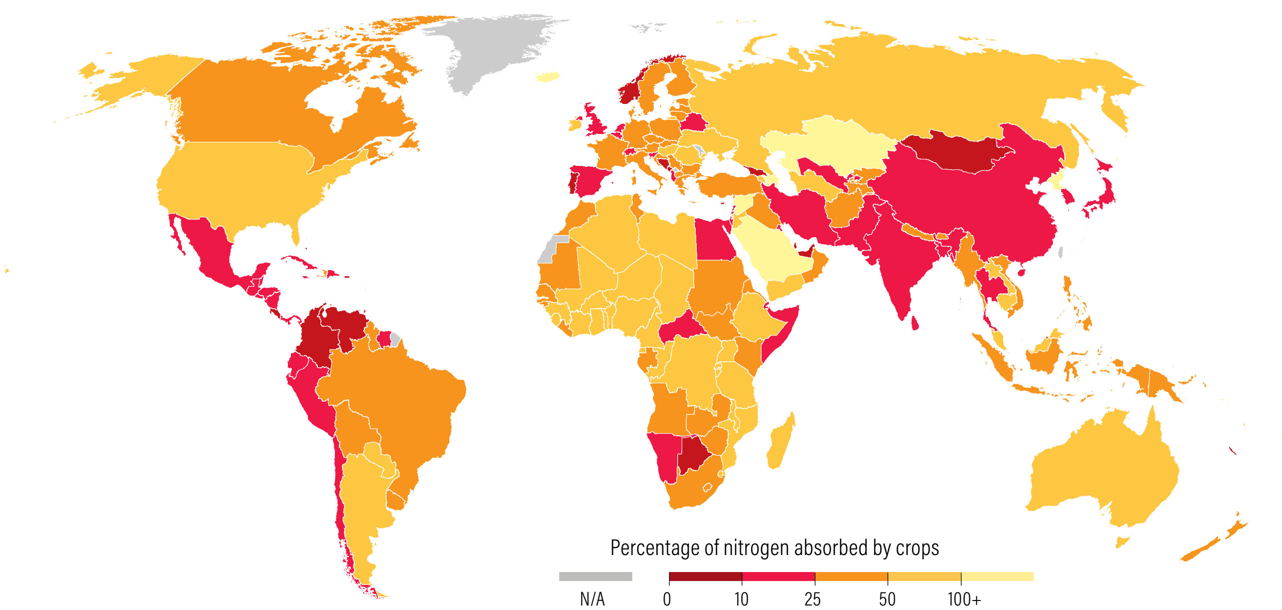
Note: Eutrophic water occurs when water bodies are oversupplied with nutrients and support rich plant and algal growth. Hypoxic water occurs when abundant plants and algae die and decompose, consuming oxygen and depriving other aquatic life of oxygen.
Maps are for illustrative purposes and do not imply the expression of any opinion on the part of WRI concerning the legal status of any country or territory, or concerning the delimitation of frontiers or boundaries.
Source: WRI (2013).

Increasing food production implies a growing demand for fertilizer and higher associated emissions and pollution. How much higher depends on how efficiently crops use nutrients. On a global basis, estimates of the efficiency with which crops absorb the nitrogen (from all sources) added to croplands range from only 42 to 47 percent.[89] As Lassellatta et al. (2014) found, this nitrogen use efficiency (NUE)[90] actually declined from around 68 percent to 47 percent between 1961 and 1980 as farmers around the world adopted synthetic fertilizers, and it has remained roughly at that level since.[91] Put another way, more than half of the nitrogen applied to crops is lost to the environment.

Countries differ greatly in both their NUE (Figure 27-4) and rates of nitrogen fertilizer application per hectare (Figure 27-5). Regions group into four broad categories. At one extreme, most countries in sub-Saharan Africa use little fertilizer, and whatever fertilizer they use is more fully absorbed by crops, leading to an average NUE of 72 percent and above.[92] At the other extreme, China and India—which accounted for 80 percent of the global increase in total nitrogen use between 2000 and 2009[93]—generally overapply fertilizer and have NUEs of roughly 30 percent.[94] In a third category, a few developed countries, such as the United States, Canada, and France, have NUEs approaching 70 percent. In the fourth category is the rest of the world which has NUEs of around 50 percent.[95]

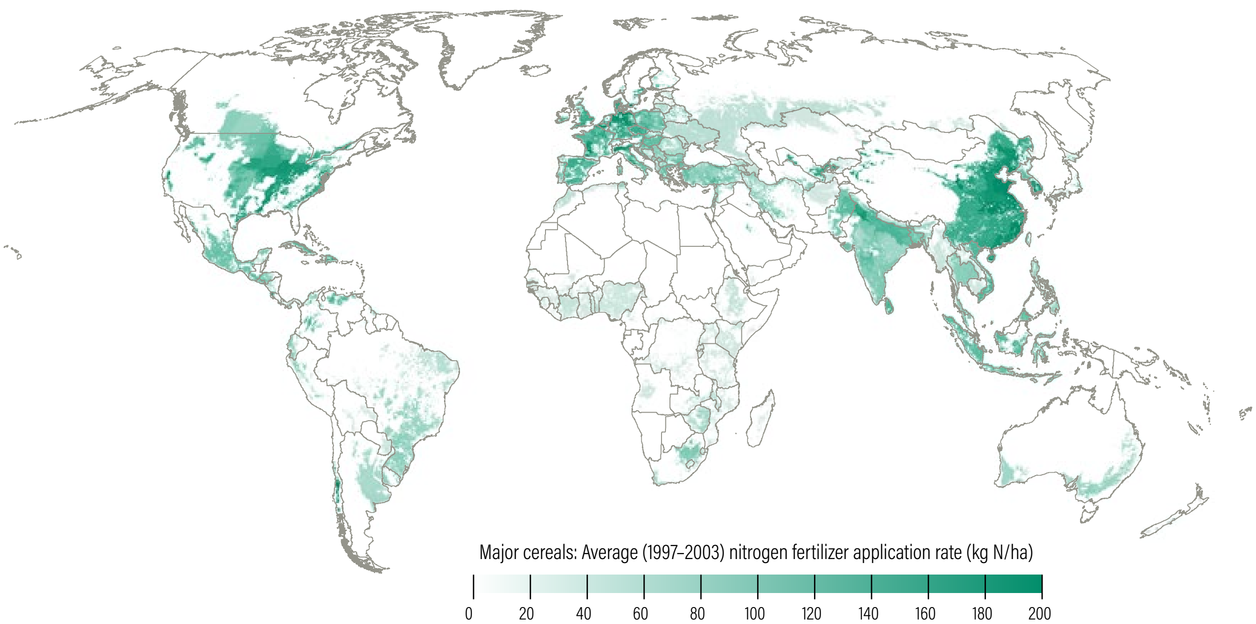
Rising NUEs in some regions and for some crops inspire confidence that increases in NUE are both possible and practical. The Netherlands, for example, cut back its nitrogen use from an astonishing level of around 600 kg per hectare in the late 1970s to around 300 kg in more recent years, mostly by exporting or processing some of the manure from the country's dairy farms instead of spreading it excessively on farm fields.[96] France, whose agriculture is more focused on crops, applies fertilizer at only a little more than half the per-hectare rate of the Netherlands. Total fertilizer application rates per hectare in France have remained stable now for many years. Yet yields in France have increased, meaning that fertilizer use per ton of crop has decreased, and NUE has increased from roughly 30 percent in the late 1970s to approximately 70 percent in 2010.[97] Nitrogen use efficiencies have also

Figure 27-4 | The percentage of applied nitrogen that is absorbed by crops varies widely across the world



Note: Absorption rates greater than 100 percent mean crops are mining nitrogen from soils. Maps are for illustrative purposes and do not imply the expression of any opinion on the part of WRI concerning the legal status of any country or territory, or concerning the delimitation of frontiers or boundaries.
Source: Zhang et al. (2015b).

Figure 27-5 | Total nitrogen fertilizer application is heavily concentrated in China, the United States, India, and Western Europe



Note: Maps are for illustrative purposes and do not imply the expression of any opinion on the part of WRI concerning the legal status of any country or territory, or concerning the delimitation of frontiers or boundaries.
Source: Mueller et al. (2012).

been growing in the United States, from roughly 60 percent in 1990 to around 70 percent in 2010, according to one study.[98]

Despite these improvements, there are reasons not to be overly optimistic about potential reductions in nitrous oxide emissions from fertilizer use.

First, in Africa, nitrogen use efficiency is likely to decline. The region's farmers today apply so little fertilizer that the annual removal of crops depletes the soils of nitrogen and phosphorus.[99] As farmers in Africa apply more fertilizer, which is necessary to boost yields, plants will be less able to absorb all the nitrogen and nitrogen use efficiency will decline.

Second, although Zhang et al. (2015b) showed that nitrogen use efficiency has stopped declining in most countries, and has improved in some, it has yet to start improving in most countries.

Third, major agronomic reasons help to explain the wide differences in NUE among countries. One reason China's NUE is so low is that it produces large quantities of rice and vegetables, which have low NUEs. Rice NUEs are low in part because the flooding and drainage required for paddy rice leads to increased nitrogen loss, while fruit and vegetable NUEs are low probably because their high economic value makes it economical for farmers to apply more nitrogen even when it leads to only modest additional production. According to Zhang et al. (2015b), half of the difference between NUEs in China and the United States is explained by China's crop mix.[100] In addition, farmers in countries with greater rainfall variability and less rich soils will find it harder to use nitrogen efficiently because crops will not be able to fully absorb available nitrogen in bad rainfall years. These differences help to explain why countries with similar yields for the same crops have different NUEs.[101]

Even for farming regions such as the U.S. corn (maize) belt that have achieved large increases in NUE, those increases have still been insufficient to reduce nitrogen losses to the environment because nitrogen used for higher production exceeds the nitrogen saved through higher efficiency.[102] Despite increases in NUE since 2005, U.S. agricultural nitrous oxide emissions have increased by 7 percent,[103] and the corn belt remains a global hotspot for nitrous oxide.[104] Over the same period, the region's contribution of nitrogen to the major dead zone in the Gulf of Mexico has remained roughly constant.[105]

Overall, studies reveal no clear trend line in NUE across different crops and regions.[106] For this reason—although some increases in NUE would also be plausible—our baseline 2050 projection assumes that farmers in each region will produce each crop with the same NUE as today. As a result, we project an increase of 48 percent in the use of nitrogen fertilizer from 2010 to 2050, which is roughly in the middle of other prominent estimates.[107] That increased use is likely to increase overall losses of nitrogen to the environment by roughly 50 percent.[108] We also project in our baseline that annual total emissions from fertilization will grow to 1,741 Mt CO_2e by 2050, an increase of 35 percent over 2010 levels.[109]

The Opportunity

Strategies for improving NUE typically focus on fertilizer management by farmers and these well-understood practices have an important role to play. But the scale of improvement required is so great that additional measures are necessary to exceed what farmers can achieve alone. We therefore focus also on measures to improve nitrogen fertilizer compounds themselves, as well as advances in breeding.

Better general agronomy and nutrient management

The traditional focus of fertilizer management has been characterized by the International Fertilizer Institute as the "Four Rs": the **r**ight source, at the **r**ight rate, at the **r**ight time, in the **r**ight place.[110] In effect, this means applying fertilizer at a rate that does not exceed what crops can use at a time when they can use it. As an example of improved timing, many farmers in the United States and Europe have split their nitrogen load into two applications. The right place means applying nitrogen to a plant's root zones. Some forms of nitrogen are injected into the soil to limit losses.

Despite these opportunities, improved NUE in the United States is probably due mostly to general improvements in agronomy. Data from the U.S. Department of Agriculture suggest that only 25 percent of cropland is fertilized in line with the "Four Rs" recommendations,[111] and that adoption of these recommended practices has not increased.[112] NUE improvements probably owe more to breeding crops with higher yields, which has simultaneously increased their nitrogen uptake efficiency.[113] In addition, there has been an overall increase in management intensity, including weed and pest control, optimal seeding rates, and improved irrigation practices. These changes have led to greater yield stability, which increases NUE because there is a greater likelihood that the nitrogen farmers apply will be used by the growing crop.

Manure management is also relevant because the concentration of livestock production today in many parts of the world leads to the "dumping" of excess fertilizer on nearby farm fields, much of which escapes to the environment. In Europe, the Nitrates Directive of 1991 has restricted the quantity of manure nitrogen applied per hectare. Despite some implementation exceptions, the directive has played a significant role in the improvements in some European countries, such as the Netherlands and Denmark, which apply a large quantity of manure to crop fields. The limits have often required transport of excess manure to where it can be well used.[114]

These experiences suggest that some technical potential exists everywhere to increase NUE without any major technological breakthroughs. The largest opportunities exist in China and India, where nitrogen overuse is high[115] (Box 27-1).

The United States and Europe also have potential to increase their NUE through more sophisticated "precision" agriculture. Many farmers already use precision agriculture techniques, which allow them to deliver different quantities of nitrogen to different portions of fields. Yet the information about precisely how much to deliver in different portions of fields is less developed. Researchers and industry are cooperating on some projects to develop more detailed and consistent data for analyzing how to adjust rates and application times in the corn belt, which should help to tailor recommendations more precisely.[116]

Alternative nitrogen fertilizer compounds

We project growth of more than 50 percent in the amount of crops that will need to be fertilized by 2050. This means that even if changes in farming practices using existing technologies were able to improve NUE globally by about 50 percent over the same period—a large ambition—the world would still need to use roughly the same amount of fertilizer that it does today. Because even greater increases in NUE will be required to reduce nitrous oxide emissions and other forms of nitrogen pollution, we believe that technological advances are also needed. We believe that significant opportunities exist to increase the use of fertilizer additives that can control the release of nitrogen into the environment and develop this whole class of technologies further.

Appreciating the importance of such compounds requires an appreciation of how important timing is to the efficient use of nitrogen. Most nitrogen fertilizer is applied as ammonium or a form of nitrogen (such as urea or ammonia) that quickly converts to ammonium in soils. Ammonium is relatively immobile in soils, but microorganisms convert it easily into nitrate. It is nitrate that is highly soluble in water and easily runs off, and it is the breakdown of nitrate when soils are waterlogged that leads to emissions of nitrous oxide.

If economics did not matter, farming could achieve high levels of nitrogen use efficiency by frequent applications of just enough fertilizer to feed crops for a few days. Crops generally need little nitrogen early in the growing season, large quantities of nitrogen at peak growth periods, and then little nitrogen thereafter.[117] Chen et al. (2011) describe a series of experiments in China that combined detailed crop modeling of maize by region to determine the best crop varieties and planting dates, and the likely nitrogen needs of the crop over the course of its growth. Researchers then fertilized the maize five times over the course of the year with the estimated quantities needed for that part of the growth cycle. The experiment doubled yields with no increase in nitrogen quantities and nearly eliminated nitrogen surplus. If farmers everywhere were willing and able to apply fertilizer many times during a cropping season and to devote equivalent scientific effort to estimating plant needs, they could probably achieve very high NUEs as well.

BOX 27-1 | Improving nitrogen management in China

In 2011, farmers in China applied 51 percent more nitrogen to each hectare of maize than farmers in the United States, yet yields were 18 percent lower.[a] Most farmers in China could probably cut their nitrogen application rates without any negative effect on yields, and many farmers apply so much nitrogen that reducing rates would increase yields.[b] In addition, while the amount of manure produced in China increased fourfold from 1949 to 2005, the proportion applied to agricultural soils fell from almost all the manure to slightly more than half, which means that nutrients in this manure are being dumped elsewhere where they cannot be used.[c] A partnership of researchers from China and the United Kingdom has comprehensively investigated opportunities to reduce fertilizer use or better use manure while maintaining yields. In a summary, these researchers stated that by using simple nitrogen management practices, China could reduce fertilizer use—without altering yields—enough to reduce total Chinese GHG emissions by 2 percent.[d]

A first level of progress can probably be achieved mainly by working closely with farmers to educate them about nitrogen management. A group of scientists in China undertook such an effort without substantial government support by developing a multiorganization collaboration of more than 1,000 researchers, working with extension agents and agribusiness to reach 21 million farmers managing 38 million hectares (Mha).[e] Their efforts increased yields on average by roughly 11 percent, and decreased nitrogen application by 15–18 percent, depending on the crop. Despite an elaborate network of extension agents (people assigned to help farmers), China's agricultural extension system is known to be ineffective, and this collaborative effort delivered more compelling results.

Notes and sources:
a. Li et al. (2014).
b. A national meta-analysis found that decreasing N input rate by 28 percent (national average) would on average slightly increase yields (Xia et al. 2016), and a study in Shaanxi Province found that nitrogen use in maize and wheat could be reduced by 70 percent and 20 percent, respectively, without changing or only slightly decreasing yield (Zhang et al. 2015a).
c. Li et al. (2014).
d. SAIN (2011).
e. Cui et al. (2018).

Such a solution unfortunately is not practical, given that applying nitrogen so frequently is expensive.

Without some cost-effective measures to keep nitrogen on the farm field until crops can absorb them, NUE improvements will be limited. And to the extent that soils hold nitrogen in the form of nitrate, some of that nitrate will probably be converted to nitrous oxide after rainfall that saturates soils, even briefly.

Fortunately, compounds generally known as "enhanced efficiency fertilizers" (EEFs) can keep nitrogen in the soil available to crops longer by delaying the chemical progression to nitrous oxide. One approach involves coatings or other compounds that protect the fertilizer from dissolving in water. Another is the use of urease inhibitors, which inhibit the conversion of urea fertilizer to ammonia. Although ammonia is not a GHG, it is a volatile gas that can be lost to the atmosphere, reducing NUE and contributing to air quality problems. As ammonia is also an intermediate stage in the production of nitrate, these inhibitors can also reduce nitrous oxide emissions. The third group of compounds is nitrification inhibitors that slow the conversion of ammonium to nitrite, and from nitrite to nitrate. The International Fertilizer Institute lists seven patented nitrification inhibitors as of 2010.[118]

All of these compounds can increase NUE and reduce nitrous oxide by delaying the conversion processes by which nitrogen is turned into the forms in which it easily escapes (ammonia and nitrate). Despite great variation in results from field to field and year to year—probably heavily influenced by weather patterns—the great majority of studies have found, on average, substantial reductions in nitrogen losses to the environment when using any of the three types of compounds.[119]

Metastudies have also found that nitrification inhibitors and polymer-coated fertilizers on average reduced nitrous oxide emissions by between 35 and 40 percent.[120] There are two main reasons to believe that controlled-release fertilizers can become still more effective. One is simply the lack of research. One report estimates that the entire global research and development budget of the fertilizer industry for all purposes is only around $100 million per year, equal to 0.1–0.2 percent of its revenue.[121] By comparison, pharmaceutical companies and seed industries devote 10–20 percent of their revenues to research.[122] Probably only a fraction of this fertilizer R&D spending goes into EEFs. As a result, little funding has been made available by fertilizer companies to pursue new, better, and cheaper EEFs or to demonstrate where existing products will work best.

A second reason lies in the large variation in effectiveness of different compounds in different agronomic conditions.[123] Although some variability is likely inevitable because of variable weather patterns, compounds can respond differently to these patterns, as well as to different crops and soils. Better understanding of this variability should enable more effective and efficient use of compounds that delay the conversion of nitrogen in other forms into nitrate. There is no reason that fertilizer compounds, with different types and quantities of EEF compounds, could not be tailored to different conditions.

Because of their potential to reduce nitrous oxide emissions, nitrification inhibitors are often included in studies that examine cost-effective steps for climate mitigation.[124] For example, applying nitrification inhibitors to average corn fields in the United States might have a gross cost of around $50 per ton of CO_2e reduced.[125] But the evidence is growing that these compounds can have substantial economic benefits that at a minimum greatly reduce the net costs.

One potential source of economic savings is reducing nitrogen application while maintaining yields. Many studies do not test whether these compounds allow lower overall fertilizer use. Accordingly, one scientific review in 2009 concluded that there was no good evidence that inhibitors reduce the amount of fertilizer needed and therefore no good evidence that lower fertilizer costs offset the cost of the inhibitors.[126] However, other studies have found that these kinds of compounds make it possible to apply substantially less nitrogen while maintaining or boosting yields.[127] One such metastudy found that controlled-release fertilizers on average increased NUE by 13 percent.[128] Based only on this reduced need for fertilizer, one European study estimated that reduced fertilizer application would in general fully offset the costs of inhibitors.[129]

Increases in yield are also possible. A recent meta-analysis of nitrification inhibitors for farms applying nitrogen at recommended rates observed wide variability in yield effects but found average yield increases of 7.5 percent—with bigger increases in irrigated fields.[130] Another meta-analysis found average yield increases of 9 percent for grains, 5 percent for vegetables, and 14–15 percent for hays and straws.[131] If these kinds of yield gains are real, using nitrification inhibitors should be profitable. For example, one study estimated an additional cost of only $26 per hectare for good U.S. corn fields, and a yield gain equal to $164 per hectare.[132] The potential to increase yield, however, probably depends on how much nitrogen farmers are already applying. Where they apply too much fertilizer, an inhibitor is less likely to boost yields, so the main potential savings are probably from reduced use of fertilizer.

Given this potential for positive responses, McKinsey & Company has gone so far as to assume that these compounds save money overall, which leads to "negative costs" for reducing nitrous oxide through their use.[133] Yet one global marketing company estimated sales of controlled-release fertilizers to be only around 2 percent of global sales of nitrogen fertilizers in 2012–14.[134] If these compounds are profitable, then why do farmers use them so little?

Much of the explanation probably lies in the high variation and, therefore, uncertainty in the costs and benefits farmers will face.[135] For example, while one recent meta-analysis found increased yields on cereal crops, another found increased yields only on forage and vegetable crops, but not cereals.[136] Given this uncertainty, compounds are marketed to those farmers who face the greatest threat of losing nitrogen before crops can use it—such as those who apply fertilizer for the next year's crop in the fall, or those who farm on sandy soils. Despite the promise of this technology, increased use probably depends on regulations that not only directly require more use but also encourage development of information about when and where these compounds work best. Such a regulatory push is probably also necessary to persuade the fertilizer industry to explore the full potential development of these technologies.

Breeding opportunities

Chapter 12 discussed the promising option of deliberately breeding crops to utilize nitrogen more efficiently, as well as the increases in NUE that probably occur when breeding for increased yields alone. Taking a more radical step, and therefore with less chance of success, some breeders are trying to breed major grains to fix their own nitrogen.[137] Although this effort has received some publicity, the minimal literature on breeding to increase NUE—even at the level of discussion—suggests that research efforts are small.

Biological nitrification inhibition (BNI) for crops, similar to that for pasture grasses discussed earlier, provides another major opportunity. Just as researchers found that the *Brachiaria humidicola* grass exudes a chemical that inhibits nitrification, so they have found that each of the world's major grains, including wheat, maize, rice, and sorghum, has either wild or cultivated varieties with some level of BNI. A research partnership is under way to increase the production of the natural inhibitor sorgoleone in sorghum, and a BNI sorghum will probably be available within five years.[138] Research is also under way to transfer the chromosome region that controls BNI function from wild wheat strains into modern elite wheat varieties.[139]

As these researchers point out, BNI has potential advantages over chemical additives because BNI would come as an integral part of the plant and require no additional labor. In addition, the biology of plants has evolved to exude these inhibitors precisely into the parts of soils where nitrogen builds up and to continue to do so as plants grow. As a result, they can potentially achieve more inhibition than chemical inhibitors, which to date can last no more than a few weeks.

Improving balance among multiple nutrients

For most of the world's farmers, fertilization focuses on the macronutrients nitrogen, phosphorus, and potassium and ignores additional nutrients that can be both deficient and important to crop growth, such as sulfur, calcium, iron, zinc, and nickel. Unfortunately, the needs for these micronutrients are poorly understood, and the quantity of micronutrients needed may depend on the availability of other micronutrients.[140] Soil and root interactions are poorly understood, especially complex microbial influences. Greater knowledge would probably enable improved breeding of crops and increased "inoculation" of soils by spreading microorganisms that help roots fix nutrients. Seed coatings with either micronutrients or one of the major nutrients have shown promise in some cases. In other situations, the best opportunity may involve directly spraying micronutrients onto the crops.

In all cases, more efficient fertilization has the potential to increase NUE and reduce emissions by leading to greater crop growth and more efficient use of the principal, potentially polluting, macronutrients nitrogen and phosphorus. But this whole field of knowledge receives limited research funding.

Estimating the opportunity

Although the evidence suggests that some improvement in NUE and consequent reduced nitrous oxide emissions would be cheap or even profitable, there is no sound basis for estimating what level of NUE is economically achievable or cost-effective. Zhang et al. (2015b) developed global NUE targets for major crop categories, which would raise the global average efficiency for all crops from 42 percent to 68 percent.[141] The 68 percent target includes NUEs of 85 percent for soybeans, 60 percent for rice, 40 percent for sugar crops and fruits and vegetables, and 70 percent for all other crops. In the GlobAgri-WRR model, we developed four scenarios in which farms in each of the world's regions close the gap between present performance and the goals of Zhang et al. (2015b) by 25 percent, 50 percent, 75 percent, and 100 percent.

Table 27-1 shows the results. Although all NUE progress contributes to significant emissions reductions, only achieving a global average NUE of 71 percent—slightly above the target in Zhang et al. (2015b)—would keep fertilizer emissions close to their 2010 levels. An NUE of 71 percent would reduce 2050 emissions by more than 600 Mt, roughly a 35 percent reduction. Yet even under this most optimistic scenario, fertilizer emissions would still remain above 1.1 Gt per year in 2050—more than one-quarter of our target for total agricultural production emissions of 4 Gt per year.

Table 27-1 | Global effects of scenarios of improved nitrogen use efficiency on agricultural greenhouse gas emissions

SCENARIO	GLOBAL AVERAGE NITROGEN USE EFFICIENCY (PERCENT)	EMISSIONS FROM SOIL FERTILIZATION[a] (MT CO_2E)	TOTAL PRODUCTION EMISSIONS (MT CO_2E)	PRODUCTION EMISSIONS GHG MITIGATION GAP (GT CO_2E)
2010	**46**	**1,289**	**6,769**	**–**
No productivity gains after 2010		1,758	11,251	7.3 (2.2)
2050 BASELINE	**48**	**1,741**	**9,023**	**5.0**
25% NUE gap closure *(Coordinated Effort)*	56	1,459	8,741	4.7 (-0.3)
50% NUE gap closure *(Highly Ambitious)*	62	1,306	8,588	4.6 (-0.4)
75% NUE gap closure (*Breakthrough Technologies)*	67	1,205	8,487	4.5 (-0.5)
Meets high NUE target[b]	71	1,130	8,412	4.4 (-0.6)

Notes:
a. "Emissions from soil fertilization" includes emissions from the energy used to produce and transport fertilizer.
b. Defined in Zhang et al. (2015b) as 70 percent for most crops, 85 percent for soybeans, 60 percent for rice, and 40 percent for sugar, fruits, and vegetables).
Numbers not summed correctly are due to rounding. Numbers shown in parentheses are changes relative to 2050 baseline.
Source: GlobAgri-WRR model.

BOX 27-2 | Possible refinements of nitrous oxide emission rates from fertilizers and their significance for nitrogen use efficiency (NUE)

Nitrogen use efficiencies may play an even more prominent role in determining global GHG emissions than our model calculates. GlobAgri-WRR uses a "default" emission standard adopted by the IPCC, which assumes that nearly all nitrogen deliberately applied to cropland, and all fertilizer applied to grassland, generates the same quantity of nitrous oxide per kilogram of nitrogen. The percentage in Tier 1 calculations works out to 1.45 percent of all nitrogen applied. As a result, 10 percent more nitrogen applied to farm fields means 10 percent more nitrous oxide. There is also a higher, fixed IPCC Tier 1 rate of 2 percent for nitrogen excreted in manure and urine by grazing animals, and that too is the same on all fields. But estimating nitrous oxide emission rates is challenging because the bulk of a field's emissions often will occur over only a few hours on one or a few days per year. The resulting data have enormous variation. In recent years, evidence has been growing that these estimates are too simple, which has important implications for mitigation strategies.

First, data are accumulating that emission rates likely overestimate emissions in drier regions, such as Australia and much of Africa,[a] but also likely underestimate emissions from wetter regions, at least on farms that use large quantities of nitrogen. Some of these underestimates may result from an underestimate of indirect emissions when nitrogen runs off into streams.[b] As soils around the world become increasingly saturated with nitrogen, emission rates may also increase.[c] These findings make intuitive sense because nitrous oxide should be higher where soils are more likely to become saturated and where there is more nitrogen available to the microorganisms that release nitrous oxide.

Second, there is a good chance that nitrous oxide emissions will increase as yields grow because, even with constant NUE, higher yields mean a larger nitrogen surplus per hectare. To use a simple numerical example, if crops remove half of the applied nitrogen and the rest is surplus, then doubling the yield while maintaining the same NUE will double the surplus. Unfortunately, evidence is increasing that the greater the surplus of nitrogen, the higher the rate at which nitrogen turns into nitrous oxide.

One meta-analysis of data from several studies indicated low nitrous oxide emissions at high rates of NUE but high exponential growth in emissions thereafter as NUE rates decline: emission rates could potentially approach 10 percent of all applied nitrogen rather than the 1 percent used by the IPCC.[d] Two other meta-analyses found a slower, but still exponential growth rate tied to application rates,[e] which should be generally correlated with surpluses. These results tally with several experimental field trials in different countries.[f]

These studies have several policy implications, and are cause for both optimism and pessimism:

- The studies suggest that nitrogen emission rates may vary significantly both from country to country and among types of farms within a country. Once scientists can define these conditions better, mitigation efforts can focus on the high-emission sources.
- The data suggest that the problem is more acute in wetter regions that use abundant fertilizer, such as North America, Europe, and China. Because of the technical sophistication of agriculture in these regions, they are better positioned to use advanced technology to apply nitrogen more efficiently.[g] The studies also suggest that increasing nitrogen use in Africa, which will result in declining NUE, might not result in nitrous oxide emissions as high as the levels we estimate using IPCC default emission rates.
- Global accounting rules may lead to a global underestimation of emissions. Under approved guidelines by the UN Framework Convention on Climate Change, countries are allowed to use lower emission rates if they can document and justify them. As a result, countries with drier climates have an incentive to document their lower emissions rates, while countries with higher actual emissions will lack this incentive and may instead adhere to IPCC methods that underestimate emissions. If science bears out these patterns, the IPCC should adjust its default emissions methods and countries should accept those changes.
- These data make increasing NUE even more important. On the one hand, as yields grow, just maintaining the same NUE means that surpluses of nitrogen per hectare will keep growing as yields increase. To illustrate, an NUE of 50 percent means that 50 percent of applied nitrogen is surplus to crop requirements. As a result, fertilizing a hectare that yields 10 tons of maize versus one that generates 5 tons will result in twice the nitrogen surplus per hectare. If the emissions rate is always 1 percent, as we and the IPCC assume, then emissions double, but if the emissions rate were to jump from 1 to 2 percent with the higher surplus, then the level of emissions would quadruple when the yield grows to 10 tons.
- Overall, if nitrogen surpluses dictate the rate of nitrous oxide emissions, then inefficient nitrogen use becomes even more harmful and highly efficient nitrogen use becomes even more beneficial.

Sources:
a. Hickman et al. (2014, 2015).
b. Turner et al. (2015).
c. Reay et al. (2012).
d. Van Groenigen et al. (2010).
e. Shcherbak et al. (2014); Hickman et al. (2015).
f. Hickman et al. (2015); McSwiney and Robertson (2005).
g. Gerber et al. (2016).

There are, however, several good reasons to believe these efficiencies underestimate the benefits of the measures we propose.

- First, nitrification inhibitors might be able to reduce nitrous oxide even more than improvements in average NUE by keeping nitrogen in the form of ammonium longer or perhaps at key times. Our analysis does not factor in additional benefits beyond the increases in NUE.
- Second, our analysis uses the simplest IPCC emission factors for emissions of nitrous oxide from farm fields. This emission factor applies the same emission rate to each kilogram of nitrogen regardless of how large the amount of nitrogen surplus is on the field and regardless of the amount not used by crops (Box 27-1). If farms achieved the higher efficiencies proposed in our model scenarios, even though the quantity of nitrogen used would still grow modestly compared to 2010, the surplus nitrogen not absorbed by crops would decline disproportionately—by approximately 50 to 80 Mt according to one study.[142] New science suggests that the emissions depend on the amount of this surplus nitrogen, as discussed in Box 27-2, and not the total amount of nitrogen. If correct, then emissions in our mitigation scenarios could decline much further.
- Third, science increasingly suggests that present systems are underestimating various indirect sources of nitrous oxide, which do not result from the farm soil itself but from the nitrogen after it is lost from the soil. One paper suggests that the major sources of loss from the U.S. corn belt could be occurring in the many drainage systems for farm fields plus the tiny streams that receive water flowing from them or from leaching of farm water through the ground.[143] Because large increases in NUE could disproportionately reduce these waterborne losses, they could also reduce nitrous oxide by more than we estimate.

Overall, some improved management with existing technologies could lead to meaningful progress. Major progress seems possible with use of enhanced efficiency fertilizers, and truly impressive progress may be possible with technological breakthroughs.

Recommended Strategies

The true scope of the nitrogen challenge by 2050 indicates that large improvements in both practices and technology are required. Our four recommendations reflect that challenge.

Establish flexible regulatory targets to push fertilizer companies to develop improved fertilizers

Our assessment is that nitrification inhibitors and related compounds hold great promise to increase NUE, boost yields, and reduce nitrogen runoff and nitrous oxide emissions in cost-effective ways. In some circumstances, farmers may experience increased profits. This potential exists on a variety of farms even with present technology, and the variability in performance suggests high potential both to make compounds better and cheaper and to target them where they are most effective. Yet this potential is going unrealized because compounds have variable and uncertain effects on different farms and crops, because farmer decisions do not need to reflect environmental costs, and because industry devotes too little research funding to inhibitor technology. A flexible regulatory approach therefore seems appropriate to encourage the industry to market more vigorously to the farms that would benefit the most with current inhibitor technologies, to improve understanding of optimal uses over space and time, and to improve the technology.

One approach is to mimic vehicle fuel efficiency standards, as elaborated in Kanter and Searchinger (2018). In the United States, as a result of fuel efficiency standards in place since the 1970s, auto manufacturers are responsible for increasing the fuel efficiency of their fleets over time. This obligation created the incentive to design the most efficient cars for consumers, and to improve fuel-efficiency technology over time.[144] It also probably encouraged innovation in marketing. The need to sell small, more fuel-efficient cars to average out their fleet efficiencies gave auto manufacturers an incentive to improve them and target consumers most likely to appreciate such cars.

A similar program might impose obligations on fertilizer companies to incorporate compounds into their mix of fertilizer sales to achieve increasing levels of nitrous oxide reductions over time. For example, a law might start with a requirement for 15 percent of sales to incorporate EEFs and steadily increase the requirement to 30 percent in 15 years. An alternative could vary the quantity of EEFs sold based on their effectiveness. Companies would have to demonstrate quantities sold and likely reductions based on how farmers use their product. This approach would allow companies to choose the types of compounds they sell and to target compounds where they would have the most impact. It would also encourage manufacturers to research where compounds would be most effective to support their sales efforts and give them incentives to improve their products and tailor them to different farming conditions.

To justify this kind of regulation, it is not necessary to downplay other nitrogen-reduction strategies. Nor do EEFs need to be effective for all farms or be used by all farmers. The evidence merely needs to show, as we believe it does, that EEFs have the technical and economic potential to play a larger part in a cost-effective nitrogen-management effort. Phasing in higher efficiency standards over time would allow companies to start by selling the least-expensive yet effective compounds to a small share of farms that existing science indicates would benefit the most.

The fertilizer production industry is highly concentrated, but its distribution system relies heavily on independent retailers and distributors. However, the U.S. Renewable Fuel Standard (RFS) illustrates how to address this complexity. The RFS requires that increasing quantities of renewable fuels be blended with gasoline or diesel over time and in this way is similar to our proposal for steadily increasing percentages of EEFs. As with the fertilizer industry, the fuel distribution network can be complex. The RFS deals with this complexity by assigning responsibility for meeting blending requirements to refiners or importers of oil. A fertilizer program could imitate this approach by applying requirements to producers and importers of fertilizers. However, the RFS program awards credits to producers of renewable fuels. Producers and importers meet their obligations by acquiring these credits from other producers, from other actors who blend further down the fuel chain, or from a credit market, which ensures that standards are met overall even if a particular blender falls short.[68] In this way, producers and importers of fuel do not have to produce renewable fuels themselves;

they just need to make sure that someone along the supply chain is doing so, and in an amount that meets the percentage requirement of the producer or importer. In the same way, fertilizer manufacturers or importers could meet their obligations without producing EEFs themselves and without having to track their own fertilizers by assuring that sufficient quantities of EEFs are sold somewhere.

India provides the closest example to date of this approach with its New Urea Policy, adopted in 2015.[145] It requires that fertilizer manufacturers coat all domestically produced urea with neem, a natural coating substance that delays nitrogen release over the course of the growing season.

Any country or subnational government could move this process along by adopting this kind of regulatory standard. For example, the state of California has led climate change efforts in the United States and is a natural candidate for pioneering this approach. Large food companies could also encourage this process through their own purchasing standards. For example, Walmart announced in 2013 that it would require its suppliers to submit plans to cut their nitrogen fertilizer use substantially.[146] Increasing use of advanced fertilizer compounds could play a valuable role in such plans.

Shift fertilizer subsidies into support for higher NUE

A wide range of economic research supports the view, predicted by basic economic theory, that farmers' fertilizer application rates reflect the ratio of fertilizer prices to crop prices in both developed and developing countries.[147] The price ratio helps explain differences in application rates across countries.[148] If subsidies artificially lower fertilizer prices to farmers, then farmers will use more fertilizer than they otherwise would.

In Africa, where farmers currently use little fertilizer, the case for and against fertilizer subsidies is complex (and we evaluate these arguments in Chapter 36). But in Asia, the case seems clear that fertilizer subsidies should be phased out. Economic studies have found that fertilizer subsidies in Asia contributed to agricultural growth and poverty reduction in the early years of policy implementation but that their effect declined thereafter.[149] Since the early years of subsidy programs, other efforts to raise agricultural productivity have had far greater impact. These efforts include agricultural R&D, roadbuilding, irrigation, and education. Reforms in tenure law and agricultural market liberalization have had even bigger effects.[150]

The evidence is strong that farmers in both China and India overuse fertilizer.[151] This overuse leads to particularly high emissions in China because much of the fertilizer in China is generated using energy from coal.[152] Fertilizer subsidies in China reached $18 billion in 2010 through various mechanisms.[153] In a bold step forward, China decided in 2015 to phase out the principal subsidies by the end of 2017, which had been artificially lowering prices for fertilizer manufacturers.[154]

Nitrogen fertilizer subsidies remain high in many other Asian countries, including India, Bangladesh, and Indonesia.[155] In India, fertilizer subsidies reduced domestic nitrogen prices to less than one-fifth of international prices from 2011 to 2014.[156] The annual cost of up to nearly $15 billion[157] constituted 5.6 percent of total government spending in 2011.[158] For many years, fertilizer subsidies have been particularly distorting because they more generously supported nitrogen than other nutrients, resulting in unbalanced fertilizer application. This structure has led to both reduced yields and highly inefficient use of nitrogen.[159]

The challenge of reforming fertilizer subsidies is mainly socioeconomic and political. All Asian countries with high fertilizer subsidies have large numbers of small farmers whose economic conditions are stressful and who benefit from fertilizer subsidies. Realistically, there is probably greater opportunity to reorient subsidies than to eliminate them.

We therefore recommend shifting subsidies from fertilizer toward NUE. Governments could start by shifting subsidies toward fertilizers that include nitrification inhibitors or other delayed-release compounds. Governments also should develop incentives to shift to application techniques that apply fertilizer more frequently and in balanced amounts.

Support critical research and development

Reaching long-term nitrogen management goals requires major innovations. Highly promising options include improved development and use of chemical EEFs and BNI. Less developed but also promising options include nitrogen-fixing cereals and crop breeding targeted to increase NUE. As we discuss in Chapter 12, funding for all these categories of research is minimal in relation to their importance and promise, and governments need to increase this funding.

At a more applied level, governments and the private sector need to pursue the kinds of detailed, site-specific agronomic analyses that can lead to more tailored application and use of fertilizers. The examples described above of researchers working with farmers in China or coming together to improve data in the U.S. corn belt illustrate the kinds of effort needed.

Fund demonstration projects of advanced technologies

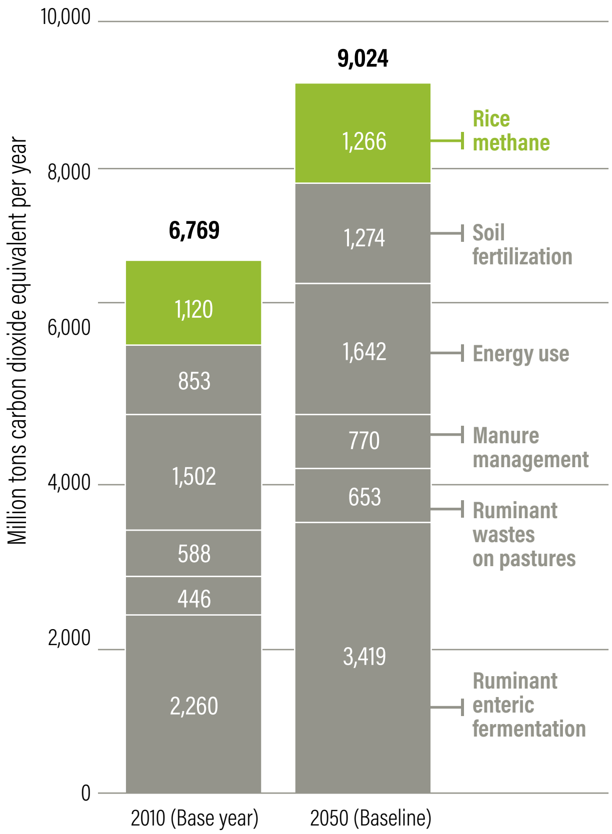
Governments already support agricultural conservation efforts through national conservation funding and international aid projects. Outside of Africa, where fertilizer application rates are simply too low, the focus of such efforts should be on advanced technologies, such as use of inhibitors, or highly site-specific application levels. One option governments should pursue involves performance-based projects that reward producers, or fertilizer contractors, for achieving high levels of NUE.

CHAPTER 28

MENU ITEM: ADOPT EMISSIONS-REDUCING RICE MANAGEMENT AND VARIETIES

Rice is one of the world's most important staple crops, but its production is a potent source of GHG emissions, primarily in the form of methane generated by flooded or "paddy" rice. This menu item focuses on strategies to reduce the GHG emissions produced by rice-growing and the potential of these strategies to increase rice yields and save water.

Figure 28-1 | Greenhouse gas emissions from agricultural production, 2010 and 2050



The Challenge

Rice is the largest staple crop for roughly half of the world's population.[160] Most rice is produced in flooded fields and, as in wetlands generally, flooding blocks oxygen penetration into the soil, which allows archaea that produce methane to thrive. Common estimates put paddy rice methane emissions at roughly 500 Mt CO_2e per year,[161] but adjusting for the IPCC's more recent estimates of the potency (global warming potential) of methane increases those estimates to 800 Mt CO_2e per year. In addition, paddy rice fields emit roughly 15 Mt CO_2e in the form of nitrous oxide.[162] The GlobAgri-WRR model estimates methane emissions from rice in 2010 at 1,120 Mt CO_2e,[163] using the more advanced methods for estimating methane rice emissions (so-called Tier 2 methods).

In short, paddy rice methane contributed at least 10 percent (and possibly more) of all global agriculture-related emissions in 2010 and approximately 2 percent of total human-generated GHG emissions. For most rice-growing countries in Southeast Asia, rice contributes around 50 percent of agricultural production GHG emissions and between 2.5 percent and 20 percent or more of total national emissions.[164]

Because the amount of methane emitted by rice cultivation depends more on the area of irrigated paddy rice land under production than on the amount of rice produced, boosting yields provides one way to reduce emissions per unit of production.[165] In 2014, farmers harvested rice on 163 Mha worldwide, an area roughly half the size of India. Ninety percent of production was in Asia.[166] Irrigated, flooded rice, which is responsible for the bulk of methane emissions, accounts for roughly half of total rice-growing area and 75 percent of the world's rice production.[167] Building on FAO projections, we project an increase in demand for rice of 32 percent between 2010 and 2050.[168] Using FAO projections for rice yields in 2050, we estimate some modest growth in paddy rice area, which means emissions will rise by roughly 150 Mt to 1,266 Mt of CO_2e in our baseline (Figure 28-1).

Unfortunately, the impacts of climate change, although uncertain, could decrease rice yields and increase GHG emissions from production. Some estimates of higher temperature effects on rice yields are harsh, on the order of an 8–10 percent decline in yield for every 1 degree Celsius increase in local temperature.[169] Millions of hectares of high-quality, low-lying rice lands in Asia could be affected by sea level rise, increasing the risks of salinity and flooding.[170] In addition, higher concentrations of carbon dioxide in the atmosphere may directly increase methane emissions by increasing the supply of carbon to the microorganisms that produce methane.[171] Although the science is evolving, one study estimated that the combination of lower yields and rising methane emissions could double the emissions per unit of rice by 2100.[172] This threat of growing emissions creates a powerful need to reduce rice emissions in ways that boost—or at least do not harm—yields and therefore hold down the need to expand rice-growing area.

The Opportunity

Four main strategies exist for mitigating GHG emissions from rice production: increase rice yields more rapidly, breed rice that produces less methane, improve management of rice straw, and reduce periods of flooding.

Increase yields more rapidly

The first strategy is to increase rice yields fast enough to reduce the necessary amount of future rice-growing area. FAO projects yields of 5.3 tons per hectare per year in 2050, which would be 23 percent higher than in 2010.[173] This yield growth is equivalent to only half of the annual absolute growth rate from 1962 to 2006, and the lower projection reflects judgments by experts that rice has decreasing potential to grow at higher yields. But if rice yields could grow at 62 percent of the annual rate that was achieved from 1962 to 2006, and reach 5.5 tons per hectare per year, rice-growing area would not need to expand.[174] An expert review on rice has found sufficiently high technical growth potential for rice yields to meet 2050 demand without land expansion. Fischer et al. (2014) estimated that the global potential yield for rice is 7.4 tons per hectare per year, well beyond the yield necessary to hold rice area constant.[175] Increasing yields beyond 5.5 tons per hectare per year could lead to an actual decrease in rice area and future emissions.

Breed lower-methane rice

Scientists have long known that some rice varieties emit less methane than others.[176] One 2017 paper showed that some high-yielding rice varieties already in use generate roughly 10 percent less methane than the average rice variety.[177]

More ambitiously, in 2015, a group of researchers reported developing a new breed of rice that generates only 10 percent or less of the methane emissions of normal rice under controlled conditions in small pots during parts of the rice-growing seasons.[178] The researchers had added a barley gene, which had the effect of transferring growth from roots to granules, resulting in higher (but starchier) yields and providing less feeding opportunities for methane-producing archaea in the roots. The results were promising, but there are also reasons for caution. This 90 percent reduction occurred only during early parts of the rice-growing season and therefore would not alter the methane emissions that occur later. The researchers have added the gene to only one variety of rice so far. And field experiments would be necessary to determine both how well rice plants do with more limited root growth and how methane emissions react under broader, real-world field conditions.

Minimal efforts are devoted to deliberately breeding low-methane rice varieties and encouraging their wider use. Overall, research results suggest that a deliberate effort to do so should be able to reduce methane emissions.

Remove rice straw

Rice straw is the nongrain portion of rice plants. Methane emissions increase when farmers add fresh (noncomposted) rice straw to flooded fields, which increases the carbon available to produce methane, particularly if farmers do not plow the straw under before planting. Yet burning, a common alternative for rice straw in some regions, also creates methane and other GHGs as well as local air pollution. Strategies to reduce emissions include incorporating rice straw into fields well before the new production seasons start. Another option is to remove rice straw from fields to use for other productive purposes, such as growing mushrooms, generating energy, or creating biochar.[179]

Reduce flood periods

Various practices can reduce or interrupt periods of flooding. The longer rice remains flooded, the more methane-producing archaea grow, and the more methane they generate. Decreasing the duration of flooding therefore reduces methane production and emissions.[180] The drawdown of water in rice paddies is accomplished by temporarily halting irrigation, allowing water levels to subside through evapotranspiration, percolation, and seepage. Interrupting flooding even with occasional drawdowns has a dual effect: it quickly drives down the population of methane-producing archaea, and it stimulates the breakdown of methane by bacteria. Although the reduction in methane emissions is not necessarily proportional to the duration of the drawdown, studies have found that almost any means of reducing or interrupting this flooding reduces methane emissions.[181] Even reducing flooding during the off-season—as many Chinese farmers do—can reduce emissions.

Systems for reducing flooding and emissions during the crop-growing season fall into four categories:

- **Dry seeding.** Most paddy rice production in Asia follows the traditional pattern of transplanting seedlings grown in nursery areas into already flooded paddies. But direct seeding of rice into dry fields is spreading in Asia and probably now accounts for one-quarter of all rice production in the region.[182] Farmers in the United States use direct seeding because it requires less labor.[183] Direct seeding can be practiced in flooded fields ("wet seeding") or by drilling seeds into dry fields ("dry seeding"). Wet seeding in flooded fields is unlikely to reduce methane emissions.[184] But dry seeding reduces emissions because it shortens the flooding period by roughly a month.[185]

- **Single midseason water drawdown.** Studies have shown that a single drawdown during the crop production season, sufficient to allow oxygen to penetrate the soils, substantially lowers GHG emissions. Typically, this kind of drawdown must occur for 5–10 days to generate methane benefits.[186] Most farmers in China, Japan, and South Korea already practice this drawdown to increase yields.

- **Alternate wetting and drying (AWD).** This practice involves repeatedly flooding a farm field, typically to a water depth of around 5 centimeters, allowing the field to dry until the upper soil layer starts to dry out (typically when the water level drops to around 15 centimeters below the soil surface), and then reflooding the field. This cycle can continue from 20 days after sowing until two weeks before flowering.[187] This approach is also known as "controlled irrigation" or "multiple irrigation," depending on the country and the research context. Because each drying cycle sets back the generation of methane-producing bacteria, AWD achieves even larger reductions in methane emissions than a single drawdown. AWD can be practiced along a continuum of less to more frequent drawdowns.

- **Aerobic rice production.** Like AWD, this system involves adding irrigation water only when needed. It avoids standing water, aiming instead to keep soils moist. This system can drastically reduce—or nearly eliminate—methane production. In general, however, aerobic rice production has lower yields than rice produced through traditional methods or the three methods listed above. Still, as the case study below shows, some farmers in China are maintaining high yields by constructing raised beds and ditches, which limit standing water to furrows.

Effectiveness of reducing flood periods

All reductions in flooding can reduce methane emissions. Various studies have found that dry seeding can lead to reductions in GHG emissions of 30 percent or more.[188] IPCC guidance provides that a single drawdown will reduce emissions that would otherwise occur by 40 percent, and multiple drawdowns by 48 percent.[189] However, these figures are global averages. Evidence from the U.S. state of Arkansas indicates that AWD could reduce emissions by as much as 90 percent.[190] There is also evidence that combining different water-saving approaches can have additive benefits for mitigation. For example, studies combining dry seeding with AWD have found emissions reductions of 90 percent.[191]

One concern is that while drawdowns decrease methane emissions, they tend to increase emissions of nitrous oxide, another powerful GHG. Nitrous oxide emissions are generally low in continuously flooded rice systems. However, under water-saving strategies, nitrous oxide emissions tend to increase because alternating periods when oxygen is and is not present in soils maximizes the opportunities for nitrous oxide production. In general, studies that have measured nitrous oxide emissions under different water management regimes have found that increases in nitrous oxide have substantially less climate significance than the reductions in methane as long as excessive nitrogen is not introduced through high doses of fertilizer.[192] Reflecting this difference in impact, the IPCC guidelines do not account for increases in nitrous oxide emissions under water-saving techniques, and below we have chosen to follow this convention in our consideration of these techniques' GHG mitigation potential.

Significantly, one study using a more frequent sampling technique found very high emissions of nitrous oxide from three Indian rice farms that flooded their fields for only a few days at a time. The emissions were so high that the researchers suggested these brief flooding conditions could cause nitrous oxide emissions in excess of methane savings.[193] Overall, the farms in this study that contributed the high nitrous oxide emissions were flooded for only a small portion of the growing season, and the study did not present any continuously flooded farms as a control. This type of wetting and drying, lasting for short periods, contrasts with standard AWD, which has much longer cycles and which therefore maintains flooding much longer. When analyzing this form of AWD in contrast with continuous flooding, researchers have found that nitrous oxide emissions increase a little but not enough to cancel out savings from reduced methane.[194] The India study therefore does not cast doubts on the standard way of practicing AWD but it does raise concerns about whether such briefly flooded rice fields are common and whether all such fields contribute high nitrous oxide emissions. It therefore makes a case for efforts to replicate these findings on other farms and to analyze how many other farms may be flooded so briefly.

Because farmers do not directly benefit from reducing GHG emissions, emissions reductions alone do not motivate adoption of rice water management techniques. In contrast, many farmers directly benefit from saving water, which provides a potential incentive to reduce flooding. Rice production uses around 40 percent of the world's irrigation water,[195] and almost one-third of rice-growing areas face high levels of water stress.[196] AWD and dry seeding would lead to the largest reductions in water consumption because they involve the shortest inundation periods.

Yet current estimates of water savings are at the field level; they do not necessarily reflect water savings for a local area. Evidence suggests that most or perhaps nearly all of the water savings will result from reduced percolation,[197] which implies that some of the irrigation water saved by an individual field would otherwise have recharged groundwater or been used further downstream.[198] However, in periods when surface soils are allowed to dry out, evaporation from soils should decrease, which means that reduced flooding should also make some more water available at the system level. Further analysis in each district is necessary to determine the extent to which field-level water savings translate into savings for the district or aquifer.

Evidence of the effect of these water management practices on rice yields is mixed. Many early studies found yield declines from AWD.[199] But as AWD becomes more widely practiced, studies in Asia typically found yield gains, including in the Philippines,[200] Vietnam,[201] and Bangladesh.[202] Studies in India have found yield gains from AWD when practiced as part of a broader rice production system known as the "System of Rice Intensification."[203] In China, an estimated 80 percent of farmers perform a single midseason drawdown for 7–10 days because they have found that doing so increases crop yields.

Determining the precise reason for these yield gains requires further investigation, but there are at least three possible explanations:[204]

- Better resistance to lodging (bending over) of stems, attributable to better anchoring of well-developed roots or sturdier stems.
- More profuse early rice tillering (additional shoots), while midseason drawdowns suppress unproductive late tillering, which consumes the plant's energy while producing few or no rice grains.
- Less susceptibility to disease in some cases (although some studies have found greater susceptibility to disease and weeds).

Recent studies in the United States have found that AWD has no effect on yields as long as soils retained an acceptable level of moisture at all times. Studies also indicate that yields could drop dramatically if soil was allowed to dry too much at any one time. U.S. yields are nearly universally high, indicating a persistently high quality of management, which may help explain why changes in water management have not boosted yields.

Unfortunately, just because some of these water management practices are possible does not mean they are feasible everywhere or all the time. For example, to be able to practice AWD, farmers realistically need a number of physical conditions to be met. They require well-leveled fields to avoid pockets that dry excessively. They must also be able to manage their water reliably, which means they must be able to drain their fields effectively and then they must also have a reliable source of water to rewet their fields as soon as needed. But most rice-growing regions have distinct wet and dry seasons. In the wet season, farmers may not be able to drain their fields adequately. In the dry season, only some irrigation systems can provide water reliably enough to encourage farmers to practice AWD.

In a series of case studies, we highlight what is known and not known about the opportunities and challenges of using some form of water management to reduce methane emissions during rice production. The case studies are drawn from key rice-producing areas in India, the Philippines, the United States, and China.

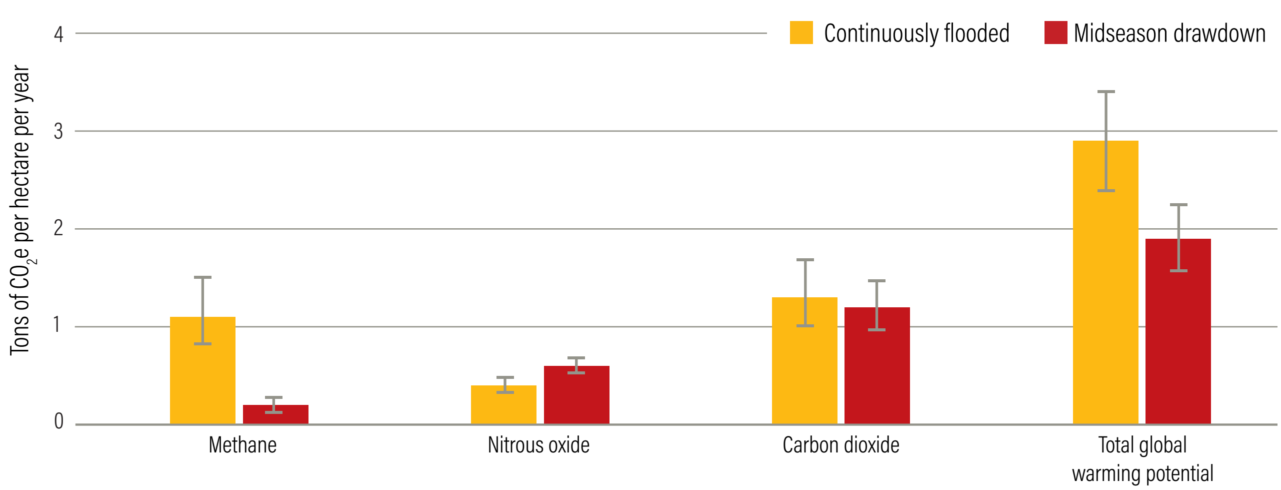
INDIA

India produces more rice than any country but China, and the states of Tamil Nadu in the south and Punjab in the north illustrate the opportunities and challenges for water management. Rice is the dominant crop in both states. Small farmers (working less than 2 hectares [ha]) farm half of the land in Tamil Nadu and one-third in Punjab and constitute the majority of farmers. Farms of 2 to 10 ha make up the majority of the remainder in both states. Both states also experience great water scarcity, withdrawing roughly 40 percent more water than rainfall replenishes each year. Farmers mine groundwater to meet their needs, and water tables are falling. In parts of Punjab, water tables have been falling by up to one meter per year, increasing pumping costs severalfold, and leading to contamination of soils with salt and wells with arsenic. Unable to conceive of an alternative solution, a recently released government plan proposed to reduce rice farming in Punjab by more than 40 percent.[205]

Researchers have performed at least a few studies of AWD or midseason drawdowns[206] in each region and have found substantial GHG emission reductions, yield gains, and water savings at the farm level (Figure 28-2).[207] Based on these water-saving and production benefits, government policy in both regions has promoted the System of Rice Intensification (SRI), which includes many practices of which one is, in effect, AWD. Although many farmers in Tamil Nadu and Punjab have adopted some components of SRI, few have adopted some kind of midseason drawdown.

The technical potential to engage in AWD, or even one midseason drawdown, varies in both regions. Because of porous soils, drainage is possible even during the wet seasons. However, many farmers

Figure 28-2 | Midseason drawdown reduces greenhouse gas emissions from rice production in Punjab by one-third



Note: Solid bars show average statewide emissions. Error bars represent one standard deviation.
Source: Pathak et al. (2012).

rely exclusively on surface water irrigation networks, which are too unreliable in both regions to practice wetting and drying. Somewhat more than half the farmers in Tamil Nadu and most farmers in Punjab also pump groundwater.[208] These farmers could therefore time their irrigations to perform AWD. Many farmers in Tamil Nadu also receive irrigation water from large earthen pits used to store water from the rainy season.[209] The potential probably exists to time water deliveries from these pits to allow AWD, although designing such a system would be more complicated than just turning pumps on and off. For many of these farms, additional leveling would also be necessary to ensure that drying the lower portions of fields does not lead to excessive drying of higher areas.

Dry seeding of rice is also starting to emerge as an alternative production system in Punjab, though it was practiced on only 5,000 ha in 2012.[210] Some studies have found GHG benefits and large irrigation savings at the field level.[211] One study found modest declines or increases in yields depending on the variety of rice used,[212] but follow-up studies found that these yield declines occurred where farmers did not follow recommended regimens of fertilizer and pesticide use.

Despite the potential for many farmers to practice AWD, two factors greatly limit their incentive to do so. First, farmers currently enjoy essentially free water. Second, governments heavily subsidize the electricity used to run pumps in both states. Unless it is proven to increase yields substantially, farmers have little individual incentive to implement some form of water management.

PHILIPPINES

The Philippines ranks eighth in global annual rice production, with around 4.4 Mha in production in 2010.[213] It is also the world's largest rice-importing country. Roughly 70 percent of the Philippines' total rice area is irrigated, but it produces relatively low yields of around 3.3 t/ha.[214] As in India, a few research studies in the country have found substantial reductions of methane emissions from midseason drawdowns, although there are no studies yet of AWD.[215] Yet few rice farmers engage either in drawdowns or dry seeding. One limitation is physical. One rice-growing season in the Philippines occurs during periods of heavy rainfall, which are heavy enough to limit the potential of most farms to dry their fields unless they employ drainage systems that are not now common. It is possible that one midseason drawdown might be possible on some of these fields, but that requires further analysis. Dry-season irrigation limitations are also important. Nationally, 86 percent of irrigation water comes from surface water irrigation, primarily rivers. The water supply is typically too unreliable for farmers to have confidence that they could replenish fields if they drain them. Two experiences, however, show some potential.

Roughly one-quarter of all rice farms use pumps to access groundwater, typically those at the last stage of surface water irrigation systems, where water deliveries are most unreliable.[216] These farmers can face high pumping costs. According to one study, half of all such farmers targeted by government initiatives to adopt AWD did so.[217] An analysis of an initiative in Central Luzon that targeted farmers with pumps found no statistically significant impact on yields under AWD. It also found no change in labor costs, which also suggested no increase in weeding problems.[218] This study also found that farmers employing AWD reduced their hours of irrigation by 38 percent[219] (while other studies found water savings of 15–30 percent).[220]

In general, these studies have confirmed farmers' willingness to switch to AWD where the costs of pumping water are high but not where costs are low.[221] Beyond physical limitations of surface-water irrigation schemes, farmers currently would also have little incentive to adopt AWD because they typically pay a fixed irrigation fee per hectare, usually about $50–$70 per season, and therefore have little financial incentive to use irrigation water judiciously. Creating incentives for AWD would thus require changing payment systems.

An irrigation project on the island of Bohol in the Visayas illustrates another potential model for some areas. In 2005 the National Irrigation Administration constructed a new dam with Japanese assistance to address declining and unreliable water supply. This new dam generated a far more reliable source of irrigation water; to optimize its use, the administration imposed an AWD irrigation schedule in 2006. Each farmer has irrigation water for three days, then none for the next 10 to 12 days. The project allowed farmers to cultivate in a manner that resulted in overall yield increases of 11–13 percent, an increase of 16 percent in irrigated land, and two rice crops instead of one in some parts of the island.[222] This project suggests how irrigation improvements could be tied to AWD for both GHG benefits and water savings.

UNITED STATES

The United States produces only 1.1 percent of the world's paddy rice and harvests only around 0.6 percent of the world's rice area.[223] Nevertheless, it has high yields of more than 8 tons per hectare and contributes 10 percent of internationally traded rice.[224] Six states produce nearly all U.S. rice: Arkansas, California, Louisiana, Missouri, Mississippi, and Texas, with half of production from Arkansas alone. In both the southern United States and California, recent studies have confirmed large GHG reductions via AWD of 50 percent or more.[225] In California, a study found emissions reductions of 90 percent when AWD was combined with dry seeding.[226] Rice farmers already mostly dry seed rice in Arkansas but not in California, where one study found nearly 50 percent reductions in methane emissions from dry seeding.[227]

In theory, AWD could prove attractive in both states because both suffer from severe water shortages and falling aquifer levels. One Arkansas study found increases in water use efficiency from AWD of 22 percent at the field level.[228] However, in California, AWD could lead to higher rates of water loss into groundwater because soils are heavy clay, which allows little percolation when flooded but cracks when dried.

Growing season rainfall is sufficiently low in Arkansas that farmers can dry their fields, and farmers are able to use pumps or on-farm reservoirs—filled in the winter—that provide sufficient and reliable water supplies. The main physical limitation in Arkansas is the size of fields. Unlike the small rice fields of Asia, single rice fields in the Arkansas are typically between 20 and 50 ha, with some much larger. Most are carefully leveled, which makes them promising for AWD. But because of their size, farmers usually divide fields into separate basins, separated by levees and weirs to control water heights and to allow water to move from one basin to another in a controlled fashion. To provide the level of water management for AWD, farmers would probably have to make adjustments to be able to deliver water separately to each separate part of the field.

Opportunities for AWD adoption are considerably lower in California. Because the state's Mediterranean climate generates little to no rainfall during the summer growing season, farmers rely on water deliveries from large, regionally managed water systems fed heavily by snowmelt and reliant on gravity. Farmers therefore do not have direct control over their water, and California's irrigation systems are generally unable to supply water quickly enough to all farmers at the time it is needed. Dry seeding probably provides the best option for water saving. Since dry seeding can increase the need for weed control, additional incentives would probably be necessary to persuade farmers to adopt the practice.

The other main concern is potential impacts on yield. Unlike in other countries, there is no evidence from U.S. tests that AWD would increase yields, and some earlier studies suggested yield declines. Meanwhile, there is some risk of lower yields if farmers overdrain fields.[229] The fact that Chinese and Japanese farms experience yield gains from at least one midseason drawdown but U.S. farmers do not presents a scientific puzzle.

Overall, it would appear that most Arkansas farmers, with reasonable adjustments, could implement AWD, while dry seeding should be an option for most California farmers. As in other countries, essentially free water limits their incentives to do so even while there might be collective benefits to farmers through water savings from broad adoption of these practices.

CHINA

Farmers in China harvest almost 20 percent of the world's rice fields by area and produce almost 30 percent of the world's rice.[230] The vast majority of China's farmers practice at least one midseason drawdown. Although most rice is grown on well-irrigated flatlands, much is still grown in hill environments, including two-thirds of Sichuan Province's 3 Mha of rice. The hilly terrain limits yields, increasing GHG emissions per ton of rice. Although farmers have long practiced intermittent flooding to reduce water consumption—with the side benefit of reducing methane—farmers also tend to keep fields flooded in the winter to ensure that water is available in the spring, when droughts are frequent. This maintenance of standing water in the winter increases emissions.

One new technique used in Sichuan relies on plastic covering as mulch. As shown in Figure 28-3, farmers construct a series of furrows and raised beds, cover the beds with long strips of thin plastic film 1.5 to 2 meters wide, punch holes in the film, and transplant rice into the holes. Farmers maintain water in the furrow for approximately 1.5 months after transplanting seedlings but no water on the bed surface, and furrows themselves are drained for around two weeks in the middle of the season to inhibit late-emerging unproductive tillers, to remove toxic substances, and to improve root activity.

Research has found that plastic film mulching reduces GHG emissions by maintaining higher oxygen content in the rice bed, thereby inhibiting methane-producing bacteria.[231] Counting all sources of emissions, these studies suggest GHG emissions reductions of roughly 50 percent per hectare, and 55–60 percent per ton of rice, and even more if farmers use nitrification inhibitors.[232] Studies have also found yield and water benefits. In controlled comparison studies, plastic film mulching tends to improve yields by 5 to 20 percent, probably by raising temperatures.[233] Scientists have reported water savings per hectare of 58–84 percent and increased water use efficiency of 70–106 percent when factoring in the benefits of increased yields.[234] Economic studies have also found economic benefits through decreased costs of fertilizer, pesticides, weeding, and yield gains.[235]

In lowland parts of Sichuan Province, the use of plastic does not boost rice yields because soils are warm enough that they do not benefit from the increased warming, but a similar cultivation method has been developed without the film. Called either "ridge-ditch cultivation" or "aerobic cultivation,"[236] it too involves construction of raised beds and then maintenance of water in the furrows but not on the bed surface. As with plastic film mulching, studies have found that ridge-ditch

Figure 28-3 | New rice-growing techniques in Sichuan Province use furrows, raised beds, and plastic covering as mulch

Image source: Jing Ma.

cultivation significantly reduces methane emissions from paddy fields.[237] Studies also have found that this practice can enhance water use efficiency, improve topsoil temperature and soil aeration, reduce the amount of toxic substances, enhance soil microbial activities, and therefore promote soil nutrient transformation.[238] By improving soil conditions, ridge-ditch cultivation has also been measured to improve rice grain yields by 12.3 percent to 45.8 percent in comparison with traditional cultivation systems.[239]

Despite the promising results, these practices occur in only a small fraction of suitable rice-growing areas in the province. One reason is that these practices require more intensive labor during rice transplanting. Purchasing the plastic film also adds to production costs.

Model Results: Mitigation Potential

We used GlobAgri-WRR to explore six rice mitigation scenarios plus a number of variants:

- Mitigation scenario 1 includes rates of crop yield gains from 2010 to 2050 that are 20 percent higher than projected by FAO, which reduces the area under cultivation and therefore methane emissions. Instead of projecting increases from a global average of 4.3 tons of rice per hectare in 2010 to 5.3 tons in 2050 in our baseline scenario, we project that yields will grow to reach 6.4 tons per hectare. This growth would reduce rice area by 27 Mha compared to the area in our baseline.
- Mitigation scenario 2 involves a 10 percent reduction in methane emissions from rice production "across the board" due to improved breeding.
- Mitigation scenario 3 involves adoption of water drawdowns. In our baseline, we estimate that 90 percent of irrigated rice farms in China, Korea, and Japan already employ a midseason drawdown and 10 percent use continuous flooding, but we estimate that outside of these three countries, 90 percent of farms use continuous flooding.
    - In mitigation option 3a, we estimate that only 50 percent of farms outside of China, Korea, and Japan use continuous flooding, 25 percent employ one midseason drawdown, and 25 percent employ multiple drawdowns.
    - In mitigation option 3b, we assume that 90 percent of all irrigated farms outside of these three countries employ multiple drawdowns.
- Mitigation scenario 4 involves shifts in rice straw management so that rice straw is removed or mulched in some manner outside of the growing season. In some areas with double or triple cropping, a new rice crop is planted within a few days of the last rice crop. In those situations, we assume farmers have no time to remove their rice straw.
    - In mitigation option 4a, we assume half of all farms that are not growing a new rice crop in such a short time switch to out-of-season straw management.
    - In mitigation option 4b, 100 percent of all such farms employ out-of-season straw management.
- Mitigation scenario 5 combines options 3a and 4a, simulating a combination of low water-level drawdowns and a low level of straw mitigation.
- Mitigation scenario 6 combines faster growth in yields to 6.4 tons per hectare per year, a 10 percent across-the-board reduction in emissions due to plant breeding, and our first-level improvements in water and straw management (options 1, 2, 3a, and 4a).

Table 28-1 shows the results. Each of the mitigation options achieves substantial GHG emissions reductions relative to the baseline in 2050. Most options close the total GHG mitigation gap by between 1 and 3 percent, but scenario 6—which also includes yield gains and thus avoids future land conversion and associated emissions—closes this gap even more. Scenario 6, which puts together different forms of mitigation at plausible levels, would cut rice-production emissions by nearly 40 percent, close the production emissions GHG mitigation gap by 10 percent, and close the total GHG mitigation gap by 7 percent.

Table 28-1 | Global effects of scenarios of improved rice management on agricultural greenhouse gas emissions

SCENARIO	DESCRIPTION	METHANE EMISSIONS FROM RICE PRODUCTION (MT CO_2E)	TOTAL PRODUCTION EMISSIONS (MT CO_2E)	PRODUCTION EMISSIONS GHG MITIGATION GAP (GT CO_2E)
2010		**1,120**	**6,769**	**–**
No productivity gains after 2010		1,696	11,251	7.3 (2.2)
2050 BASELINE		**1,266**	**9,023**	**5.0**
1: 20% yield gains	Global rice yields reach 6.4 tons/hectare instead of 5.3 tons/hectare in 2050 (and 4.3 tons/hectare in 2010)	1,055	8,806	4.8 (-0.2)
2: new low-methane rice breeds	10% across the board reduction in rice methane due to new breed varieties	1,139	8,896	4.9 (-0.1)
3a: 50% water management	In countries that do not already employ drawdowns, half switch to midseason drawdown(s) or AWD	1,111	8,869	4.9 (-0.2)
3b: 90% water management	In countries that do not already employ drawdowns, 90% switch to midseason drawdowns or AWD	960	8,717	4.7 (-0.3)
4a: 50% off-season straw management	Roughly half of all farms manage rice straw out of season in all seasons where that is possible	1,170	8,927	4.9 (-0.1)
4b: 100% off-season straw management	All farms manage rice straw out of season in all seasons where that is possible	1,075	8,832	4.8 (-0.2)
5: 50% water management + 50% off-season straw management *(Coordinated Effort, Highly Ambitious)*	Combination of scenarios 3a and 4a	1,032	8,789	4.8 (-0.2)
6: Combined *(Breakthrough Technologies)*	Combination of scenarios 1, 2, 3a, and 4a	774	8,526	4.5 (-0.5)

Notes: Numbers not summed correctly are due to rounding. Numbers shown in parentheses are changes relative to 2050 baseline.
Source: GlobAgri-WRR model.

Recommended Strategies

From a purely technical perspective that ignores economic cost, available research suggests a high potential for mitigating GHG emissions from rice production. For example, although our case studies revealed a number of technical obstacles to employing midseason drawdowns on all farms, most farms could implement dry-seeding, many farms could implement water drawdowns today, and the obstacles facing other farms seem reasonable to overcome (such as the need for more level rice paddies in India or for more field pipes for distributing irrigation water in Arkansas). Faster yield gains are technically feasible and could do much to mitigate emissions. The most speculative mitigation option involves breeding low-methane rice varieties. But lower-methane varieties already exist, and science suggests real potential from more extensive breeding.

The mitigation options all have significant potential to provide economic returns through higher yields and reduced water consumption, which provides benefits even if subsidies presently keep many farmers from realizing them, but these options also have unknown costs. The lack of detailed analyses of mitigation costs and benefits in specific rice-producing areas makes our estimates somewhat speculative. Unfortunately, we are aware of no coordinated national, let alone international, projects to mitigate emissions and to systematically improve our understanding of how to do so.

Based on these assessments, we offer the following recommendations:

Development agencies and national governments should fund a coordinated series of rice emissions mitigation projects that focus on synergies with water savings and yield improvements. Among criteria, projects should be chosen because of their potential for synergies and to test synergistic mitigation options in a range of different rice-growing settings.

Development agencies and national governments should similarly support coordinated technical support, research, and assessment of such projects through an international, collaborative technical team. Such an effort would help maximize impacts per dollar, assess results, and steadily improve technical understanding of how to pursue rice mitigation over time. The team should incorporate experts with a range of expertise, including knowledge of rice emissions and plant breeding, hydrology, irrigation management, and economics. The team should ensure that projects generate information not only on project design but also on yield, disease management, water conservation, and cost implications of various production options.

Governments should reform water and energy subsidies that distort mitigation goals and structure incentives and rules to encourage mitigation. Farmers practicing improved water management techniques typically do so because they anticipate yield gains, reduced pumping costs, and—in the case of dry-seeding—sometimes reduced labor costs. However, subsidies for water and energy distort these incentives. Subsidies to small farmers can be provided in ways that do not encourage excess water use. At a minimum, in areas where rice farming is already threatened by insufficient water supplies, water allocation systems should reward farmers who use water more efficiently by giving them priority access when water is short.

Crop breeding institutions should prioritize breeding of low-methane crop varieties. As discussed in Chapter 12, breeding for environmental goals can complement the primary breeding goal of increasing yields—or at least maintaining yields in the face of climate change. This should involve immediate efforts to cross-breed low-methane varieties with those that produce the highest local yields. Governments and international aid agencies should support large-scale pilot efforts to explore new varieties that produce lower amounts of methane.

International institutions should offer a prize for low-methane rice. The Green Climate Fund or another international funder should create a prize for a variety of rice that comes into widespread usage and reduces methane emissions in real-world conditions by 50 percent or more.

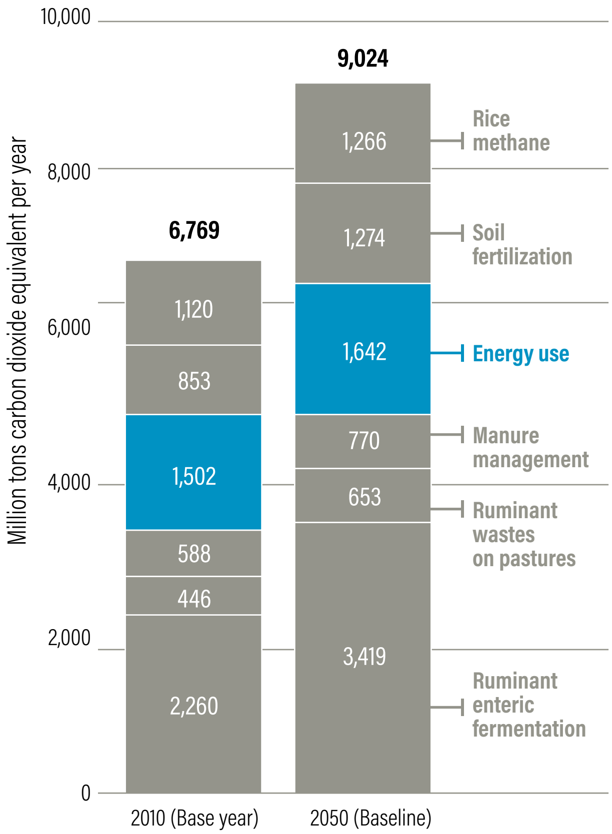
For more detail about this menu item, see "Wetting and Drying: Opportunities and Challenges for Rice Management," a working paper supporting this World Resources Report available at www.SustainableFoodFuture.org.

CHAPTER 29

MENU ITEM: INCREASE AGRICULTURAL ENERGY EFFICIENCY AND SHIFT TO NONFOSSIL ENERGY SOURCES

Agriculture uses energy to produce and transport inputs such as fertilizer and animal feeds, to heat and cool farm buildings, and to run on-farm vehicles and machinery. This menu item focuses on increasing energy efficiency in agriculture and shifting to low-carbon energy sources to reduce emissions.

Figure 29-1 | Greenhouse gas emissions from agricultural production, 2010 and 2050



The Challenge

We estimate that total GHG emissions related to energy use in agriculture will be 1,642 Mt CO_2e in 2050 (Figure 29-1). Of these emissions, 1,062 Mt result from on-farm energy use, 408 Mt result from manufacturing and transporting nitrogen fertilizers, and 172 Mt result from manufacturing and transporting all other inputs of nutrients and pesticides. (These total estimates of energy use emissions are somewhat higher than previous estimates in our *Creating a Sustainable Food Future* series[240] because they incorporate newer, higher estimates of on-farm energy use by FAO.)[241]

Overall, these emissions are only about 9 percent higher than in 2010, but our estimate is based in part on difficult projections. As poorer countries develop, they are likely to adopt more mechanization, and even developed countries may use more machinery than they do today. At the same time, there is likely to be some growth in efficiency of energy use, probably modest in tractors[242] but higher in other applications. In our baseline scenario, on-farm emissions stay the same because we assume that a 25 percent growth in energy use efficiency on farm cancels out a 25 percent growth in the level of energy use. The baseline also factors in a slightly smaller 23 percent increase in the energy efficiency of nitrogen production at fertilizer plants. This projection is based on a time lag that can be observed in the past: it takes 30 years for the average efficiency of all fertilizer plants to improve to the point where it matches the efficiency of the most efficient plants at the beginning of the 30-year period.[243] Yet, even under these generally optimistic assumptions, emissions from agricultural energy use in 2050 would amount to 1.6 Gt, filling 40 percent of our target budget for total agricultural production emissions (4 Gt CO_2e). Efforts to reduce these emissions are necessary.

The Opportunity

The opportunities to reduce emissions from energy use in agriculture mostly match the opportunities to reduce emissions from energy use in other economic sectors, which are the subject of many other studies.[244] They center on energy efficiency measures and on shifts from fossil-based energy feedstocks to zero-emission feedstocks such as solar, wind, and—in some studies—nuclear power.

Energy efficiency

One mitigation opportunity involves improvements in energy efficiency. Although we have found few studies of this potential in agriculture, one Indian study from 2013, for example, found potential to improve the energy efficiency of irrigation pumps by 40 percent.[245] Another study of cassava drying found potential for doubling efficiency.[246] More broadly, studies identify significant potential increases in energy efficiency in the aviation, maritime, and manufacturing sectors, and we doubt that agriculture is fundamentally different.[247] Although little explored, potential for efficiency gains in agriculture is likely larger than we have assumed in our baseline.

Renewable energy sources

Energy efficiency measures alone will not be sufficient to address climate change, and further mitigation will have to be achieved through shifts in energy supply. Electricity provides probably the easiest way to switch to low-carbon energy sources. Electricity accounts for approximately 40 percent of the roughly 1.2 Gt of baseline energy emissions in 2050 that result from on-farm energy use and manufacturing of inputs other than nitrogen fertilizers.[248] Another 25 percent of emissions from on-farm energy use and manufacturing involves direct on-farm use of coal for heat.[249] To reduce these emissions, farms need to shift to solar heat supplies or to electricity powered by low-carbon sources, such as solar or wind. The challenges and opportunities involved in energy shifts are likely to mirror those of shifting to low-carbon energy sources in other sectors. However, agriculture might enjoy an advantage in that farms generally have land available to generate their own solar or wind energy.

A greater challenge is the need to replace diesel fuel, which generates around one-third of agriculture-related energy use emissions. Agriculture uses diesel fuel for tractors and other farm equipment, and for some heavy machinery used in mining phosphate and potash. Battery-powered equipment may be a partial solution, but some of these end uses require such concentrated power that they will be difficult to electrify. Some experts view them as primary targets for biofuels. Because the capacity to produce truly low-carbon biofuels is limited (Chapter 7), we see less potential, although powering heavy equipment would be a good use of biofuels supplied by truly "additional" biomass. Another alternative might be the use of fuel cells powered by renewably generated hydrogen, or synthetic, carbon-based fuels made from renewable energy. However, the economical deployment of such fuels will require technological enhancement.[250]

Nitrogen fertilizer manufacturing

Dramatically reducing emissions from nitrogen fertilizer manufacturing presents a particular challenge. We estimate that the production process for fertilizer will emit 408 Mt CO_2e in 2050, an increase from 359 Mt CO_2e in 2010. Nitrogen fertilizer production generates high emissions because the Haber-Bosch process requires high temperatures, high pressures, and therefore high energy levels to break the double nitrogen atom bond of nitrogen gas into nitrogen atoms that can be bound in various fertilizer compounds.

One opportunity involves making this process more efficient. Modern production facilities use 36 gigajoules (GJ) of energy per ton of nitrogen fixed, but this is already roughly three times more efficient than the original Haber-Bosch method.[251] Most of the improvement has been in the "upstream" supply of hydrogen and nitrogen to the synthesis process,[252]and further improvements seem plausible because different fertilizer manufacturing plants have different efficiencies. Plants with the lowest energy requirements are roughly 25 percent more efficient than the global average.

China provides a special opportunity because it produces roughly one-quarter of the world's fertilizer[253] but uses 15 percent more energy than the global average and 35 percent more than the most efficient plants.[254] China also uses coal mined in ways that produce disproportionate emissions. One study estimated that China could reduce its emissions from nitrogen production by 30 percent just by moving to global average manufacturing standards for nitrogen.[255] Our 2050 baseline already incorporates 23 percent reductions in the global average fertilizer manufacturing emissions rate, bringing energy use down from an average of 36.6 to 28.0 GJ per ton of nitrogen fertilizer, which is the standard for the most efficient plants today. The theoretical limit to the efficiency in modern production systems is 20 GJ per ton of nitrogen fertilizer, and we hypothesize that it might be possible to reduce energy use to 24 GJ in real conditions still using the Haber-Bosch method.

In addition to efficiency measures, a wide variety of technologies will need to be deployed. The most straightforward opportunity involves a shift to producing fertilizer with electricity generated from solar or wind energy. The principal requirement would be to use solar or wind power to produce hydrogen, which is used in the production of ammonia. Hydrogen production in conventional ammonia plants accounts for approximately 85 percent of the energy requirements for nitrogen fertilizer production.[256] Given this heavy energy use to produce hydrogen, it might be practicable to retrofit existing ammonia production facilities with "bolt-on" facilities for supplying hydrogen and ammonia.[257] Long-established "electrolyzer" technologies exist to make hydrogen from electricity, but their use to produce relatively cost-effective low-carbon hydrogen is impeded by the higher costs of low-carbon electricity, by inefficiencies in converting that electricity into hydrogen fuel, and by the costs of the electrolyzers themselves. Substantial research therefore focuses on improving efficiencies and reducing these costs, as well as on designing systems that can utilize cheap, intermittent solar or wind power. None of the barriers seem insurmountable.[258] In addition, research is ongoing into ways to use solar radiation directly to generate hydrogen without first generating electricity,[259] and these approaches have the potential to be cheaper and more efficient. Two prototype solar fertilizer plants are being built in Australia.[260]

Mitigation Potential

As with crop yields and livestock systems, our baseline factors in an increase in energy efficiency of 24 percent per unit of agricultural output—sufficient to cancel out the effects of increased mechanization—and this increase will already require significant effort. We therefore treat our baseline also as our Coordinated Effort scenario.

Our Highly Ambitious scenario contemplates a 50 percent reduction in emissions per unit of output, with the exception of nitrogen fertilizer production, where we project slightly lower efficiency gains of 45 percent, which represents the limits of the Haber-Bosch system.

Our Breakthrough Technologies scenario reduces emissions by 75 percent from the baseline level of efficiency and applies to emissions from all energy uses including production of nitrogen fertilizers. Such a significant reduction would require deployment of breakthrough technologies in both heavy machinery use and production of nitrogen from renewable sources of energy.

Model results are shown in Table 29-1. Our Highly Ambitious and Breakthrough Technologies scenarios reduce the production emissions GHG mitigation gap by 8 to 18 percent and reduce energy emissions from nitrogen production and transportation by 14 to 67 percent.

Recommended Strategies

For the most part, strategies for reducing energy emissions in agriculture are the same as those for reducing energy emissions more generally across all economic sectors. They involve measures that increase the price of fossil-based energy sources (e.g., carbon taxes, GHG cap-and-trade systems), measures that lower the price of zero-emissions sources (e.g., incentives to purchase equipment that generates or uses zero-emissions energy), and technical and financial support for research. Because these issues are large and the subject of a vast amount of academic literature, we do not discuss them further here. However, we offer three specific recommendations related to agriculture:

Integrate low-carbon energy sources into all government agricultural investment programs and projects. On-farm renewable energy programs already exist to encourage alternatives to fossil fuels. Opportunities include low-carbon technology systems for aquaculture,[261] "passive solar" food storage,[262] solar- and wind-powered irrigation pumps,[263] and manure digesters.[264] Efforts to reduce energy emissions from farms should be built into national government agriculture projects and international aid projects and should be a focus of dealings between larger food companies and their suppliers.

Invest in research into low-carbon fertilizer production and build pilot facilities. The world's research agencies that are now funding energy innovations should invest heavily in research to develop production of nitrogen from renewable electricity. Much of that work could be linked to work now being done on developing hydrogen fuel produced by solar and wind power. Because these facilities will operate for two decades or more, moving the technologies forward quickly is necessary to avoid locking in highly polluting technologies for decades.

Apply carbon pricing or regulation to fertilizer. Governments should apply the same taxes or other regulations on emissions from manufacturing facilities to fertilizer production. Europe has included fertilizer manufacturing in its emissions trading system. As in the case of aircraft manufacturers, in initial years fertilizer manufacturers may need to purchase offsets, but this approach would create incentives to engage in their own R&D and to shift toward low-carbon fertilizer production.

Table 29-1 | Global effects of scenarios of agricultural energy use reduction on agricultural greenhouse gas emissions

SCENARIO	DESCRIPTION	TOTAL EMISSIONS FROM ENERGY USE IN AGRICULTURE (MT CO_2E)	PORTION OF ENERGY EMISSIONS FROM NITROGEN PRODUCTION AND TRANSPORTATION (MT CO_2E)	TOTAL PRODUCTION EMISSIONS (MT CO_2E)	PRODUCTION EMISSIONS GHG MITIGATION GAP (GT CO_2E)
2010		**1,502**	**359**	**6,769**	**–**
No productivity gains after 2010		1,982	374[a]	11,251	7.3 (2.2)
2050 BASELINE and Coordinated Effort	25% reduction in energy emissions per unit of agricultural output in 2050 relative to 2010 but energy use for nitrogen fertilizer manufacturing reduced from 36.6 to 28.0 GJ per ton.	**1,641**	**408**	**9,023**	**5.0**
50% Energy Emissions Reduction *(Highly Ambitious)*	50% across the board emissions reductions per unit of agricultural output. For nitrogen, the reduction is 45%, which achieves the thermodynamic limit of the Haber-Bosch process.	1,280	349	8,661	4.7 (-0.4)
75% Energy Emissions Reduction *(Breakthrough Technologies)*	75% reductions in energy emissions per unit of agricultural output across the board, including nitrogen production.	762	134	8,143	4.1 (-0.9)

Notes:
a. Emissions in the "no productivity gains" scenario are lower than our baseline scenario because lower livestock productivity leads to production of more manure, which partially substitutes for fertilizer.
Numbers not summed correctly are due to rounding. Numbers shown in parentheses are changes relative to 2050 baseline. Coordinated Effort scenario assumes no reduction in emissions from energy use relative to levels projected in the 2050 baseline.
Source: GlobAgri-WRR model.

CHAPTER 30

MENU ITEM: FOCUS ON REALISTIC OPTIONS TO SEQUESTER CARBON IN AGRICULTURAL SOILS

Some researchers are optimistic about the potential for large-scale sequestration of carbon in agricultural soils. Other researchers are more skeptical. This chapter analyzes both optimistic and more pessimistic claims and concludes that the realistic potential for sequestering carbon in agricultural soils is limited and that efforts should focus on sequestration as a cobenefit of boosting productivity, with a goal to stabilize soil carbon.

The Sequestration Debate

Many strategies for agricultural GHG mitigation have focused less on directly reducing agricultural emissions and more on offsetting them by sequestering more carbon in soils or trees on agricultural land.[265] The 2007 integrated assessment of the IPCC, the so-called AR4, estimated that various forms of carbon sequestration on agricultural land provided 80–90 percent of the global technical and economic potential for agricultural emissions mitigation.[266] The subsequent assessment, the AR5, in 2014 reproduced this figure.[267] The analysis that went into this figure has remarkable staying power: a 2017 paper in *Nature* quantifying estimates of the mitigation potential for soils in agriculture is based on essentially the same modeling analysis that generated the AR4.[268] Today, there is also a major international initiative with the stated goal of increasing global soil carbon by 4 percent per year, which would remove more than 4 Gt of carbon dioxide from the atmosphere each year.[269]

Some of these climate mitigation strategies focus on restoring agricultural land to forests or other natural vegetation. We explore these strategies in Chapter 20 and conclude that some important options exist to reforest both marginal and realistically unimprovable agricultural land, and that restoring drained peatlands should be a priority. Much larger-scale reforestation depends on—and must wait for—a high level of success in implementing the strategies described in this report.

The claim of large potential to store carbon in soils gained wide attention with publication of a paper in *Science* in 2004.[270] As this paper argued, use of land for cropland has undoubtedly led to great carbon loss, which is probably on the order of 25 percent of the carbon within the top meter of soil.[271] Loss rates, however, vary greatly and are probably due in part to management. At least some management practices can undoubtedly increase carbon in soils, such as adding manure, mulch, or more crop residues. There is also no doubt that many grasslands have lost carbon and could store more.

Claims of achievable carbon sequestration rates per hectare vary,[272] but, if all of the world's agricultural lands could sequester 0.5 tons of carbon per year, then the world could achieve something on the order of 2.5 Gt of carbon storage each year (roughly equal to 9 Gt of carbon dioxide, almost 20 percent of annual anthropogenic emissions from all sources).[273] Supporters of such soil carbon sequestration efforts also cite multiple cobenefits, such as aiding productivity and helping soils hold water and resist droughts, which would increase resilience to the rainfall variability likely to result from climate change. Many researchers have continued to make the case for large soil carbon sequestration potential using approaches that are, in effect, based on the physical potential of agricultural soils to store more carbon and the fact that a variety of practices can in theory increase soil carbon.[274]

In response to these claims, a number of other researchers have published articles expressing strong disagreement.[275] Our analysis of these claims leads us generally to side with the doubters. We believe that the realistic potential for soil carbon sequestration is far more limited than has been claimed and that before soil carbon sequestration can be treated as an offset for other emissions, it needs to be used to stabilize current global soil carbon stocks.

The Challenge

There are only two ways to boost soil carbon. One is to add more carbon to soils, and the other is to lose less. Losing less primarily means trying to manage soils so that microorganisms are less effective at consuming carbon and respiring it back into the atmosphere. We agree with the observations of others that carbon sequestration claims based on adding more carbon have frequently double-counted carbon sources, and that there are serious scientific, technical, and economic doubts about the ability to manage soils to starve microorganisms.

Building soil carbon with manure, mulch, and crop residues

Farmers can build soil carbon by cutting up parts of trees and shrubs and adding the mulch to soils, by adding manure, and by leaving more crop residues in the soil.[276] Yet in each case, the primary effect is to divert carbon from some other storage location or use to storage in soil. Pruning and mulching trees only shifts carbon from above-ground to below-ground storage—unless the trees were going to be pruned and burned. (As discussed in Chapter 7 on bioenergy, even though trees might eventually grow back, cutting down trees to use them for energy will increase carbon in the atmosphere for decades, and cutting wood to add to soils is likely to do so as well.)[277] Cows produce a given quantity of manure, so using manure on one farm usually means using less in another place. Although some crop residues are burned, most that are not already left on the soils are used for animal feed or household energy, so their use as mulch has both economic and carbon costs because their replacement as fuel or feed also causes emissions.[278]

Available carbon is finite, and any calculation of the sequestration benefits when carbon sources are used as a soil amendment in one location must count the costs of not using that carbon for another purpose or for soil amendment in another location. This calculation is typically ignored by the more optimistic carbon sequestration analyses.

There are some sources of wasted or inefficiently used carbon, such as organic municipal waste now landfilled, that could be added to soils. In China much manure is discharged directly into streams,[279] so diverting this manure onto farm fields would avoid pollution and sequester additional carbon in soils.

Another potential source of soil carbon is crop residues that are currently burned. These arise in some cropping systems including sugarcane harvested by hand, rice straw in much of India, and many cereals in northeastern China.[280] Crop residues are burned for a variety of reasons: to get rid of bulky wastes; to make it easier to harvest some crops, particularly sugarcane; to control pests; and sometimes to improve the pH of soils. The need to burn residues can be reduced by mechanization and pesticide use. For example, in Brazil, the shift to mechanized harvesting of sugarcane has greatly reduced burning of sugarcane leaves and appears to contribute to higher soil carbon compared to burned systems.[281]

The potential soil carbon gains from further residue incorporation are limited, however, if only because only around 10 percent of crop residues are burned.[282] According to FAO estimates for 2016, these residues globally amounted to only 381 Mt of dry matter, which therefore probably contain 190 Mt of carbon. The amount of carbon in residues incorporated into soil probably depends heavily on availability of nitrogen, but may be around 10 percent in nitrogen-rich environments.[283] Therefore, elimination of all residue burning and incorporation of all residues into soils would result in soil absorption of only about 19 Mt of carbon, equivalent to roughly 70 Mt of carbon dioxide per year, or less than 1 percent of likely agricultural production emissions in 2050.

Even increasing these estimates severalfold would create soil carbon gains on cropland of only a small fraction of the more enthusiastic estimates. It would also require overcoming the many practical challenges faced by farmers who burn residues to control pests and reduce soil acidity, and who lack mechanized means to mulch residues.

Crop residues are also commonly targeted as feedstocks for biofuels. We are sympathetic to the use of residues as a soil amendment primarily because of likely benefits for soil fertility, which include not just increased carbon content but other improved soil properties.[284] Yet this use reduces the potential for biofuels even more than we analyze in Chapter 7.

Overall, there is probably some potential to add otherwise underutilized organic material to soils, but the quantities are limited and there are real obstacles.

Reducing carbon losses through changes in tillage practices

In the normal course of farming, crop roots and residues left in the field help replenish carbon released into the atmosphere by soil microbes. Much hope has rested on "no-till" techniques that drill seeds into the ground without turning over the soil. Because the original plowing of grassland or of cut-over forests contributed to the loss of soil carbon, the plausible theory has been that reducing annual soil turnover should expose less of that soil carbon to decomposition by microbes. Many field studies initially appeared to support this view.[285] But in 2007, a scientific debate broke out when some researchers pointed out that past studies focused only on shallow soil measurements, often the top 10–30 centimeters, and that studies measuring soils to a depth of a full meter showed no consistent pattern of change in soil carbon.[286] In effect, analyses measuring carbon only at shallow depths ignored a variety of potential ways in which tillage could transfer more carbon deeper into the soil, so even if no-till practices increase carbon in the top layer of soil, that might be offset by reduced carbon at lower depths.[287] Scientists defending no-till argued in return that the statistical variability in measuring soil carbon changes at depth blocked any solid conclusion that soil carbon gains had not occurred,[288] but the proper inference is that we do not really know.[289] A consensus appears to be emerging that results are highly variable. In some areas, no-till appears to have no effect on soil carbon, and in other areas it appears to have a small effect of perhaps 0.3–0.4 tons of carbon/hectare/year (tC/ha/yr) (assuming continuous use).[290]

No-till has probably been most widely adopted in Brazil where, in 2012, the practice reached 29 Mha,[291] roughly half of all cultivated land. High adoption rates in Brazil probably reflect the high risk of soil erosion due to intense storms and the discovery of some additional agronomic benefits; for example, reductions in soil acidity. Brazil also widely cultivates glyphosate-resistant soybeans, so farmers can use glyphosate to control weeds without the need for tillage. No-till in Brazil tends to persist year after year. A number of studies have shown that the consistent practice of no-till—at least of recently cleared areas in the Cerrado—has maintained soil carbon levels comparable to those of soils under natural vegetation, while areas under conventional tillage have lost carbon.[292]

Where no-till generates small carbon gains, it still faces many practical challenges.

No-till agriculture is hard to maintain over time. Outside of Brazil, even where no-till is practiced, periodic plowing still commonly occurs to control weeds, deal with soil compaction or meet other agronomic needs.[293] There are virtually no data about how many farms employ truly long-term no-till, meaning no-till practiced for 10 or 20 years, but the data show that continuous no-till even for 10 years is infrequent. For example, in one complicated analysis of Iowa using data from the 1990s, the authors estimated that the probability of no-till persisting for even two consecutive years was only 8 percent, with the vast majority of farmers practicing no-till for a single year.[294] A study by the U.S. Department of Agriculture using more recent data estimated that only 13 percent of cropland in the Upper Mississippi River basin was in no-till for three consecutive years, the maximum period for which data could be assessed.[295] Regular or even occasional plowing probably causes much or all of any soil carbon gains to be lost, although there is some uncertainty because the data are so limited.[296]

Nitrous oxide emissions may increase. There is evidence that if practiced for only a few years, no-till may increase nitrous oxide emissions by temporarily saturating some portion of soils immediately after rainfall, leading to the low oxygen conditions that encourage nitrous oxide formation. This nitrous oxide can cancel out the benefits even of large carbon gains.[297] However, there is also evidence that nitrous oxide emissions decline after 10 years of continuous no-till on those limited areas that practice no-till that consistently. These contrasting results heighten the importance of whether no-till cultivation is practiced persistently.

No-till may reduce yields or increase costs. For many farms, no-till probably decreases yields although effects are variable. No-till appears to result in lower yields on average in wetter climates but to boost yields on average in some drier climates if combined with other practices.[298] Again, a key point is that there is high variability, but the yield consequences of practicing no-till are obviously an obstacle to adoption in many areas. Projections of large potential global carbon gains do not address this issue.

Finally, as discussed in Chapter 13 on soil and water conservation, there can be other challenges to adopting no-till, particularly in developing countries. They include the increased need for herbicides, and sometimes additional labor.

To put these numbers in perspective, if we assume that even one-third of the world's croplands were cropped using no-till—a big assumption given adverse yield and other practicable challenges on much cropland—and if we further assume that no-till is persistent on half of these croplands and that there are no offsetting nitrous oxide emissions—more big assumptions— and that half of these lands sequester carbon at 0.4 tC/ha/yr while the others do not, then the total mitigation would be ~200 $MtCO_2$ per year globally. This level of mitigation would offset only around 2 percent of likely agricultural production emissions in 2050, which would be a small contribution from such expansive efforts and given such optimistic assumptions.

Sequestering carbon on grazing land

Early studies were optimistic about the potential to increase carbon on grazing land, often by reducing the number of grazing animals.[299] Subsequent analyses have shown that the impact of improved rangeland management practices on soil carbon is highly complex, site-specific, and hard to predict.[300] In some grasslands, reduced grazing leads to more soil carbon and in some places it leads to less. Stranger still, truly poor grazing practices that undermine grassland productivity may actually promote carbon sequestration in some savannas by favoring tree growth.[301] Even in New Zealand, where grasslands are intensively managed and carefully studied, there is a high level of scientific uncertainty over the soil carbon effect of different management practices.[302]

In some cases, the claimed gains from improved grassland management probably reflect the ongoing benefits of efforts to restore cropland to grazing land. For example, one paper with careful grassland measurements in the southeastern United States, which has been cited for showing the potential gains of "improved management on grazing lands," studied a site that had recently been converted from cropland to grassland.[303] Newly established grasslands appear capable of building soil carbon quickly, and as Smith (2014) points out, may continue to gain carbon, although in declining amounts, for 100 years.[304] However, like forests, they will eventually reach an equilibrium. Management appears capable of altering the rate at which they gain carbon, but the benefits that should be counted are only the increase in the rate, not the total gain, and this increased rate may not change the ultimate carbon stock the grassland will achieve.

This long-term recovery of carbon stocks is just one of many issues to be considered when assessing claims that improved grazing can result in "climate-neutral" beef, in which soil carbon gains would cancel out emissions from animals.[305] Some studies of European grazing lands directly measured soil carbon, with some reporting these lands gaining carbon and others losing it.[306] A recent large European research project used a form of air monitoring at 15 sites to measure carbon fluxes in and out of soil and vegetation and found net gains of 0.76 tC/ha/yr.[307] That is a large figure, representing perhaps three-quarters of the common estimate of carbon sequestration by grasslands that have been newly reestablished on cropland. It was surprising because science has generally shown that long-established grasslands typically reach an equilibrium in which they stop gaining carbon.[308]

Unfortunately, this argument does not prove that carbon gains were caused by the grazing operation and does not compare the consequences of grazing to the counterfactual of not grazing. Part of the explanation may be that many of these grasslands are still recovering from previous plowing, so the gain would occur whether these lands were grazed or not.[309] In subsequent papers, the European researchers and others explain the results using modeling; they attribute half of the carbon gain to reduced numbers of animals grazing—leaving more biomass to be returned to the soil—and half to climate change and the associated rise of carbon dioxide concentrations, which stimulated more plant growth.[310] Yet if the carbon gains are the result of climate change, they would happen anyway and should not be attributed to grazing operations. In fact, assigning carbon gains to the grazing land ignores the far greater levels of carbon the land would sequester if it were allowed to return to forest, which would be the fate of the vast majority of European grazing lands if they were not grazed.[311]

In addition, moving toward less intensive grazing in Europe, even if it resulted in more carbon gains on European pasture lands, would probably lead to greater aggregate emissions globally if this shift resulted in reduced milk and meat production in Europe. Assuming the same level of global consumption, these efforts would necessitate increased production of milk and meat in regions where farming is less efficient (i.e., lower output and higher emissions per hectare), and would therefore likely trigger pastureland expansion in those regions.

We believe that a paper[312] claiming potential for "carbon-neutral" beef in the United States using only grazing land suffers from similar limitations. The authors estimated that carbon-neutral beef would require twice as much land per cow as the standard alternative using some feedlots, but they did not count the GHG emissions that would occur as more forests and savannas globally are converted to pasture. Even in an ideal situation of globally reduced agricultural land area, more grazing land would reduce the potential to sequester carbon through reforestation.

For reasons we discuss below, we believe that carbon gains on grazing land are possible but that early estimates of high potential cannot be justified.

Need for additional soil nitrogen

In 2011, Kirkby et al. pointed out that lack of nitrogen presents a major challenge to efforts to sequester carbon.[313] Soil organic matter is sequestered over the long term through microbial activity that requires 1 ton of nitrogen for roughly every 11 tons of carbon. By contrast, plant material on average has only 1 ton of nitrogen for every 100 tons of carbon. To sequester more carbon therefore requires more nitrogen, which Kirkby et al. (2011) calculated at around 80 kg of additional nitrogen for each ton of carbon. This additional nitrogen must be surplus to the amount used by plants.

In a 2017 comment, a number of other academics argued that this need for nitrogen made carbon sequestration an unrealistic climate mitigation strategy in light of both the practical challenges and environmental concerns associated with the additional nitrogen.[314] They calculated that achieving the goal of sequestering 1.2 Gt of carbon per year established by the 4 per 1000 Initiative[315] would require a 75 percent increase in the global application of nitrogen.

A number of academics known as champions for soil carbon sequestration wrote a response that only partially disagreed.[316] They did not challenge the need for vast amounts of nutrients to build soil carbon, and they agreed that trying to supply these nutrients through synthetic fertilizer would be too expensive and environmentally unwise. But they argued that regions with surplus nitrogen and other nutrients could supply the nutrients needed for soil carbon sequestration.

One major implication of this argument is that soil carbon sequestration at scale, sufficient to mitigate climate change, is enormously challenging at this time in sub-Saharan Africa. Much of the region is nutrient-deficient and is still far from being able to provide enough nitrogen even to grow crops. Building soil carbon would require nutrient additions that are high enough both to fully feed crops and to leave a surplus of nutrients to build soil carbon. This limitation does not undercut the importance of boosting soil carbon as part of the larger effort to improve yields and resilience in the region, but it does suggest that building soil carbon in this region to levels that would significantly affect carbon concentrations in the atmosphere is not feasible.

It remains highly uncertain how much even areas with nutrient surpluses could build soil carbon at scale without additional nitrogen applications. Nitrogen is released by soils or applied as fertilizer at particular times and in particular molecular forms. Microbes that turn plant carbon into stable carbon in humus probably cannot always take immediate advantage of all of this available nitrogen before it is lost from the field. A compelling study found that, if nitrogen is not available when carbon is added, soil microbes would break down existing soil organic matter in order to access the nitrogen embedded with it that would allow the microbes to feed on the new carbon source. This process would lead to a loss of soil carbon overall.[317] To build soil carbon by adding crop residues or other carbon sources (i.e., without deliberately adding more nitrogen), this study suggests that nitrogen from earlier fertilization must be freely available in soils or that it must be present in reasonable quantities as part of the added carbon material (as it is in manure or the residues of legumes).

The need for additional nutrients is a fundamental challenge to sequestering soil carbon and has received far less attention in the literature than it deserves. At the very least, it limits the capacity to sequester additional carbon in soils without the additional expense and the risk of further pollution (including GHG emissions) from additions of more nitrogen to the agricultural system.

Carbon gains or reduced losses?

Another important factor that is little discussed is the reasonable probability that the world is actually losing soil carbon today. The main goal (and likely effect) of efforts to sequester soil carbon may be to avoid further losses rather than to generate gains. One issue is that many of the studies claiming soil carbon benefits from different practices do not differentiate between actual soil carbon gains and reduced losses.[318] There are many technical reasons, including the availability of nitrogen, why it might be easier to reduce losses than to build additional carbon.

Current fluxes in agricultural soil carbon vary by region. For example, there are claims of relatively modest soil carbon gains overall in China,[319] conflicting estimates of soil carbon in the United States,[320] and estimates of soil carbon loss in Europe.[321] In general, global nitrogen studies provide the main reason to believe that carbon stocks on cropland are decreasing globally. Because nitrogen is needed to store carbon in soils, a loss of nitrogen from croplands implies that soils are losing carbon. Today, global studies that attempt to account for all inputs and outputs of nitrogen estimate that soils are losing tens of millions of tons of nitrogen.[322] In other words, even after accounting for all nitrogen that is applied to croplands, the amount of nitrogen that is removed by crops or lost to air or water indicates that, on balance, there is a net loss of nitrogen from soils. Although uncertain, if one estimate of nitrogen loss from croplands producing cereals is correct, then global soil carbon losses from these crops alone would account for 2.5 Gt of CO_2 emissions per year.[323]

Ton for ton, reducing the global loss of carbon is just as important for mitigating climate change as increasing global sinks, but standard global climate assessments do not assume any ongoing soil carbon losses on existing cropland, aside from peatlands. Because of the uncertainty, our model does not assume such losses either.[324] However, if these nitrogen budgeting studies are correct, then our projected emissions—and the projections of other modelers—are too optimistic. Additional management practices will be needed just to maintain soil carbon levels and reduce emissions to bring them into line with current projections.

Complexity of the soil carbon issue

Despite the complexity of the issues presented, our discussion still fails to communicate the full degree of uncertainty about nearly all features of soil carbon.

Accuracy of soil carbon measurements. Whether analyses are based on accurate measurements is itself a major issue. Today, it is commonly agreed that soil carbon measurements need to be taken at a depth of a full meter and adjusted to take account of the different density of soils at different depths to generate proper carbon content measurements. But vast quantities of soil data have not been collected in accordance with these practices. As a result, some meta-analyses exclude much data and end up relying on limited sources and still need to adjust for some inadequacies.[325] Many others simply rely on data measured to limited depth.[326]

Another big issue, rarely explicitly addressed, is how to define soil carbon. Much plant residue remains, at least for some time, in small pieces that will decompose as microbes turn it into more stable material. If some of this material is measured as soil carbon, there can be the appearance of large gains. At least one study that carefully considered this issue had to exclude much global soil carbon data because they not been gathered in ways that excluded larger residue particles.[327]

In addition, determining soil carbon changes over a few years is challenging because the amount of change is small by comparison with the total stock of carbon in the soil. Soils are heterogeneous and tillage practices can result in different surface configurations. Even when measurements are taken by scientists renowned for their care, different measurement techniques can result in dramatically different estimates.[328]

Accumulation and retention of soil carbon. The processes that affect accumulation and retention of carbon in soil are also enormously complex. In 2013, a large group of prominent soil scientists published an article, "The Knowns, Known Unknowns and Unknowns of Sequestration of Soil Organic Carbon," whose dominant lesson was the scope of the known unknowns.[329] Although adding carbon and nitrogen are inherently critical to building soil carbon, in some cases each is known to decrease soil carbon by "priming" microorganisms to become more active and consume more of the previously stored carbon. As summarized in this study, it generally appears that soil carbon can more easily be sequestered in clay soils, but some studies show no correlation. Soil erosion could have a large effect on the global storage of carbon, but, because eroded soils may bury carbon elsewhere, researchers disagree about whether erosion, on average, leads to more or less carbon storage globally.

In addition to all the other challenges discussed above, these complexities suggest that carbon gains are likely to be site-specific. Most conclusions to date carry with them a significant level of uncertainty, and carrying out a strategy to boost soil carbon will be hard to implement and harder still to verify.

Summary of the Challenge

Since a prominent 2004 *Science* paper,[330] researchers estimating soil carbon sequestration potential have continued to emphasize the simple fact that many of the world's agricultural soils can technically store more carbon than they do today and that practices exist to enhance their carbon levels.[331] We believe that analysis is too simple because the ability of soils to store carbon is only one factor and generally not the principal limiting factor of sequestering more carbon in soils. (Banks have additional shelf space to store more money, and there are "practices" for making money, but that does not mean it is easy for the world to become richer.) The technical capacity of soils to store more carbon does not by itself resolve the technical, practical, and economic challenges of getting the carbon into the soil and keeping it there.

At best, studies estimating large soil carbon gains focus on technical potential, which is itself complex, and do not deal with the practical and economic challenges. To summarize, these challenges include the differential yield effects; the need to count only additional carbon and biomass (or to count only net gains if diverting this biomass from another use); the need for more nitrogen; the multiple practical challenges facing farmers who try to change tillage, crop rotations, and manure- and residue-management practices; and the fact that even short-term gains can quickly be lost through changes in management due to changing markets and farm conditions.

The Opportunity

Despite the challenges and uncertainties, it is obvious that some types of farming tend to result in more soil carbon than others (even if only because they lead to smaller losses) and that increased soil organic carbon has important agronomic benefits in addition to mitigating climate change. In many systems, it will be worthwhile to continue to push no-till farming forward to help reduce soil erosion and improve water retention. Except in rice systems, where retaining rice straw increases methane, it makes sense to try to retain on the land those crop residues that are currently burned or removed. Doing so would necessitate replacing crop residues used as livestock feeds with more nutritious fodders, which would benefit livestock production where farmers are able to generate those fodders (although that may require some additional land).

On the whole, however, we believe that the realistic potential to sequester carbon is to be found in approaches such as those described below that can plausibly generate economic gains independently and that do not sacrifice carbon storage in another location.

Boost crop and pasture productivity

Measures that increase cropland and pasture productivity (Course 2) have the potential to help build soil carbon. Increasing yields will also increase crop residues and root growth, which can contribute to boosting or maintaining soil carbon. Efforts to boost crop yields are responsible for the soil carbon gains on cropland in China (at least in the top soil layers) as discussed above, and they have either modestly boosted or reduced the losses of soil organic carbon in the United States.

The same is true for grazing land. In Brazil, for example, there is consistent evidence that soil carbon is higher under productively managed pasture than degraded pasture.[332] China has made extensive efforts to restore the productivity of overgrazed land and, although the performance is variable, the evidence is strong that many grazing lands have simultaneously sequestered more carbon.[333] There is some evidence that introducing legumes into grasslands can increase soil carbon through root effects to levels beyond those achievable with improvements in fertilization.[334] A new meta-analysis found small gains from largely unspecified "improved grazing" practices on existing grazing land.[335]

A more recent global modeling study suggests that optimizing grazing globally has the *technical* potential to sequester the equivalent of up to 0.6 Gt of carbon dioxide per year[336]—around 40 percent of the IPCC's 2007 estimate of carbon sequestration *economic* potential on grazing land.[337] Because achieving this potential would require improvements in grazing practices on billions of hectares of land, including the introduction of legumes (which presents problems because legumes are often selectively grazed by animals), it should be used mainly as a theoretical estimate. Yet it does highlight that increasing productivity can increase soil carbon.

Agroforestry

Agroforestry, discussed in more depth in Chapter 13, may provide a means of boosting soil carbon by increasing carbon uptake. Unlike annual crops, trees can grow year-round and therefore take advantage even of the drier season. They can also often tap into groundwater that annual crops cannot reach. Although farmers commonly clear trees to provide more light for their annual crops, trees can sometimes boost productivity. In tropical areas, shade from trees can be less of a problem than in temperate systems because sunlight is abundant, some crops need some shading, trees can increase humidity or add nutrients, and some trees lose their leaves during the growing seasons of some crops.

Trees, of course, also store carbon in vegetation. Although this chapter has focused on soil carbon because we deal elsewhere with reforesting agricultural land, agroforestry can provide opportunities to build vegetative carbon without reducing food production.

Despite potential benefits, we believe the practical potential of agroforestry at this time is too uncertain to estimate. Agroforestry can refer broadly to any form of agriculture incorporating the cultivation and conservation of trees. It can include any form of tree-based crops, such as rubber or cocoa. Growth in the agroforestry sector is obviously limited by demand for the outputs and, although converting annual crops to tree crops would sequester carbon, the annual crops would need to be replaced by cultivation elsewhere.

In some analyses, the term *agroforestry* is applied to any trees found on farms. Using this broad definition, one recent study estimated that growth of trees on farms globally sequestered an average of 0.75 Gt CO_2e each year between 2000 and 2010, predominantly on parcels of land that are mixed combinations of forest and agriculture.[338] Findings like this must be considered in the light of numerous data and mapping challenges. We believe that this paper is probably counting as agroforestry what is primarily reforestation of abandoned agricultural land.[339]

The potential true net carbon gains from agroforestry are those that result from incorporating trees and shrubs into existing productive systems without loss of yield, such as productive silvopastoral systems discussed in Chapter 11, and park systems in the Sahel in Chapter 13. Agricultural landscapes also often include land that is producing little or no food, such as some (but not all) field borders. Some studies focusing on such opportunities have estimated meaningful opportunities for carbon gains.[340] As we discuss in Chapter 13, much of the true technical potential to expand agroforestry remains unclear and unexplored but we believe it has more potential than realized today.

Possibility for new scientific breakthroughs

Driving much of the interest in soil carbon is the basic fact that microbial decomposition of organic materials in soils and dead vegetation returns tens of gigatons of carbon to the atmosphere each year, while the amount of this carbon that is instead retained in soils varies greatly from one location to another. If changed land-management practices could retain even a small fraction of the carbon that microbes are now respiring, then the climate-mitigation impact could be significant. The conditions that influence the level of carbon retention turn out to be far more complex than thought only a decade ago. They depend significantly on soil structure and on a variety of biological and ecosystem conditions.[341] In forests, for example, research has shown that the presence or absence of one group of fungi has a major effect on levels of carbon storage.[342] New research could generate new mechanisms for increasing carbon storage. One research initiative, for instance, aims to breed plants whose roots produce more suberin, an organic compound highly resistant to breakdown.[343] The potential importance of soil carbon storage warrants research into the fundamental science of soil carbon storage and creative ways of increasing it.

Recommended Strategies

The challenges and uncertainties involved in boosting soil carbon do not imply a complete lack of opportunities to improve soil management, but the uncertainties are too high to project how much. We also believe the best evidence indicates that agricultural soils are losing carbon today—with total losses exceeding even the losses from peatlands, which are commonly counted as agricultural emissions. However, losses form nonpeatland soils are too uncertain to be reflected in our 2050 baseline. Although new science may change this impression in the future, we believe that the reasonable goal in the short and medium term should be to maintain global soil carbon. We therefore believe that improvements are necessary, but we count them only as maintaining global soil carbon, and we assume that such improvements occur in our baseline and all our mitigation scenarios.

The effort that societies can and will put into solving the food and climate challenge is not unlimited, and it should focus on the most promising options. In the case of carbon storage, we know that deforestation and other land-use changes are obvious targets. We could reduce gigatons of emissions by avoiding conversion of forests and other native landscapes and producing the food we need on existing agricultural land. Only 26 Mha of drained peatlands generate more than a gigaton of emissions, and we know those emissions can be stopped by rewetting the land. Based on these and the other promising opportunities we identify in this report, we do not believe that carbon sequestration in soils should receive much effort for climate mitigation purposes alone.

Instead, we believe that such efforts should follow a no-regrets strategy that focuses on boosting soil carbon either as a cobenefit of other actions taken for different purposes or when boosting soil carbon is critical to meeting other objectives. Such efforts include improving cropland and grazing land productivity, and appropriate development of agroforestry. No-till potentially offers other benefits, including yield gains in dry climates, reduced soil erosion, and other beneficial soil properties when practiced over the long-term. Where it is practicable to achieve truly continuous no-till beyond 10 years, reductions in nitrous oxide and yield advantages also appear achievable. Alternative animal feeds to replace crop residues will benefit livestock productivity, and any emissions reductions or soil carbon gains would be additional.[344]

In Chapter 13, we also highlight the urgent need to rebuild degraded soils in sub-Saharan Africa. This task does not represent an easy source of climate benefits—it is hard—but improving soils will be critical if Africa is to feed itself, reduce poverty, and reduce clearing of forests and savannas. Overall, we believe there are many potential opportunities for such synergies, and they should be the focus of efforts to sequester more carbon in soils.

CHAPTER 31

THE NEED FOR FLEXIBLE REGULATIONS

Among the many menu items discussed in Course 5, some common themes stand out. They include the need for greater production efficiencies and for innovation in technology and management systems. Another theme is the need for government regulations that require improved performance while allowing flexibility in implementation.

Why Regulations?

If there is no regulation—financial or otherwise—the world treats agricultural production emissions as though they are without cost. Farmers and agricultural companies have economic incentives to increase productivity, which will often have a side effect of reducing emissions, and many measures to reduce emissions will have other economic benefits, such as health benefits from reduced air pollution. Yet measures needed to solve climate change will not always be profitable to farmers, particularly when they involve technologies that are not fully developed.

Part of the need for regulation is to spur technological advances. In critical areas, our analysis shows that promising potential innovations exist to reduce emissions, including ruminant feed additives, new techniques for manure management, and different fertilizer compounds. Most of these options may—at least initially—involve additional costs, but they appear to be cost-effective relative to climate change mitigation strategies in other sectors. Many options would have large collateral benefits, such as reducing the water pollution, air pollution, and disease-bearing organisms associated with excess use of nutrients or poorly controlled livestock waste. Many might eventually more than pay for themselves as technologies evolve, including additives for enteric methane or nitrification inhibitors. Yet these technologies do not seem likely to evolve absent either strong incentives or some form of regulation designed to advance their development and deployment.

Regulatory requirements have advantages over purely incentive-based approaches because they encourage farms, like businesses generally, to find the cheapest ways of meeting new requirements. Voluntary incentives alone do not establish a level playing field, and first movers—those who act early to reduce environmental effects on their own—may suffer a competitive disadvantage when governments then subsidize efforts by those who chose to wait before acting. Regulations can also encourage the spread of cost-effective mitigation methods that farmers might otherwise ignore.

Subsidized regulations

Regulations can be advantageous even if governments choose to absorb much or all of the cost. In most of the world, regulation of agriculture has been limited either because of the political power of the agricultural community or a concern about economic impacts on farmers. Who pays the costs of environmental controls, however, is a separate question from whether to use regulations to encourage those controls. If governments reimburse the average costs of compliance, for example, farms could even make money if they find cheaper methods to meet the regulation. Over time, the costs should then come down.

Flexible regulations

Intelligent regulations can encourage innovation. In our discussion of new nitrogen fertilizer compounds, we suggest phasing in requirements for fertilizer companies to increase the market share of new compounds that increase fertilizer use efficiency (and thus reduce nitrous oxide emissions and nitrogen runoff). Preferably, such regulations would reward compounds that are more effective than others. This kind of approach would both allow and encourage companies to develop better and less expensive fertilizer compounds, gather the information to identify which farmers could most benefit from them, and market the better compounds to those farmers.

Shifting regulations to industry where feasible

One reason our recommendation for nitrogen fertilizer improvement could be effective is that the responsibility for regulatory compliance would rest with large entities. Such entities can better assemble the resources to push technologies forward and can spread the costs. Such entities can also select the most promising opportunities for improvement, such as those farms most likely to benefit from enhanced efficiency fertilizers, increasing the benefits of flexibility. For similar reasons, we recommend that requirements to improve manure management be applied to large pork businesses that control much of the pork production in the United States.

Creating future markets

Technologies have yet to be developed to control some types of emissions. In other cases, the technology has not yet been sufficiently proven to be effective and economical, as in the case, for example, with methane-inhibiting compounds for ruminant stomachs and inhibitors to control nitrous oxide from urine that can be fed to cattle. In these situations, governments can create incentives for industry to develop these techniques by committing in advance to require their use if they prove cost-effective. Innovative companies would invest in these new technologies to capture market share or otherwise gain a comparative advantage over competitors. For example, governments could commit to requiring use of a technology if and whenever its cost per ton of CO_2e mitigation reaches $25 or less. (Such costs should be a net cost, accounting for yield gains and other economic benefits.) Such promises would assure companies that they will have markets if they develop mitigation techniques that work.

Overall, our review of options to mitigate GHG emissions from agricultural production suggests some promising ways forward. Given the enormous challenge of reducing annual agricultural production emissions to 4 Gt by 2050 and the need for innovation, the key is to guarantee markets for those who develop or evolve better and more cost-effective mitigation techniques. We believe that flexible regulations—sometimes with compensation—realistically need to be a part of such approaches.

ENDNOTES

1. Hristov et al. (2014) and Gerber et al. (2013) provide good summaries of the research results to date for all these approaches.

2. Clark et al. (2011).

3. Hristov et al. (2015).

4. Hristov et al. (2015).

5. Hristov et al. (2015).

6. Hristov et al. (2015).

7. Brooke et al. (2018).

8. Hristov et al. (2015); EPA (2016).

9. AgResearch (2016).

10. Hristov et al. (2015).

11. Henderson et al. (2015). This paper reasonably assumed that these techniques would only be appropriate for the minority of ruminant production that makes heavy use of crops, and they would probably be even more expensive in other systems. This paper also analyzed the benefits of urea-treatment of straw, which is also limited and expensive. Because that technique is a means of increasing straw quality for production gains, we consider it implicitly included as one of the options in our productivity field.

12. Hristov et al. (2015); Martínez-Fernández et al. (2014); Reynolds et al. (2014); Romero-Perez et al. (2015).

13. Duin et al. (2016); Hristov et al. (2015).

14. Hristov et al. (2014). The use of 3-NOP apparently leads to increased direct emissions of hydrogen gas rather than hydrogen bound into methane.

15. Duin et al. (2016).

16. Email communication with Dr. Alexander Hristov (September 19, 2016).

17. Barns also produce a great deal of ammonia, which is not a GHG but leads to air and water pollution.

18. Data on manure management systems are rough but analysis in this paper uses estimates by FAO for the GLEAM model, provided separately but reflected in Gerber et al. (2013) and the I-GLEAM model available at http://www.fao.org/gleam/resources/en/.

19. IPCC (2006), Table 10.17, lists different conversion factors for the percentage of the potentially methane-contributing portions of manure (volatile solids) based on different manure management systems. These percentages depend on temperatures, and the ratios between liquid and dry systems vary modestly because of that, so the ratios described above are those at an average annual temperature of 20 degrees Celsius. The lagoon liquid slurry system chosen is for a liquid slurry without a natural crust cover, which tends to form in some liquid slurry systems, and which applies both to liquid slurry storage and pit storage below animal confinements.

20. Herrero et al. (2016) presents estimates from FAO (2019a; the GLEAM model); EDGAR (2011); EPA (2012); Herrero et al. (2013); Hedenus et al. (2014); and the MAgPIE model from the Potsdam Institute within this range after adjustment to the same global warming potential actors of 34 for methane and 298 for nitrous oxide. However, estimates from the GLEAM model developed by FAO were reported at these higher levels of 790 Mt. Data we received from the GLEAM modelers, however, resulted in emissions estimates of 625 Mt CO_2e, which is close to the range of other estimates.

21. These estimates for the same models or other estimation systems cited above range only from 300 to 410 Mt.

22. Owen and Silver (2015).

23. Herrero et al. (2016).

24. Data on manure management systems is rough, but analysis in this paper uses estimates by FAO for the GLEAM model, provided separately but reflected in Gerber et al. (2013) and the I-GLEAM model available at http://www.fao.org/gleam/resources/en/.

25. Owen and Silver (2015) and a companion working paper, Owen et al. (2014), do the calculations for large California dairy farms and generally. Using IPCC factors, emissions from solid manure management for California dairy farms are only 2 percent of the emissions from lagoons (calculations from Tables 7 and 8 even though the IPCC guidance estimates no nitrous oxide emissions from lagoons. Using revised emission factors based on their meta-analysis, the papers found total emissions from methane and nitrous oxide from dairies managed with dry storage to be only 5 percent of the emissions of lagoons and 10 percent of slurry pits (Owen and Silver 2015, Table 2). Interestingly, the revised figures showed total emissions from manure management and the absolute difference in emissions between the two systems to be larger (although not in percentage terms). One reason was that these actual measurements led to higher estimates of nitrous oxide emissions from lagoons than those in IPCC guidance, which would mean that lagoons generate half the nitrous oxide emissions of solid piles.

26. According to the GlobAgri-WRR model, in 2010 38 percent of manure management emissions in CO_2e were nitrous oxide and 62 percent methane. In 2050, 43 percent will be from nitrous oxide and 57 percent methane. Different studies have wide ranges in estimates of nitrous oxide, ranging from 100–120 Mt CO_2e in EDGAR and FAO (2019a) (around 25 percent) to 370 Mt (47 percent) in the GLEAM model (Herrero et al. 2016, Table S2a).

27. Zahn et al. (2001).

28. Montes et al. (2014).

29. Montes et al. (2014).

30. For example, IPCC guidance estimates emissions where average annual temperatures are above 27 degrees Celsius from liquid slurry storage systems at twice those from such systems at 19 degrees Celsius (IPCC 2006, Table 10.17).

31. For studies in the United States, see Lory et al. (2004) and Kellogg et al. (2000).

32. Wang et al. (2017); de Vries et al. (2013).

33. Kaffka et al. (2016).

34. Figures are based on personal communication with Dr. Dana Kirk, Michigan State University. These costs are $25–$50 per cow operating costs plus $25 fixed costs (assuming $150 per cow fixed costs amortized over six years). Hart (2017); Ma et al. (2013).

35. Assuming average U.S. milk production per cow of 7,500 liters per year. AHDB (2017). $17/cwt = 38.6 cents per liter. So $150 per cow would add 2 cents per liter and 5 percent to the farm gate cost of milk.

36. Ma et al. (2013).

37. Bentley (2015). This is largely attributed to the significantly lower labor costs, and increased efficiency, that come with more advanced technology.

38. Dickrell (2016); Dickrell (2014); Filtration and Separation (2014).

39. This analysis is based on estimates in the supplemental Excel file for Wang et al. (2016) (see worksheet for separation system).

40. Zhang et al. (2016); Bautista et al. (2011).

41. Vaddella et al. (2010).

42. Costs of the technologies are discussed in Box 25-1. The North Carolina State costs were calculated in a unit of dollars per 1,000 steady state live weight (SSLW)/year. SSLW represents the average number of pigs that are raised at all times of an average weight. Based on guidance from the lead economic analyst for the North Carolina State study (Kelly Zering, personal communication, November 3, 2016), we translated that figure into pounds of pork per year carcass weight based on the following conversion factors: 1,000 SSLW produces 17.5 pigs per year with a "lean carcass weight" of 210 pounds. We also assign 10 percent of the economic value of the pigs to the producing of weaner pigs because the pork operations analyzed, which the principal operations in North Carolina, purchase pig lots for finishing. The calculation (17.5 * 210 * (1-.10)) equals 3,308 pounds. Thus each $100 per SSLW/year translates into a cost of 3.3 cents per wholesale pound of pork. According to USDA/ERS (2015b), the average retail carcass price from 2010–15 was $3.59 per pound (this work adjusts the quality of carcass weight into retail price equivalents). By this calculation, every $100 SSLW translates into 0.9 percent of the retail price of pork. The same citation shows average wholesale prices over 2010–15 at 62 cents per pound (adjusted to be equivalent in quality to retail). Assuming price equals costs of production, by this calculation, each $100 SSLW/year translates into an additional 5 percent in the wholesale costs of producing pork. Based on these figures, the technology would add 5.2 cents to 9.2 cents per pound of pork, equal to 1.4–2.6 percent of the costs.

43. Washington State University Extension (2015).

44. Bruun et al. (2014).

45. Liebetrau et al. (2013) found digestate leakage rates at up to 11 percent of total methane produced in the digester.

46. The emissions for nitrous oxide depend on the quantity of nitrogen excreted but using the numbers for California dairies from Owen et al. (2014), a switch from dry storage to a 10 percent leaky digester would increase emissions of methane by 2,600 kg CO_2e per cow and reduce emissions from nitrous oxide by 360 kg CO_2e per cow.

47. A simple way to calculate how much would be to assume that each kilogram of carbon in the methane saves a kilogram of carbon from fossil use. In that event, 100 kg of carbon in methane would save 100 kg of carbon from fossil fuels but would be canceled out by a net increase in methane release from leakage of 3 percent because methane has 34 times the global warming effect over 100 years as carbon dioxide and because both methane and carbon dioxide utilize one carbon atom. If methane replaces charcoal, the savings in carbon in trees could be much larger than 1 kg of carbon.

48. Lansche and Müller (2012).

49. Liebetrau et al. (2013); de Vries et al. (2010).

50. Lansche and Müller (2012); Berglund and Börjesson (2006).

51. Vu et al. (2015).

52. Bruun et al. (2014) provide estimates that combine the GHG emissions from manure management with potential reductions in energy emissions. Counting in benefits of avoided wood harvest or reductions in coal use, this study estimated that leakage rates from digesters could be as high as 35–38 percent without actually increasing GHG emissions. For replacement of natural gas, a leakage rate of 12 percent in this calculation would eliminate GHG benefits.

53. Dhingra et al. (2011).

54. For example, for a typical large dairy farm in New York State with 500 mature cows, researchers at Cornell University estimate the costs of abating emissions in this way at roughly \$5 per ton CO_2e for an anaerobic lagoon, but the costs rise to roughly \$25 for a 100-cow operation. Calculations performed using CoversVX file authored by Shepard et al. (2008) downloaded from the Cornell University Extension Service website on July 14, 2018.

55. Gao et al. (2012).

56. Strokal et al. (2016).

57. North Carolina Department of Environmental Quality (2018).

58. Bai et al. (2016).

59. Wang et al. (2017).

60. Hristov (2013).

61. A good summary of the evidence for different management of manure by larger and smaller farms in Canada is presented in VanderZaag et al. (2013).

62. United States International Trade Commission (2014).

63. United States International Trade Commission (2014).

64. Herrero et al. (2016).

65. Doole and Paragahawewa (2011).

66. Doole and Paragahawewa (2011).

67. de Klein et al. (2011).

68. Doole and Paragahawewa (2011).

69. Ledgard et al. (2014).

70. Welten et al. (2013).

71. Minet et al. (2016).

72. Yasuhara et al. (1997); OECD (2003); NIOSH (2007). Dicyandiamide seems to be minimally toxic based on the few lab animal studies that have been performed. The Organisation for Economic Co-operation and Development released an SIDS Initial Assessment Report for cyanoguanidine, another name for dicyandiamide, which determined that the oral LD50 (median lethal dose) is greater than 30,000 mg/kg per body weight in female rats (OECD 2003). Additionally, the chemical was determined to be a skin irritant for guinea pigs. However, nonlethal doses had no effect on clinical signs, body weights, food consumption, reproductive parameters, or necropsy findings in SD rats. Due to its low hazard, potential further assignment of the chemical has remained low priority.

73. Smith and Schallenberg (2013).

74. Smith and Schallenberg (2013).

75. Byrnes et al. (2017).

76. Subbarao et al. (2006a, 2006b, 2007, 2009).

77. Ward et al. (2016); Galbally et al. (2010); Barneze et al. (2014); Mazzetto et al. (2015); Pelster et al. (2016); Sordi et al. (2014).

78. Kelliher et al. (2014); Saggar et al. (2015); Chadwick et al. (2018).

79. Chen et al. (2016); Turner et al. (2015); Miller et al. (2012); Crutzen et al. (2008).

80. Turner et al. (2015).

81. By our estimate, using the 2 percent nitrous oxide emission factor of the IPCC, grazing in arid areas generates slightly less than half of the nitrous oxide emissions from pasturelands, but if those emission rates are too high, and emissions result from hotspot areas on wetter grazing land, then these arid pasturelands probably generate a lower percentage of emissions from pasturelands.

82. Email from Subbarao Guntur (CIAT) to Tim Searchinger (February 25, 2018).

83. Total nitrous oxide emissions are higher, but they include nitrous oxide from urine left on pasture, which we address in the livestock section. Davidson and Kanter (2014) estimate that agriculture is responsible for around 80 percent of total human emissions of nitrous oxide, and nitrous oxide was estimated at 6.2 percent of total emissions in 2010 (IPCC 2014).

84. Lassaletta et al. (2014), Figure 5c.

85. Erisman et al. (2013).

86. WRI (2013).

87. Peñuelas (2013).

88. Zhang et al. (2015b).

89. Zhang et al. (2015b), Table 1, estimates crop nitrogen use efficiency (NUE) at 42 percent while Lassaletta et al. (2014) estimate crop nitrogen use efficiency at 47 percent. Different estimates of nitrogen available from nitrogen fixation, animal agriculture, and deposition help to explain the differences, as do different estimates of the portion of nitrogen fertilizer used on pasture. Some estimates of nitrogen use efficiency focus only on synthetic fertilizer, but because the nitrogen available to crops includes other sources, estimates based on all fertilizer applied are more informative.

90. Nitrogen use efficiency can be defined in different ways. We define it as the percentage of total nitrogen applied to farms that is removed in the edible portions of crops, which excludes the nitrogen returned to farm fields in the crop residues left on the farm.

91. These figures rely on estimates for NUE in China that the International Fertilizer Association recently altered, which would very modestly improve the global average (IFA 2017).

92. Zhang et al. (2015b).

93. Chen et al. (2011).

94. Zhang et al. (2015b) estimate the NUE in China in 2010 at 25 percent (harvest of 13 Mt and total nitrogen from all sources on cropland of 51 Mt), but revisions down of roughly 7 Mt based on new estimates by the International Fertilizer Association bring that efficiency up to 30 percent IFA (2017).

95. Zhang et al. (2015b).

96. Lasselatta et al. (2014), Figure 1. A European nitrogen directive limited nitrogen application to 170 kg/ha, although the Dutch obtained a waiver for dairy farms whose feed was supplied primarily by grazing land (more than 70 percent) to apply up to 250 kg/ha until 2017. A new Dutch manure management directive restricting phosphorus levels will impose tighter constraints on manure management.

97. Lassaletta et al. (2014), Figure 2.

98. Lassaletta et al. (2014).

99. Mueller et al. (2012); Liu (2010).

100. See Figure 4b in Zhang et al. (2015b).

101. This issue is discussed in EU Nitrogen Expert Panel (2015).

102. Kanter and Searchinger (2018).

103. EPA (2015a).

104. Turner et al. (2015).

105. EPA (2015b).

106. Lasalleta et al. (2014), Figure 5b; Zhang et al. (2015b).

107. Use of synthetic nitrogen rises from 104 to 159 Mt (GlobAgri-WRR model). For comparison, FAO estimated an increase from 166 Mt to 263 Mt from 2006 to 2050, an increase of 58 percent (Alexandratos and Bruinsma 2012, 127), but adjusting for the roughly 25 percent greater population growth between 2006 and 2050 now expected by the United Nations (an increase of 3.1 billion instead of 2.5 billion), this projection by FAO would now be on the order of 70 percent (although it starts in 2006). A separate study by Bodirsky et al. (2014) estimates a "middle of the road" reference with an increase of reactive nitrogen in all agriculture from 2010 to 2050 of 25 percent. One of the differences in the estimates lies in the assumptions about changes in the efficiency of fertilization, which FAO assumes increases only around 4 percent, but which Bodirsky et al. (2014) assume increases by 13 percent.

108. GlobAgri-WRR does not estimate total losses of nitrogen to the environment. Zhang et al. (2015b) calculated a nitrogen surplus on cropland of 100 Mt in 2010. Although GlobAgri-WRR incorporates most of the Zhang et al. (2015b) crop nitrogen model, it estimates lower emissions because it incorporates a lower estimate of nitrogen produced from manure based on formulas established in Herrero et al. (2013).

109. This figure is not directly comparable to many other estimates because it includes emissions from the energy used to produce and transport fertilizer, which can be controlled by more efficient use, but which we also discuss in Chapter 28 below on reducing energy emissions.

110. Fertilizer Institute (2016).

111. USDA (2017).

112. Kanter and Searchinger (2018)

113. Ciampitti and Vyn (2014); Debruin et al. (2017).

114. van Grinsven et al. (2012); Velthof et al. (2013); Hansen et al. (2012).

115. Mueller et al. (2012); Ju et al. (2009); Chen et al. (2011).

116. Kitchen et al. (2017).

117. Robertson (1997). Nitrogen is taken up for only 8–12 weeks following crop canopy closure in most cropping systems.

118. Trenkel (2010).

119. Various meta-analyses are summarized in Kanter and Searchinger (2018); and Trenkel (2010), p. 94.

120. Akiyama et al. (2010).

121. Fuglie et al. (2011).

122. Bindabran et al. (2015).

123. Trenkel (2010).

124. Beach et al. (2015).

125. According to USDA (2013c), the average nitrogen fertilizer rate on corn in the United States was 140 lbs/acre, which equals 157 kg/ha. At IPCC N_2O default emission rates of 1.45 percent for both direct and indirect emissions, \$20 per hectare to apply a nitrification inhibitor, and an effectiveness of 35 percent, nitrification inhibitors would save 0.37 tons of emissions (CO_2e) per hectare at a cost of \$54 per ton of CO_2.

126. Robertson and Vitousek (2009).

127. According to Robertson and Vitousek (2009), "Agronomic evidence that any nitrification inhibitor consistently increases NUE is lacking."

128. Abalos et al. (2014, 2016).

129. Trenkel (2010), citing Gutser (2006), estimated nitrification inhibitors would cost 8 to 20 euros per hectare but reduce fertilizer application needs with a savings of 13 to 21 euros per hectare.

130. Abalos et al. (2014).

131. Qiao et al. (2015).

132. Qiao et al. (2015) reviews a number of studies and justly finds farmers seek to apply nitrogen in the spring.

133. McKinsey & Co. (2009), 188.

134. MarketsAndMarkets (2015) estimated global sales of controlled release fertilizers at \$2.2 billion in 2014, out of worldwide nitrogen sales (for 2012) of \$99 billion (MarketsAndMarkets 2017).

135. For example, Trenkel (2010) gives a difference in materials costs for polymer coating of urea as five times the cost of urea alone. However, other compounds may be in the range of \$15 to \$25 per hectare.

136. Qiao et al. (2015); Yang et al. (2016).

137. Marino (2017).

138. Subbarao et al. (2017, 2013).

139. Subbarao et al. (2017, 2013).

140. Bindraban et al. (2015); Dimkpa and Bindraban (2016).

141. The authors in Zhang et al. (2015b) established a goal of limiting nitrogen losses to the environment from cropland to 50 Mt. Although GlobAgri-WRR uses the Zhang et al. (2015b) nitrogen model, it adjusts future food needs to meet a larger population, makes more precise calculations by crop type and location. It also uses lower estimates for nitrogen in manure applied to crops based on the underlying analysis presented in Herrero et al. (2013). Because of this, under the GlobAgri-WRR scenario that achieves the Zhang et al. (2015b) NUE target, global NUE actually rises to 71 percent in 2050.

142. Zhang et al. (2015b).

143. Turner et al. (2015).

144. Bento et al. (2015).

145. Padhee (2018).

146. Ellis (2014).

147. See papers discussed in Jayne and Rashid (2013) finding that African farmers tend to apply fertilizer at rational rates given prices. For China, see Zhou et al. (2010).

148. Zhang et al. (2015b).

149. Fan et al. (2007); Morris et al. (2007).

150. Fan et al. (2007).

151. Mueller et al. (2012); Zhang et al. (2015b).

152. Yuxuan (2014).

153. Li et al. (2014).

154. Personal communication, Jikun Huang, April 2017. These results are expressed in Huang et al. (2017).

155. Huang et al. (2017).

156. Huang et al. (2017), Figure 5.5.

157. Huang et al. (2017), Table 5.1.

158. Huang et al. (2017).

159. As one example of the differential subsidies, the prices of nitrogen rose by only 16 percent from 2000–2001 to 2013–14, while the price of phosphorus rose 250 percent from 2009–10 to 2013–14 and the price of MOP rose 355 percent in the same period (Huang et al. 2017, 152).

160. Authors' calculations from FAO (2019a). In 2011, countries with a total population of 3.75 billion reported rice consumption in excess of 500 calories per day—in each case substantially more than any other single food. The world population in 2011 was 7 billion.

161. Roughly 500 Mt are the estimates both of the Food and Agriculture Organization of the United Nations (FAO), which can be found at FAO (2019a), and of the U.S. Environmental Protection Agency (EPA), at EPA (2012). The EPA estimate uses outdated estimates of the global warming potential of methane.

162. These estimates are generated by GlobAgri-WRR using estimated nitrous oxide emission rates for rice by the IPCC.

163. GlobAgri-WRR estimates of rice emissions are based on a model of rice emissions down to the subnational level published by Yan et al. (2009) using IPCC Tier 2 methods for estimating rice. However, the originally published paper used estimates of midseason drawdowns from a report for the Asian Development Bank. We believe these estimates are accurate for China (Li et al. 2002), Japan, and Korea. Together, these three countries accounted in 2014 for 33 Mha, roughly 20 percent of global rice paddy area (authors' calculations based on FAO 2019a). However, the view among agricultural researchers is that few farmers perform midseason drainage in most other countries, which account for the remaining 80 percent of global rice paddy area. Adjusting the model in Yan et al. (2009) to reflect our rough estimate of 10 percent midseason drainage rates in other countries raises the estimate of global methane emissions to roughly 600 Mt of CO_2e. When we further adjust these figures for a global warming potential for methane of 34, as recommended by the most recent integrated assessment by the IPCC, rather than the 21 used by FAO and the EPA, emissions rise to roughly 1.1 Gt.

164. Emissions from rice in five major rice-producing countries of Southeast Asia as reported in the most recent national communication to the UNFCCC as of September, 2016. The percentage of total emissions in Indonesia is low due to very high emissions from deforestation, whereas the high percentage of the total in Myanmar is due to generally low emissions from nonagricultural sectors.

Country	Total GHG emissions from rice (Gt CO_2e)	Percentage from total	Percentage from agriculture sector
Indonesia	34,861	2.5	46.2
Myanmar	5,511	28.4	43.5
Philippines	16,437	13.0	44.4
Thailand	29,940	10.6	57.5
Vietnam	37,101	24.8	57.5

165. As yields grow, so will the production of rice straw, and methane emissions can increase with the incorporation of rice straw into the soil. If rice straw is burned in the field, that will also emit nitrous oxide and methane. However, the actual amount of GHG emissions depends on how the rice straw is managed. If it is removed and used, there is no increase in methane. Because it is difficult to predict future management of rice straw, we do not factor in this possible effect of yield increases.

166. FAO (2019a).

167. Fischer et al. (2016).

168. GlobAgri-WRR model, based on Alexandratos and Bruinsma (2012) with adjustments.

169. That estimate is based on an empirical correlation between rice yields and nighttime temperature obtained in Peng et al. (2004), a long-term field experiment in the Philippines. Zhang, Tang, et al. (2013) also showed a correlation, though the amount differs by breed.

170. Nguyen (2005).

171. Ziska et al. (2009).

172. van Groenigen et al. (2013).

173. Alexandratos and Bruinsma (2012); FAO (2019a). Global rice yields in 2010 were 4.3 t/ha.

174. Authors' calculations based on necessary rice yield growth to 5.5 t/ha by 2050 to accommodate a 28 percent increase in rice consumption between 2010 and 2050 with no land expansion. Necessary annual yield growth would be 30 kg/ha/yr between 2010 and 2050, or 62 percent of growth between 1962 and 2006 (48.4 kg/ha/yr).

175. Fischer et al. (2014), Table 4.6.

176. Gogoi et al. (2008).

177. Jiang et al. (2017).

178. Su et al. (2015).

179. Biochar is a high-quality charcoal that can be made from crop residues. It can help store carbon in soils and, in some soils, increase fertility.

180. Setyanto et al. (2000).

181. IPCC (2006).

182. Gathala et al. (2011).

183. Gathala et al. (2011).

184. Wassmann et al. (2000). The early stages of directed seeding rice require a very shallow floodwater cover, so that initial emission rates under direct seeding are typically low. However, the plants take longer to grow in the field, increasing flood duration. (Young rice plants grown in a nursery are also flooded but typically occupy only 15–20 percent of the rice area; see IRRI 2007.)

185. Pittelkow et al. (2014).

186. Itoh et al. (2011).

187. Siopongco et al. (2013).

188. Joshi et al. (2013), Table 3.

189. IPCC (2006).

190. Linquist et al. (2014).

191. Joshi et al. (2013).

192. Sander et al. (2014); Tariq et al. (2017); Oo et al. (2018).

193. Kritee et al. (2018).

194. Yan and Akiyama (2008).

195. Global Commission on the Economy and Climate (2014).

196. According to Gassert et al. (2013), 29 percent of the world's rice is grown in areas facing high to extremely high levels of water stress.

197. Li et al. (2014); Bouman et al. (2007).

198. Hafeez et al. (2008).

199. Bouman and Tuong (2001).

200. Rejesus et al. (2011).

201. Lampayan (2013).

202. Kürschner et al. (2010).

203. Water Technology Centre (2009); World Bank (2006).

204. Siopongco et al. (2013).

205. Committee for Formulation of Agriculture Policy for Punjab State (2013).

206. Rajkishore et al. (2013); Pathak et al. (2013); Rajkishore and Sunitha (2013); Bhatia et al. (2013).

207. World Bank (2006).

208. Central Water Commission (2010); Department of Agriculture, Punjab (2012).

209. Government of Tamil Nadu (2009).

210. Chauhan et al. (2012).

211. Mahajan et al. (2013).

212. Mahajan et al. (2013).

213. FAO (2019a).

214. Pinoy Rice Knowledge Bank (2014).

215. Sander et al. (2014). Studies include the following:

Study	Location	Methane	
		Emissions under continuous flooding	Relative emissions under single drawdown
		kg/ha/season [kg/ha/day]	Percent
Corton et al. (2000)	Maligaya, Nueva Ecija	89 [0.91]	57.1
		75 [0.73]	63.0
		348 [3.75]	92.5
		272 [3.23]	55.1
Wass-mann et al. (2000)	Los Baños, Laguna	251 [2.51]	17.9
		10 [0.10]	80.0
		35 [0.35]	31.4
Bronson et al. (1997)	Los Baños, Laguna	17.3 [0.20]	38.5
		371 [4.36]	57.2

216. Dawe (2005); Hafeez et al. (2008). A study of one irrigation system in Central Luzon, showed that 10,000 farms (about 20 percent of the area under rice) had a pump density of at least one pump per 10 ha.

217. Mariano et al. (2012).

218. Rejesus et al. (2011).

219. Rejesus et al. (2011).

220. Belder et al. (2004); Lampayan et al. (2009); Tabbal et al. (2002).

221. Sibayan et al. (2010); Rejesus et al. (2011).

222. Rejesus et al. (2013).

223. Authors' calculations from FAO (2019a).

224. USDA (2014b).

225. Linquist et al. (2014).

226. This is based on work by Linquist et al. (2014).

227. Pittelkow et al. (2014).

228. Linquist et al. (2014).

229. Linquist et al. (2014); California Rice Research Board (2014).

230. Authors' calculations from FAO (2019a).

231. Zhang et al. (2013b, 2013c); Liu, Zhang, Ji, et al. (2013); Zhang and Li (2003).

232. Zhang et al. (2013c).

233. Fan et al. (2005); Li et al. (2007); Liu et al. (2003); Zeng (2012).

234. Li et al. (2004); Li et al. (2007).

235. Adhya et al. (2014) include an estimate of plastic film costs of 750 RMB, but savings in pesticides and fertilizer input of 657 RMB, plus labor savings of 2,700 RMB. Zeng and Liu (2012) found similar savings.

236. Wei et al. (2000); Wang et al. (2002).

237. Cai et al. (2000).

238. Wei et al. (2000); Wang et al. (2002, 2012).

239. Wang (2008).

240. See Adhya et al. (2014), which relied on earlier FAO estimates.

241. FAO (2019a).

242. On the relatively pessimistic side, one study found only around a 6 percent increase in energy efficiency of tractors in the United States from 1979 to 2009 (Grillo et al. 2014), and a European Commission analysis shows little gain in the energy efficiency of freight transport from 1995 to 2010 (European Commission 2016, 128, Figure 31). On the optimistic side, the European Union is also projecting a 44 percent increase in the efficiency of heavy-duty vehicles between 2010 and 2050 (European Commission 2016, 131).

243. IFA (2009).

244. See, e.g., IEA (2015a); Deep Decarbonization Pathways Project (2015); and New Climate Economy (2016).

245. Saini (2013).

246. CCAFS (2016).

247. IEA (2015a); IEA (2016a); UNIDO (2010).

248. FAO (2011f). FAO's breakdown for direct energy use in agriculture in 2010 is as follows. We use this information while adding information on energy use in aquaculture from WorldFish and Kasetsart University (Mungkung et al. 2014).

FAO Breakdown of Direct Farm Energy Use in Agriculture in 2010	
Gas-diesel oil	357,532
Motor gasoline	18,172
Natural gas (including LNG)	22,924
Liquefied petroleum gas (LPG)	8,007
Fuel oil	5,723
Coal	97,982
Electricity	325,517
Total energy	835,857

249. See previous endnote.

250. IEA (2015a); U.S. DoE (n.d.).

251. Patil et al. (2016).

252. Patil et al. (2016).

253. FAO (2019a).

254. Zhang et al. (2013c).

255. Zhang et al. (2013c).

256. Michalsky et al. (2012).

257. Pfromm (2017).

258. U.S. Drive Partnership (2017); Pfromm (2017).

259. Chowdhury et al. (2018); Nakamura et al. (2015).

260. Service (2018).

261. University of Toronto (n.d.).

262. Rolex Awards for Enterprise (2005).

263. Upadhyay (2014); Enciso and Mecke (2004).

264. EPA (2017).

265. Seeberg-Elverfeldt and Tapio-Biström (2010); Smith et al. (2007).

266. Smith et al. (2007). Carbon storage represents 89 percent of the total mitigation estimated economically feasible; a few percent, however, was focused not on new sequestration but on reducing the loss of carbon in wetland soils by restoring the wetlands.

267. In Figure 11.13 of the most recent IPCC assessment, Smith et al. (2014) essentially reproduce the mitigation estimates from the 2007 assessment. In Figure 11.14, the chapter then adds bar charts showing more recent assessments—grouped into agriculture and forestry—and including mitigation through demand reductions. But this chart identifies mitigation potential only in broad categories, such as forestry or agriculture, and does not identify the types of agricultural mitigation. It therefore does not modify the impression from Figure 11.13.

268. Paustian et al. (2016) cited Smith et al. (2008), which was the peer-review paper that presented the modeling analysis that went into the 2007 IPCC report.

269. Van Groenigen et al. (2017).

270. Lal (2004).

271. Although there are great variations in soil carbon losses, this figure seems a reasonable estimate based on meta-analyses as summarized in the supplement of Searchinger et al. (2018a).

272. See examples provided in Chambers et al. (2016).

273. See Minasny et al. (2017) for articulation of this goal.

274. See Chambers et al. (2016); Minasny et al. (2017); de Moraes et al. (2017); Lal et al. (2018), and many other papers summarized in Stockman et al. (2013).

275. See, e.g., Powlson et al. (2016); Powlson et al. (2014); van Groenigen et al. (2017).

276. Poulton et al. (2018).

277. Transferring carbon from trees to soils by itself is inefficient. Most of the carbon will decompose and be released back into the atmosphere as carbon dioxide, and while the precise levels will vary, only on the order of 10–20 percent of the carbon is likely to remain in a more stable form in the soil (Liska et al. 2014). The initial result is likely to be a substantial carbon debt. If the tree regrows, it will eventually pay off the carbon debt after many years, but if a middle-age tree were used, there is actually a further net loss of carbon sequestration for probably 10 years or more because the newly planted tree would grow more slowly and therefore sequester less carbon per year than the original tree if left in place.

278. Powlson et al. (2011a); McCarthy et al. (2011).

279. Strokal et al. (2016).

280. Cassou (2018).

281. Pinheiro et al. (2010); Cerri et al. (2010).

282. IPCC (2006) (Chapter 4, Section 4A.2.1.1) estimates 10 percent of residues as burned as the best estimate for developing countries. The FAO also assumes that burning of crop residues is 10 percent of crop residue; http://fenixservices.fao.org/faostat/static/documents/GB/GB_e.pdf.

283. Liska et al. (2014).

284. Powlson et al. (2011b).

285. See papers cited in Paustian et al. (2017) and Chambers et al. (2016).

286. Baker et al. (2007). This paper was quickly followed by another important paper, Blanco-Canqui and Lal (2008).

287. Powlson et al. (2014) provides an excellent summary of the literature. Other good papers include Powlson et al. 2012) and Luo et al. (2010).

288. Kravchenko and Robertson (2011).

289. Kravchenko and Robertson (2011) argued that if we analyze each layer of the soil profile separately, we can find statistically meaningful estimates of soil carbon gain in the upper profile and no statistically meaningful signal below. If there were strong biochemical reasons to believe changes would only occur in the upper profile, this argument would be persuasive. But if you think there are biochemical reasons that changes would occur within the entire top meter, then the higher carbon content in the top layer is not meaningful by itself.

290. Powlson et al. (2014).

291. De Freitas and Landers (2014).

292. Selenobaldo et al. (2016); Zotarelli et al. (2012); Boddey et al. (2010).

293. Powlson et al. (2014), summarizing studies.

294. Kurkalova and Tran (2017). Another study with similar findings is Hill (2001).

295. Wade et al. (2015).

296. Powlson et al. (2014) cite a variety of studies showing losses of the carbon gain. One study from 2007, however, found the data to be variable (Conant et al. 2007).

297. Six et al. (2004) performed a meta-analysis and found that nitrous oxide increased enough to more than cancel out soil carbon gains unless no-till was practiced for more than six years—even using large estimates of soil carbon gains. Van Kessel et al. (2013) found the same to be true for no-till in drier climates for 10 years but found no increase in nitrous oxide in wetter climates and reductions after 10 years of continuous no-till.

298. Pittelkow et al. (2015).

299. Conant et al. (2001).

300. McCarthy et al. (2011); Derner and Schuman (2007). For example, Badini et al. (2007)—a study of grazing intensities in the western Sahel on drier, low-carbon lands—found no response in carbon content to grazing intensity.

301. Asner and Archer (2010); Giller et al. (2009).

302. Whitehead et al. (2018).

303. Franzluebbers and Stuedemann (2009) tracked 12 years of carbon sequestration on a pasture under different test management in the southeastern United States. They found that light grazing had a higher rate of carbon sequestration than no grazing, which had a higher rate than heavy grazing. Their paper was cited in Chambers et al. (2016) as a study that helped find the potential for carbon sequestration "for improved management on grazing lands." Yet, as their paper states, the study covered the period 1994–2005, and the site had been restored to grassland from cropland only in 1991. This paper is therefore truly exploring how management affects rates of soil carbon sequestration during the restoration process; it is not proof of soil carbon sequestration potential of mature grassland. Smith (2014) warns of the same potential miscommunication in a paper of which Smith was himself a coauthor. That paper, by Senapati et al. (2014), concluded, "The results clearly indicate temperate sown grasslands to be a carbon sink under grazing management," without communicating in this sentence that the carbon gains measured were of a site resown with grass seed only four years earlier.

304. Smith (2014).

305. Soussana et al. (2014); Schulze et al. (2009).

306. These "eddy covariance" studies are summarized in Soussana et al. (2014, 78).

307. Soussana et al. (2014).

308. IPCC (2014).

309. Smith (2014).

310. Chang et al. (2016).

311. To confirm this understanding, WRI underlaid maps of European grazing land with estimated natural vegetation using the LPJmL vegetation model and found that more than 80 percent of grazing land would naturally be left forest if undisturbed.

312. Stanley et al. (2018).

313. Kirkby et al. (2011).

314. Van Groenigen et al. (2017).

315. This initiative is the 4 per 1000 Initiative (https://www.4p1000.org/ —last accessed December 30, 2018), which aims to increase global soil carbon by 4 percent per year.

316. Soussana et al. (2017).

317. Kirkby et al. (2016).

318. For example, in the meta-analysis finding small carbon gains from residue retention discussed above, Powlson et al. (2011b)), many of the benefits credited were from reduced losses (email from David Powlson to Tim Searchinger, July 26, 2018).

319. Zhao et al. (2018), based on national soil surveys in top 20 centimeters, calculated a net gain of 140 kgC/ha/yr.

320. West et al. (2010) estimate small soil carbon gains while Liska estimates soil carbon losses in the Upper Midwest. The Liska analysis for Upper Midwest Soil Carbon is given in the presentation "Biofuels from Crop Residue: Soil Organic Carbon and Climate Impacts in the US and India" at Indo-US Workshop on Addressing the Nexus of Food, Energy, and Water, April 19–21, 2017, Indian Institute of Science, Bangalore, India, but it is based on the same modeling presented in Liska et al. (2014).

321. Smith and Falloon (2005).

322. Ladha et al. (2016)—a recent global nitrogen budget for cereals—estimated losses of nitrogen from soils globally from cereals at 61 Mt per year. Liu et al. (2010) also found global losses of nitrogen of 11.5 Mt per year. The Ladha paper estimates higher losses in large part because it estimated higher rates of biological nitrogen uptake by plants and therefore higher global loadings of nitrogen.

323. According to Kirkby et al. (2014), global average ratios of carbon to nitrogen in humified soils is roughly 11:1. Multiplying 61 Mt of nitrogen loss estimated by Ladha et al. (2016) by 11 to obtain carbon and then by 3.67 to convert carbon to carbon dioxide equals 2,462 million tons of carbon dioxide.

324. We use the word "essentially" because to the extent these carbon losses are occurring on recently converted cropland (e.g., last 20 years), their losses of carbon could be implicitly counted as emissions from land-use change, but this is a very small percentage of total global cropland.

325. See, e.g., Powlson et al. (2016).

326. See, e.g., Zhao et al. (2018).

327. Kirkby et al. (2011).

328. Abraha et al. (2016).

329. Stockman et al. (2013).

330. Lal (2004).

331. For a more recent study, see Zomer et al. (2017).

332. Braz et al. (2013).

333. Kemp and Michalk (2011); Wang et al. (2011).

334. Poeplau et al. (2018).

335. Conant et. al. (2017) found carbon sequestration rates for improved, on-going grazing of 0.28 tC/ha/yr.

336. Gerber et al. (2013).

337. IPCC (2007).

338. Zomer et al. (2016).

339. One reason for some skepticism is that global cropland maps generated in different ways vary greatly and all are known to have many errors (Fritz et al. 2010). Zomer et al. (2016) used GLC, one of the global maps, which identifies cropland on around 2.2 billion hectares, which is roughly 600 million more than identified by FAO and nearly all other studies. This map therefore captures substantial land that is not truly in cropping use but is part of the farming landscape. A breakdown in the paper also showed that the carbon gains occurred overwhelmingly on land estimated to have more than 50 tC/ha, which means a high level of tree cover. Satellite maps are particularly prone to erroneously estimating cropland in such mixed environments. More specifically, by examining changes on the same land between 2000 and 2010, and focusing on such areas of high forest, the paper could quite possibly be identifying not growth of trees on cropland but reversion of agricultural land to forest, which occurs at high rates globally even as other lands are cleared. They may also just be capturing a thickening of tree cover on nonagricultural land.

340. Henry et al. (2009).

341. Schmidt et al. (2011).

342. Treseder and Holden (2013).

343. Salk Institute (n.d.).

344. For example, Bryan et al. (2011) found that many farmers would achieve net economic gains by leaving 50 percent to 75 percent of their residues on soils to boost yields, even if that required them to buy napier grass to replace their crop residue as feed for their cows, assuming they also had access to fertilizer. Tui et al. (2015) found a chance for profitability in shifting crop residues to soils in Zimbabwe if farmers could produce mucuna, a forage legume, to replace the residues.

REFERENCES

To find the References list, see page 500, or download here: www.SustainableFoodFuture.org.

PHOTO CREDITS

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