WORLD RESOURCES INSTITUTE

A PATHWAY TO CARBON NEUTRAL AGRICULTURE IN DENMARK

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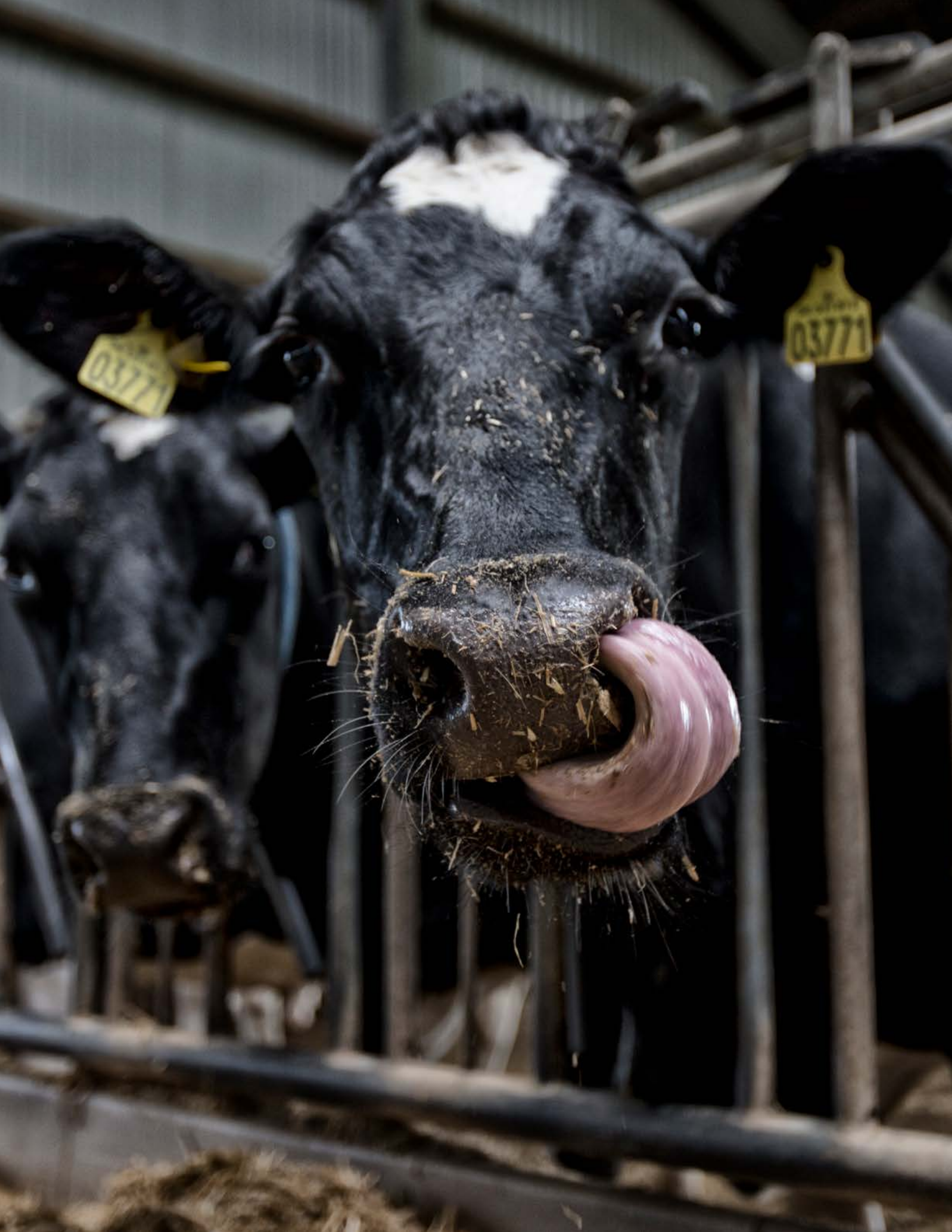
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Foreword

Can the world meet growing demand for food while sharply reducing greenhouse gas emissions from agriculture – and without converting more forests into agriculture? In the World Resources Report: *Creating a Sustainable Food Future*, WRI set forth a challenging, global five-course menu of actions to do so.

How should a country adapt this menu to its own agricultural context? *A Pathway to Carbon Neutral Agriculture in Denmark* answers this question for Denmark, a country whose major agricultural organizations have committed to become carbon neutral by 2050.

We believe this report is the first detailed country study to set forth a technical pathway to achieve carbon neutrality while boosting food production. As such, it can help inform how other advanced agricultural economies in Europe, North America, and elsewhere also can achieve carbon neutral agriculture. The findings therefore should be of wide interest to political and civil society leaders, officials in agriculture ministries, agribusiness executives, farmers and farm associations, and any climate advocate or scientist.

Three findings stand out. First is the importance of investing in developing, deploying, and continuously improving agricultural technologies to mitigate climate change. Doing so requires money and a target-driven approach akin to what the United States employed in the 1960s to reach the moon or that Apple employed to build an iPhone. Right now, the world lacks "off-the-shelf" technologies to dramatically reduce agricultural emissions.

But this report identifies a set of highly promising technologies. They include feed additives to reduce cattle methane, replacing imported feed crops with protein-rich grasses grown domestically, use of microbes to help grain crops fix nitrogen, and breeding wheat that inhibits soil formation of nitrous oxide. They also include such simple practices as removing manure from barns daily.

Although we tailor these recommendations to Denmark, most of the technologies and lessons apply to other advanced agricultural economies as well. But these kinds of innovations can only be achieved if farmers, industry, and other stakeholders scale up research, development, and deployment.

A second insight is that reducing emissions by producing less food is not a solution. WRI's global five-course menu calls for large consumers of meat, particularly of beef, to moderate their consumption. That recommendation applies to Denmark. But because most of the world's people – particularly in lower-income countries – eat so few animal products, demand for animal-based products is projected to grow. The world needs ways to produce additional food, but with much lower emissions and with no conversion of natural ecosystems into livestock grazing lands or feed croplands.

This report estimates the world will likely need to produce 45 percent more food in 2050 than it produced in 2017 – even if high-income people curb their consumption of beef and otherwise reduce demand for land-intensive agricultural products like biofuels. To do so without clearing more forests and other natural ecosystems, each hectare of agricultural land on average will need to produce 45 percent more food by 2050 than it did in 2017.

A third insight is that people in heavily agricultural countries like Denmark need to see improvements in their own environment if they are to support their contributions to the global demand for food. Accordingly, this report urges Denmark to create a "social compact" that links increased food production to progress in mitigating emissions and restoring large areas of domestic peatlands and forests.

While the pathway set forth in this report may be challenging, it is necessary. To achieve a sustainable food future, countries must achieve agriculture that's both climate friendly and more productive. The well-being of billions of people and the planet count on the world reaching this ambitious – but achievable – goal.

Manish Bapna

Interim President and CEO
World Resources Institute

EXECUTIVE SUMMARY

This report develops a possible strategy for Danish agriculture to achieve "carbon neutrality" by 2050, a goal adopted by its major agricultural organizations. The term *carbon neutral*, as used in this report, applies to all agricultural greenhouse gas emissions, including methane and nitrous oxide. We identify a pathway of possible cost-efficient measures to reduce by 80 percent the emissions per output of food (the emission intensity) of agricultural production processes within Denmark (all emissions attributable to agriculture other than lost carbon from land use).

Highlights

- Danish agriculture, mostly pork and dairy, annually generates 17.4 million tons of greenhouse gases (GHGs) (carbon dioxide equivalent, or CO_2e).
- Conversion of native ecosystems used for agriculture in Denmark has resulted in the loss of 48 million tons of CO_2 on an annualized basis, establishing a baseline that "carbon neutral" agriculture should not increase.
- Danish agriculture has relatively low emissions per unit of food, so reducing production in Denmark would shift food production to other locations and probably increase global emissions.
- Promising measures might reduce domestic production emissions by 80 percent.
- To be "land area carbon neutral"—to do its equal share to avoid deforestation as global food production rises—Danish agriculture likely needs to produce 45 percent more food per hectare between 2017 and 2050.
- Through feed efficiency and yield gains, crop shifting, novel uses of grasses, and improvements abroad, Denmark could improve land use efficiency even more, and restore enough peatlands and forests to offset remaining production emissions.
- This strategy requires ambitious efforts to develop and deploy new technologies.
- Danish agricultural mitigation efforts are most valuable if they develop the technology, business, and policy innovations to drive mitigation globally.

We also identify ways Denmark could sufficiently increase the efficiency with which it uses land—its food output per hectare—to restore enough forests and peatlands to remove enough carbon from the air to offset the remaining 20 percent of production emissions and thereby achieve carbon neutrality. Denmark could plausibly do so even if it increases its food production enough to maintain its present share of global production, a likely 45 percent increase. If successful, this strategy would also greatly increase wildlife habitat in Denmark and curb Denmark's nitrogen pollution.

As in energy and other sectors, achieving carbon neutrality in agriculture is neither easy nor certain because it depends on the successful development and deployment of a variety of innovations. This report identifies many promising opportunities: some that can be implemented right away, some probably within four to six years, and some in a decade or two. Some of these potential solutions may ultimately not fully work, but others could work even better than we estimate.

The report's central recommendation is that Denmark should vastly expand cooperative efforts of researchers, farmers, and private businesses to test, deploy, and continually improve these innovative approaches. Denmark can pay for these efforts in part by phasing out some present spending that is not cost-effective in reducing emissions and may not be reducing emissions at all.

Although Denmark is a major agricultural producer, its agricultural sector contributes less than 0.04 percent to global emissions. Globally, however, growing emissions from agriculture will make it impossible to stabilize the climate without major changes. Denmark has the potential to contribute to solving climate change far in excess of reducing its own agricultural emissions by developing these technologies and providing a model of rigorous climate action and accounting that other countries can use and follow.

Global context and implications for "carbon neutral" agriculture in Denmark: The central challenge for agriculture globally is the need to produce far more food by 2050, with far fewer emissions from the production process, and using less land than it uses today. Agriculture already occupies half of the world's vegetated land—land that is not desert or covered by ice—and contributes one-quarter of global greenhouse gas emissions when also counting emissions from agricultural expansion. As analyzed by the World Resources Institute (WRI) and others in a World Resources Report, *Creating a Sustainable Food Future* (Searchinger et al. 2019), due to population growth and rising incomes, global crop production is on a course to rise more than 50 percent between 2010 and 2050, and meat and milk production by 70 percent. As a result, emissions will likely rise to 15 billion tons CO_2e by 2050; agriculture would then by itself fill 70 percent of the emissions budget for all human sources—even though agriculture will likely contribute only 2 percent of global economic output. Even if agriculture maintains historical rates of yield gain, hundreds of millions of hectares of forests and woody savannas are likely to be cleared for food production between 2010 and 2050.

Creating a Sustainable Food Future maps out a global strategy to feed 10 billion people while halting deforestation and reducing emissions, which includes sustainable reductions in consumption, including reducing meat (particularly beef) consumption by the world's wealthier consumers. Denmark is one country with high meat consumption that should decrease it. Plant-based meat substitutes are one way of encouraging this shift, and Denmark, like other countries, has opportunities to move into this field.

Yet even if the world's present high meat and milk consumers greatly change their diets, world consumption of meat and milk is still likely to rise by 2050 because of a projected increase in population by more than 2 billion people. In addition, billions of people who presently consume little meat and milk are likely to enter the global middle class and increase their consumption. Our global report therefore finds that increases in crop and grassland yields and increases in livestock feed efficiency are critical to freezing—let alone reducing—agriculture's land footprint.

Overall, the global strategy for agriculture itself—in addition to strategies focused on consumption changes—involves a variety of innovative measures to reduce emissions from the production process; for example, by making more efficient use of nitrogen fertilizer or reducing emissions from manure management. It also involves increases in yields and livestock feeding efficiencies enough to avoid further land clearing for agriculture, which we call "land area carbon neutrality." Finally, the strategy identifies measures that could free up enough global agricultural land that carbon sequestered through reforestation could offset remaining agricultural production emissions and make agriculture carbon neutral.

Our strategy for achieving carbon neutrality for Danish agriculture is consistent with this global strategy. Like other countries, to achieve carbon neutral agriculture, Denmark must greatly reduce its production emissions. It must also increase its crop yields and livestock feeding efficiencies to freeze its "land use carbon footprint" even as the world increases food production. With those gains, Denmark can achieve "land area carbon neutrality." With sufficient increases in yield and livestock efficiencies, Danish agriculture can reforest enough land and sequester enough carbon to offset and balance the remaining agricultural production emissions. This strategy reflects several important principles.

Reduce global emissions. Denmark could reduce its own food production, and some greenhouse gas accounting systems would count doing so as reducing Denmark's agricultural emissions, but given ongoing growth in global food demand, such efforts would just transfer food production and emissions elsewhere. To test likely net effects, we modeled the emissions intensity of Danish dairy and pork production and compared them with those of other major national producers of pork and dairy. We found the emissions per kilogram (kg) of milk or pork of Danish agriculture to be in the most climate-efficient of three tiers of countries. As a result, reducing production, which would effectively shift production elsewhere, would generally increase global emissions. We also used our global land use and emissions model (GlobAgri-WRR), and similarly found that reducing Danish agricultural production by 2050 would likely increase global agricultural emissions and land use.

Despite these findings, the differences between Denmark and many other major agricultural producing nations are not great. The relative benefits of Danish agriculture become much greater if Denmark becomes a leader in achieving carbon neutral agriculture.

Match global strategies. Typical global strategies to mitigate climate change do not rely on elimination of all methane and nitrous oxide emissions from agriculture, which would be impossible, but they do require reductions in agricultural land sufficient to free up land for reforestation or other carbon gains. Although those carbon gains would not continue indefinitely, they could still be consistent with a long-term stable climate. Following our global strategy in *Creating a Sustainable Food Future*, a Denmark carbon neutral agriculture strategy should greatly reduce production emissions but can rely on land sparing and reforestation to offset remaining emissions for several decades.

Become cost-effective. A variety of climate policies today may use carbon prices of $200 per ton of CO_2 mitigated or more, but the total cost of mitigation at that price would roughly equal the full "value added" of all Danish agriculture. Even if Denmark were willing to invest this much money on agricultural mitigation, other countries are unlikely to do so. To maximize the leadership role of Danish agriculture, we focus on technologies that have the potential to cost less than $50 per ton in the long run and particularly strategies that have the potential to cost less or even to be profitable. However, just as solar and wind power initially needed subsidies before becoming cost-efficient by themselves, advancing these solutions will require substantial funding in the short term.

Help solve related environmental challenges. Mitigation strategies must not exacerbate, and should help solve, other Danish environmental challenges, including enhancing biodiversity and reducing water pollution.

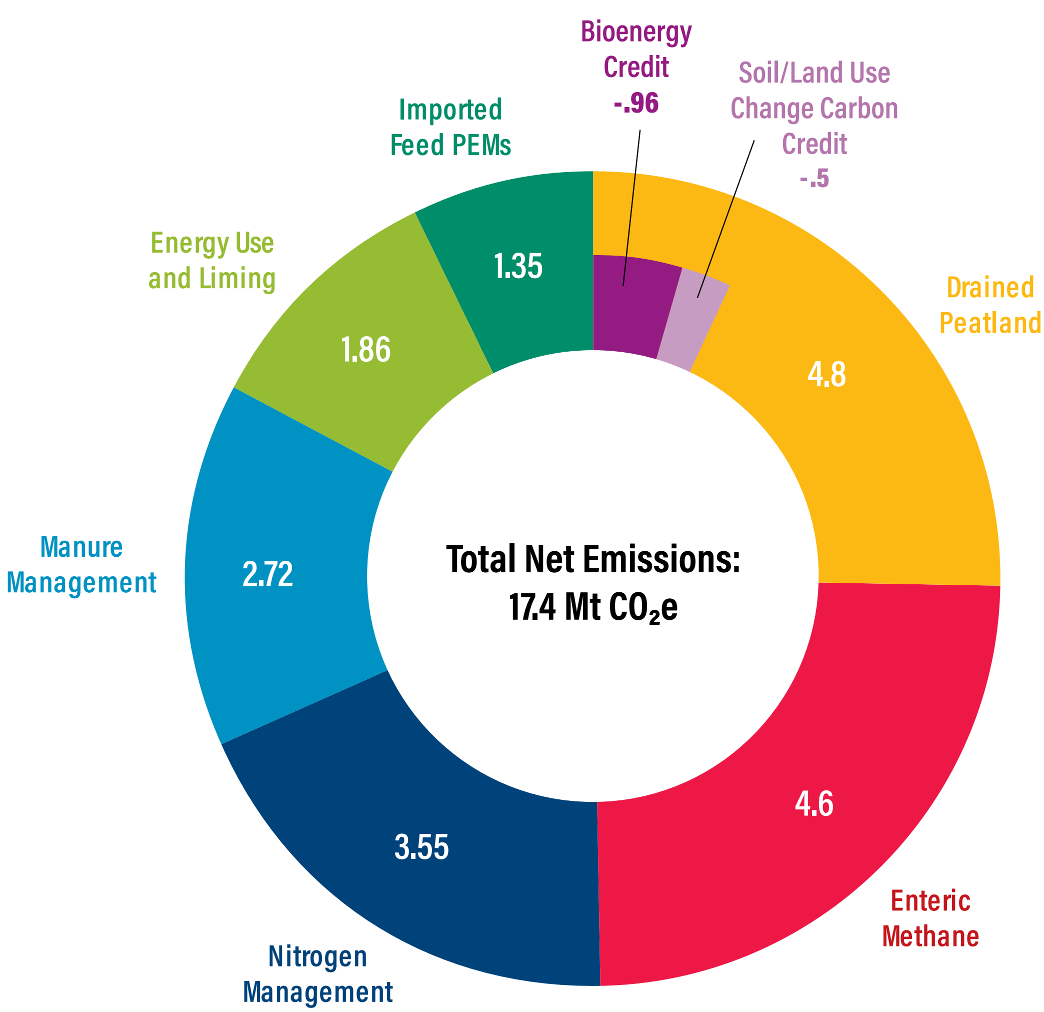
Separate efforts to mitigate emissions through production and consumption. Finally, although we strongly encourage Denmark to reduce its consumption of meat and dairy, such efforts do not mean Denmark should reduce its dairy and pork production. The world needs more climate-efficient consumption of food, but it also needs more climate-efficient production. Global consumption of pork and dairy is rising rapidly, and our global projections for future consumption assume that almost two thirds of the population in 2050 consumes per person from one half to one quarter of the overall meat, milk and fish of people today in Europe and the United States. In addition, a dietary shift should focus first on reducing beef and other ruminant meats, which generate five times the emissions of dairy and at least nine times the emissions of pork and poultry. Even with big efforts to reduce overall meat and dairy consumption in wealthier countries, there are still likely to be large increases in global demand for dairy and pork.

Reducing production of meat and dairy in Denmark—which is relatively climate-efficient compared to other countries—is not likely to lead to less consumption of meat and dairy because people will mainly switch to less efficient suppliers in other countries. This principle is broadly understood in the energy sector. The world needs people to drive less, and it also needs cars to be more climate-efficient. Reducing production of hybrid-electric or fully electric cars is not a good way to reduce driving because people will mainly just shift to cars that use more fuel. While Denmark works to reduce meat and dairy consumption, Danish agriculture can also help to address climate change by producing milk and pork with far fewer emissions and exporting what is not ultimately consumed in Denmark to other countries.

Denmark's agricultural emissions today. To accurately reflect the real greenhouse gas costs of Danish agriculture, our estimate uses a life-cycle approach that counts all emissions involved in Danish production. It therefore counts both the emissions that occur in Denmark on farms (ending at the farm gate) and those that occur "upstream" in the production of imported feed, of farm inputs such as fertilizer, and of the electricity used on the farm. Denmark, like other countries, estimates its emissions in national inventory reports filed with the United Nations. We used those official estimates for the categories of agricultural emissions reported (although we rearrange some results into categories most useful for identifying solutions). We do our own analysis for other emissions not separately reported, such as those from agricultural energy use, fertilizer production, and imported feeds. We separate emissions into two categories: those from the production process, such as those from using fertilizer and managing manure, and those that represent the carbon costs of Denmark's "land carbon footprint."

Production emissions. We find that in 2017, our base year for analysis, Danish agriculture produced a net of roughly 17.4 million tons of greenhouse gas emissions (CO_2e) from the production process (Figure ES-1). That net total includes 11.2 million tons as conventionally attributed to agriculture in national emissions inventory reports, which primarily involve methane from cattle digestion ("enteric fermentation") and nitrous oxide and methane emissions from use and management of fertilizer and manure. Total production emissions also include 1.5 million tons from energy use in agriculture (including emissions from production of fertilizer), and 4.8 million tons from the ongoing degradation of drained peatlands. These types of emissions are reported elsewhere in Denmark's (and other countries') national inventory reports or left out entirely, as in the example of imported fertilizer. We estimate 1.4 million tons of emissions from these same production processes for imported livestock feeds, which are not counted by Denmark (or by other countries in their national inventories). Our total also credits to agriculture an offset of almost 1.5 million tons due to its use of straw (a by-product of cereal production) for bioenergy that displaces fossil fuels and due to soil carbon gains estimated by Denmark in excess of some emissions from grassland losses.

Figure ES-1 | Denmark's Agricultural GHG Emissions from the Production Process, 2017 (Million Tons of CO_2e)



Source: Authors' calculations from NIR (2019) and other sources.

Land use carbon footprint. We also count Danish agriculture's global land carbon footprint because increases in that footprint cause carbon to be released while decreases potentially allow carbon to be removed from the air through ecosystem restoration. We measure this carbon footprint based on the "carbon opportunity cost," an annualized value that represents the carbon lost from the original clearing of native vegetation and soils on the land used to produce Denmark's agriculture.

Many other life-cycle analyses do not attribute greenhouse gas costs to the use of land at all. Others only assign carbon costs to crops grown on land that has been recently converted from forests or if a crop comes from a country where both that specific crop and cropland overall are expanding. These approaches fail to appreciate that any ongoing use of land for agriculture by itself has a carbon opportunity cost because it displaces carbon that would otherwise be stored in native vegetation. (Urban land uses do as well, but they are much smaller globally because urban areas occupy a small fraction of the land used by agriculture.) Accounting methods that only assess recent changes in land use can encourage trivial changes in production by assigning them large reductions in emissions.

For example, using some GHG accounting methods, Denmark could greatly reduce its emissions by changing its source of soybeans from South America (where deforestation is ongoing) to the United States (where deforestation happened decades ago) even though that would mainly just cause other countries to import more soybeans from South America. By contrast, reducing the quantity of crops needed for each kg of pork or dairy reduces total global agricultural land demand and therefore has a global benefit to forests and the climate. Failure to properly count the carbon opportunity cost of land may even encourage changes that increase the overall demand for agricultural land (and therefore increase pressure on forests and the climate) by discouraging land-efficient production.

The use of roughly 2.6 million hectares of land in Denmark for agriculture and roughly 700,000 hectares abroad to produce feed imported to Denmark has an annualized land carbon footprint—an annual carbon cost—of 48 million tons of carbon dioxide (CO_2) per year. That calculation uses a method of time-discounting that reflects the value of reducing emissions earlier rather than waiting. (For most purposes in this report, the choice of discount rate is unimportant.) This estimate includes roughly 36 million tons of CO_2 in Denmark and 12 million tons from production of feed in other countries. Land use is a real cost of agriculture. If Danish agriculture disappeared and were not replaced—if this much food consumption could be reduced—roughly this amount of carbon in trees and soils could be removed from the atmosphere per year for decades.

"Land area carbon neutrality" does not require that Danish agriculture disappear. Instead, it requires that Danish agriculture not clear land directly and sufficiently contribute to increases in global land use efficiency—output of food per hectare—that it does not contribute to increases in global agricultural land demand.

2050 baseline of emissions. The efforts needed to mitigate emissions in 2050 depend on Denmark's level of food production in that year. We examine three 2050 scenarios: present food production (using 2017 as our base year), 25 percent higher production, and 45 percent higher production. The 45 percent scenario is our estimate of the increase in total annual food production the world will likely need between 2017 and 2050. The 45 percent figure for all foods weights different foods based on their land use requirements and the size of their projected increase in production (Appendix A). We call this 45 percent figure the "proportionate global growth" scenario because it means Denmark would continue to produce the same share of the world's food in 2050 as it does today.

For each of these future possible levels of food production, we create a future baseline of emissions assuming that food would be produced using today's farming techniques. We similarly estimate future additional land area required to produce that food with today's farms. Even without added policy efforts, farms will change, and yields will likely grow. But this definition of a baseline makes it possible to estimate all the changes in production methods from today's farms necessary to achieve carbon neutrality regardless of whether some of those changes are likely to happen anyway.

Although these different baselines result in different total emissions, the changes needed to reduce emissions from these future baselines by the same percentage are largely the same. In other words, changes in practices like nitrogen fertilizer use and livestock management required to obtain an 80 percent reduction in their emissions remain the same, regardless of the future level of agricultural production.

Reductions in agricultural production emissions. Our strategy identifies a variety of promising ways of reducing production emissions, with the potential summarized in Figure ES-2 and Table ES-1. Highlights of our analysis include the following:

Improved feed conversion efficiency. By raising the average feed efficiency of dairy cattle to match Denmark's present top performing dairy herds, and by making more modest improvements in pork efficiency, we estimate that Denmark could reduce nearly all the major categories of production emissions by roughly 20–30 percent. Improvements in feed efficiency can be done in ways that raise animal welfare concerns, but other ways could have no effect on animal welfare, such as breeding animals with lower need for feed, most feed quality improvements, and additives that inhibit enteric methane. Some methods can improve welfare while boosting output, such as improving animal health.

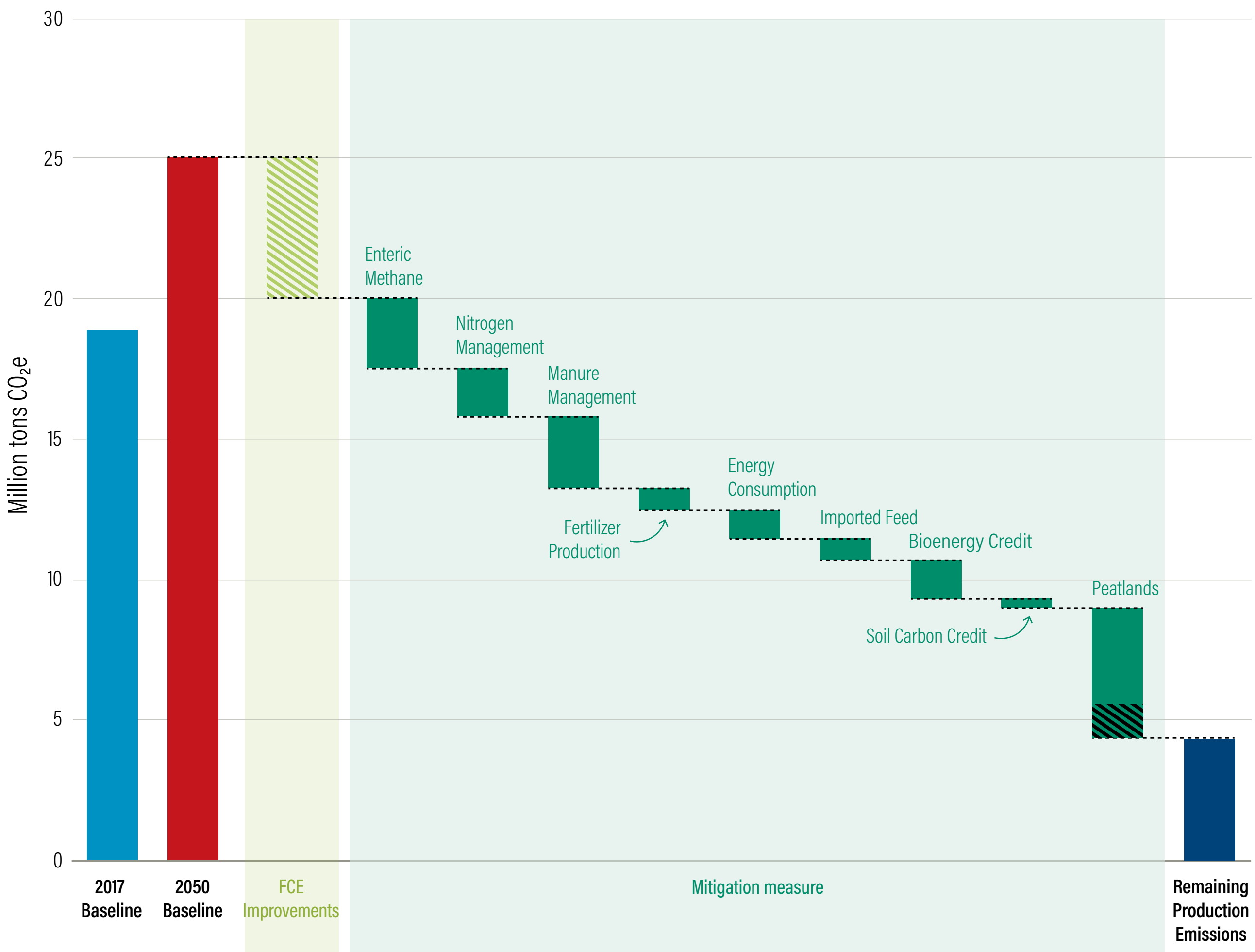
Enteric methane. A feed additive will likely be approved in Europe soon that in several tests so far seems capable of reducing enteric methane by 40 percent and increasing milk fat, offsetting some or all costs depending on pricing. Along with potential improvements in breeding, we estimate a possible 55 percent emissions reduction by 2050. Red algae appear capable of even larger reductions, but their active ingredient poses environmental challenges. Recent scientific results justify ambitious rapid efforts to explore the use of this algae, its production in closed loop systems, and alternative ways of generating and using its most active, methane-inhibiting ingredient.

Nitrogen management. Roughly half of total nitrogen applied to Danish crop fields is lost, and a variety of measures can both reduce these losses and the conversion of nitrogen to nitrous oxide. They include synthetic nitrification inhibitors, which should be aggressively tested for effectiveness, toxicity, and yield effects in different soils and crops, including with coatings that prolong the effects. Longer-term opportunities include biological nitrification inhibition. Both have potential to spur yield increases if matched with properly selected and bred crop varieties to exploit advantages to crops of a greater share of ammonium in total nitrogen supply. Potential also exists to develop tools to apply more of the nitrogen fertilizer farmers use later in the season to wheat and barley using modeling or remote sensing methods that account better for the nitrogen that has become available to crops from soils. Earlier wheat planting and steady improvements to cover crops can reduce late fall and winter losses.

Some improvements might come from a microorganism that allows nonleguminous crops to fix their own nitrogen and might be able to boost yields by supplying more nitrogen directly to the chloroplast in the form of ammonium. Although it needs independent verification and adaptation to more crops, such a microbe might be able to replace up to a quarter of applied nitrogen.

Manure management. Based on present emission estimates, the majority of Denmark's manure management emissions appear to occur while manure is held for a few weeks in the barns used to house cows and pigs. The financially cheapest solution to reduce these emissions is to remove this manure once or twice per day, which is already typical in Sweden. Such changes can start on some farms right away and can certainly occur by 2050. Within the typical tanks used for manure storage, adding some acid is likely to reduce nearly all methane. One unproven, much cheaper option that requires testing might be to use modest levels of sulfate. By reducing the methane this way, preserving a manure crust would no longer be necessary, and eliminating a crust would eliminate nearly all direct nitrous oxide from manure management. Manure removal and changed flooring can likely reduce ammonia emissions by 50 percent. Land application of acidified manure also generates far less ammonia and may reduce nitrous oxide. There is conflicting evidence about whether acidification can generate yield gains, which may depend on other nitrogen limits.

Figure ES-2 | Pathway for Reducing Danish Production Emissions by Category from Emissions in 2050 "Proportionate Global Growth" Scenario



Note: Food conversion efficiency (FCE) improvements occur first, reducing the size effect of remaining measures. The dark green striped portion of the peatland bar represents a cost in reduced food production unless made up by other land use efficiency gains.

Source: Authors' calculations.

Roughly consistent with a study at the University of Copenhagen, we find that mitigating greenhouse gas emissions from manure digesters would likely cost \$200–\$300 per ton of CO_2e even if the digester could operate entirely with manure using some solid separation based on cost estimates by others. We are also skeptical that such use of solid separation will be practical or as economical as others have estimated, and the cost per ton of CO_2e would rise even more if digesters continue to require other dry biomass as most do today. We also find that digesters today could be increasing overall greenhouse gas emissions when factoring in the carbon opportunity costs of the land used to produce maize fodder crops that are now commonly added to the digester with manure. Denmark's work on digesters has advanced the technology, which will be cost-effective in some other countries. But in Denmark, the relatively cooler climate appears to result in relatively low methane losses from manure storage tanks, so the methane saved by digesting that manure is relatively small. Given these conditions and the work that has already gone on to improve digesters, we see little likelihood that digester costs can be sufficiently reduced in the future to be cost-effective in Denmark.

Peatland restoration. Our analysis confirms the large benefits of rewetting peatlands even if the crops they now produce need to be replaced elsewhere. Rewetting peatlands often requires taking additional cropland beyond the peatlands out of production. We believe peatland restoration should still occur even where that is necessary, but Denmark should pursue enough gains in land use efficiency to ensure that doing so offsets these reductions in production and therefore does not lead to additional land clearing elsewhere. Because peatland emissions vary, we assume that rewetting 85 percent of agricultural peatlands could reduce their emissions by 95 percent.

Bioenergy and soil carbon. We find that growing willow for bioenergy would likely lead to an increase in GHG emissions when factoring in carbon opportunity costs from land use. Modest increases in the use of straw (with higher cereal production) and more efficient use of straw, plus the biorefinery idea described below could combine to generate "offsets" of 1.3 million tons of CO_2e when sharing credit for reduced fossil emissions with the energy sector. Soil carbon can also continue to find modest offsets, but, following Danish research, we estimate that potential to be modest and assume only 400,000 tons of CO_2e per year.

Combined production emissions mitigation. Overall, we develop a possible scenario that would reduce domestic production emissions by 80 percent and overall production emissions by 75 percent. In the proportionate global growth scenario, Danish annual domestic production emissions would fall to 3.4 million tons of CO_2e, and emissions for imported feed would fall to roughly 1 million tons.

Achieving land area carbon neutrality. To be carbon neutral, Danish agriculture must also be at least "land area carbon neutral," meaning it does not contribute to any global emissions from land use change between 2017 and 2050. Our approach to this concept starts from the mathematical truth that if the world's food production increases by 45 percent, the land use efficiency of food production on average must also increase by 45 percent to avoid agricultural expansion and resulting deforestation and other emissions from land use change. This relationship holds with any percentage increase in future food production. In effect, to avoid emissions from land use change, agricultural land use efficiency on average must keep pace with rising food production: to avoid land use change, agriculture must "keep running just to stay in place."

This increase in global land use efficiency could be achieved with high growth rates in livestock feeding efficiencies and crop yields by some countries and less by others, so some countries could claim that they are entitled to increase efficiency less than others and still be considered land area carbon neutral. For example, Denmark could claim that because its agriculture is already high-yielding and thus land-efficient, Denmark should be considered land area carbon neutral even if its future efficiency gains are lower than the global average need. In contrast, many poorer countries may face greater economic and logistical challenges in increasing yields and could claim that it is they who should have to increase efficiency less while richer countries do more. If the marginal costs of improvements everywhere were known, economists would favor strategies that reflect these different costs, but these costs are not truly known, let alone real costs when reflecting all practical obstacles. Although we recognize possible different arguments, we adopt as the basic rule that to be counted as achieving land area carbon neutrality, agriculture everywhere should share equally in this burden to increase land use efficiency.

This need to increase land use efficiency applies regardless of Denmark's future level of production. Even if Denmark only maintains its present level of food production, we believe that the land use efficiency of food production must increase at the global rate of increased food production because otherwise Denmark is just shifting the burden to increase yields to other countries. To analyze future mitigation, however, we use the "proportionate growth" scenario of 45 percent higher production because of its mathematical simplicity. In that scenario, we can count the greenhouse gas costs or savings from land use by counting the changes in carbon storage that result from changes in hectares needed to produce that additional food (Appendix A).

To achieve overall climate neutrality, Denmark can achieve yield and livestock efficiency gains that go beyond land area carbon neutrality, use those land savings to restore forests in Denmark, and claim an offset about remaining production emissions. That is consistent with global strategies for agriculture. Unlike offsets in other sectors, these offsets are directly undertaken by agriculture and therefore do not represent a shift in mitigation burdens to other sectors.

As illustrated by Figure ES-3, to produce 45 percent more food with today's farms would require roughly 1.1 million more hectares of cropland in Denmark. (That obviously exceeds potential area but is useful for the calculation.) However, we estimate that land efficiency gains are possible from feed conversion efficiency and crop yield gains, successful implementation of the so-called biorefinery option, some reduction of fallow lands, and the shift of some land from cereals to beets. We estimate these changes together might allow Denmark to produce 45 percent more food and still reduce agricultural land in Denmark from today's level by 450,000 hectares.

These land "savings" of 450,000 hectares could then be used to restore almost 85 percent of peatlands, roughly 140,000 hectares, without sacrificing overall food production, and also to reforest 310,000 hectares, which could remove roughly 3.45 million tons of CO_2 from the air per year (Figure ES-3). Doing so would offset the vast majority of Denmark's remaining domestic production emissions of 4.4 million tons of CO_2e, which could then be fully offset with some bioenergy from straw and soil carbon gains.

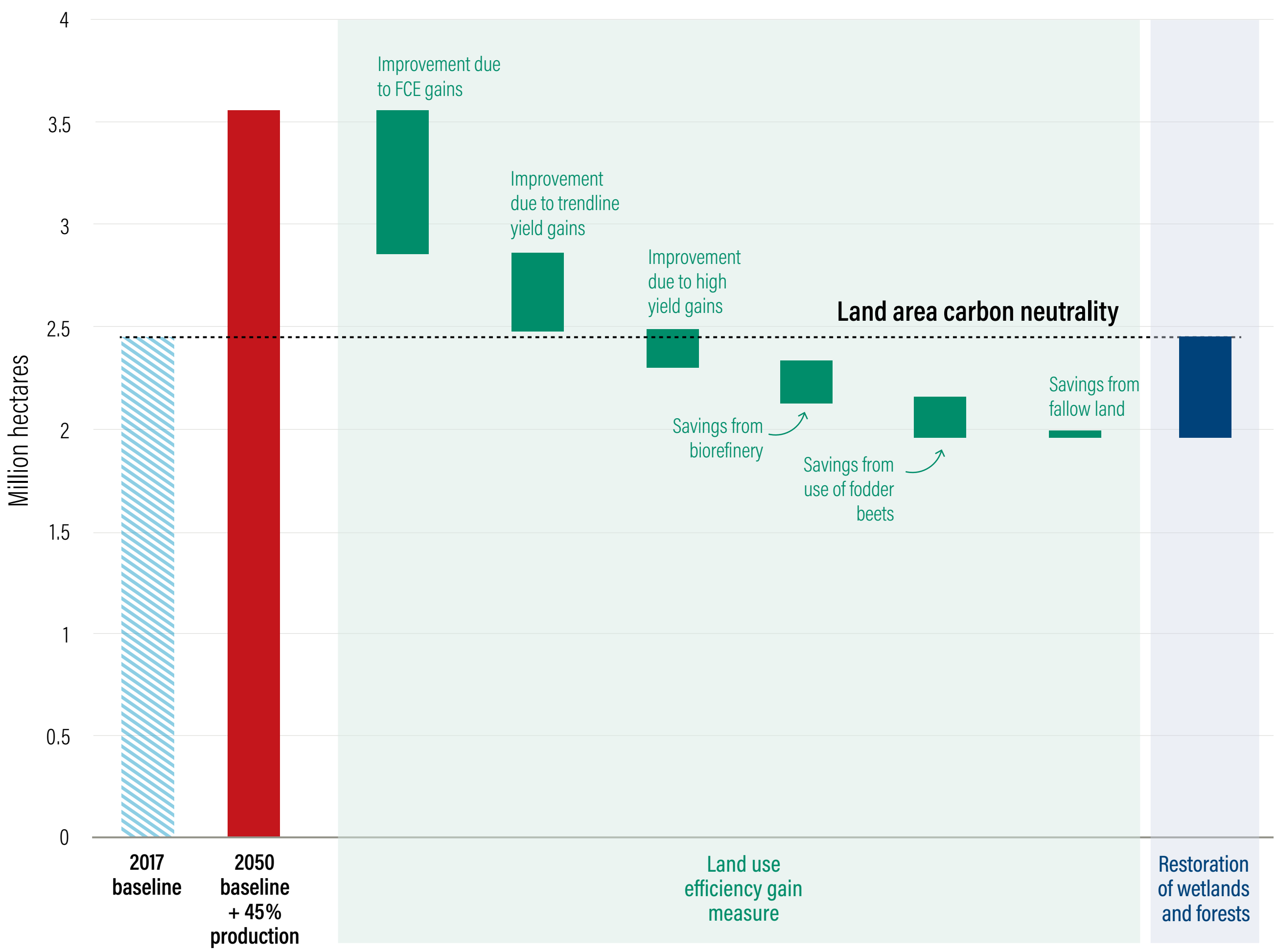
The crop yield gains required by 2050 are challenging, particularly given a plateauing of wheat yields in Europe since around 2000, but growth rates required are less than long-term rates since 1960. Winter wheat yields, for example, would have to rise in 30 years from an average of 7.6 to 9 tons per hectare per year, and winter barley yields from 6.3 to 8.3. Some gains could be achieved by management, including addressing problems with soil compaction. Most would require crop breeding improvements. We provide examples of a variety of promising nitrogen use and breeding strategies that might contribute to those improvements.

The "biorefinery" system would switch fodder crop production in Denmark to high-protein, perennial grasses. When pressed, these grasses would generate some high-protein feed for pigs and dairy animals, which would replace imported soybean feeds. The majority of the grass would still be used for a good fodder to replace silage maize or mixtures of grass and legumes. With high enough grass yields, the combination would be equivalent to large increases in production from the perspective of land savings and would contribute roughly 200,000 hectares toward the potential land savings we estimate.

Land area carbon neutrality also requires that imported feed increase its land use efficiency by the proportion of the global food increase. To do so, the Danish agricultural industry and government could work with groups of farms in South America on "produce and protect" projects that boost yields and use those gains to protect and restore forests. Overall, we estimate a possible pathway not just to avoid emissions from land use but to generate more than enough carbon gains from avoided deforestation or reforestation in South America to offset an expected remaining 1 million tons of production emissions from imported feed.

The quantity of land restoration in Denmark should be a societal decision that reflects not just climate considerations but the value people in Denmark assign to increasing biodiversity in their country and the social amenities from increased natural habitat. Only a tiny percentage of Denmark is presently in any kind of natural forest or other habitat. In present discount value terms, the cost of forgone agricultural production and initial planting for climate benefits alone could reach $90 per ton of CO_2. But this cost reflects value created by government financial support for agriculture, which is not a true economic cost. The cost to the government would be reduced if farmers reforesting land were allowed to keep subsidies or if the Danish government could redirect those subsidies for this purpose. Because of Danish commitments to improve biodiversity, we also assume that other environmental and social benefits could justify restoration even without climate benefits if Denmark values them highly.

Figure ES-3 | Pathway to Land Area Carbon Neutrality, Land Sparing, and Reforestation to Achieve Carbon Neutrality in Proportionate Global Growth Scenario



Note: Y-axis shows hectares of cropland used (counting all land used for animal feed). Each gray bar shows the contribution of the measure to saving land while meeting the 45 percent food growth target, as discussed in report. The light part of some bars is the part of that reduction not necessary to achieve the 450,000 hectare target for restoration. The green bar shows the area that would be rewetted or reforested to offset remaining production emissions.

Source: Authors' calculations.

Timing. To realize this strategy, work of some kind on all types of mitigation must start now: some can be implemented immediately on a large scale, some need pilot testing, and some must start with basic research. Table ES-2 identifies the timing for the start of large-scale implementation of different measures.

Recommendations. Our report contains detailed recommendations for each mitigation measure. More generally, to achieve Denmark's announced goal of agricultural carbon neutrality, we recommend the following:

Technology development and implementation

1. Denmark should move forward ambitiously with piloting and associated research of the various technologies identified in this report and should implement them at scale on appropriate timelines. This work should

be supported by a budget equivalent to the funding Denmark now spends on methane digesters, or roughly $250 million per year. Short-term opportunities include peatland restoration, quick removal of manure from barns, adoptions of enteric methane inhibitors (after quick, larger-scale tests). Large-scale use of nitrification inhibitors and acidification of manure or use of sulfate require a few years of testing.

2. Denmark should establish a technical team with subteams to be responsible for the development and implementation of solutions for each major source of emissions. Each subteam should have mitigation targets, should develop and revise technology roadmaps, and should compete for funding.
3. Denmark should quickly eliminate use of any crops in manure digesters and place a moratorium on subsidizing new digesters as it assesses various emission factors. If this work confirms our analysis that digesters are not cost-effective, Denmark should phase out use of existing digesters as they age and reach the end of their productive lives. As this phase-out occurs, Denmark should redirect the roughly $250 million per year into more effective ways of mitigating climate change.

Assessing, planning, and tracking emissions reductions

4. Denmark should quickly resolve key uncertainties about emission factors. For example, better understanding of manure emission factors would have saved money now spent on digesters, and a budget of $7 million could clearly establish proper emission rates for manure management within three years.
5. Denmark should establish an emissions accounting system for planning and tracking mitigation progress. This system should factor in carbon opportunity costs as a tool for assessing changes in Denmark's land carbon footprint. Such a system can build on Denmark's national inventory reporting system but should be adjusted so that this system can be better used to plan improvements and estimate their GHG benefits using representative farm types.

Ensuring broad social support

6. To assure different stakeholders that they will all benefit from agricultural improvements, Denmark should seek a social agreement that increased food production, mitigation of emissions, and land restoration will occur in parallel.
7. Denmark should also seek agreement about which costs of mitigation are borne by agriculture and which by the government in a way that provides incentives for agriculture to advance mitigation technologies.
8. Denmark should manage land removed from agricultural production to maximize carbon and biodiversity values, both to achieve multiple societal objectives and to ensure that the Danish environment is not sacrificed for climate-efficient, global food production. Some restored lands could be established with new production forests if matched by efforts to transition older production forests to more natural forests with greater biodiversity values.

International cooperation

9. Danish agriculture and the government should cooperate on "produce and protect" partnerships in South America to increase land use efficiency of Danish feed imports and to use those gains to protect and restore forests.
10. Denmark should work to reform global carbon accounting rules so they avoid incentives that primarily result in shifting emissions abroad, recognize the greenhouse gas benefits of consumption changes, and properly factor in the carbon opportunity costs of land use.
11. Denmark should seek international partners for expanded collaboration and funding of several research objectives. Two of these objectives should be biological nitrification inhibition and the potential to select for and enhance varieties that can most increase yields with a higher share of soil nitrogen in the form of ammonium. Breeding improved wheat, barley, and grass yields and more feed-efficient cattle are other high priorities.

Table ES-1 | Greenhouse Gas Emissions in 2050 with and without Mitigation with Different Future Levels of Food Production (Billion Tons of CO_2e)

CATEGORY	MITIGATION MEASURES	2017 PRODUCTION BASELINE	AFTER MITIGATION	25% HIGHER PRODUCTION BASELINE	AFTER MITIGATION	45% HIGHER PRODUCTION BASELINE	AFTER MITIGATION
Nitrous oxide from fertilizer	FCE improvements; improved nitirification inhibitors, precision nitrogen timing, nitrogen-fixing microbes, biological nitrification inhibition, early winter wheat planting, improved cover crops	1.14	0.30	1.42	0.38	1.65	0.44
Nitrous oxide from manure		1.01	0.36	1.27	0.45	1.47	0.52
Nitrous oxide from residues		0.61	0.25	0.76	0.31	0.88	0.36
Other		0.05	0.03	0.07	0.03	0.08	0.04
Grazing manure		0.18	0.05	0.22	0.06	0.25	0.07
Indirect–leaching		0.19	0.10	0.24	0.12	0.28	0.14
Indirect–atmospheric deposition		0.38	0.20	0.47	0.25	0.54	0.29
NITROGEN EMISSIONS TOTAL		**3.55**	**1.28**	**4.44**	**1.60**	**5.15**	**1.86**
Enteric dairy	FCE improvement; 3-NOP, Breeding, BCM, Compound X	2.77	0.82	3.46	1.03	4.01	1.20
Enteric cattle non-dairy		1.26	0.37	1.58	0.47	1.83	0.54
Enteric pigs		0.42	0.18	0.53	0.23	0.61	0.27
Enteric other		0.16	0.08	0.20	0.10	0.23	0.11
ENTERIC TOTAL		**4.60**	**1.46**	**5.75**	**1.83**	**6.67**	**2.12**
Energy emissions field operations	Energy efficiency, low carbon electricity from grid; electrified farm equipment, hydrogen tractors	0.52	0.05	0.65	0.06	0.75	0.07
Energy barn operations		0.29	0.02	0.36	0.03	0.42	0.03
Production of nitrogen fertilizer		0.72	0.10	0.90	0.12	1.04	0.14
Production of phosphorus & potassium fertilizer		0.04	0.00	0.04	0.01	0.05	0.01
Production of pesticides		0.08	0.01	0.10	0.01	0.12	0.01
TOTAL ENERGY USE		**1.64**	**0.18**	**2.05**	**0.22**	**2.38**	**0.26**
Manure management dairy	Daily evacuation of manure from barns, slurry storage acidification sulfate addition; slurry tank covers; simple aerobic storage; high value manure options; low carbon fertilizer production	-	-	-	-	-	-
Methane		0.85	0.07	1.06	0.09	1.23	0.11
Nitrous oxide		0.29	0.03	0.36	0.04	0.42	0.04
Manure mangement pigs		-	-	-	-	-	-
Methane		1.36	0.18	1.70	0.22	1.97	0.26
Nitrous oxide		0.22	0.03	0.28	0.03	0.32	0.04
TOTAL MANURE MANAGEMENT		**2.72**	**0.31**	**3.40**	**0.39**	**3.94**	**0.45**
Peatlands	Restoration	4.80	0.24	4.80	0.24	4.80	0.24
Liming	None explored	0.21	0.21	0.21	0.21	0.21	0.21
Other (residue burning CO_2 from urea)		0.01	0.01	0.01	0.01	0.01	0.01
Bioenergy	Increased straw, higher value uses	(0.48)	(0.95)	(0.48)	(1.14)	(0.48)	(1.31)
Soil carbon (including land conversion)	Increased cover crops, but reduced gains as soils saturate	(0.30)	(0.35)	(0.35)	(0.40)	(0.35)	(0.40)
International production emissions	Similar to domestic crop options; tree-based oilseed	1.35	0.67	1.68	0.83	1.95	0.97
TOTAL PRODUCTION EMISSIONS DOMESTIC & INTERNATIONAL		**18.10**	**3.13**	**21.52**	**3.78**	**24.29**	**4.39**

Source: Author's calculations.

Table ES-2 | Timing of Possible Large-Scale Implementation of Mitigation Measures

MITIGATION TYPE	COMMENT
Ongoing	
Feed conversion efficiency gains	Steady gains through management and breeding, new breeding emphasis on residual feed intake.
Yield gains	Steady annual gains and some opportunities for major breakthroughs.
Cover crop use	Continued implementation with steady innovations in management and breeding to reduce costs and increase cover crop growth.
Earlier winter crop planting	Start now but management and innovations needed to reduce pest problems with earlier planting to allow broader scale-up.
Immediate Start and Available Now	
Peatland restoration	Projects have started and can expand with more relaxed criteria. Trial methods needed to address phosphorus releases.
Remove barn manure daily	Can be mostly done immediately with added labor, and new barn design for replacement barns can make removal easier over time.
Expanded fodder beet use	Technologies available today.
"Produce and protect" projects in South America	Doable with pasture improvement today, while tree-based oilseeds need pilot projects.
Eliminate use of crops in digester, and stop subsidizing new digesters	Possible now.
Almost Immediate Start—Still Some Uncertainty	
Feed 3-NOP enteric methane inhibitor	Still awaiting EU regulatory approval, likely to come soon. Must prove that effect is sustained year-on-year. Adjustments over time may enhance benefits.
Acidified manure storage	Available now but first steps should be a variety of full-scale pilots of acid in storage, including tests with only limited sulfate and to assess yield effects on crops. Also, need for two-year project to better quantify manure emissions. Then scale up quickly.
~4–6 Year Time Horizon before Scale-Up	
Large-scale use of nitrification inhibitors	Although available now, large-scale pilot projects and assessments needed, including inhibitors with coatings, to maximize benefits and to ensure no water quality effects. Longer-term effort needed to develop better inhibitors.
Precision agriculture guidance for delayed nitrogen application	Development of model and/or remote testing to guide nitrogen application in-season for wheat and barley.
Nitrogen-fixing microbe	Work on maize can be tested immediately; methods to use on wheat and barley need to be developed.

Table ES-2 | Timing of Possible Large-Scale Implementation of Mitigation Measures (cont.)

MITIGATION TYPE	COMMENT
BCM enteric methane inhibition	Large-scale pilots of red algae use and closed-loop production warranted. Approvals needed to test bromochloroform (BCM) with feeds other than algae and then testing required.
Biorefinery	Expanded pilot projects needed along with expanded efforts to breed and grow high-yielding, perennial grasses, such as festulolium.
Time Horizon of 10+ Years	
Biological nitrification inhibition	Merits intensive research.
High-value uses of manure	Creative proposals but none is cost-effective yet.
Shift bioenergy uses of straw to harder to abate fossil fuel uses	Alternatives required because electrification is possible to replace present residential heat uses; alternatives could include industrial heat or airplane fuels but require development.
Tree-based oilseeds at scale	Might be able to replace soybeans at a fraction of land but need pilots to move first.
Hydrogen or electric or other alternative energy farm equipment	Depends on broader progress in the energy sector.
Nitrogen fertilizer from low-carbon energy	Likely depends on progress in making low-carbon hydrogen, but some ideas exist for alternative methods.

Source: Author's Authors' analysis.


FIONA

Introduction

How can Danish agriculture achieve its announced goal to become carbon neutral by 2050? Landbrug & Fødevarer ("LF," known in English as the Danish Agriculture and Food Council), declared this goal in March 2019. This report, commissioned by LF but also funded by other sources, provides a pathway and recommendations for achieving this goal. LF has provided some information and facilitated contacts in Denmark but has provided no direction regarding the substantive content of the report.

This strategy focuses on changes in Danish agricultural production. WRI's global report, *Creating a Sustainable Food Future* (Searchinger et al. 2019), focuses not just on production but also on ways of holding down the demand for agricultural land through measures such as shifting diets and reducing food loss and waste. Denmark can also contribute to solving climate change through such measures, but, for reasons we explain more below, they do not alter the strategy for addressing emissions from Danish production, particularly because Denmark's agriculture is so heavily export-oriented.

Part 1 sets forth key relevant findings from WRI's global report, *Creating a Sustainable Food Future*, to provide guiding principles for a Denmark strategy that reduces global emissions.

Part 2 analyzes Denmark's greenhouse gas emissions.

Part 3 analyzes the life-cycle carbon intensity of Danish pork and dairy production, the dominant agricultural industries in Denmark, and compares those emissions with the emission intensity of other major dairy- and pork-producing countries. It also analyzes the potential global climate consequences of reducing Denmark's agricultural production.

Part 4 shifts toward mitigation strategies by 2050. The first question is to define future baselines. We do so by defining three future food production levels and then estimate emissions if agricultural production systems remain the same as in 2017. This concept of a baseline is not a prediction but allows calculation of all the different changes necessary to reduce emissions, including some that are likely to occur without added efforts. Part 4 then analyzes the principal technical opportunities we have identified, or others have suggested, for mitigating the five major categories of production emissions: drained peatlands, manure management, nitrogen use, enteric methane, and energy use. We find a possible pathway to reduce those emissions generated within Denmark by 80 percent from each future baseline.

Part 5 analyzes what Denmark can do, first, to avoid emissions attributable to land use between now and 2050 and, second, to generate offsets

for its remaining production emissions. We underscore that because the world will increase its food production, global food production must increase its efficiency in the use of land by a similar percentage to avoid expanding agricultural land area and releasing carbon from native vegetation and soils. We therefore believe that regardless of Denmark's future production levels, it must increase the land use efficiency of its own agricultural production by the same percentage to be considered land area carbon neutral. We explore how it can do so and how it can increase its land use efficiency even more through improvements

in crop yields and the feed conversion efficiency of livestock, and then reforest land and obtain offset credits for sequestering the carbon. Because this strategy involves offsetting annual production emissions with one-time land use change sequestration, we explain how the two types of emissions are made equivalent, using discounting.

Part 6 analyzes the potential for Danish agriculture to offset production emissions with bioenergy and soil carbon gains. Because producing willow or other energy crops requires land, which has a carbon opportunity cost, we find that doing so is unlikely to produce net gains. Denmark can continue to build some soil carbon, can modestly increase its present bioenergy production from grain straw, and can supply biomass for energy through the biorefinery system, although we assign half of the benefit from bioenergy use in 2050 to the energy sector.

Part 7 summarizes the mitigation potential and offers recommendations for moving forward.


GEA

PART 1

The Global Challenge and Principles for Pursuing Carbon Neutral Agriculture

Creating a Global Sustainable Food Future Report

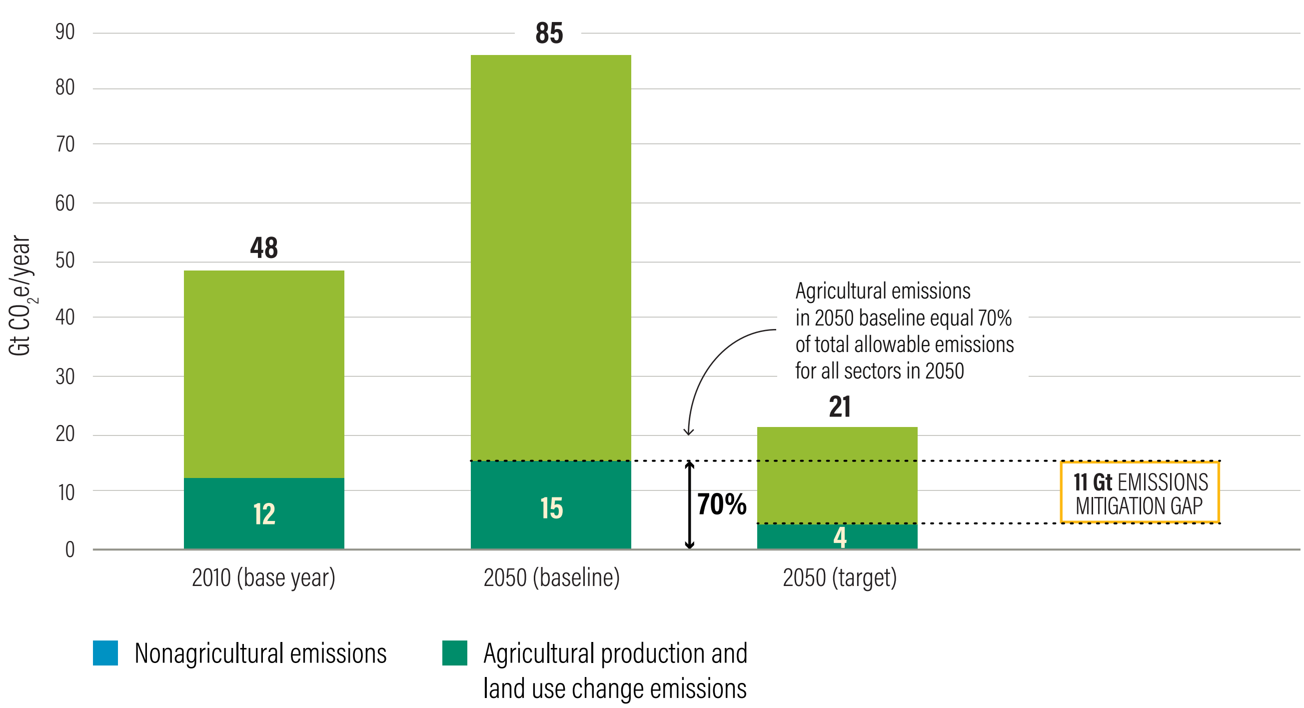
This work originated in part as an opportunity to extend the analysis in a World Resources Report issued in 2019 by WRI, the World Bank, and the United Nations called *Creating a Sustainable Food Future: A Menu of Solutions to Feed Nearly 10 Billion People by 2050* (Searchinger et al. 2019). That report has several findings and recommendations of importance to crafting a carbon neutral strategy for Danish agriculture.

Large agricultural climate challenge. *To meet climate targets, agriculture likely needs to produce at least 50 percent more food in 2050 than it did in 2010 while reducing existing agricultural emissions by two-thirds.* Today, agriculture and associated land use change contribute around 12 gigatons (billion tons) of greenhouse gas (GHG) emissions (measured by carbon dioxide equivalent emissions, or CO_2e). With growth in food production, these emissions are projected to grow to 15 gigatons in 2050. Even optimistically treating 21 gigatons as an allowable level for total human emissions in 2050, that means agriculture alone (generating only around 2 percent of global economic output) would generate 70 percent of all allowable emissions (Figure 1.1). That leaves too little room for other human activities to meet climate goals. For agriculture to do its proportionate share, emissions must be reduced to 4 gigatons.

Land use. *Land use is a big part of the challenge.* Producing all the food likely demanded in 2050 with today's farms would require more than 3 billion hectares of land, leading to the loss of most of the world's remaining forests (Figure 1.2, 4th column). Even if crop yields and livestock productivity globally rise roughly at their rate of the last five decades, global agricultural land use would expand by almost 600 million hectares—an area equal to almost twice the size of India (Figure 1.2). That would cause large-scale loss of forests and woody savannas, releasing large quantities of carbon dioxide. Nearly all climate strategies require that there be no additional clearing of agricultural lands in that time, and nearly all strategies focused on holding climate warming to 1.5 degrees (Celsius) require a decline in agricultural land by 2050, so land can be reforested or otherwise used to remove carbon from the air. Avoiding this land clearing is therefore critical.

Increasing land use efficiency of both production and consumption. *Any possible way of avoiding this additional clearing of forests and other lands requires both large yield gains and beneficial ways of reducing consumption.* Figure 1.3 shows one menu of solutions to close the gap between the likely emissions of 15 gigatons in

Figure 1.1 | Agricultural Emissions in 2010 Base Year, Business-as-Usual Projection in 2050, and Climate Mitigation Target



Source: GlobAgri-WRR model, WRI analysis based on IEA (2012); Houghton (2008); OECD (2012); and UNEP (2013).

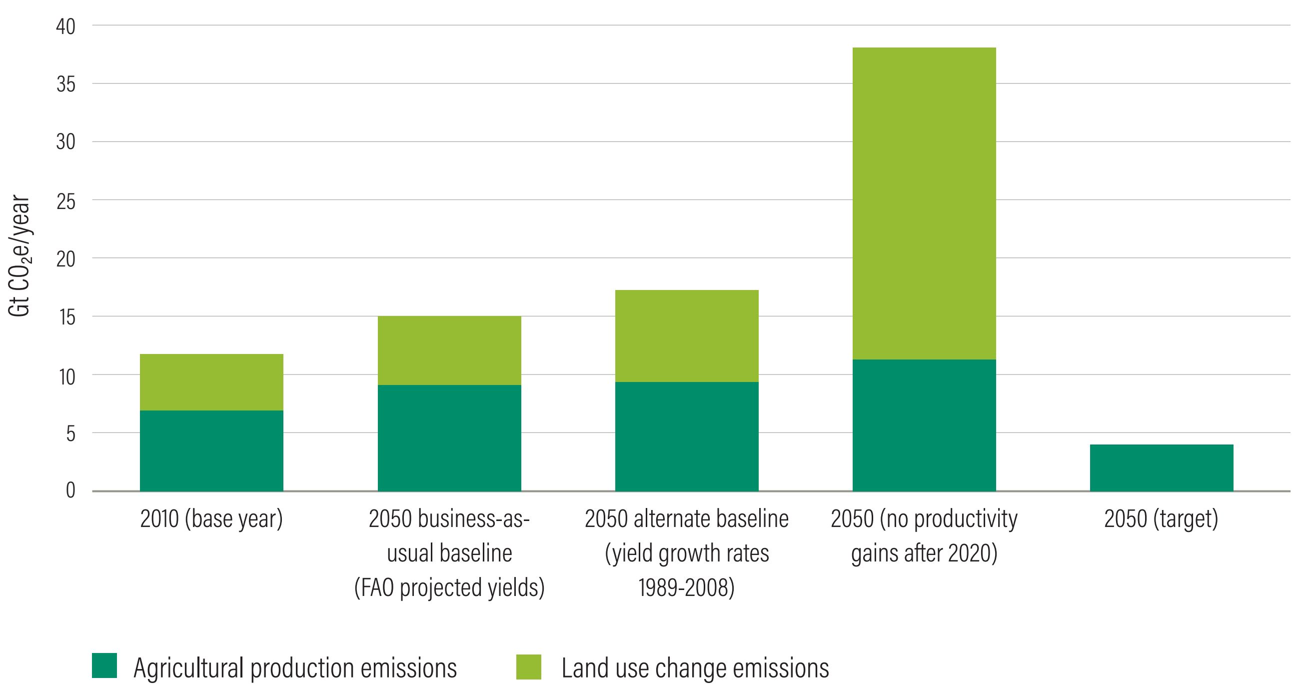
2050 and our target of 4 gigatons. These solutions rely partially on productivity gains and heavily on holding down the growth in demand. Holding down this demand requires that the 20 percent of the world that eats abundant beef, lamb, and goat shift much of that consumption to other foods. It also requires other demand-reduction strategies, like reducing food loss and waste and avoiding biofuels from the dedicated use of land.

Even with ambitious reductions in demand, however, gains in land use efficiency play the most important role in reducing overall emissions. Figure 1.3 starts with an estimate of likely emissions in 2050 that already assumes historic rates of gains in crop yields and substantial increases in livestock efficiency. By contrast, the second column of Figure 1.4 shows what emissions would be if the world produced the food likely needed in 2050 with today's yields and livestock productivity: Greenhouse gas emissions would rise to 38 gigatons, roughly twice the acceptable level from all human activity in that year. Much of these emissions would occur from the need to convert to agriculture most the of world's remaining temperate and tropical forests. Although holding down demand is critical, boosting crop and livestock yields is also critical.

This need means that it is not normally beneficial for the climate to remove highly efficient agricultural land from production on the theory that people could then avoid clearing more land by eating less meat or by reducing food waste. It would be equally invalid to suggest that people do not need to reduce food waste because farmers could instead boost their yields. *Both* more efficient food production *and* demand reductions are needed.

As applied to Denmark, this principle means that Denmark can and should contribute to solving climate change by shifting diets to consume less milk and meat and by reducing food loss and waste (Box 1.1). However, because the world is almost certainly still going to need more milk and meat, Danish agriculture can contribute most to the world by still producing milk and meat with fewer emissions and less land use.

Figure 1.2 | Increases in Agricultural Land Emissions in 2050 Compared to 2010 with Different Rates of Yield and Livestock Efficiency Changes



Source: GlobAgri-WRR model.

BOX 1.1 | Denmark's Role in Shifting Diets and Reducing Food Loss and Waste

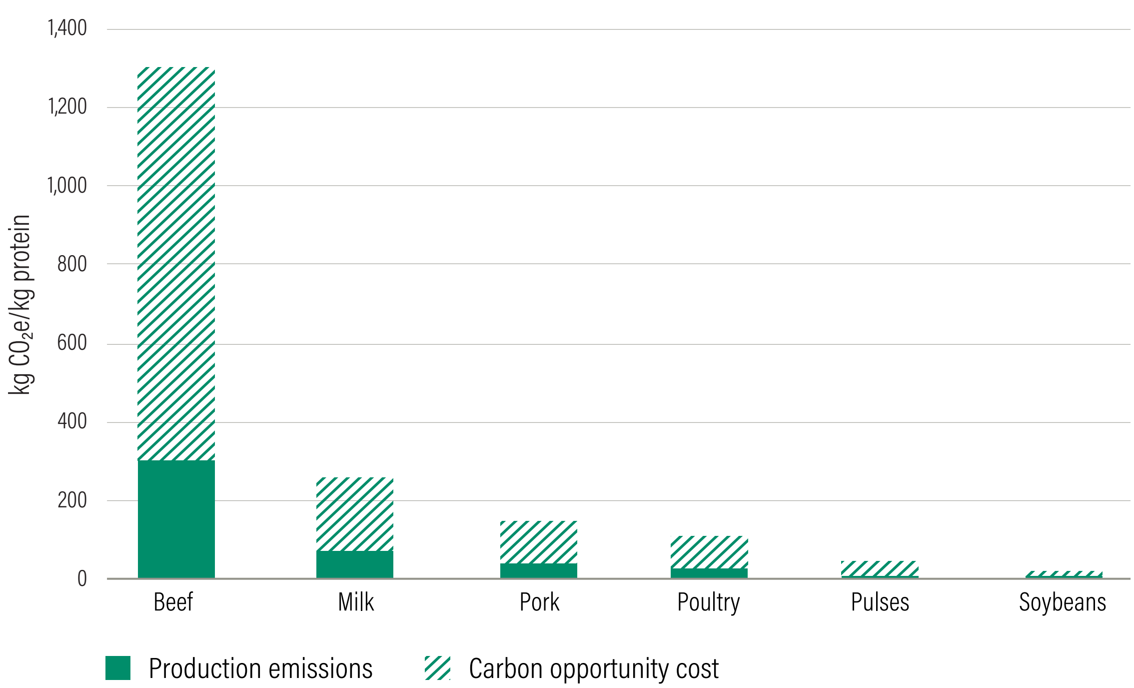
Although this report focuses on changes in Danish agricultural production, *Creating a Sustainable Food Future* (Searchinger et al. 2019), like many other studies, identified broader changes to the overall food system that are needed to stabilize the climate. These changes include reductions in food loss and waste and efforts to reduce the overall demand for agricultural products, particularly ruminant meats such as beef. Both measures are important in Denmark.

Denmark has a high and growing per capita consumption rate of animal products. According to the Food and Agriculture Organization Corporate Statistical Database (FAOSTAT), the average Danish person consumes 1,300 calories of animal products per day, an amount even higher than the European average of 950 calories per day (FAOSTAT 2020). This is not justified by any need for protein, and there is evidence that this level of meat consumption is not healthy (Tilman and Clark 2014; Searchinger et al. 2019). Despite Denmark's reputation for pork and dairy production, beef consumption is also 70 calories per day, which places Denmark's consumption in the top quarter of global consumers.

A variety of strategies exist to reduce consumption of meat and milk. They can include changes in how plant-centered meal options are presented and offered in restaurants and supermarkets, labeling strategies, and promotion of plant-based meat alternatives (Temme et al. 2020; Attwood et al. 2020).

In *Creating a Sustainable Food Future*, we particularly focus on reducing consumption of beef and other ruminant meats. Using the carbon opportunity cost method as in this report, emissions per kilogram of beef are more than five times those of dairy, and nine times those of pork (Figure B1.1). Unlike overall meat consumption, historical evidence exists for success in reducing per capita beef consumption. Consumption of beef per person has declined by roughly one-third since 1970 in both Europe and the United States (FAOSTAT 2020).

FIGURE B1.1 | GLOBAL AVERAGE EMISSIONS FROM BEEF PRODUCTION (CO_2 PER KG PROTEIN)



Source: Searchinger et al. (2018).

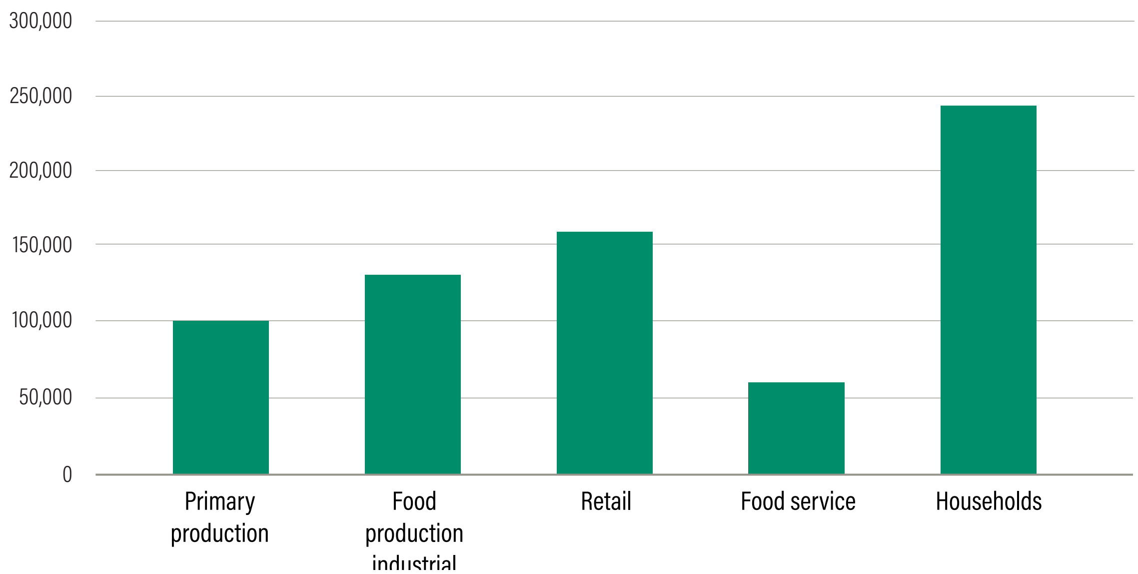
BOX 1.1 | Denmark's Role in Shifting Diets and Reducing Food Loss and Waste (cont.)

Denmark has recently made some progress in reducing food waste. Denmark generates approximately 700,000 tons of food waste per year (Danish Ministry of Environment and Food 2018). More than one-third occurs at the household consumption stage of the food supply chain and more than 20 percent at the retail stage (Figure B1.2).

Between 2011 and 2018, Danes reduced consumption-level food waste by about 8 percent per person (Danish Ministry of Environment and Food 2018). Strategies to reduce food loss and waste include revising product labels, allowing "expired food" to be sold if there is no health risk and it is labeled, encouraging consumption of unusually shaped fruits and vegetables, changing food promotions to avoid excessive purchase, changing packaging, and increasing food donations (Flanagan et al. 2019). In 2020, Denmark took another step forward when it announced a voluntary agreement among approximately 20 of Denmark's leading food companies to reduce food loss and waste by 50 percent.

Consumption-side efforts are critical to reducing agricultural land use and greenhouse gas emissions. But for reasons we explain elsewhere in the report, the world is still going to demand far more food and will therefore need both more food production and reductions in emissions from agricultural production.

FIGURE B1.2 | FOOD WASTE ALONG THE FOOD SUPPLY CHAIN IN DENMARK (2018)



Source: Adapted from Danish Ministry of Environment and Food (2018). The graphic is based on figures from various sources: DTU FOOD (National Food Institute), "Climate-Friendly Dietary Guidelines," 2012; Danish EPA, "Survey of Food Waste in the Food Sector," 2014; Danish EPA, "Survey of Domestic Waste in Denmark," 2017.

Sources: Attwood et al. (2020); Searchinger et al. (2019) ; Flanagan et al. (2019); Temme et al. (2020); Tilman and Clark (2014).

Global challenge. *The challenge, and therefore the solution, is global.* Most of the growth in demand for food will occur in developing countries, partially as a result of rising population and partially as a result of rising incomes. Rising incomes lead to more resource-intensive foods, including more meat and dairy, and even more vegetable oil and vegetables. As a result, the Global South is where most land clearing will occur. This clearing also will have harsh effects on biodiversity. This challenge means that increasing crop and livestock yields everywhere is critical because both are needed to avoid expanding overall agricultural land.

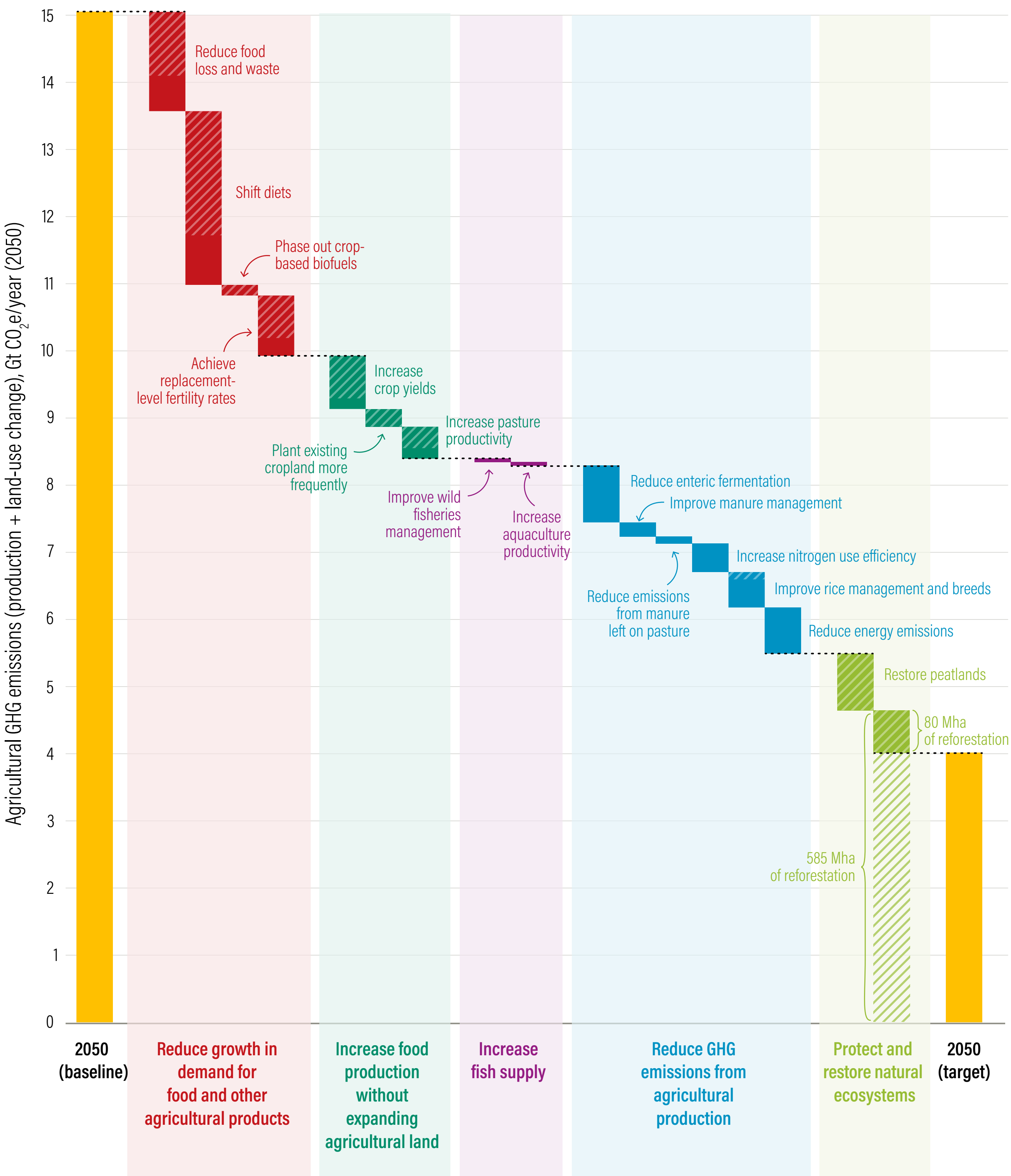
Challenge of changing the location of agricultural land. *In addition to expanding, agricultural land is also changing location—not merely traditional rotational agriculture in developing countries but also shifting from one part of a country to another or even from one continent to another.* In general, agricultural land is shifting into more carbon-rich, tropical lands, such as tropical forests. This shifting causes climate challenges because the loss of carbon from forest clearing is immediate, while carbon gains occur slowly as abandoned lands reforest. These shifts also cause both biodiversity and climate challenges because the land being cleared is more pristine and more carbon-rich. Solving climate change requires avoiding these shifts to the extent possible.

Produce and protect. *To avoid these shifts in land, efforts to boost yields must be linked to protection of forests and other natural habitats.* Unfortunately, yield gains can encourage this changing location by giving new areas a stronger competitive position to supply global markets. If Brazil had never developed high-yielding ways of producing soybeans or even somewhat more productive beef, it would not have cleared vast areas of savanna and forest, and the same is true for oil palm in Indonesia and Malaysia. Without yield gains, forest loss is certain; but with yield gains, tropical forest loss can also occur. The world has a global interest in boosting yields in developing countries for the climate benefit of everyone, but to avoid encouraging further agricultural expansion from shifting agricultural locations, these efforts need to be tied to forest protection. This dual need, known as "produce and protect," plays a significant role in our analysis.

More efficient use of natural resources. *Much mitigation of agricultural production emissions results from more efficient use of natural resources in agricultural production.* In addition to efficiencies in land use, mitigation requires more output per kilogram (kg) of fertilizer, per kilowatt hour of energy, and per animal. Developing countries can use many techniques already known, but innovation is required to make large-scale progress in these efficiencies in developed countries.

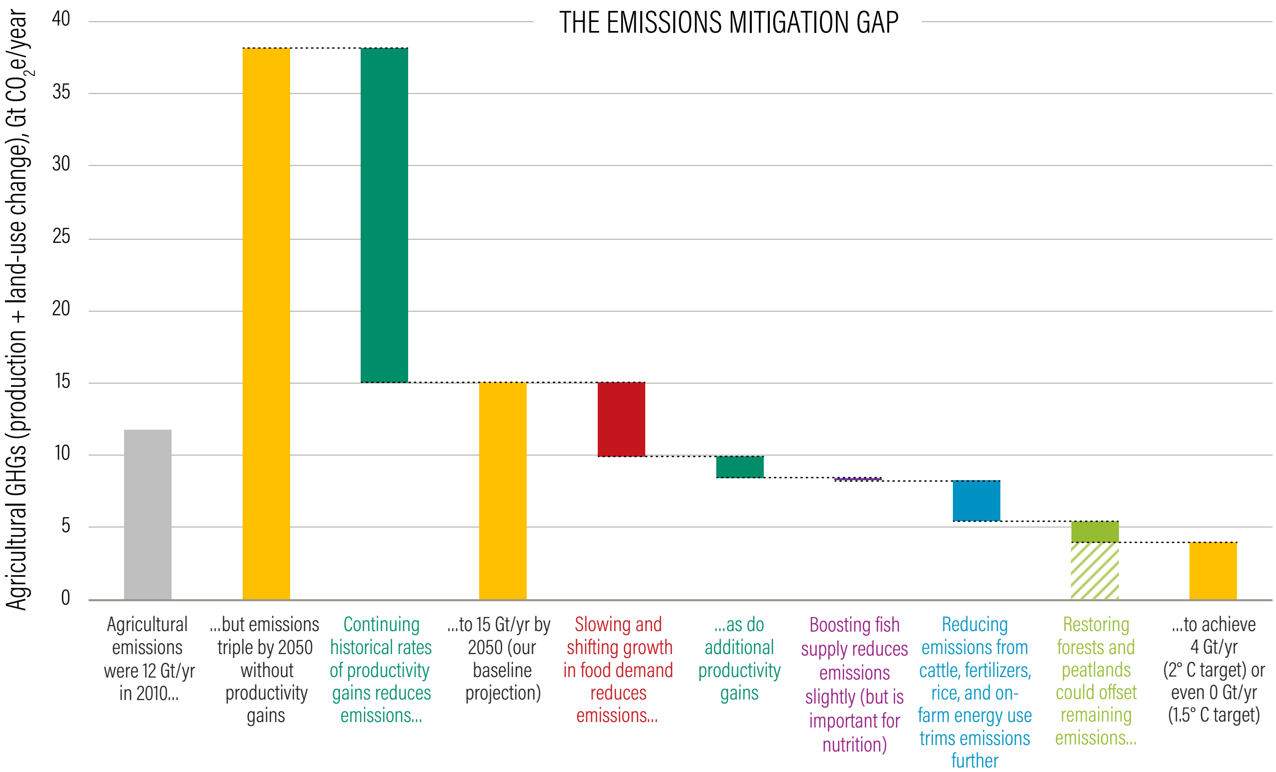
Innovation. *Achieving climate goals will require both a commitment to implementing known measures that reduce production emissions and a strong push to innovate.* Fortunately, for virtually every need, there is at least a promising scientific innovation. Developed countries need to take the lead in developing and implementing innovations.

Figure 1.3 | Menu of Solutions for Mitigating Agricultural Greenhouse Gas Emissions



Source: Searchinger et al. (2019).

Figure 1.4 | Mitigation Actions and Greenhouse Gas Reduction Quantities Required to Achieve 2-Degree Climate Target



Source: Searchinger et al. (2019).

Guiding Principles for Developing a Carbon Neutral Strategy for Danish Agriculture

Based on this analysis in *Creating a Sustainable Food Future*, we apply the following principles in developing a strategy to achieve a sustainable food future for Danish agricultural production.

A. Global effect. *Emissions should be reduced in ways that also achieve global reductions.* Denmark could always reduce the emissions from agricultural production by shrinking its agricultural sector. But solving climate change is a global challenge, and the world is on a path to need increases in food production by more than 50 percent between 2010 and 2050. Shrinking Danish production would only be beneficial if replacing the food abroad would lead to fewer emissions. Our analysis, as discussed below, concludes the opposite.

B. Cost-effective. *Danish agriculture will make the biggest contribution to solving global warming by innovating and demonstrating sufficiently cost-effective ways of reducing emissions that others will follow.* Although Denmark has a large agricultural sector, Denmark is still a small country. As reported in Denmark's national inventory report, Danish agricultural emissions are less than 0.04 percent of global, human emissions. Even if the Danish agricultural sector or government were willing to absorb high costs to mitigate Danish emissions, Danish agriculture could contribute more to solving global warming by developing methods that are cheap and easy enough for others to follow—just as Denmark has contributed to mitigation in the energy sector by being a leader in developing wind energy.

We adopt a working assumption to identify only mitigation that could cost less than $50 per ton of reduction of CO_2e. Some climate strategies are willing to pay $200 or more per ton of reduction in carbon dioxide. At this cost, the cost of mitigating agricultural emissions would reach almost as much as the roughly $4 billion per year economic contribution of Danish agriculture.[1] If no other strategies can prove cost-effective, such costly mitigation may be necessary. At this time, we believe the strategies we encourage have potential to be cheaper than even $50 per ton or ultimately costless when factoring in effects on yields or other benefits. As in the energy sector, however, achieving these cheap solutions is not cost-free. Significant funding is necessary for research and development and to encourage initial adoption of these measures.

C. **2030.** *Reductions by 2030 also matter and should be structured to also assist meeting 2050 goals.* In addition to LF's self-adopted goal for 2050, the Danish government has committed to achieving a 70 percent reduction in Danish emissions (relative to 1990) by 2030 and is expecting the agricultural sector to contribute. These goals are independently important, and it is equally important that the manner of achieving these goals contribute to achieving the even greater goals by 2050.

D. **Actively exploring new and uncertain approaches.** *To approach carbon neutrality, Danish agriculture must pursue multiple technical approaches because some will fail.* Having already made many improvements in reducing inputs per hectare, per animal, and per chemical, Denmark has fewer "easy" known ways to reduce emissions further. To achieve the ambitious goal of carbon neutrality, Danish agriculture must be willing to invest resources in exploring promising ideas even if their realization is uncertain. Because not all promising ideas are likely to work, it must also explore multiple approaches to addressing the same problem.

E. **Denmark's environment.** *Denmark's environment matters also.*[2] Because Danish agriculture is mostly climate-efficient, the high level of agricultural production in Denmark can be viewed as having global climate benefits—and even more so if Denmark reduces its emissions yet further. Yet agriculture by its nature has significant environmental costs, and the extent of agriculture in Denmark is costly to its environment. Denmark's 57 percent of land in arable use is among the highest of any country in the world. (According to the World Bank, only Bangladesh and Ukraine are slightly higher.) According to FAOSTAT, Denmark also has the highest concentration of dairy and pigs per hectare of any country in the world. As a result, Denmark's forest area is only 15 percent of its area, and three-quarters of these forests are highly managed and therefore support much lower biodiversity than natural forests. Despite great effort by Denmark's agricultural community, Denmark contributes significantly to nitrogen pollution in the Baltic Sea. Many Danes are understandably anxious to improve Denmark's environment, and arguments can be made that each country should support some of the world's biodiversity. We therefore seek here to identify climate solutions that could meaningfully contribute to these goals.

Danish agriculture will make the biggest contribution to solving global warming by innovating and demonstrating sufficiently cost-effective ways of reducing emissions that others will follow.

F. Sound analytics. *Getting the analysis right is fundamental to contributing to global solutions.* Unlike emissions from energy use, which can be estimated by counting fossil fuels used, it is not possible to directly measure most agricultural emissions. They must be estimated using emission factors with substantial uncertainty. This uncertainty makes it possible that initial decisions, based on the best available evidence, will turn out to be inaccurate. It may also create temptations to too readily adopt inappropriate accounting rules or use default factors that seem to minimize emissions. However, that will not benefit the climate. And even from an economic standpoint, it is risky because direct monitoring methods are going to improve. For example, while methane emissions from livestock operations are somewhat uncertain, it will soon be possible to monitor those emissions from individual farms using satellites. In our analysis, we therefore adopt the approach of (1) using the best available science today, (2) calling attention to important uncertainties, (3) identifying priority needs for supplemental monitoring where they exist, and (4) identifying measures that are likely to be beneficial even if today's emission estimates turn out to be somewhat inaccurate.

How Global Climate Strategies Help to Define Danish Agriculture's Carbon Neutrality Goal

In one sense, global climate change strategies do not require that the agricultural sector become carbon neutral, and in one sense they do. Climate researchers plan out potential future solutions using estimates of "least cost mitigation" opportunities. Those estimates obviously involve a high level of guesses about future costs, particularly for new or evolving technologies. In the agricultural sector, scientists have been less willing to speculate about new technologies than in the energy sector, and that helps explain why cost-effective mitigation estimates for agriculture have generally been modest. Assuming those modest projections, modelers have tended to rely less on mitigation of agricultural production emissions from methane and nitrous oxide (the dominant production emissions), imposing more burdens elsewhere in the economy in their climate plans.[3]

Based on this approach, modeled mitigation strategies appear to assume continued agricultural production of methane and nitrous oxide at levels of around five or six gigatons, not much lower than those today (see van Vuuren et al. 2010 and 2017). Achieving even these goals would still require much mitigation to avoid increasing emissions with increasing food production (Searchinger et al. 2019). Yet these assumptions do not mean such high emissions are acceptable. Strategies assume these high emissions only because they assume that reducing emissions further is not achievable. To compensate for these high emissions, most climate strategies therefore require even larger and uncertain "negative emissions" in some way after 2050 to achieve acceptable climate targets (Sanderson et al. 2016; UNEP 2017; IPCC 2018). The basic lesson is that reducing agricultural production emissions should still be done as much as possible, but no one has assumed that they can be eliminated.[4]

Even with these assumptions about production emissions, climate strategies still implicitly rely on agriculture even more to achieve climate goals in another way that approaches climate neutrality. Strategies do so by building large, land-based climate mitigation through reforestation into mitigation strategies (IPCC 2018). These strategies can also rely on devoting land to bioenergy (an approach with which we disagree because it is not climate-beneficial when accounting for the opportunity cost of not using land for forests or other purposes (Searchinger et al. 2019), chap. 7). Either way, strategies implicitly require that agricultural area be reduced to make land available for these other purposes. In that sense, climate strategies require not only some reductions in production emissions but also vast increases in production of food per hectare. These vast increases in output required are a type of climate mitigation and should be analyzed and "credited" as such.

Our approach to Danish agriculture's carbon neutrality pledge follows this outline. The first focus is to achieve large reductions in production emissions. As set forth below, we find strategies that collectively could reduce the intensity of agriculture's production emissions—its emissions per kg of food—by 80 percent in Denmark.

The second focus is to ensure that Danish agriculture does not contribute to increasing global land use area, which we call being "land area carbon neutral." As we explain further below, we believe that doing so requires that all countries contribute equally to increasing global agricultural land use efficiency enough to avoid the need to expand agricultural land globally and avoid further deforestation. Land use efficiency refers to the quantity of land used to produce each output of food.

The third part is then to achieve offsets for the remaining production emissions. We here use the term *offsets* to refer to any activity that does not by itself avoid agricultural emissions but instead either removes carbon from the air or replaces fossil energy emissions. As in the case of our global analysis, and implicitly other climate strategies that rely on "natural climate solutions," these offsets require agricultural land use efficiency gains at a level sufficient to reduce global demands for agricultural land. If Denmark can achieve yield and livestock efficiency gains that go beyond "land area carbon neutrality," it can use these land savings to restore forest in Denmark and claim an offset against residual production emissions. (Bioenergy from crop residues and soil carbon gains also play a small role.) Unlike offsets in other sectors, these offsets are directly undertaken by the agricultural sector and therefore do not represent a shift in mitigation responsibilities to other sectors.

We apply the same approach to Denmark's imports of feed, which are part of the GHG cost of Danish agriculture. For reasons we discuss below, we generally favor domestic efforts to achieve carbon neutrality for agriculture in Denmark itself and separate efforts in other countries to achieve carbon neutrality for imported feed.

PART 2

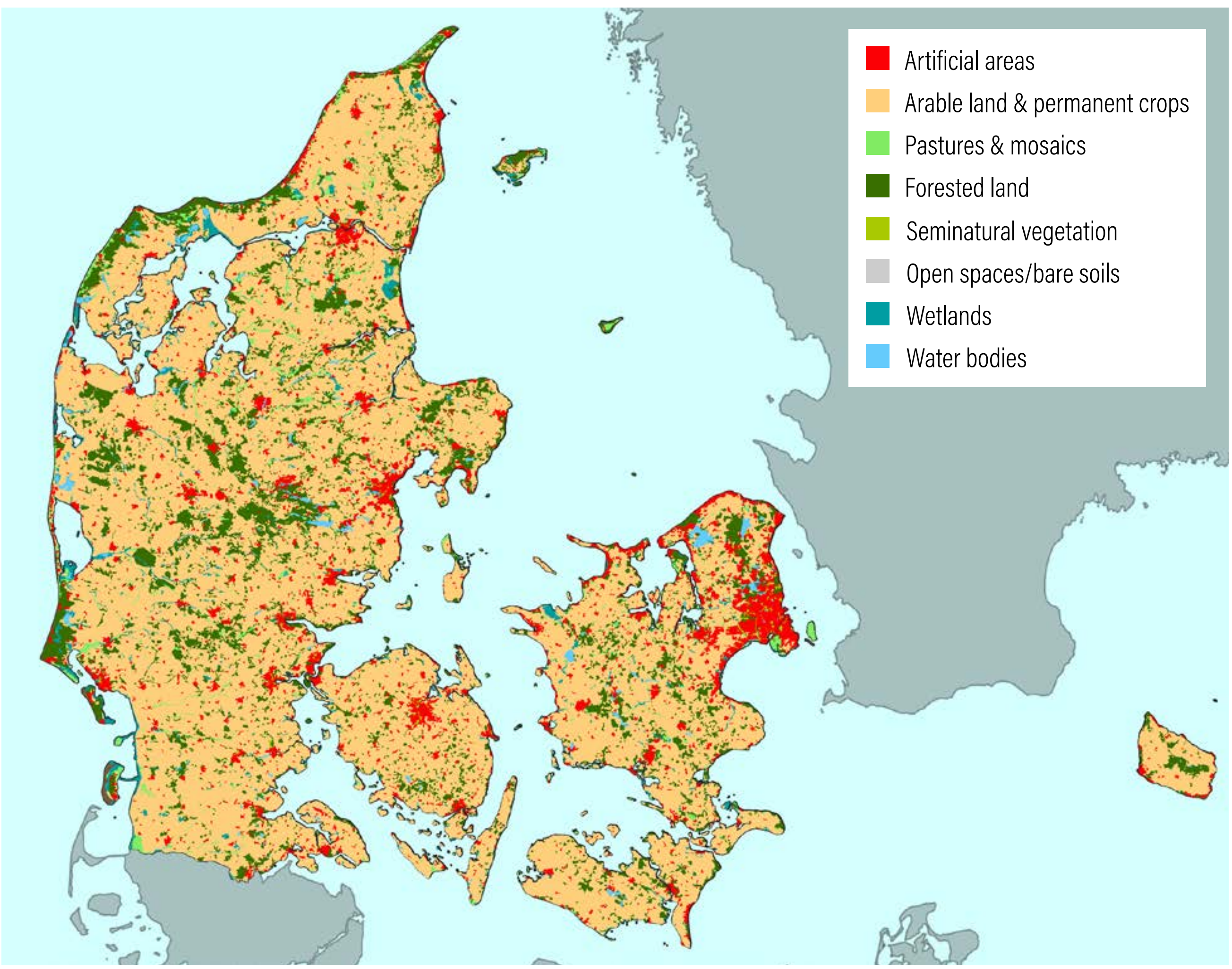
Danish Agriculture's GHG Emissions Today

Denmark is a country whose land is heavily devoted to agriculture and primarily focused on production of pork and dairy. Out of a total of 4.3 million hectares, 2.6 million (62 percent) is devoted to agriculture (Figure 2.1).

Based on value added, 28 percent of agricultural "value-added" output comes from pork, 18 percent from dairy, and 34 percent from crops.[5] Until recently, 6 percent of agricultural production was for mink fur, but the extermination of virtually all mink animals during the COVID-19 pandemic may permanently eliminate the mink industry. The remaining 14 percent of production is attributed to beef, poultry, and eggs. These figures by themselves fail to convey the dominant roles of pork and dairy, as 95 percent of crops are used for animal feed,[6] and Denmark's beef production is itself almost entirely a coproduct of dairy, taking male calves and dairy cows at the end of their lives.

Of the agricultural land, roughly 1.4 million hectares are devoted to wheat, barley, and rye, nearly all used for animal feed.[7] Additionally, roughly 500,000 hectares are devoted to some kind of fodder, evenly divided by silage maize and cereals and grass or grass/clover combinations. Only roughly 220,000 hectares are permanent grasslands. Danish dairy production makes little use of grazing except for a growing organic dairy sector.

Figure 2.1 | Agriculture Occupies 62 Percent of Danish Land



Source: Corine Land Cover (CLC) 2018, version 2020_20u1.

There are different ways of estimating emissions from any production activities and particularly different possible methods in agriculture for assigning GHG costs to land use. There is no perfect solution, and some choices involve policy questions that are neither analytically correct nor incorrect. However, that does not mean that all accounting rules are "equally valid": some rules are counterproductive because they create perverse incentives. Getting the accounting rules right is critical both for Denmark and to ensure that Denmark's influence on climate mitigation globally is beneficial.

Here we present three categories of greenhouse gas costs attributable to the agricultural sector. They are (1) national emissions from the production process for agricultural land, including changes in the soil carbon of existing agricultural lands, which include drained peatlands; (2) additional life-cycle emissions from energy use whether in Denmark or for producing fertilizer or other inputs abroad, as well as the production emissions for imported animal feed; and (3) carbon opportunity costs attributable to Denmark's land area footprint both for agricultural production in Denmark and for feeds imported from abroad. Because it is important to understand these different approaches, we describe them in the following pages in detail.

Emissions from Denmark's National Emissions Inventory

Denmark reports its greenhouse gas emissions in a national emissions inventory report (NIR 2019) based on methodological guidance provided by the Intergovernmental Panel on Climate Change in 2006 (IPCC 2006). This guidance is strongly recommended but not mandatory and leaves a certain amount of discretion to each country. Conceptually, the key principle of the guidelines of the Intergovernmental Panel on Climate Change is that they focus on the emissions that physically occur in Denmark.

Denmark has a thorough and well-explained NIR and associated report. IPCC guidance instructs countries to develop their own "activity data," such as data on quantities and types of livestock and quantities of fertilizer used (IPCC 2006, 2019). The IPCC then provides "emission factors" that countries can use that in some way multiply the "activity data" by the quantity of emissions each unit of activity creates. Countries can sometimes use Tier 1 emission factors that require a smaller amount of activity data or Tier 2 emission factors, which require more detailed activity data and which countries can vary based on local information. Countries can also develop their own modeling tools, known as Tier 3. Denmark uses a mix of these tiers in a reasonable way.

Denmark's emissions attributable to agriculture in the NIR equal roughly 14.4 million tons (NIR 2019). Table 2.1 presents them and includes not merely emissions reported by Denmark as agriculture but also those emissions reported in the category of

land use and land use change (LULUCF) that are properly attributed to agricultural activities. In Denmark, such LULUCF emissions are dominated by emissions from drained peatlands. They also include a credit for soil carbon gains primarily in sandy soils in western Denmark due to increased crop and grassland productivity. (A credit means a reduction in emissions.) Table 2.1 presents some categories differently from the NIR to more clearly indicate the activity responsible for the emissions. For example, while the NIR includes nitrous oxide from peatlands in the soils category, we put these emissions in the peatland category because they are a result of drainage, not of applied fertilizer.

We have also adjusted Denmark's emissions reporting to evaluate methane using a global warming potential (GWP-100) of 31 (in other words, each kg of methane causes warming equivalent to that caused by 31 kg of carbon dioxide). Doing so is necessary for consistency with our calculation of international emissions in the GlobAgri-WRR model. This approach reflects a middle ground of methane GWP between purely direct effects and the higher number that reflects various biophysical feedbacks (Dean et al. 2018). Compared with Denmark's use of a GWP of 25 for methane, this approach increases methane emissions by 24 percent.

Overall, four major categories of emissions are reported by Denmark: (1) enteric fermentation, (2) nitrous oxide from nitrogen applied to soils, (3) manure management, and (4) the ongoing consequences of using drained peatlands. We also factor in one "offset," which is an estimate of Danish soil carbon gains. We call it an offset because it removes carbon and compensates for other physical emissions but does not physically stop these other emissions (for the use of the term *offset*, see Box 2.1).

Table 2.1 | Denmark's Domestic Production Emissions, National Inventory (Partially Recategorized)

EMISSIONS CATEGORY	EMISSIONS (THOUSAND TONS OF CO_2E)
ENTERIC METHANE	
Dairy cows	2,765
Nondairy cows	1,262
Pigs	420
Other	156
TOTAL ENTERIC	**4,603**
CROPLAND AND GRASSLAND NITROUS OXIDE FROM APPLIED NITROGEN (DIRECT AND INDIRECT)	
Nitrogen fertilizer	1,135
Nitrogen from applied manure	1,015
Nitrogen from crop residues	608
Other (mineralization, sewage sludge, other organic)	54
Grazing manure	176
Indirect: leaching	191
Indirect: deposition	375
TOTAL NITROUS OXIDE FROM APPLIED NITROGEN TO AGRICULTURAL LAND	**3,554**

Table 2.1 | Denmark's Domestic Production Emissions, National Inventory (Partially Recategorized) (cont.)

EMISSIONS CATEGORY	EMISSIONS (THOUSAND TONS OF CO_2E)
MANURE MANAGEMENT	
CATTLE	
Methane	848
Nitrous oxide	287
PIGS	
Methane	1,361
Nitrous oxide	222
POULTRY	
Methane	16
Nitrous oxide	6
OTHER LIVESTOCK	
Methane	57
Nitrous oxide	60
TOTAL MANURE MANAGEMENT	**2,855**
Total peatland	**4,800**
Total soil carbon credit	**(514)**
OTHER EMISSIONS	
Carbon dioxide from urea and other carbon-containing fertilizers	9
Field burning agricultural residues	4
Liming	210
TOTAL OTHER	**223**
NATIONAL TOTAL	**15,521**

Source: Denmark's national emissions inventory reports and appendixes covering years 2016–18 with adjustments by authors for alternative methane GWP-100, and adjustments to peatland emissions based on Klimarådet (2020).

Box 2.1 | How We Use the Term *Offset* in This Report

In this report, the term *offset* refers to any removal of carbon from the air, or emission reduction by another sector that we count as compensating for actual physical emissions by Danish agriculture. Offsets compensate for but do not reduce agricultural emissions in a physical sense. Offsets in this report include bioenergy, which reduces emissions from fossil fuel use, and reforestation and soil carbon gains, which absorb carbon from the atmosphere.

In other contexts, the word *offset* might be applied only to activities outside of the control of any particular entity. By that definition, activities under Danish agricultural control could not be offsets. We use the term differently because of the importance of distinguishing activities that compensate for a remaining level of agricultural production emissions after mitigation efforts but do not by themselves reduce those production emissions.

Additional Danish Life-Cycle Emissions Excluding Land Use

Danish national inventory emissions for agriculture do not count (a) any emissions that occur outside of the country, including emissions from the production of feed imports, and (b) energy emissions associated with the running of the farm or the production of inputs, such as fertilizer, whether those inputs are produced in Denmark or elsewhere. The purpose of a life-cycle analysis (LCA) is to count all the emissions that result from the production of a product regardless of where they occur. In this section, we present our estimate of Denmark's life-cycle emissions, again excluding those from land use change. Our LCA analysis includes "upstream" emissions to produce inputs like fertilizer. But emissions end at the farm gate: We do not count "downstream" emissions, such as food processing, because we treat them as belonging to the food rather than the agricultural industry.

Denmark is a large importer of feed. Some LCAs try to attribute emissions to other production processes based on the specific country the feed comes from. The problem is that in a global market, purchasing feed from one country is likely just to cause others to purchase feed from another. For example, if Denmark were to obtain soybeans from the United States rather than South America, South America would likely sell its soybeans elsewhere, and vice versa. Far more important than where Denmark obtains its feed is how much feed Denmark uses. Even tracking country sources can be difficult. For example, Denmark imports large quantities of soybean cake from Germany, but Germany produces very few soybeans and is overwhelmingly crushing soybeans it receives from the United States and Argentina, producing vegetable oil and protein cakes. Because the dominant land uses involve use of soybean cakes imported into Europe, we decided to use the global number. The differences are small.

Table 2.2 identifies the additional emissions from the production of imported feed that are part of the life-cycle calculations, which amount to 1.35 million tons of CO_2e using an average of global and regional sources of those feeds.

Table 2.2 | Additional Annual Life-Cycle "Production" Emissions from Imported Feed

CROP	GLOBAL PEM PER KG	TOTAL USING GLOBAL PEM (KT CO_2)	REGIONAL PEM PER KG	TOTAL USING REGIONAL PEM (KT CO_2)
Wheat	0.7	67.4	0.5	45.8
Maize	0.5	60.8	0.4	43.7
Soy cakes	0.3	482.0	0.1	221.7
Rapeseed cakes	0.7	156.6	0.3	70.8
Beets	0.3	344.0	0.3	344.0
Remainder		236.2		585.5
TOTAL IMPORT PEM		**1,347.0**		**1,311.6**

Notes: PEM = production emissions; kt = 1,000 tons.

Source: Authors' calculations using production emissions from GlobAgri-WRR model.

Table 2.3 | Annual Emissions from Energy Use for Production in Denmark

SYNTHETIC NITROGEN FERTILIZERS	TOTAL (KT CO_2E)
Nitrogen synthetic fertilizer	722
OTHER INPUTS	
Phosphorus fertilizer	8
Potassium fertilizer	27
Pesticide active ingredients	80
TOTAL OTHER INPUTS	**115**
ENERGY USE IN FIELD	
Tractors for harvest	223
Tractors for tillage	297
TOTAL FIELD	**520**
BARN OPERATIONS	
Fuel	146
Electricity	146
Total barn operation	291
TOTAL ENERGY USE	**1,649**
Bioenergy Credit	Displaced emissions (kt)
Straw	963

Source: Author's calculations.

Table 2.4 | Total Net Annual Production Emissions

TOTAL PRODUCTION EMISSIONS	KT CO_2E
Total domestic PEMs, excluding energy and soil carbon credit	16,035
Total import PEMs	1,347
Total energy use	1,649
Total bioenergy and soil carbon credit	-1,477
Total net domestic production emissions	17,554

Notes: Nitrogen fertilizer production emissions (PEM) are mainly energy emissions of carbon dioxide, but they also include a small amount of nitrous oxide emitted for production of synthetic fertilizer. Energy emissions used to produce imported feed are included with imported feed. Bioenergy is the credit for fossil fuel emissions displaced by straw. This number includes manure management emissions for livestock other than dairy and pork, which are left out of other figures & tables due to changes in the mink industry.

Source: Author's calculations; imports based on GlobAgri-WRR model.

Table 2.3 includes the emissions attributable to energy use for production that occurs in Denmark (excluding those for imported feed counted in Table 2.2), and these sources add 1.64 million tons of emissions per year.

We also factor in an offset for “bioenergy” use from straw. The agriculture sector produces straw as a by-product mostly of cereal production, which is harvested for energy. This straw is primarily used for district heating facilities to supply residential heat. If this straw replaces natural gas, we estimate that it reduces emissions from fossil fuel use by 0.96 million tons of CO_2e. (As articulated below in our discussion of bioenergy, we assign this full credit to agriculture today because using biomass rather than fossil fuels does not require major spending in the energy sector, although this approach changes by 2050.) Overall, the net life-cycle production emissions of imported feed, energy use, and bioenergy credits add 2 million tons CO_2e to overall emissions.

Our total life-cycle emissions for the Danish agriculture production processes add these emissions to the NIR emissions, reaching a total of roughly 17.4 million tons (Table 2.4).

Greenhouse Gas Costs of Denmark's Land Carbon Footprint

The single-largest greenhouse gas cost of agriculture, the increase in carbon in the atmosphere, results from the reduced storage of carbon in forests, wetlands, and grasslands due to conversion of land to agricultural use. This cost can be thought of as agriculture's "land carbon footprint." Agriculture occupies almost half of global vegetated land—land other than ice or desert—and the conversion to agriculture from forests, woody savannas, wetlands, and grasslands is likely responsible for one-third of the added carbon in the atmosphere (Ciais et al. 2013; Arneth et al. 2017). This footprint is an ongoing cost of agricultural activity because if agriculture did not occupy this land, it could revert to forest and other natural vegetation and sequester carbon.

Agriculture is also continuing to expand, with the resulting conversions of forests and savannas responsible for roughly 4 billion tons (gigatons) of carbon dioxide emissions each year according to common estimates (Searchinger et al. 2019). Because of a rising and increasingly affluent global population, most models estimate that the world will convert hundreds of millions of additional hectares of forests and woody savannas to agricultural use by 2050. Yet most climate strategies require not just quickly eliminating deforestation but also reducing agricultural land area to reforest land or otherwise sequester carbon.

Unfortunately, global land area is fixed. Avoiding additional land use change emissions therefore requires that agriculture freeze its global land carbon footprint, and sequestering more carbon requires that it reduce that footprint. That includes increasing crop yields and meat and milk output per hectare, as well as equitably holding down the growth in demand. Only by doing so is it possible to avoid clearing more land and make more land available for reforestation.

There is broad agreement about the importance of land use change emissions and the need to freeze and then reduce agricultural land area, but there is confusion about how these needs should be reflected in life-cycle calculations of food consumption or production. We believe there is at least one simple principle: *Because reducing the need for more agricultural land is critical to climate strategies, any method for evaluating the greenhouse gas consequences of food production must recognize and reward increases in yield and overall land use efficiency*. (For the same reason, any proper life-cycle analysis of changes in food consumption, such as shifts in diet or reductions in food loss and waste, must also recognize changes in consumption that reduce or increase land use requirements.) If accounting methods fail to do so, they will not only fail to encourage these necessary efforts to spare land, but they may discourage them.

Our accounting method is based on the basic idea that land used for agriculture has a carbon opportunity cost; in other words, the land itself has a carbon value and its use therefore has a cost. Increasing yields has a value because doing so avoids the need to clear more land while meeting the same food needs; decreasing production has a cost, because it requires that land be cleared elsewhere to meet the same food needs. Other typical methods do not properly reward changes in production that reduce demands for global land. Some may even reward changes that increase demands for global land. Because our treatment of land is critical to our analysis of a carbon neutral strategy, we describe our approach and how it differs from others in some detail in this section.

A. Limitations of other land use accounting methods

Life-cycle calculations for agricultural production have employed a variety of methods for addressing land use that we believe in different ways fail to account for its significance.

- *Ignore land use*. One basic method of many LCAs is to identify hectares of land used but not attribute greenhouse gas emissions to them, so the LCA only counts emissions from the production process. This approach provides no incentive to increase yields. It can also encourage changes in management that greatly reduce yields and therefore increase agricultural areas required to meet food needs so long as production emissions decline even a little. To illustrate with an extreme example, if a farm reduces emissions per kg of wheat even

a little, this method will treat that change as beneficial for climate even if that would cause yields to decline by half.

- *Count land use change emissions only if a crop is produced on newly cleared land*. This method, known as direct land use change, has the same limitations. So long as a farm does not clear land, it is rewarded for reducing emissions at the expense of yields and is not recognized for increasing yields, or, in the case of a livestock farm, of reducing feed demands.
- *Count land use change if a crop is expanding and produced in a country that is expanding agricultural land*. This method, for example, would assign no or few greenhouse gas emissions to a pork operation that purchased soybeans from the United States but would assign larger emissions to feed purchased from Brazil, where both soybeans and agricultural land overall are expanding. This approach recognizes properly that increased soybean demand can encourage agricultural expansion even if soybeans are only replacing grazing or other crops, which in turn are pushed into forest. But it rewards a farm for just shifting purchases from one country to another, for example, from Brazil to the United States. That is true even though the total demand for agricultural products does not change and it is likely that the first country's crops will just be sold to another. In addition, so long as a farm avoids purchasing soybeans or another crop from an offending country, the farm has the same flawed incentives as with other methods: It receives no incentive to boost yields and can be rewarded for decreasing them.

  To summarize the limitation of all these methods, none provides any incentive to farms to decrease their overall land use footprint or to increase overall land use efficiency. In fact, each method can encourage the opposite. For example, soybeans are used for animal feed rather than pulses such as lentils because soybean yields globally are roughly three times those of typical pulses. In part for that reason, pulses are not expanding. According to these accounting methods, however, switching from soybeans to pulses would count as a greenhouse gas reduction even though doing so would require three additional hectares of land in most pulses for each hectare saved from soybeans.
- *Use economic models to estimate indirect land use change or leakage*. This method uses economic models to estimate how changes in production on one piece of land alter global land use change. For example, if Denmark were to decrease production by taking some wheat land out of production, this method would estimate how much land would be cleared elsewhere to replace the wheat and what the resulting carbon emissions would be.

  One problem with this approach is that the analysis requires vast numbers of estimates of economic relationships. All have high uncertainties and most have not been, and could not be, estimated well econometrically, if only because of insufficient data.

  A more fundamental problem is that this approach rewards changes that are counter to public policy. For example, if Denmark reduced its wheat area, the model might estimate that a slight increase in global wheat prices would cause global food consumption to decline. (Such estimates of changed food consumption are in fact prominent in many models of this kind [Searchinger et al. 2015a; Hertel et al. 2010].) This reduced consumption avoids land use change and emissions but at the cost of higher food prices and often consumption by the poor. Yet countries like Denmark, and agricultural industries like the Danish industry, are actively trying to increase agricultural productivity in part to make sure the world is well-fed. It would be contradictory for Denmark to pursue such policies because they will increase prices and reduce food consumption while seeking to do the opposite.

These market-induced changes are also avoidable. For example, shifting consumption of beef to almost any other food would reduce the demand for agricultural land. However, if people in Denmark reduced their beef consumption, the global price would decline and other people would consume at least a little more, offsetting some of the benefits. These "rebound effects" can be avoided by other pricing policies to provide incentives to avoid increasing beef consumption elsewhere.

This potential rebound effect can apply to use of oil and other products. If one person drives an inefficient car and uses more oil as a result, the price of oil will increase just a little and other people will consume less (Anson and Turner 2009). But we do not typically say, therefore, that people who consume oil are responsible only for two-thirds of the emissions from that oil. Conversely, if people consume a liter less oil, it is not common to still assign them emissions for one-third of that oil anyway because other people will consume more. It is useful to know these potential consequences, but public policy can eliminate these price effects on others, and it is generally unreasonable to blame or reward people for the consumption choices of others.

(Sometimes the use of economic models is justified as a "consequential" life-cycle approach. Appendix C discusses the significance of the terms *attributional* versus *consequential* in reference to life-cycle analyses.)

B. Measuring the land carbon footprint through "carbon opportunity costs"

Our approach builds on a paper in the journal *Nature* in 2018, which relies on the simple idea that all agricultural uses of land have a carbon cost because using land for agriculture typically reduces the carbon that is stored on the land (Searchinger et al. 2018). If this land were not used for agriculture, it would, or at least could, be used to store carbon. In this way, land is conceptually the same as fertilizer or any other productive inputs: its use has a cost. The carbon opportunity cost for a country is the carbon lost from clearing native vegetation and soils on the agricultural land used by that country.

Of course, all agriculture does and must use land. Viewed this way, there is no way to have carbon-free food: if the world did not produce and eat food, it would restore vast areas of forests and native grazing lands and store vast quantities of carbon. Because the world needs food, the goal cannot be to eliminate all agricultural land use. But it is also true that if the world can avoid converting more land for agriculture, it will not be adding more carbon to the atmosphere (even though the carbon added to the air from previous land clearing remains). Land area carbon neutrality for a group of farmers, such

> Land area carbon neutrality for a group of farmers, such as Danish farmers . . . means that they do their part to avoid expanding agriculture's global carbon footprint.

as Danish farmers, therefore, means that they do their part to avoid expanding agriculture's global carbon footprint.

To do that, the world must increase agricultural land use efficiency, the output per hectare, at a level that matches the increase in food production. For example, if the world produces 45 percent more food, then land area carbon neutrality requires that agriculture produce 45 percent more food on the same land. If agricultural land use efficiency increases even more than the production increase, in this example more than 45 percent, then land can be restored on a net basis and sequester carbon, creating offsets against other emissions.

We first estimate Danish agriculture's land carbon footprint by measuring the absolute carbon lost from converting Denmark's native vegetation (overwhelmingly forest) to roughly 2.6 million hectares of agricultural land.

Denmark also imports feed, which has its own land-use footprint. However, for imported feed, it is not clear which precise lands the feed comes from or whether that matters. We calculate the land use carbon cost of this feed by estimating the average carbon lost to produce each kg of feed that Denmark imports. We do this one way using a global average carbon loss and another using European regional carbon losses. (In each case, we also annualize this cost.) We call these costs carbon opportunity costs (COCs). For this project, we are using an average of these regional and global carbon opportunity costs for feed imports.

The combination of Denmark's domestic carbon opportunity costs and imported feed carbon opportunity costs equals Denmark's total carbon opportunity costs. These total costs are Denmark's land carbon footprint.

Counting these carbon opportunity costs requires some judgment about time. When land is cleared to produce more food, the carbon loss occurs mostly right away, typically with the burning of vegetation, while soil carbon losses continue to occur over several years. Yet in theory the food production on that land could continue indefinitely. Over hundreds of years, the carbon cost per kg of a food would be very small. But the world does not have hundreds of years to solve climate change; it needs to reduce emissions quickly. (That is why LF has pledged to go carbon neutral by 2050 and why the Danish government has pledged 70 percent reductions by 2030.) That is why when governments have factored in the cost of converting land for biofuels, they have decided to amortize those emissions over 20 or 30 years, which means they factor in the net effect on carbon in the atmosphere after 20 or 30 years.

In this report, and in the calculation of carbon opportunity costs, we use a method similar to amortizing but that instead applies a discount rate to the loss of carbon. Amortizing emissions makes a judgment about the value of reducing emissions in a certain time period. Time discounting does the same but in a more rigorous fashion. An earlier emission costs more than a later emission, and earlier mitigation is therefore worth more. In this report, we use a 4 percent discount rate—in part for theoretical reasons and in part because its result is similar to 30-year amortization.[8] The carbon opportunity costs assigned to agriculture each year are therefore a fraction of the total carbon lost to clear land to produce that year's food—very roughly around 1/30th of that carbon loss.

In the end, our choice of discount rate is only significant for limited purposes. We ultimately estimate the changes in land use efficiency such as increasing crop yields that are necessary to meet targets for more global food in the future without clearing more land. We also estimate the changes necessary to go beyond that and free up land for reforestation. On that reforested land, we then count the actual carbon that will be absorbed each year as an offset for remaining production emissions. As a result, changing the discount rate would not greatly change our ultimate results.

What carbon opportunity costs add is a method of comparing what otherwise seem like apples and oranges. For example, if land producing wheat were to be turned into willows to produce biofuels, it calculates the amount of carbon that would on average be lost to replace the wheat elsewhere and therefore the opportunity to continue to store that


30

carbon elsewhere if wheat production continued instead. For this purpose, the choice of discount rate could make a difference, just as amortizing conversion of land over 60 years instead of 30 years would change biofuel calculations. The carbon opportunity cost also provides a way of calculating in one number the increased demand for many different kinds of foods.

These carbon opportunity costs are true carbon costs of agriculture. They are roughly equivalent also to the amount of carbon the world could store each year for decades on the land that could be reforested if the agriculture somehow disappeared.[9] Yet these costs (and benefits) are hidden from most traditional carbon accounting, including national emissions inventory reports. Those reports do not count an opportunity cost for land in the form of the carbon that could be gained on agricultural land if reforested. They also do not count the carbon lost from native forests because those losses and therefore emissions occurred in the past. This approach makes sense for national inventories. The purpose of the national inventory approach is to estimate global changes in emissions each year, not the ongoing opportunity cost of continuing to use agricultural land. However, this national inventory method does not make sense for evaluating the ongoing, global consequences of Denmark's agricultural production.

To summarize, we estimate a baseline land carbon footprint for Danish agriculture using carbon opportunity costs. To avoid further emissions from deforestation and other land use change globally, the world must increase its land use efficiency enough to match global increases in production. To avoid assigning emissions for land use change to Danish agriculture, we believe Denmark should make its equal contribution to that effort. If Denmark can increase its own agricultural land use efficiency at the globally necessary rate, it is land area carbon neutral. If it does more, it can reforest land and agriculture can claim credit for the carbon sequestered.

C. Denmark's land carbon footprint

Tables 2.5, 2.6, and 2.7 present our estimate of Denmark's land carbon footprint measured in carbon opportunity costs. The annual land use cost for Danish agriculture is roughly 48 million tons of CO_2 (Table 2.7). That includes roughly 36 million tons within Denmark (the total domestic discounted annual carbon loss shown in Table 2.5). It also includes 12 million tons outside of Denmark to produce imported feed as measured by the average of global and regional carbon opportunity costs for each type of feed.[10] These COCs represent the cost of using roughly 2.6 million hectares of land for agriculture within Denmark and roughly 700,000 hectares outside of Denmark to produce feed imported into Denmark. This 48-million-ton annual number is almost three times the annual production emissions.

Table 2.5 | Denmark's Domestic Annual Land Carbon Footprint

LAND TYPE	CARBON LOSS (MILLION TONS CO_2)	DISCOUNTED, ANNUAL CARBON LOSS (MILLION TONS CO_2)
Cropland (including annual fodder)	1,189	34
Permanent grassland	82	2.3
TOTAL DOMESTIC	**1,272**	**36.3**

Source: Author's calculations.

Table 2.6 | Denmark's Imported Feed Annual Land Carbon Footprint

CROP	GLOBAL LAND USE (MT CO_2)	REGIONAL LAND USE (MT CO_2)	AVERAGE (MT CO_2)	QUANTITY (KILOTONS FRESH WEIGHT)
Wheat	0.17	0.20	0.19	151.3
Maize	0.28	0.20	0.24	284.3
Soy cakes	8.34	7.07	7.70	520.3
Sunflower cakes	1.02	1.34	1.18	
Rapeseed cakes	0.86	0.67	0.77	220.3
Beets	0.99	1.06	1.03	1,558.3
Remainder	0.52	0.59	0.55	367.7
TOTAL IMPORT CARBON OPPORTUNITY COSTS	**12.18**	**11.13**	**11.66**	

Notes: PEM = production emissions; kt = 1,000 tons.

Source: Authors' calculations using production emissions from GlobAgri-WRR model.

Table 2.7 | Total Annual Land Carbon Footprint for Both Domestic Agricultural Land and Imported Feeds

	TOTAL CARBON OPPORTUNITY COSTS
Global	45.78
Regional	44.73
Average	45.26

Source: Author's calculations.

PART 3

Benchmarking Danish Agriculture and Analyzing Potential Consequences of Reducing Denmark's Production

A useful starting point to inform a carbon neutral strategy is to determine where Danish agricultural production lies in comparison with other major global producers.

This information also makes it possible to assess whether reducing Denmark's agricultural production would likely decrease or increase global emissions. We focus on pork and dairy, which are responsible for the great majority of Danish emissions. Wirsenius et al. (2020) provides a fuller discussion of these results and the model and data used to generate them.

Comparison of Danish Pork and Dairy Industries with Several Other Major Agricultural Countries

To compare pork and dairy emissions, we refined the "ClimAg" life-cycle model developed by one of our authors (Wirsenius et al. 2020) and used it to estimate emissions of average dairy production in 13 countries and average pork production in 11. A life-cycle GHG model estimates the emissions attributable to pork or dairy production from all stages of the production process, including the production of feed and the fertilizer used to generate that feed. For this analysis, as in the rest of the report, the emissions end at the "farm gate" and so do not count subsequent processing or retail. ClimAg has all the categories of any good life-cycle analysis and has several advantages. First, as a new product, it uses some more recent data and reflects changes in estimates of agricultural emission factors. Second, the core ClimAg model builds in a range of biophysical relationships that help to ensure the consistency of data assumptions as well as to fill in for some missing data. The most important relationships are those between quantities of feed, number of animals, and the production of milk and meat. Third, the model incorporates land using carbon opportunity costs, which is a major change compared with nearly all other LCAs.

These calculations have many uncertainties because agricultural emissions, unlike energy emissions, are not easily measured. Uncertainties include substantial limitations on data as well as uncertainties related to emission factors, such as the methane emissions attributable to a manure storage facility of a specific type under different weather conditions. In this analysis, we use emission factors reported by the countries where available, which may not be entirely consistent because of different local judgments. In addition, each farm is different, and the numbers we calculate are based on the construction of a national average farm based on such factors as average feed per animal or average manure management methods. Despite these uncertainties, the emissions estimate is so heavily influenced by the quantity of feed required to produce a kg of milk or pork that we consider the estimate useful. Yet because of these uncertainties, we consider relatively small differences in country performance unreliable. We accordingly group countries into similar tiers and believe countries within each tier should be treated as equal.

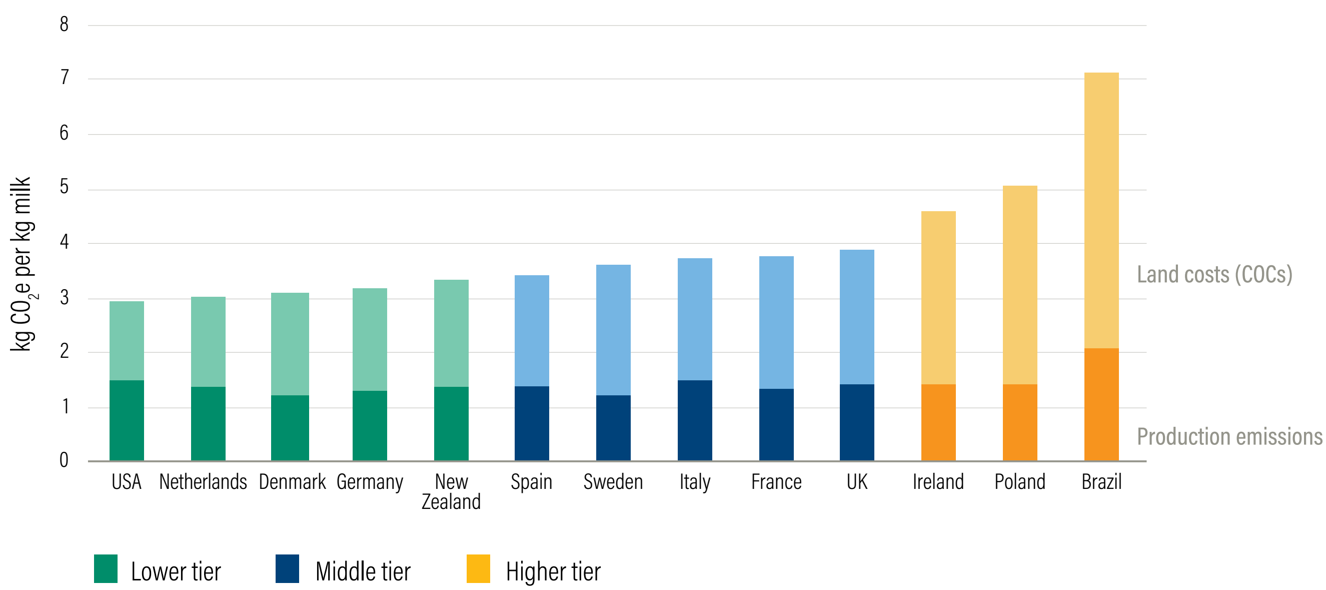
Tables 3.1 and 3.2 and Figures 3.1 and 3.2 show our results for the different production emissions, land use COCs, and total GHGs.

Table 3.1 | Emissions for Dairy by Country and Emissions Category

DAIRY	KG DM/ KG MILK	KG CO_2E/ KG MILK	KG CO_2E/ KG MILK	KG CO_2E/KG MILK	KG CO_2E/ KG MILK	KG CO_2E/KG MILK	KG CO_2E/ KG MILK	KG CO_2E/KG MILK	KG CO_2E/KG MILK	KG CO_2E/ KG MILK	
COUNTRY	FEED CONVERSION EFFICIENCY	ENTERIC	FORAGE N (EXCEPT MANURE)	FEED CONCENTRATE PRODUCTION EMISSIONS (PEM)	MANURE ON PASTURE	MANAGED MANURE APPLIED TO CROPLAND	ON-FARM ENERGY USE	MANURE MANAGEMENT	TOTAL PRODUCTION EMISSIONS (PEM)	LAND COST (COC)	TOTAL EMISSIONS (PEM+COC)
Denmark	1.00	0.56	0.07	0.14	0.00	0.03	0.10	0.32	**1.22**	**1.89**	**3.11**
Brazil	2.83	1.49	0.39	0.07	0.13	0.00	0.00	0.01	**2.08**	**5.05**	**7.13**
France	1.27	0.71	0.10	0.14	0.01	0.02	0.08	0.28	**1.34**	**2.43**	**3.77**
Germany	1.10	0.63	0.07	0.12	0.01	0.02	0.14	0.30	**1.30**	**1.88**	**3.17**
Ireland	1.37	0.77	0.12	0.09	0.04	0.01	0.12	0.29	**1.44**	**3.14**	**4.58**
Italy	1.25	0.70	0.09	0.12	0.01	0.02	0.15	0.42	**1.50**	**2.22**	**3.72**
Netherlands	0.99	0.56	0.08	0.12	0.01	0.02	0.12	0.46	**1.37**	**1.65**	**3.02**
New Zealand	1.59	0.87	0.13	0.05	0.09	0.00	0.02	0.24	**1.40**	**1.95**	**3.35**
Poland	1.31	0.75	0.10	0.10	0.01	0.02	0.23	0.22	**1.44**	**3.64**	**5.08**
Spain	1.07	0.60	0.08	0.14	0.00	0.01	0.11	0.42	**1.37**	**2.06**	**3.44**
Sweden	1.06	0.60	0.09	0.14	0.01	0.02	0.07	0.30	**1.21**	**2.39**	**3.61**
UK	1.01	0.59	0.09	0.13	0.01	0.01	0.14	0.43	**1.40**	**2.48**	**3.88**
USA	0.88	0.50	0.06	0.10	0.00	0.01	0.12	0.69	**1.49**	**1.47**	**2.96**

Source: Authors' calculations as first presented in Wirsenius et al. (2020).

Figure 3.1 | Dairy Production and Land Use Emissions by Country by Tier



Note: Because of many data uncertainties in these calculations, countries within each tier should be considered to be equal (with the likely exception of Brazil).

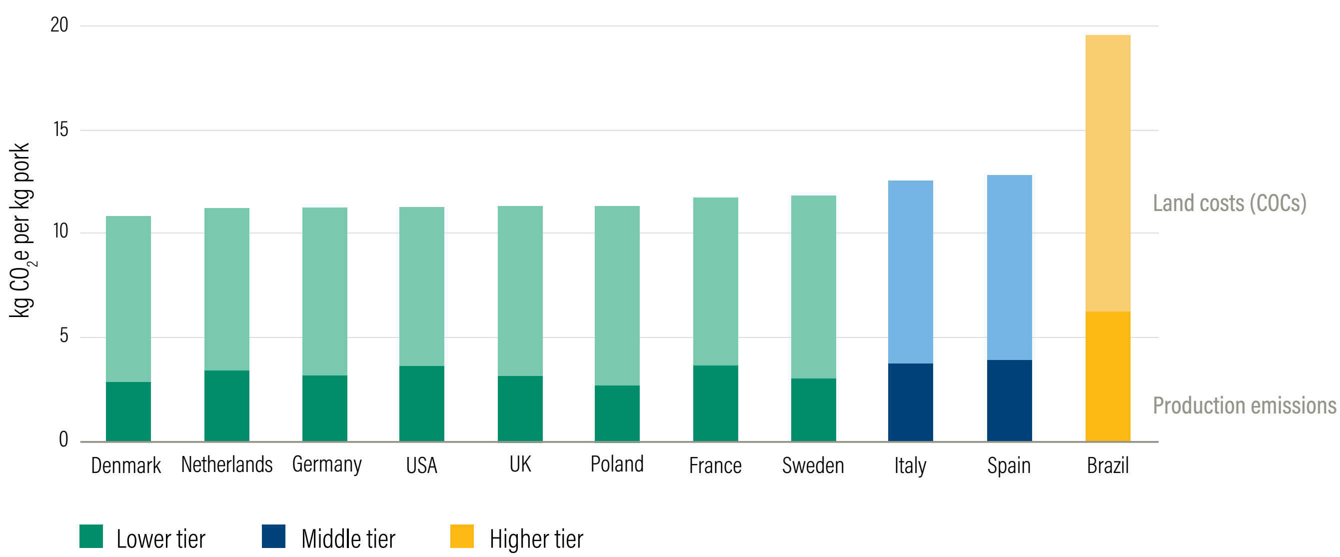
Source: Authors calculations as first presented in Wirsenius et al. (2020).

Table 3.2 | Pork Emissions by Category and Totals across Countries

		PRODUCTION EMISSIONS					LAND COST	TOTAL EMISSIONS
	KG DM/KG MEAT	KG CO_2E/KG MEAT	KG CO_2E/KG MEAT	KG CO_2E/KG MEAT	KG CO_2E/KG MEAT	KG CO_2E/KG MEAT	KG CO_2E/KG MEAT	KG CO_2E/KG MEAT
COUNTRY	FEED CONVERSION EFFICIENCY	ENTERIC	MANURE MANAGEMENT	ON-FARM ENERGY USE	FEED CONCENTRATE PRODUCTION EMISSIONS (PEM)	TOTAL PRODUCTION EMISSIONS (PEM)	LAND COST (COC)	TOTAL EMISSIONS (PEM+COC)
Denmark	3.03	0.25	0.91	0.12	1.61	**2.89**	**7.91**	**10.80**
Brazil	4.25	0.35	3.68	0.09	2.17	**6.28**	**13.22**	**19.51**
France	3.17	0.26	1.73	0.07	1.61	**3.67**	**8.10**	**11.77**
Germany	3.09	0.26	1.21	0.15	1.56	**3.17**	**8.07**	**11.24**
Italy	3.34	0.28	1.88	0.09	1.51	**3.75**	**8.78**	**12.53**
Netherlands	3.03	0.25	1.49	0.14	1.51	**3.39**	**7.84**	**11.23**
Poland	3.21	0.27	0.75	0.22	1.58	**2.81**	**8.58**	**11.39**
Spain	3.40	0.28	1.97	0.12	1.63	**4.00**	**8.83**	**12.83**
Sweden	3.41	0.28	0.93	0.06	1.77	**3.04**	**8.77**	**11.81**
UK	3.22	0.26	1.11	0.17	1.70	**3.24**	**8.13**	**11.37**
USA	3.21	0.27	2.01	0.15	1.28	**3.70**	**7.63**	**11.33**

Source: Authors' calculations as first presented in Wirsenius et al. (2020).

Figure 3.2 | Pork Emissions per Kilogram of Pork by Country by Tier



Note: Because of many data uncertainties in these calculations, countries within each tier should be considered to be equal (with the likely exception of Brazil).

Source: Authors calculations as first presented in Wirsenius et al. (2020).

Our results include the following highlights:

- *Denmark is in the best-performing of the three tiers*. According to our estimate details, Denmark is lowest among pork producers and is fourth-lowest among dairy producers, but because the differences are very small and the uncertainties are substantial, emissions among all countries in this top tier should be considered equivalent. Despite a variety of uncertainties, Denmark's ranking in the top tier results makes sense for two critical reasons. First and foremost, Denmark has high feed efficiency for both pork and dairy—in other words, the quantity of feed needed to produce a kg of pork or dairy is relatively low. Second, the country's cooler temperatures hold down manure management emissions.
- *Differences among agricultural advanced countries are mostly not large*. Although Denmark ranks well, another major result is that the differences in emission intensity among advanced agricultural countries are not great. For concentrated dairy operations in seven different countries, the emissions vary by at most 25 percent. Pork production is even more similar because the basic feed rations are similar with similar feed conversion efficiencies. For pork production, in each country other than Brazil, the maximum variation in emissions is 15 percent, and eight countries vary by at most 8 percent.
- *The differences we find are much lower than those identified in two prior European studies* (Weiss and Leip 2012; Lesschen et al. 2011). We are unsure of all the reasons, but an important one is our method of analyzing land use costs. It is based on the overall land area required to produce the milk or pork and that only varies so much. Other studies can vary emissions based on just where the feed originates. For example, some analyses assign emissions from land-use change only to soybeans from Latin America. As a result, different countries can have very different emissions based only on the differences in countries that supply the soybeans.
- *Land use is the predominant GHG cost*. We find that carbon opportunity costs, with some exceptions, tend to range roughly from 1.5 to 2 times the production emissions for dairy and from 2 to 3 times the production emissions for pork. These figures are much higher than land use costs measured in other estimates, which use different methods, and they highlight the importance of limiting land requirements to achieve GHG goals.
- *Feed efficiency is a key factor that influences emissions*. Feed efficiency heavily influences the land required, the nitrogen used to produce that feed, the enteric methane generated, and the quantities of manure and therefore emissions it generates.
- *For production emissions, temperature and manure management systems play a significant role because they help to determine the quantities of methane emitted from manure storage*. European countries have higher manure management emissions the farther south they are located. The United States also has high manure management emissions because of its use of large lagoons, big earthen ponds, to store manure.
- *Increased reliance on grazing makes it harder but not impossible to have low dairy emissions*. In dairy systems, the big contrasts are between systems that rely on concentrated feeds and many that rely more heavily on grazing. Although grazing systems have less

Reducing Danish livestock production . . . is unlikely to reduce global emissions because replacing the food elsewhere would likely generate higher emissions.

soil erosion, require fewer pesticides, and can improve animal welfare, they typically have higher emissions because they typically have lower feed efficiency. That occurs mainly because grains and oilseed meals are more digestible than nearly all pasture grasses, which compensates for more emissions in producing crops. As other LCAs have also found, the more confined systems tend to have lower emissions than those that use more grazing. Brazil is an extreme example of high emissions with more grazing. New Zealand, however, shows that it is possible to be in the lowest tier with intensively managed grazing.

- *Adjusting for the export or import of young pigs is critical for an accurate analysis.* Some countries export large quantities of young pigs, called weaners, which are fattened elsewhere; in turn, some countries import large quantities of weaners. Denmark and the Netherlands are large exporters, and Germany and Poland are large importers. Producing a 25 kg weaner requires more feed and generates more emissions than increasing the weight of a purchased weaner by 25 kg. This difference occurs because in addition to the feed that is nourishing the young pig, there must also be feed for the mother sow. This difference means that just measuring the emissions from pork production by the weight of the pigs sold can be misleading. A country that imports many weaners can appear to have lower emissions, even if it is an inefficient pork producer, than a more efficient country that produces its own weaners or exports weaners. (In the same way, an electric car company that buys batteries from others could appear to be more climate efficient than a car company that makes its own batteries because producing batteries is an energy-intensive part of production process.)

Our analysis controls for this distinction in determining the efficiency of production by examining the emissions assuming each country produces its own weaners. If we counted Denmark's export of weaners just by their weight, its emissions per kg of pork would rise roughly 25 percent to more than 13.5 kg CO_2/kg pork. That would be substantially higher than all other country results we have calculated, except for Brazil. Similarly, Germany's emissions would appear much lower. When we count Denmark's total agricultural emissions, we do include emissions from its production and export of weaners, but to evaluate the efficiency of Denmark's production per kg of output, it is important to control for this export of weaners.

- *Yields of forage grasses also matter for dairy.* Forage grasses are a sizable portion of dairy feed and their yields help determine their carbon opportunity costs. Because the carbon opportunity cost divides the carbon loss on a typical hectare of land by the yield of the crop or forage, the lower the forage yield, the higher its carbon opportunity cost. Among more concentrated systems, Poland stands out, with COCs 50 percent to almost double those of other European countries. One reason is a relatively low milk yield per cow and a high percentage of grass in the share of feeds. But another reason is low yields from forage grasses. The yield of 4.4 tons of dry matter per hectare per year is roughly half of the grass forage yields in Denmark and only a little more than one-third of the maize silage yields.

We draw three policy conclusions from these results.

First, these results suggest that reducing Danish livestock production just to reduce Denmark's reported GHG emissions is unlikely to reduce global emissions because replacing the food elsewhere would likely generate higher emissions.

Second, because the differences with other advanced countries are not large, the environmental argument for a strong Danish agriculture sector would greatly increase if Denmark's agriculture could become carbon neutral.

Third, because there are no clear examples of better performance, reducing Denmark's GHGs will require that the dairy and pork sectors employ a variety of innovative management practices to become carbon neutral.

Modeling a Reduction in Denmark's Agricultural Production

Under the accounting systems of both the European Union and those used by most countries to report emissions to the United Nations, Denmark could reduce its emissions by reducing agricultural production. To explore the possible global consequences, we used the GlobAgri-WRR model to estimate the global greenhouse gas consequences if Denmark reduced its food exports by 50 percent in 2050 from what they are otherwise likely to be in that year. The GlobAgri-WRR model uses current trade patterns, and Denmark's loss of exports would have to be made up by increasing exports from other countries. We assumed that Denmark's exports would be replaced not from elsewhere in the European Union but rather from other countries.

These results also estimate that reducing Danish production would increase global emissions. As Table 3.3 shows, to fully replace this food, this 50 percent cut in exports compared with our "business as usual" 2050 scenario would lead to an increase in global production emissions by 1.7 million tons (CO_2e), roughly a 10 percent increase over Denmark's present emissions. More significant, doing so would require the release of an annual level of emissions of more than 15 million tons from additional land use (almost equal to Denmark's present production emissions). Global cropland would expand a little, but most of the expansion would occur from grazing land.

Table 3.3 | Estimated Change in Global Emissions Due to 50 Percent Decrease in Danish Agricultural Exports if Replaced Outside of Europe

DANISH EXPORT REDUCTION	INCREASE IN PRODUCTION EMISSIONS (MILLION TONS CO_2E)	ANNUAL INCREASE IN CARBON OPPORTUNITY COSTS (MILLION TONS CO_2E)
50%	1.7	15

Source: GlobAgri-WRR.

To avoid causing more emissions abroad, some have suggested that Denmark focus on reducing its consumption of meat and milk and then also reduce its production (Prag and Henriksen 2020). Although we strongly support efforts to reduce meat and milk consumption, the benefits from these reductions occur independently of whether Denmark itself then reduces food production. As Box 3.1 discusses, regardless of the success of such efforts, the climate effects of reducing Denmark's production are still based on the consequences of producing less food in Denmark and more food abroad, and such a shift is not beneficial.

BOX 3.1 | What Role Should Reductions in Danish Food Consumption Play in Strategies to Reduce Danish Agricultural Emissions?

Many previous studies, including *Creating a Sustainable Food Future*, have found that reducing food consumption through diet shifts and reducing food loss and waste plays a critical role in meeting future food demands with acceptable emissions and without deforestation (Searchinger et al. 2019; Springmann et al. 2016). As explained in Box 1.1, people in Denmark eat large quantities of animal products and are among those who should reduce consumption. Based on these benefits, others have argued that the way to reduce emissions from Danish agriculture is for Danes to reduce their meat and milk consumption and then for Danish agriculture to produce less (Prag and Henrickson 2020). We agree on the need to reduce consumption but do not agree that doing so is a reason for Danish agriculture to produce less food for four reasons.

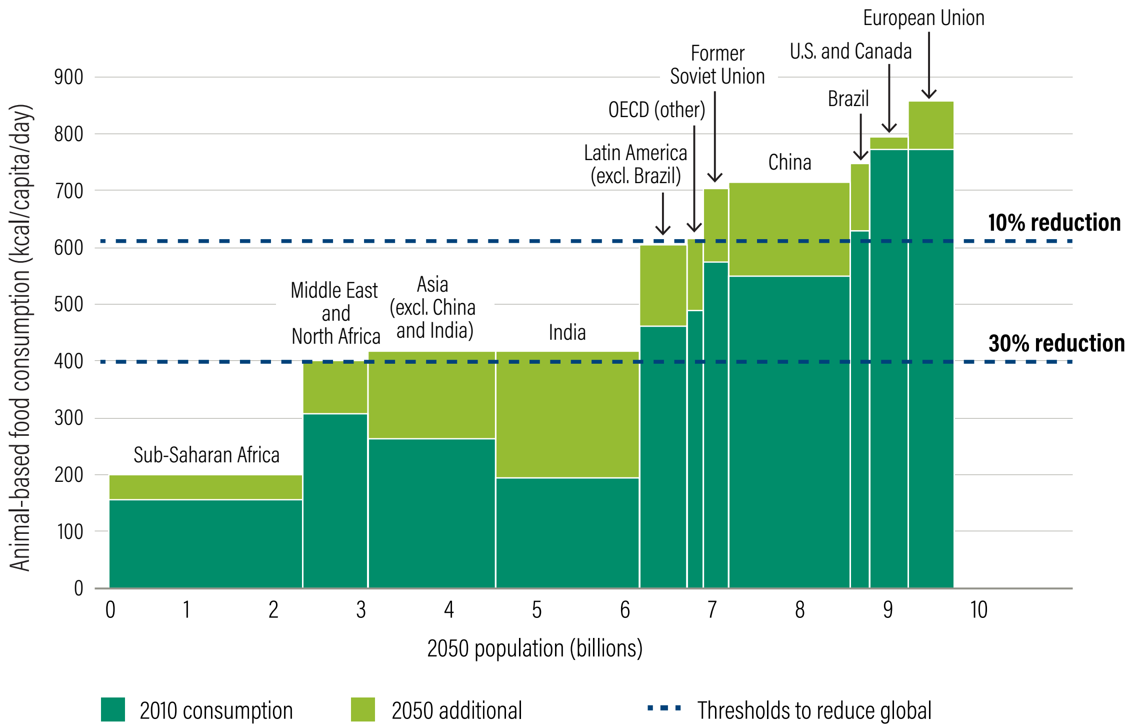
First, Denmark exports roughly 90 percent of its pork and 50 percent of its dairy. For pork, there is little correlation even now between how much Denmark consumes and how much it produces. For dairy, there is little reason to believe that Denmark could not export any extra production not consumed in Denmark.

Second, changing meat and milk *consumption* in Denmark does not alter the benefits or costs of changing Denmark's production. So long as there is still demand for meat and milk in the world, it is not helpful to climate change to reduce meat and milk production where that production is climate-efficient. Doing so will mainly just shift production to where it is less efficient. The same principle applies to cars. The world needs to drive less, but decreasing production of efficient cars from one factory, such as a plant that builds hybrids, will mostly just shift production to other factories making less efficient cars. Put another way, we need strategies both to reduce consumption of meat and milk and to make production more efficient, and they should be considered as being separate.

Third, we foresee little prospect at this time that the world will consume less pork and dairy, even if the world's large meat consumers eat less. That is because the vast majority of people in the world now eat very few animal products but are likely to eat and have an equitable right to eat more. Figure B3.1 shows projected 70 percent increases in meat and dairy consumption by 2050 relative to 2010, but even so, 6 billion people will still likely eat half or fewer animal products than a typical European today. Two billion people will eat less than 25 percent of the animal products eaten by the average European. Even if the world's wealthy held their consumption to less than half of present European levels (showed by the 30 percent reduction dotted line), global consumption would increase. Even larger reductions by the wealthy would be necessary just to create global space for 2 billion more people to consume half of present European levels. In addition, growth in global dairy and pork production has continued at a high rate in recent years and shows no sign of declining (with the exception of a decline due to swine flu in China in 2019) (Figure B3.2).

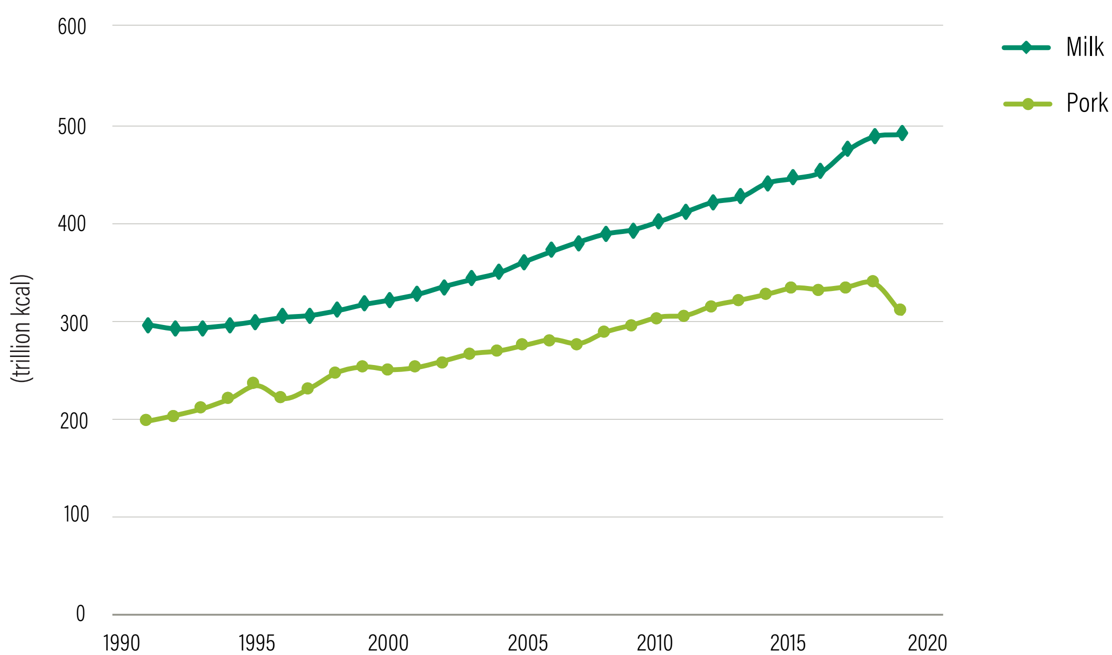
Finally, from a greenhouse gas perspective, the highest priority should be placed on holding down the growth in consumption of beef and other ruminant meats. As we found in *Creating a Sustainable Food Future*, and as others have shown as well, the emissions for beef, lamb, and goat meat are in the range of 5 times those of dairy and 10 times those of pork. For any person reducing meat consumption by 1 kg, the best greenhouse gas results therefore occur if that reduction occurs of beef. In Denmark, the overwhelming production is of pork and dairy.

FIGURE B3.1 | GLOBAL MEAT AND DAIRY CONSUMPTION BY REGION 2010 AND PROJECTED 2050



Source: Searchinger et al. (2018).

FIGURE B3.2 | GLOBAL CONSUMPTION OF MILK AND PORK BY YEAR



Source: FAOSTAT (2021).

PART 4

Mitigation of Production Emissions

How can Danish agriculture reduce its emissions and achieve climate neutrality? This part of our report examines ways of reducing production emissions.

Part 5 discusses ways of achieving land area carbon neutrality and potentially reducing Denmark's land carbon footprint sufficiently to reforest lands as offsets for remaining production emissions. Part 6 explores bioenergy and soil carbon, which also provide offsets, but which we do not believe are likely to increase in excess of current levels. Part 7 then puts the pieces together and offers recommendations for moving forward.

Our emissions reduction estimates calculate emissions in the same way, and using the same life-cycle approach, as our emission estimates in Part 2. Both because of this life-cycle approach and the use of carbon opportunity costs, these estimates do not always equal emissions as estimated in conventional ways by the United Nations or European Union. In general, with UN and EU rules, Danish emissions count only the direct production emissions that occur in Denmark, plus the direct changes in land-based carbon in Denmark only (including losses from degrading peatland soils). Accordingly, only mitigating these emissions count as reductions. Our approach differs. In Part 7 we include some discussion of the resulting perverse incentives of international accounting rules and reasons Denmark should seek to reform them.

[B]aselines for domestic production emissions in 2050 are 17.3 million tons at present production levels, 21.4 million tons with 25 percent increase in production, and emissions of 24 million tons with a 45 percent increase in production.

As a general rule, our analysis of livestock systems focuses on dairy and pork, which use more than 90 percent of the feed and generate the vast majority of the emissions. Denmark also produces beef, some from mature cows culled from dairy after their milk production decreases, and some using calves generated in the dairy system. In our base year of 2017 Denmark also produced some poultry and fur-bearing animals (although culling of mink due to COVID-19 may lead to the elimination of fur production in Denmark in the future). We are implicitly assuming that the levels of mitigation achieved in dairy and pork systems apply to other livestock systems as well, and that is particularly appropriate because our analysis of dairy systems incorporates much of the production of beef. In reality, the mitigation techniques for those additional livestock systems still need to be analyzed, and we offer a few comments where we believe they raise particular challenges.

Future Baseline

The first step in estimating future mitigation is to establish a 2050 baseline of agricultural emissions. Future baselines can be constructed in different ways, which may include efforts to estimate changes in production methods under "business as usual." Here we use the estimate of a future baseline to estimate all the changes necessary to existing farming systems needed to achieve carbon neutrality. Often future baselines try to include some projection of changes in farming systems under "business as usual," in other words, without enhanced efforts. By establishing a baseline using present farming systems, we estimate all the changes necessary to achieve carbon neutrality whether some would occur under business as usual or not.

The critical variable in establishing a future baseline then becomes what is Denmark's future level of food production. That is not only uncertain but itself a matter of public policy. We therefore calculate emissions in 2050 using three scenarios of future food production. One is the future where Denmark only maintains existing food production, using our starting year of 2017. We consider that scenario unlikely and probably undesirable, but it provides a useful basis for analysis. A second

scenario is with 25 percent growth in production of all foods. The third scenario is with a 45 percent growth in production. As we discuss in Appendix A, the 45 percent scenario is a reasonable estimate of the growth in global consumption weighted by its land use requirements, so we call this scenario the "proportionate global growth scenario."

Table 4.1 shows the 2050 baseline emissions at the different levels of production. If Denmark increases its production, the precise level of increase will likely vary by type of food. However, projections are uncertain, and by using simple percentage growth rates that apply to all foods produced in Denmark, it is possible to easily evaluate any percentage change and make it easy to understand. Using these assumptions, baseline 2050 emissions—except for peatland emissions, which remain fixed—scale up in proportion to the increase in total food production; for example, a 45 percent increase in food production means roughly a 45 percent increase in production emissions. Our three baselines for domestic Danish production emissions are 17.3 million tons at present production levels, 21.4 million tons with a 25 percent increase in production, and emissions of 24 million tons with a 45 percent increase in production.

All these estimates assume no changes in agricultural production methods. The Danish agricultural land areas in the baselines of the 25 percent and 45 percent increased production scenarios are purely theoretical because Denmark lacks the land to increase agricultural area by that much. These theoretical baselines, however, do make it possible to determine what changes in production systems would be necessary to achieve carbon neutral production emissions and land area carbon neutrality while increasing food production by these amounts.

Table 4.1 | Estimated Denmark Production Emissions in 2050 at Different Levels of Production

	2050 PRODUCTION LEVEL		
CATEGORY	**BASELINE**	**25%**	**45%**
Nitrous oxide from fertilizer	1.14	1.42	1.65
Nitrous oxide from manure	1.01	1.27	1.47
Nitrous oxide from residues	0.61	0.76	0.88
Other	0.05	0.07	0.08
Grazing manure	0.18	0.22	0.25
Indirect: leaching	0.19	0.24	0.28
Indirect: atmospheric deposition	0.38	0.47	0.54
TOTAL NITROGEN	**3.55**	**4.44**	**5.15**
Enteric dairy	2.77	3.46	4.01
Enteric cattle nondairy	1.26	1.58	1.83
Enteric pigs	0.42	0.53	0.61
Enteric other	0.16	0.20	0.23
TOTAL ENTERIC	**4.60**	**5.75**	**6.67**
Energy emissions field operations	0.52	0.65	0.75
Energy barn operations	0.29	0.36	0.42
Production of nitrogen fertilizer	0.72	0.90	1.04
Production of phosphorus and potassium fertilizer	0.04	0.04	0.05
Production of pesticides	0.08	0.10	0.12
TOTAL ENERGY USE	**1.64**	**2.05**	**2.38**
manure management dairy	-	-	-
METHANE	0.85	1.06	1.23
Nitrous oxide	0.29	0.36	0.42
Manure management pigs	-	-	-
METHANE	1.36	1.70	1.97
Nitrous oxide	0.22	0.28	0.32
TOTAL MANURE MANAGEMENT	**2.72**	**3.40**	**3.94**
PEATLANDS	**4.80**	**4.80**	**4.80**
LIMING	**0.21**	**0.21**	**0.21**
OTHER (RESIDUE BURNING CO_2 FROM UREA)	**0.01**	**0.01**	**0.01**
INTERNATIONAL PEMS	**1.35**	**1.68**	**1.95**
Total Production Emissions	**17.54**	**20.66**	**23.17**
Total COC	**45.88**	**57.34**	**66.52**

Source: Author's calculations.

Improving Feed Efficiency for Pork and Dairy

The overwhelming majority of Denmark's production and land use requirements are related to its livestock production, and the single most significant way to reduce agricultural emissions is to reduce the quantity of feed required to produce each kg of pork or meat. Reducing this feed quantity reduces every major category of emissions. The quantity of feed determines the quantity of crops needed for feed and therefore land use requirements and the quantity of nitrous oxide and all other emissions that result from crop production. The quantity of feed required also greatly influences the quantity of enteric methane emitted, as well as both the quantity of manure and its nitrogen content. Improvements in feed efficiency explain a one-third reduction in nitrous oxide emissions from manure management between 1990 and 2017 (NIR 2019, Table 5.12). Denmark can significantly reduce its emissions further if it can increase the feed conversion efficiency—in other words, if it can reduce the feed needed for each kg of meat and milk.

Danish pork and dairy are already highly feed-efficient, and because there must be biological and animal welfare limitations to feed efficiency, scientists disagree about the potential to improve these efficiencies much more. For example, a European research effort concluded in 2012 that pig, poultry, and dairy production in Europe was likely to improve in feed efficiency by only roughly 1 percent or less in total by 2050.[11] Other studies are more optimistic about potential gains. For example, although it relied on somewhat older studies, Lamb et al. (2016) suggested potential ongoing improvements of 1 percent per year for decades until 2050 based on trend lines.

Feed efficiency gains can be achieved in several possible ways: breeding more efficient cattle, changing the types of feed, "herd management" improvements that increase offspring, improve health, or reduce the time when animals are not producing. Due to management, researchers at Arla Foods report that the top 10 percent of Danish dairy farms have a 10 percent greater feed efficiency than average Danish dairy farms, which in turn are 10 percent more feed-efficient than the lowest 10 percent.[12]

The feed efficiency of milk production is strongly influenced by the milk yield per cow (VandeHaar et al. 2016). Up to an eventual limit, the more milk per cow, the lower the share of feed energy used to maintain the cow and the higher the share incorporated into the milk. That can be influenced by breeding, changes in diet, and other management changes. There are potentially some trade-offs: feeding more grains tends to generate higher output per cow, but because grains have lower yields than some forage crops, such as silage maize, that does not necessarily translate into an equivalent savings in land.

There is also a growing research field focused not on increasing milk per cow or daily weight gain per pig but just on increases in milk or daily weight gain per kilocalorie of feed. This field seeks to reduce the "residual feed intake," a measure of the portion of feed energy not actually used by a cow, pig, or other animal for life or growth. Researchers have shown a significant diversity in this efficiency in cows and have also shown that much of this diversity can be inherited (VandeHaar et al. 2016). In modern U.S. herds, some data suggest that the top 20 percent of cows require 6 percent less feed for the same output ("Sire Evaluations" n.d.). Exactly how much improvement is possible is unclear, but one U.S. projection shows a reduction in feed of roughly 10 percent (Michigan State University n.d.). Showing the genetic potential of breeding for pigs, an older study claimed that breeding specifically for feed efficiency increased that efficiency by 35 percent in seven generations of pigs (Patience et al. 2015).

Exactly how much feed efficiency gain Denmark could achieve by 2050 is uncertain. We constructed one estimate for dairy and one for pigs and estimated changes in different feeds, as well as various emission categories, using the ClimAg model. The dairy scenario was based heavily on the trend in the national average milk yield since 1975. Extrapolating this trend linearly gives a yield of 15,600 kg per cow per year in 2050. This is only slightly higher than the average in 2015 of the 10 Danish farms with the highest milk yields (Kristensen et al. 2019). We therefore consider this goal to be a reasonable target for the national average in 2050. We also assumed some efficiency gains from herd management[13] and a 5 percent increase in pure metabolic efficiency by cows. For pork, we assumed increases in herd productivity based on continuing trend lines of annual improvements done by specialists at SEGES[14] plus a 5 percent increase in metabolic efficiency.

Overall, these changes result in a total feed efficiency gain of 13 percent for pork and 35 percent for dairy measured by dry matter of feed per unit of output. The large reductions in dairy result in particularly large reductions in the use of forages, both silage maize and grass/legume mixes. These changes result in substantial reductions in emissions and land use GHG costs measured by COCs (Table 4.2).

Table 4.2 is somewhat simplified because it assumes that the feed efficiency gains for pork and dairy apply to all feed in Denmark, including for beef, poultry, and fur. Danish statistics do not indicate how much feed is consumed by each use, but we estimate likely shares of feed using likely feed conversion efficiencies and quantities of production of each animal product. We estimate that roughly 5 percent of feed is consumed by beef production not included in our dairy estimates. Another 3 percent of feed is consumed for poultry production. By applying our dairy and pork improvement estimates to all feed, we are implicitly assuming that these other livestock products can achieve the weighted average efficiency gain of dairy and pork. We have not analyzed that potential for beef and poultry, and for both, achieving these levels of gains may be challenging. These sectors should be examined more carefully to refine targets for overall feed conversion efficiency.

These results represent only one scenario of many possible future changes. We use this scenario for our "carbon neutral" analysis, but Denmark should examine alternative scenarios. Some of the work to increase feed efficiency will occur as an outgrowth of the continuous search for improvements to reduce costs. However, we recommend that Denmark develop a partnership with other countries using similar animal breeds to incorporate increased feed efficiency more heavily into breeding. Because these increases may involve shifts in the types of feed, tools such as those we are using here to evaluate the GHG consequences (including land use) and different feeding strategies should help guide what is adopted.

Some but not all of the ways of increasing feed efficiency could work against the humane treatment of animals. For example, the poultry industry, by promoting the rapid weight gain of birds, has been criticized for breeding chickens unable to handle their own weight or to provide sufficient blood or oxygen to their breasts, and Danish producers have been appropriately moving back to slower-growing breeds. In contrast, selecting cows or pigs for more efficient uptake of nutrients or lower maintenance metabolic requirements may have no humane consequences. And gains that result from improved health, which can result from more humane conditions, have animal welfare benefits. These issues need to be evaluated and factored into strategies for improving feed efficiencies.

Table 4.2 | Effects of Projected Feed Efficiency Gains on GHG Emissions in Proportionate Growth Scenario

PARAMETER	REDUCTION (%)
Pork feed reduction (dry matter)	13
Dairy feed reduction (dry matter)	35
Reduction in domestic COCs	12
Reduction in international COCs	12
Reduction enteric methane	30
Applied nitrogen emissions reductions	33
Reduction in manure management	24

Note: COC = carbon opportunity cost.

Source: Authors' calculations using in part using ClimAg model.

Restoring Danish Peatlands

Peatlands are wetlands that build up carbon in their soils precisely because their wet conditions prevent microorganisms from decomposing plant material. When peatlands are drained for agriculture or another use, microorganisms can obtain the oxygen they need and decompose the carbon, releasing carbon dioxide. Globally, around 2 percent of all human emissions result from drained peatlands, primarily for agricultural use (Searchinger et al. 2019).

The NIR we use to estimate Danish emissions was based on an area estimate of 118,000 hectares of peatlands, but a new estimate of 170,000 hectares is now broadly recognized (Klimarådet 2020). Although the previous estimate therefore generated 3.74 million tons of emissions (including nitrous oxide as well as carbon dioxide), we here use the revised estimate of 4.8 million tons from the broader area. However, we did some data analysis previously using a map of peatlands based on the smaller estimate, and because the purposes of that analysis are not significantly affected, we continue to use those results for some purposes.

Technically, many lands talked about as peatlands in Denmark have a much lower soil organic carbon content than lands often considered to be peatlands globally (as low as 6 percent carbon in Denmark, while some global assessments require at least 20 percent). That may be due to the loss of carbon as a result of decades of drainage. Actual emissions per hectare per year for each drained peatland are also somewhat uncertain. However, the national report makes reasonable assumptions from IPCC emission factors and other literature, and we accept them here. Those emissions are generally 46 tons of CO_2 per hectare per year for peatland soils greater than 12 percent organic matter, and 25 tons of CO_2 for peatlands with 6–12 percent organic matter.

There are some likely important exceptions, however. According to recent studies, 29 percent of the drained peatlands are cultivated occasionally but are often left as grass fields for several years. A significant portion of that area is probably not as well drained, which should result in fewer emissions (Gyldenkærne 2019).

In general, it should be possible to eliminate the carbon dioxide emissions from degrading peat by rewetting them. We briefly explore three issues: (1) What are the relative greenhouse gas benefits of rewetting versus reduced food consumption? (2) Should these benefits be adjusted for some likely increases in methane? and (3) How feasible is such restoration?

A. Factoring in lost food production

Although restoring peatlands stops emissions from soil degradation, it can sacrifice food production, which has a carbon cost to replace the food. Because degrading peatlands are often included in production emissions, we are examining them in this part, but rewetting peatlands requires eliminating or reducing agricultural production, so we need to compare the benefits of rewetting with the land use costs of replacing the food elsewhere. Using the previous peatland map, we first used a global information systems analysis to determine the area of peatlands devoted to each crop (Table 4.3) (based on the earlier peatland map). Using carbon opportunity costs, we then estimated the carbon cost of losing this food production—the typical carbon that would be lost to replace the food elsewhere (Table 4.4, column 2). The actual yields on this land are important for such an estimate.

Table 4.3 | Area of Mapped Drained Peatlands Producing Each Crop

CROP	≥12% OC	DISCOUNTED, ANNUAL CARBON LOSS (MILLION TONS CO_2)
Oats	1,102	2,009
Wheat	6,220	11,477
Barley	7,390	15,035
Rape	1,175	2,923
Silage maize	1,635	5,137
Maize	95	221
Potatoes	1,279	1,552
Beet	88	261
Seeds	699	1,073
Fodder grass	10,642	14,852

Note: OC = organic carbon.

Source: Author's calculations.

Denmark should be able to identify yields on individual fields, but for this analysis we assumed 90 percent of average Danish yields because these peatlands are generally of lower quality than most Danish croplands.

According to this analysis, there would be net gains to restoring peatlands regardless of the present crop grown or whether the peatland has organic matter above 12 percent or between 6 and 12 percent (Table 4.4, columns 3 and 4, and Figure 4.1). Using a weighted average, we estimate that the carbon opportunity cost of removing land from production is 12 tons of CO_2/ha/year, while the benefits are generally 46 tons for the more carbon-dense peatlands (greater than 12 percent) and 25 tons for the less carbon-rich lands (6–12 percent).

The one possible exception involves the 1,552 hectares of potatoes grown on land between 6 and 12 percent carbon, for which the benefits and costs are close. Even there, improved science may yield a clearer result because there is evidence emerging from Germany that the emission factor on these lower-carbon lands are close to those of the higher-carbon peatlands (Klimarådet 2020).

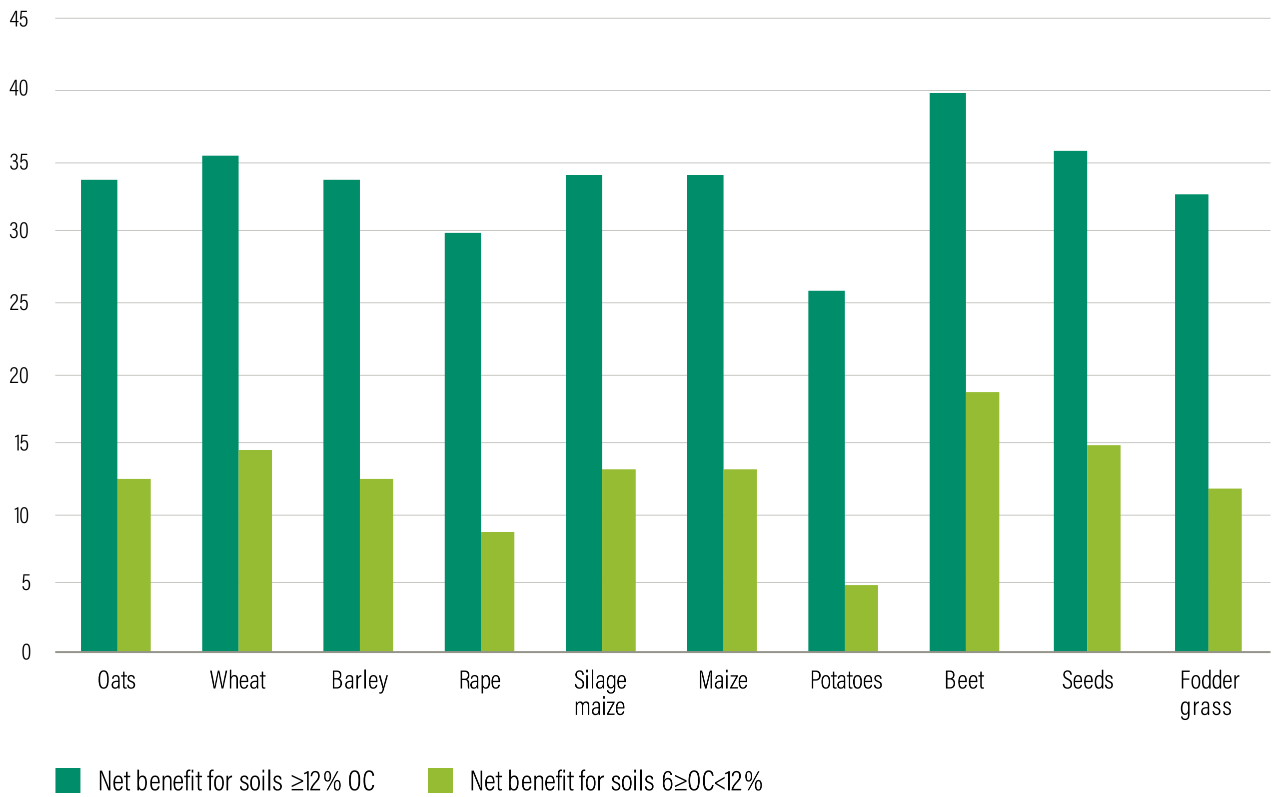
Table 4.4 | Carbon Costs and Benefits per Hectare of Restoring Drained Peatlands with High and Lower Concentrations of Organic Carbon in Soils by Crop

CROP	CARBON COST OF RESTORATION (KG CO_2 PER HECTARE AT 90% OF NATIONAL AVERAGE YIELD)	NET BENEFIT FOR SOILS ≥12% OC (KG CO_2/HA)	NET BENEFIT FOR SOILS 6<OC<12% (KG CO_2/HA)
Oats	12.4	33.6	12.6
Wheat	10.6	35.4	14.4
Barley	12.4	33.6	12.6
Rape	16.2	29.8	8.8
Silage maize	11.9	34.1	13.1
Maize	11.9	34.1	13.1
Potatoes	20.1	25.9	4.9
Beet	6.2	39.8	18.8
Seeds	10.2	35.8	14.8
Fodder grass	13.2	32.8	11.8

Note: Gross benefits of rewetting are 45 kg CO_2/ha for >12 percent soil organic carbon and 25 kg CO_2/ha < 12 percent soil organic carbon.

Source: Author's calculations.

Figure 4.1 | Net Annual Benefit of Peatland Restoration Accounting for Lost Food Production (Tons CO_2 per Hectare)



Source: Author's calculations.

B. Methane emissions

Another issue is whether rewetting will increase methane in a way that significantly reduces the climate benefits.

Wetlands produce methane. Relying on some German data, a recent study by the Denmark Climate Council estimated that rewetting would cause roughly 7 tons of emissions (CO_2e) per hectare per year through increased methane based on some recent data from Germany (Klimarådet 2020). A paper reviewing data from northern European peatlands in 2016 estimated that peatlands on average generate around 5 tons of emissions (CO_2e) per hectare per year (Abdalla et al. 2016). This paper also found that data on the emissions of rewetted peatlands were even more limited, but the data available suggested a methane emission rate of only around one-quarter of those of never-disturbed peatlands, although the scientific rationale for that is unclear. In contrast, once wetlands are restored, they should start to rebuild carbon. For example, one analysis found a soil carbon gain of roughly 1.5 tons of CO_2 per hectare per year (Mrotzek et al. 2020). If so, the net effect of methane and soil changes would be emissions of 3.5 tons of CO_2 per hectare per year.

These analyses also do not factor in the potential benefits of reestablishing vegetation. One of the uncertain questions is the potential to restore trees to areas with 6–12 percent organic soils. This potential has not been studied. One theory is that most of these lands are full, proper peatlands, which should not support trees if rewetted. Even so, some are likely to gain some carbon in shrubland vegetation. Another theory is that some of these lands are not true peatlands but rather highly organic wetlands, which might be forested. Further evaluation is required.

Although an increase in methane has real climate effects, we believe it does not affect our estimate of reductions from agricultural emissions. Once agricultural use ceases, methane produced is a natural phenomenon that cannot be assigned to agriculture. We therefore do not factor methane emissions from restored peatlands into our analysis.[15]

C. Practical challenges

The last question is whether such restoration can work broadly or universally. Between 2013 and 2018, Denmark funded rewetting of 575 hectares of peatlands, but two-thirds of proposed peatland restoration projects did not meet government technical criteria (Filso 2019). A variety of practical obstacles to peatland restoration have been raised.

- One problem is that peatland drainage tends to mobilize phosphorus in soils, which can be released when rewetted, causing downstream water pollution. We here assume this problem can be solved. Researchers have argued that the formula for assessing such release levels in Danish rules is inaccurate for many soils, and also that mitigation options should be available (Filso 2019). There are also strategies developing for their mitigation. One paper, for example, has suggested removing nutrient-rich topsoils and depositing them in adjacent, subsided areas, which it estimates would essentially eliminate these nutrient losses (Harpenslager et al. 2015). Another option might be to cultivate some kind of grass without fertilization for some years to absorb the free phosphorus.
- The second major challenge is that rewetting projects often cannot be practically limited to the actual area of peatland because blocking a drainage channel causes rewetting of more than the peatland. That is particularly likely in the river bottom projects that have been explored so far. To proceed practically, the projects must therefore take more land out of production than just the peatlands, and that amount of land has been limited by regulations. These effects on adjacent nonpeatlands are considered a large obstacle to some peatland restoration. As we discuss below, Denmark has high potential to free up substantially more cropland for restoration over time even while greatly increasing production. If it uses these "land savings" to reforest areas adjacent to peatland as part of peatland restoration projects, more peatland restoration becomes practical.
- A third claim is that some of these wetlands are sufficiently waterlogged today that they are likely not emitting much carbon and so are not cost-effectively removed from production. If that turns out to be true, that will reduce the area rewetted, but it will not significantly reduce the mitigation. We build some assumptions of such lands into our scenario.
- Finally, there is a claim that 40,000 hectares of peatlands are in patches under 10 hectares in size, and that restoring small peatlands is challenging. Without further analysis, we do not understand the rationale. Although avoiding small peatland areas in larger farm field areas can be a challenge for large farm equipment, it is not clear why smaller peatlands are harder to restore.

We also believe mitigation is likely to be cost-effective. The Climate Council estimated the maximum cost at 171 Danish kroner (DKK) per ton of CO_2 mitigated ($27), even without fully factoring in the benefits of nitrogen reduction or benefits for biodiversity (but also without factoring in carbon opportunity costs from lost food production). This cost seems reasonable as an average. The average rental rate of cropland in Denmark is $650 per hectare per year,[16] and although there will be significant variation, peatlands are likely to have lower values overall. At the net carbon gain for deeper peat soils (34 tons of CO_2/ha/y) and adding $50 per hectare per year for restoration costs, the cost per ton of CO_2 abated would be $21. For shallower peats, the cost would rise to $40 per ton. But these estimates do not factor in biodiversity gains, which could justify peatland restoration on their own given Danish government policies to improve biodiversity. They also do not factor in the portion of land returns that represents the effect of public financial support from the EU Common Agricultural Policy. From an economic standpoint, these costs are not true economic costs, and, as discussed below, they can be avoided either if landowners are allowed to keep these subsidies or, alternatively, if the government is allowed to keep the subsidies avoided.

D. Peatland restoration scenario and recommendations

Overall, although likely challenging, we here assume that Denmark can plausibly restore 140,000 hectares of peatlands (almost 85 percent). By leaving in place those peatlands that already have the lowest emissions, we then assume that would reduce peatland emissions by 95 percent.

Without sufficient increases in land use efficiency, the lost food production would result in carbon opportunity costs that would cancel out around one-third of these carbon savings. But Denmark could realize all these carbon savings with sufficient increases in land use efficiency on other lands. We discuss that potential in Part 6.

Based on this analysis, we offer the following recommendations:

- Expand and expedite peatland restoration efforts. Denmark has prioritized restoration of more organic rich peatlands, and it should do so, but it should also expedite this restoration. The cost of restoration will remain the same in the future, but the benefits will be larger because of more years with fewer emissions.
- Reforest peatlands where and if that is appropriate and if they will survive the higher water tables after being rewetted.
- Compensate for the lost production on these lands through increases in yield on other Danish cropland.
- Seek to maximize biodiversity benefits through peatland restoration. In the short run, it may make sense to use fast-growing grasses to remove phosphorus that is easily mobilized, but, in the long run, peatlands provide an excellent opportunity to restore some of Denmark's biodiversity. Failure to utilize peatlands where feasible to restore biodiversity could lead to pressure to remove more productive land from agricultural production with less clear carbon benefits.

Reducing Emissions from Manure Management

Manure management generates 2.7 million tons of emissions, roughly 16 percent of Denmark's production emissions. We focus on pork and cattle because they contribute 93 percent of these manure emissions (NIR 2019, Supplement, Tables 3.B[a and b]). Roughly three-quarters of these emissions are methane and one-quarter is nitrous oxide.[17] Controlling these manure emissions has been a major focus of Danish policy, including large subsidies to digest this material and use the resulting biogas. Our analysis suggests a new approach is appropriate.

A major reason for the new approach is Denmark's present estimate that most of the greenhouse gas emissions from methane from manure management occurs while manure is temporarily stored in the barn rather than in outdoor slurry tanks, based on S. Petersen et al. (2016). Under IPCC 2006 guidance for national emissions inventories, Denmark's emissions would be entirely based on its outdoor storage system, which primarily counts as "slurry tank" storage. The default factor from this guidance for Denmark's temperature estimates that 10 percent of the portion of manure that could turn into methane is released as methane. This percentage is known as the methane conversion factor (MCF). However, based in part on two Swedish studies, which found low emissions from studied tanks in similar climate conditions (Rodhe et al. 2012, 2015), Denmark has used a very low MCF. Recently Denmark recalculated cattle methane emissions. This change more than doubled estimates of the overall MCF for cattle from undigested slurry, which went from 4.59 percent to 12.4 percent. The overall MCF for undigested pig manure is 13.37 percent (NIR 2020, Table 3D-22). But the recalculation estimates that 50 percent of cattle methane emissions and 70 percent of pig manure emissions occur in the barn (NIR 2020, 829; NIR 2019). This fact implies an outdoor storage MCF for pig manure of roughly just 3.4 and 6.2 percent for cattle manure.

Although these Danish estimates are based on site-specific studies, they are also based on a limited number of measurements, and they are uncertain. Even as Denmark used these studies to estimate low emissions from external storage, the IPCC in 2019 raised its estimated emission factor for slurry storage in Denmark's climate to 21 percent (IPCC 2019). This is a higher emission factor, but the IPCC does not distinguish emissions from within the barn and from outside storage.

These differences have substantial implications for policy. As we show below, Denmark's low estimated emissions from external storage make the use of digesters a very expensive mitigation option per ton of CO_2. That is an obvious result. Because most of a manure digester's GHG benefit must come from reducing the methane from outdoor storage of manure, the digester will provide relatively little benefit if that storage is emitting relatively little methane anyway. Even at higher emission factors, our analysis below suggests that digesters are still expensive in Denmark, but it is important for Denmark to be more certain what the real emission factors are. Knowing the real emissions rate is critical for deciding how much money should be spent on reducing methane in the barn versus in outside storage.

In this subsection we mostly assume that Denmark's existing emissions estimates are correct, but we do note how different estimates might alter the focus of efforts as we analyze potential solutions.

A. More frequent removal of manure from barns

Overall, using NIR numbers, in-barn emissions of methane from pork and dairy contribute almost 1 million tons of annual emissions. These emissions assume that manure on average remains roughly 19 days in the barn for cattle and 17 days for pigs. To our understanding, the NIR and Aarhus University researchers also assume that emissions are proportionate to the days remaining in the barn. In general, if barn manure were removed once every week, there should be a roughly 60 percent reduction in-barn. If manure were removed every day, there would be a 95 percent elimination of in-barn methane emissions from manure management.

Barns are also sources of nitrous oxide emissions. In fact, evidence from California for dairy suggests that IPCC nitrous oxide emission factors are generally underestimated (Owen and Silver 2015), although the much cooler temperatures in Denmark may differentiate it. More frequent manure removal would also greatly reduce barn nitrous oxide emissions. The NIR estimates overall nitrous oxide emissions from manure management at roughly 500 million tons annually. Assuming that the great majority occur in outdoor storage, we discuss below ways to virtually eliminate these emissions in storage. To the extent greater emissions do occur in the barn, frequent removal of manure should greatly reduce those emissions.

An Aarhus University agricultural mitigation analysis for 2030 assumed no improvement from existing livestock facilities in the short term, on the grounds that removing manure more frequently would require rebuilding barns. Even so, it estimated that half of barns would be rebuilt by 2030, allowing more frequent removal. For the long term, the potential to virtually eliminate these emissions is clear. In Sweden, the common practice today is to remove pig manure twice per day (Rodhe et al. 2019).

Even in the short term, we think the potential is significant. Pig farms are drained through pipes stopped by a plug, and the plug must be pulled manually. Yet SEGES has provided information that the cost of pulling a plug once per week would add DKK 5 ($0.50) per pig place per year. Because each pig place produces four slaughter pigs per year, and each pig gains 85 kg, the cost would seem to be DKK 5 for 340 kg of pork, which is small. There might also be challenges with draining manure before enough has accumulated. We suspect some pressure hosing might facilitate this effort. More frequent removal of manure, by reducing various gases in the barn, may also have health benefits for pigs that offset some of these costs.

Overall, we believe that a target of removing barn manure twice per week by 2030 should be reasonable for most farms. And a target of emptying the barn twice per day should be achievable by 2050. We assume that doing so would eliminate 90–95 percent of the emissions of methane from within the barn.[18]

The percentage of mitigation of total methane from manure is unclear because more rapid removal should increase the emissions from outdoor storage. Exactly how much is unclear because of the uncertain emission factors for outdoor storage and the influence of different quantities of the more degradable components of the manure on the MCF of outdoor storage. The net effect of removal for cattle manure is less clear than for pigs because higher in-barn temperatures for pigs probably contribute to the high methane emissions there. Fortunately, methods discussed below should be able to greatly reduce the emissions from storage as well.

B. Digesters

Denmark has provided large subsidies for digesters, reaching $241 million in 2017 (Boesgard 2019). According to a University of Copenhagen report, 15 percent of manure is currently used for biogas (Dubgaard and Ståhl 2018). Some government plans would increase this figure to 28 percent by 2030, although an agreement in 2018 called for restricting future biogas subsidies to around an additional $36 million per year (Dubgaard and Ståhl 2018). Even with restrictions on new subsidies, large existing subsidies will continue though subsidized prices for electricity and natural gas from digesters.

As we understand the history, digesters were initiated when Denmark estimated much higher emission rates from stored manure. We find the following:

- Based on the present understanding of manure emission factors, manure digesters are not cost-effective ways of mitigating manure emissions even when factoring in fossil fuel emissions savings.
- Today, digesters may even be increasing Denmark's gas emissions when factoring in the carbon opportunity costs of using land for crops that are added along with manure to digesters, and which can provide much of the dry biomass used.
- The present rules allow up to 12 percent of biomass by wet weight to be energy crops, which means that energy crops can legally be the dominant source of biomass being digested when measured in dry weight. When factoring in the carbon opportunity costs of this level of land used for this level of crops, the 12 percent rule would allow for highly adverse climate consequences.

As discussed above, the outdoor storage MCF for manure reported by Denmark is only roughly 4–6 percent. By contrast, lagoons in warmer environments may produce 70 percent of this potential (IPCC 2006; IPCC 2019). The much lower methane savings for digesters in Denmark greatly reduces their cost-effectiveness for mitigating greenhouse gas emissions.

Using NIR estimates, researchers at the University of Copenhagen have estimated that the cost of additional digesters is roughly DKK 1,000 to DKK 2,000 (roughly $170–$330) per ton of emissions mitigation (CO_2e). If there were good prospects that digester costs could be greatly reduced in the future, such initial spending might be justified. But the great majority of digester costs are structural, and we are not aware of any ideas for large cost reductions. Our view is that this cost is excessive, and Danish resources are better spent on alternatives.

Because of the importance of this topic, we have carefully evaluated the costs under different assumptions. There are some factors that could, and probably do, increase the costs of digesters or reduce the greenhouse gas benefits relative to those in the University of Copenhagen analysis, and also some factors that could improve greenhouse gas benefits. We discuss them here and evaluate their implications.

Use of separated slurry for more concentrated biomass. The University of Copenhagen study (Dubgaard and Ståhl 2018), and the Aarhus University study it uses (Olesen et al. 2018), make the key assumption for future digesters that 17 percent of the digester dry biomass will consist of dewatered, "separated" slurry, which has a much higher dry matter content (30 percent) than raw slurry (6–8 percent). Today, such digester feedstock with a dry matter content comes primarily from waste sources (such as slaughter waste), in addition to maize silage as mentioned above. Using separated slurry substantially reduces the digester cost per unit of raw slurry because most of the costs are proportional to the volume of the feedstock. By using separated slurry, roughly half of the water of the slurry is removed before it enters the digester, which means that the same digester can treat more raw slurry at the same total cost.

We have doubts about the practicality or cost-effectiveness of this assumption. The cost estimates provided for slurry separation in the University of Copenhagen study are only a few percent of the costs of purchasing silage maize. Yet digester operators are reported by the Danish Energy Agency to be adding crops, primarily silage maize, for 4.2 percent of their biomass by weight (Wenzel et al. 2020), which means far more (about 20 percent) by quantity in dry weight. We do not understand why digester operators purchase silage maize if separating slurry is very cheap. One reason these costs may be underestimated is that the liquid fraction of the separated study still has to be stored and managed, increasing the costs of storage. We therefore doubt that additional future digester "biomass" will be provided entirely by separated slurry, so the current use of maize silage may continue.

Carbon opportunity costs from the use of crops. A second, large, and widely ignored problem is that using crops increases the greenhouse gas costs of producing biogas, potentially dramatically. One source of emissions comes from the production emissions, such as those of fertilizer used to produce the crops. Another, larger climate impact is the loss of carbon storage in native vegetation caused by land use, measured by the carbon opportunity cost quantity. Depending on other assumptions, factoring in carbon opportunity costs for the use of silage maize at just 4 percent either means that digesters are increasing emissions,

Based on current understanding of manure emission factors, manure digesters are not cost-effective ways of mitigating manure emissions even when factoring in fossil fuel savings.

not decreasing them, or that the cost per ton of mitigation is very high (Table 4.5). If using 12 percent maize silage (the maximum extent currently permitted by Danish law), digesters are likely to increase emissions overall under any other scenario and hence would be a major climate problem rather than a solution.

Leakage rates. The University of Copenhagen study assumes that leakage rates from digesters in the future will be only 1 percent. That leakage rate includes only 0.1 percent leakage from the process of upgrading raw biogas into high-concentrated gas (more than 97 percent methane) that can be inserted into the natural gas grid. These leakage rates are important because digesters are designed and able to convert a high percentage of the manure potential into methane, so each percentage of leakage translates into significant emissions.

Yet today, studies have estimated an average leakage rate for digesters of 4.2 percent (IEA Bioenergy 2017), which is used by the NIR. That estimate also does not include any leakage from the process of upgrading and injecting biogas into the national gas grid. Other estimates for leakage rates in that process are much higher than assumed in the University of Copenhagen report, about 1 to 2 percent (Dumont et al. 2013; Lantz and Björnsson 2016). The NIR also estimates low emissions from the storage of the "digestate," the remaining liquid mix after the digester has completed its work. That is based on the relatively small quantity of biomass that can be turned into methane after digestion. However, these numbers are uncertain. A 2015 Swedish study found much higher total methane emissions from the digestate than even normal slurry storage (Rodhe et al. 2015).

Although a University of Aarhus study has estimated that a 1 percent leakage rate is achievable, relying on such a low leakage rate is uncertain because even occasional disruptions could result in high average leakage rates. Using the larger 4 percent digester leakage rate cuts the GHG savings significantly depending on the scenario. For example, for a 5 percent MCF scenario with separated slurry, the higher leakage rate reduces the emissions savings and increases the cost per ton of CO_2 by roughly 70 percent.

Higher MCFs from slurry storage. There are also factors that could increase the emissions savings and make digesters more cost-effective. As noted above, the older IPCC emission factor that would apply to Denmark advises an MCF of 10 percent (IPCC 2019), and a newly revised IPCC recommendation could mean 21 percent (IPCC 2019, Table 10.17), although how much is supposed to be from slurry storage rather than in-barn storage is not clear.

To examine the GHG effects and cost-effectiveness of digesters more broadly, we used the biogas module in the Clim-Ag model to evaluate outcomes with different emission factors and leakage rates. We also assumed use of both whole slurry and separated slurry, as well as different quantities of maize silage as additional digester feed. To the extent practical, we used the physical and cost assumptions built into the University of Copenhagen report, which are based in part on an Aarhus University report (Olesen et al. 2018). To credit the digester for the avoided emissions from displaced fossil fuel use, we assumed that the biogas is upgraded and inserted into the gas grid, and we credited the digester with reducing the fossil fuel emissions that would result from use of natural gas. We used the model with a wide range of assumptions about MCF, about leakage rates, and about use of silage maize or separated slurry. For the MCF, we do estimates using 3 percent, which is roughly equivalent to the Swedish findings in Rodhe et al. (2015); 5 percent, which is an average MCF for pig and cattle manure under the new Danish NIR; and up to 21 percent, which is from new IPCC guidance but does not separate in-barn emissions from outside storage emissions.

We also made one significant adjustment in economic methodology from the University of Copenhagen report in valuing the energy emissions savings. That adjustment has the effect of reducing the costs of mitigation using a digester.[19]

Table 4.5 | Effect of Different Assumptions on Net GHG Effects (Including Land Use Carbon Opportunity Cost) and Costs of Mitigation of Diverting Manure to Digesters

SCENARIO ASSUMPTIONS			CHANGE IN EMISSIONS AND MITIGATION COST				
METHANE EMISSION RATE FROM OUTDOOR SLURRY STORAGE	METHANE LEAKAGE RATES	DIGESTER FEEDSTOCK (WHOLE DAIRY AND PIG SLURRY WITH ADDITIONAL FEEDSTOCK)	NET (KG CO_2E/ TON MANURE)	DIFFERENCE IN PEM[1] (KG CO_2E/ TON MANURE)	FOSSIL ENERGY SAVINGS (KG CO_2E/ TON MANURE)	LAND USE COC[2] (KG CO_2E/ TON MANURE)	MITIGATION COST (US$/TON CO_2E)
3% MCF	Digester: 4%	17% organic waste	-25.0	26	**-51**	**0**	**$510**
	Upgrading: 1.5%	17% separated slurry	-14.1	7.9	**-22**	**0**	**$460**
		4% maize silage	1.9	19.1	**-34.6**	**17.3**	**NA**
		12% maize silage	37.7	39.5	**-53.7**	**51.9**	**NA**
3% MCF	Digester: 0.9%	17% organic waste	-54.5	-2.1	**-52.4**	**0**	**$230**
	Upgrading: 0.1%	17% separated slurry	-27.1	-4.5	**-22.6**	**0**	**$240**
		4% maize silage	-18.7	-0.5	**-35.6**	**17.3**	**$970**
		12% maize silage	7.1	10.3	**-55.2**	**51.9**	**NA**
5% MCF	Digester: 4%	17% organic waste	-32.2	18.8	**-51.0**	**0**	**$390**
	Upgrading: 1.5%	17% separated slurry	-19.9	2.0	**-22**	**0**	**$320**
		4% maize silage	-5.4	11.9	**-34.6**	**17.3**	**$3,370**
		12% maize silage	30.5	32.2	**-53.7**	**51.9**	**NA**
5% MCF	Digester: 0.9%	17% organic waste	-61.7	-9.3	**-52.4**	**0**	**$200**
	Upgrading: 0.1%	17% separated slurry	-34.3	-11.7	**-22.6**	**0**	**$190**
		4% maize silage	-26.0	-7.8	**-35.5**	**17.3**	**$700**
		12% maize silage	0	2.9	**-55.1**	**51.9**	**NA**
10% MCF	Digester: 4%	17% organic waste	-50.4	0.7	**-51.0**	**0**	**$250**
	Upgrading: 1.5%	17% separated slurry	-33.9	-11.9	**-22**	**0**	**$190**
		4% maize silage	-23.5	-6.2	**-34.6**	**17.3**	**$770**
		12% maize silage	12.3	14.1	**-53.7**	**51.9**	**NA**
10% MCF	Digester: 0.9%	17% organic waste	-79.9	-27.4	**-52.4**	**0**	**$160**
	Upgrading: 0.1%	17% separated slurry	-46.6	-24	**-22.6**	**0**	**$140**
		4% maize silage	-44.1	-25.8	**-35.6**	**17.3**	**$410**
		12% maize silage	-18.3	-15	**-55.2**	**51.9**	**$1,700**
21% MCF	Digester: 4%	17% organic waste	-90.0	-39.0	**-51.0**	**0**	**$140**
	Upgrading: 1.5%	17% separated slurry	-73.5	-51.6	**-22**	**0**	**$87**
		4% maize silage	-63.2	-45.9	**-34.6**	**17.3**	**$290**
		12% maize silage	-27.3	-25.5	**-53.7**	**51.9**	**$1,150**
21% MCF	Digester: 0.9%	17% organic waste	-119.5	-67.1	**-52.4**	**0**	**$110**
	Upgrading: 0.1%	17% separated slurry	-86.2	-63.6	**-22.6**	**0**	**$74**
		4% maize silage	-83.7	-65.5	**-35.6**	**17.3**	**$220**
		12% maize silage	-58	-54.7	**-55.2**	**51.9**	**$540**

Note: NA indicates cannot be cost-effective because digester increases emissions. PEM = production emissions; COC = carbon opportunity cost; MCF = methane conversion factor.

[1] Difference in production emissions between the baseline (storage of slurry in outdoor tank) and digestion of slurry for biogas production.

[2] Includes only the land use COC of additional nonslurry feedstock. The effect on soil carbon from the loss of organic carbon in the digester was ignored.

Source: Author's calculations.

Table 4.4 shows the results. Our estimate of $240 per ton of CO_2 saved is similar to that by the University of Copenhagen (DKK 1,400 or $230) when we use similar assumptions (3 percent MCF, 1 percent leakage rate, and use of separated slurry to replace waste and crops for addition of solids). We believe the University of Copenhagen estimate was based on a similar, implicit MCF. For what we consider a more likely, average present scenario with 4 percent silage maize, the cost is $3,370 per ton (5.5 percent leakage rate and an MCF of 5 percent). In this scenario, there is a small increase in methane emissions, but the energy savings create a small net climate savings for each ton of manure. If the leakage rate is in fact only 1 percent, this cost is still $770 per ton of CO_2e.

The use of 4 percent silage maize is a national average. Many digesters instead use some source of waste biomass. If we assume that digesters use a financially free source of organic waste and the 5 percent MCF used by Denmark's NIR, the cost is still $390 per ton at 5.5 percent leakage rate and $200 per ton at a 1 percent leakage rate.

From our analysis, we reach the following conclusions:

- So long as the methane emissions from outdoor slurry storage occur at the low rates specified in the Denmark NIR, the use of digesters for manure is expensive even under the most favorable other assumptions. At a 5 percent MCF, 1 percent leakage rate, and even assuming use of separated slurry, the cost would be $190 per ton.
- Even if outdoor slurry storage rates double (to a 10 percent MCF), and even in the best-case scenario for all other conditions (very low methane leakage, maximum use of separated slurry), mitigation through digesters is still expensive, at around $140 per ton of CO_2e abated.
- Under one possible assumption about methane emissions from outdoor slurry storage, use of maize silage at 4 percent, and factoring in the carbon opportunity costs of land, the use of digesters causes a net increase in global emissions. At present emission estimates for outdoor slurry, the cost ranges from roughly $1,000 to $3,000 per ton of mitigation depending on the leakage rate.
- At the 12 percent use of crops allowed by present Danish law, digesters would be a significant net source of emissions.
- Only if methane emissions for outdoor slurry storage are as high as implied in IPCC (2019), if leakage rates are held to 1 percent, and if only separated slurry is used does the cost fall to $74 per ton CO_2e. However, we find this scenario unlikely both because such high methane emissions are four times larger than those presently estimated and because we are skeptical about the feasibility and cost of using separated slurry.

Based on this analysis, we make the following recommendations:

- Denmark should put a moratorium on subsidizing new methane digesters.
- Denmark should rapidly phase out all use of crops, including maize silage, in existing digesters, substituting waste biomass sources.
- Denmark should probably plan to phase out the use of digesters from manure over time as existing digesters age and would otherwise need major structural replacements. In the next few years, Denmark can gather better information to evaluate digesters' overall performance and cost-effectiveness to confirm or adjust the results presented here. This effort should include improved information on the following:
  - slurry storage MCFs, both with and without rapidly removed manure
  - the practicalities and costs of using separated slurry for additions of drier biomass
  - realistic leakage rates (including those from gas upgrading)
  - the practicality of operating digesters with slurry removed daily
  - the costs of alternative manure management mitigation

C. Acidification

Acidifying manure is the most discussed alternative to digesters and typically involves adding sulfuric acid. Although full-scale pilot tests are required for acidifying stored manure, this method has the potential to be a cost-effective strategy for nearly eliminating manure management emissions. It also can offer other environmental benefits.

Acid can be added in the barn, in the slurry tank, or just prior to spreading of manure (Figure 4.2). The stage of manure management where it occurs leads to different effects. If acid is added just prior to field application, it does not reduce methane emissions from manure storage but will typically reduce ammonia emissions from field application of manure by roughly half (SEGES 2017). If acid is added into the storage tank, it can reduce both ammonia emissions and methane emissions by more than 90 percent (although in some experiments this figure is as low as 60 percent).

Figure 4.2 | Farmers must mix manure before spreading it on farm fields and can add acid just before to reduce ammonia emissions in the field.

Source: Finn Udesen

If acid is added into the slurry storage in the barn before manure slurry is removed to the tank, it can reduce ammonia and methane emissions from both the barn and the storage tank (Lyngso 2019; Olesen et al. 2018). As of 2014, 18 percent of Danish manure was acidified just before application to a farm field (SEGES 2017).

In its mitigation potential analysis, Aarhus University uses a conservative reduction number of 60 percent of methane and ammonia and assumes that mitigation will be provided in the barn stage (Olesen et al. 2018). Adding acidification in the barn—although it will help address the large methane emissions Denmark estimates from the barn—is substantially more expensive than in later stages and requires large investments that are significantly independent of farm size (Olesen et al. 2018). The additional energy required to operate this system also adds emissions that reduce the net GHG benefits of acidification by 42 percent for cattle manure and 21 percent for pig manure. Focusing on this high-cost strategy and using these abatement numbers, the University of Copenhagen estimated a gross abatement cost of DKK 844 (or $136) per ton of CO_2e abatement for pig manure, and DKK 1,899 ($306) per ton of CO_2e for cattle manure (Dubgaard and Ståhl 2018). These costs exceed our maximum planning cost for mitigation of $50 per ton.

However, these gross costs do not count the benefits of reduced nitrogen pollution from the reduced ammonia emissions. When factoring in these (and some other smaller) societal benefits, the University of Copenhagen estimated a net cost savings of DKK 118 (per pig) and DKK 28 per ton for cattle manure. In other words, the nitrogen pollution reductions more than fully pay for the costs of the greenhouse gas savings. In many situations, these societal benefits do not reduce costs to farmers, but in Denmark existing (and likely growing) regulations addressing nitrogen create real costs for farmers that they can avoid using acidification. Today, many farmers are required by regulations either to inject their manure subsurface or to acidify their manure to reduce ammonia losses. The Baltic Slurry Acidification project funded by the European Union has calculated that it is substantially cheaper to use some form of acidification rather than injection (Lyngso 2019). That helps to explain why 18 percent of manure is already acidified in Denmark prior to field application. Ultimately, the University of Copenhagen study is favorable toward acidification, and we are substantially more favorable for several reasons.

First, we recommend focusing acidification in the slurry tanks not in the barn. Acidification in the storage tank will be substantially cheaper and more practical to implement because it does not involve retrofitting the barn or dealing with a variety of corrosion problems potentially caused by pumping the more acidic slurry (Rodhe et al. 2019). Doing so will not save methane emissions from the barn stage, but we believe those emissions can be avoided far more cheaply by quickly removing the manure—certainly by 2050 when barns will have been rebuilt.

Second, we think the potential for crop yield gains due to acidification is an open question. In a 2017 report, based on 13 field trials of barley and wheat, SEGES calculated yield benefits that fully paid for the more limited costs of acidification shortly prior to application (SEGES 2017). The University of Copenhagen study did not factor in such economic benefits based on the reasoning that changed regulations have allowed farmers to apply more fertilizer, so they would not benefit from the increased nitrogen available through acidified manure. However, as discussed below, there are potential ways in which a change in the form of nitrogen applied to crops could boost yields not just the quantity of nitrogen. In one field trial by the Baltic Slurry Acidification project, acidifying slurry increased ryegrass yields by 40 percent and maize yields by 20 percent (Loide 2019). We therefore consider yield gains a possibility that requires further study.

Third, in addition to reducing methane, acidification can also contribute to large reductions in nitrous oxide mostly not counted in the University of Copenhagen study. Recent papers analyzing acidification count small nitrous oxide reductions that result indirectly from reduced ammonia losses—which cause nitrogen to be deposited on land and in water bodies and get turned into nitrous oxide (Lyngso 2019; Dubgaard and Ståhl 2018). But there is a much larger potential source of nitrous oxide reductions.

According to IPCC guidance, nitrous oxide from slurry manure is entirely a result of microbial interactions that occur when there is a crust cover of the manure in the storage tank. A crust is maintained today to control both ammonia and methane. But if ammonia and methane are controlled by acidification, a crust is not needed. For pork manure, additional solids need to be added to create a crust, so just by failing to add these solids, farmers can achieve these reductions in nitrous oxide. For dairy manure, additional efforts would be needed to avoid formation of a crust. These approaches would largely eliminate the nitrous oxide emitted from storage tanks and further improve the cost-benefit ratio of acidification.

To illustrate the possible methane mitigation costs of acidifying manure only in storage, we use cost figures provided in SEGES (2017). Based on the numerous studies finding greater than 90 percent reductions in methane (Petersen et al. 2014; Kavanagh et al. 2019), we assume reductions should be achievable consistently in the future at that level. The cost-effectiveness depends heavily on a few key assumptions: the methane emission rate in outdoor storage, the types of offsetting costs, and the amount and costs of acid required to sustain acidification continually. (This last assumption is necessary because research papers have focused on shorter periods, typically of around three months, and these same analyses show that slurry returns to higher pH levels slowly after application.) Even so, using our main assumptions for additional acid and costs,[20] we estimate reductions are marginally cost-effective to cheap, even before factoring in nitrous oxide reductions. Different scenarios show the potential:

- Costs per ton of mitigation for methane will be highest if the methane emission rate from external storage is low. If we use an external MCF of only 3 percent, the gross cost of acidification is DKK 1,478 to DKK 1,738 (\$238–\$280) per ton of CO_2e mitigated. But if we assume that farmers would alternatively have to pay for acidification before application of slurry, that cost declines to DKK 392 to DKK 721 (\$63–\$116). By itself, this cost estimate is too high to be justified.

- Yet this analysis assigns no extra benefit for the substantially higher reduction in ammonia (estimated by SEGES as a 65 percent reduction in the spreading rather than a 40 percent reduction for acidification prior to field application). If we adjust for these extra benefits,[21] the ammonia savings alone more than pay for the costs of acidification for cattle manure, and the extra cost of acidification for swine manure is only $7 per ton of CO_2e abated.
- If the outdoor MCF is 10 percent, the gross cost of methane mitigation alone ranges from $72 to $85 per ton of CO_2e abated. But if we assume field acidification would otherwise be required to control ammonia, the extra cost of doing acidification in the storage tank becomes only $19–$35. If we then factor in the value of additional ammonia reductions, as estimated by the University of Copenhagen study, the cost becomes negative. Either with or without factoring in these extra ammonia reduction benefits, these costs are reasonable.
- As noted, it is possible that the MCF for outdoor storage is even higher. If so, the cost-benefit ratio improves.
- If the yield gains projected in the SEGES paper occur, the economic benefits of these yield gains equal or outweigh the costs, so both the methane mitigation and the ammonia mitigation are free.

Before moving forward on full-scale acidification, there are issues to resolve, including the many uncertainties identified in this discussion. The main immediate need is for full-scale, full-season acidification projects that measure methane and nitrous oxide. Today, large-scale, in-storage acidification efforts mainly focus on reducing ammonia and therefore only acidify shortly before field application. Examples are needed using real, full-sized slurry tanks in operation that are acidified to reduce methane throughout the entire storage period.

The other major issue is the potential for environmental effects from such large increases in land application of sulfur. If sulfur is applied beyond crop needs, it might mobilize phosphorus from soils. Some sulfur in manure replaces sulfur that would need to be added to crops, but achieving low ammonia losses in storage all year might require more sulfur than needed by crops. Scientific tests need to be made quickly to evaluate potential impacts.

However, there are also alternatives. For example, less acid is probably required to nearly eliminate methane emissions than to nearly eliminate ammonia emissions (Olesen et al. 2018; Petersen et al. 2012). That would require less sulfuric acid, and in that event, ammonia from slurry storage, which is not a large source of ammonia anyway, could be controlled by tank covers. In addition, other acids, such as acetic acid, could be added at some additional cost (Kavanagh et al. 2019). Acetic acid use raises some issues regarding potential soil impacts on nitrous oxide but may work and be cost-effective if used only as a supplement for sulfur.

One of our major recommendations is that acidification efforts focus on in-storage additions. In the short term for some facilities that cannot more quickly remove manure, in-barn acidification might make sense. But in general, even today and certainly in the medium and long term, finding ways to quickly remove manure must be the cheaper method to address all types of emissions from the barn (methane, nitrous oxide, and ammonia). Although one paper for the Baltic Slurry Acidification research project recommended moving forward with a mix of addition methods between barn, storage, and field application, that was due to its limited focus on ammonia (Lyngso 2019). Once acidification of some kind is required to address ammonia from land application of manure, it will very likely be cost-effective to mitigate methane, nitrous oxide, and additional quantities of ammonia by focusing on acidification in the storage tank, which would also provide benefits when manure is applied to fields.

D. Variations of acidification

Researchers have identified at least two possibly cheaper variations of conventional acidification. We strongly recommend that they be quickly explored.

One is to reduce methane through use of a much lower quantity of sulfate than is necessary to reduce methane just by lowering pH using sulfuric acid. This idea is supported by work at Aarhus University, which found that adding sulfur reduced methane emissions from manure slurry by 60–70 percent even when added in two molecular forms (sulfate, methionine) that did not increase acidity to maintain low pH (Petersen et al. 2012, 2014). This work suggests that in addition to pH, sulfur is reducing methane in other ways, possibly by allowing sulfate-reducing bacteria to overcome the archaea that produce methane, possibly because sulfate is a stronger electron receptor than carbon dioxide (the electron receptor for methane formation), and possibly through toxic effects of the production of hydrogen sulfide. Canadian studies provide some support by finding that sulfur dioxide additions could greatly reduce methane even at only modestly lower pH levels of 6.5 (Sokolov et al. 2019). If a sulfate strategy is confirmed, it should be possible to dramatically reduce methane emissions at a substantially lower cost because the quantity of sulfur required would be far less than that required for full-scale acidification. Such an approach could also avoid potential water quality concerns related to sulfur additions as well as corrosion issues.

It may be that a higher level of acidification is still necessary to nearly eliminate ammonia, but ammonia might be addressed without such high levels of acid by combining a slurry tank cover and then just adding enough acid to lower pH prior to field application. As we discuss elsewhere in this report, slurry tank covers are relatively cheap and have other benefits. Focusing on the acidification benefits for ammonia may have distracted from the greater potential benefits for methane and nitrous oxide.

The second option involves self-acidification (Bastami et al. 2019, 2016). Research experiments have shown that when sucrose or glucose is added to manure slurry in slurry-tank conditions,

microbial production of lactic acids can greatly reduce the pH and in turn greatly reduce methane emissions The same researchers have achieved similar results using additions of various forms of waste biomass. In Denmark, sources of waste biomass are presently being used for digesters. But if digesters are phased out, as we recommend, this waste biomass might become available to contribute to acidification.

Both these ideas have been subjects of limited research. The sulfate addition is particularly exciting because, if it works, it should be able to greatly reduce the cost of acidification. Both these ideas should be quickly and immediately explored in pilot projects. If successful, Denmark can move rapidly forward with full-scale implementation.

E. Simple aerobic storage

Another approach might be based on the experience of several pig and dairy farms in South Dakota, which installed a floating mechanical mixing device to gently bring slurry from the bottom of a tank up to the top and back (Tooley 2013). Doing so allows enough oxygen to penetrate into the slurry to keep it from forming the anaerobic conditions that lead to methane production. But oxygen levels are not high enough to transform the nitrogen into nitrate or, it appears, to cause large releases of ammonia. (In the past, adding oxygen to manure has been accomplished with air pumps, but that technology is expensive and creates ammonia losses.) This simple aerobic mixing system was funded on several farms by the U.S. Department of Agriculture.

The report from that project claims many additional benefits, including virtually no odor and extremely low bacteria concentration as measured by E. coli. Farmers quoted in the report claim to have increased pig growth and reduced feed requirements by providing an odor- and gas-free barn environment. The report also claims that 85 percent of the total nitrogen in the slurry is in ammonium form, so that its ultimate application to crops provides more usable nitrogen than normal slurry. Although agitation of manure is often believed to increase ammonia, the project report claimed low ammonia releases at least in part because of a partly lowered pH created by the aerobic digestion processes, but ammonia losses might be addressed by a slurry cover.

One additional cost would result from a need for more dilute slurry, roughly twice as wet as normal slurry. On the one hand, that would appear to work with more frequent slurry removal from the barn using water. On the other hand, storage would have to be roughly doubled in volume. This added water content might also lead to more costs associated with spreading the manure. To avoid ammonia losses in Denmark, manure if not acidified should be injected, and that is expensive. One alternative might be to separate some of the slurry and reuse the additional water to flush the barns and thereby avoid added costs of land application.

We have followed up the initial report by talking with the primary engineer and with the supervising official at the U.S. Department of Agriculture. We believe it is sufficiently promising to justify further analysis by Danish engineers. Its costs would need to be more carefully worked out for Denmark, and if promising, a trial performed.

F. Reducing nitrous oxide from manure

According to the 2018 Danish national inventory report, direct nitrous oxide emissions from manure amounted to 0.59 million tons in CO_2 equivalent (NIR 2020, Appendix, Table 3B[b]), with another 0.15 million tons from indirect emissions. For both dairy and pig farms, roughly 85–90 percent of these direct emissions are estimated to occur with liquid slurry storage, so we focus on these sources, while the indirect emissions must be addressed through reductions in ammonia. Using IPCC emission factors, the emissions are attributed to the microbial interactions in the crust that either forms naturally with dairy farms or that is created by addition of straw and other solids for pig manure.

There is a basic solution to these emissions, which is to avoid creating the crust. The principal cost, then, is abating the ammonia through other means. Slurry acidification throughout the entire year is one option, as discussed above, and can reduce ammonia by more than 90 percent. Another option is to replace a crust with a fixed cover of a slurry tank, which reduces ammonia emissions 50 percent compared to the crust.

Already, according to one recent report, 50–70 percent of new slurry tanks are being installed with fixed covers, and the level of fixed covers has reached 30 percent (Jacobsen 2019). These high adoption rates suggest that covers are already viewed as cost-effective alternatives to crusts for many farmers. For pig farmers, covers eliminate the need to add material to form crusts, but there are also other benefits, including a higher nitrogen value for their manure, reductions in odor, and a reduction in the amount of slurry that must be delivered to the field because rainwater is kept out of the tank.

Cost estimates for a fixed cover range from DKK 1 to DKK 2.5 per ton of manure treated (Jacobsen 2019), with the lowest number deemed the most likely. Based on these costs and IPCC emission factors, this cost translates into roughly DKK 100 to DKK 250 per ton of CO_2e abated from direct nitrous oxide, or \$16–\$40 per ton. These estimates—particularly the lowest one—are reasonable in and of themselves, even while ignoring the benefits from additional reductions in ammonia.

Roughly 20 percent of the manure management nitrous oxide emissions result from indirect sources due to the emissions of ammonia and subsequent deposition (excluding indirect sources from manure application to fields). Assuming that slurry tanks today nearly all have some kind of crust cover, the vast majority of the ammonia losses from manure will occur in the animal housing, as the ammonia emission factors in the barn per unit of nitrogen—total ammonia nitrogen—are generally from around 4 to 10 times higher than those of a slurry tank with a crust.[22] There are uncertainties in all these emission factors, but a study in the Netherlands found that in-barn ammonia emissions exceeded external storage emissions by a ratio of 17 to 1 (Velthof et al. 2012).

Both improvements in feed efficiency and more rapid removal of manure should help to reduce these ammonia emissions. The feed efficiency improvements are already counted above. Daily removal of manure appears likely to reduce ammonia emissions from pig farms by roughly 20 percent, but not more, because most of the ammonia results from the interaction of urine with surfaces (Heber et al. n.d., 4). Air filtration systems are another option and can remove up to 90 percent of ammonia (Jacobsen and Ståhl 2018). Reducing slatted floors in favor of solid floors reduces emissions by around an additional one-third when combined with rapid removal of manure (Heber et al. n.d., 4; Jacobsen and Ståhl 2018). Increasing use of solid floors is already likely to be required by regulation.

Overall, studies have found vastly varying quantities of ammonia emissions from otherwise similar swine and dairy houses, even without sophisticated air scrubbers or other controls (Sommer et al. 2019). Most of these changes will be required to address ammonia pollution regardless of climate objectives. We assume that over a 30-year period, during which virtually all barns will be rebuilt, cost-effective means will achieve roughly 50 percent reductions when combined with feed conversion efficiency improvements.

Overall, we assume a 90 percent reduction in direct nitrous oxide emissions and a 50 percent reduction in indirect nitrous oxide emissions from manure management. (Both direct and indirect emissions from applied manure are addressed separately.)

G. More innovative manure management options

Manure contains carbon and nutrients, and it is frustrating that they cannot now be used for higher-value products like higher-value fertilizer or feed. A variety of speculative but innovative methods have been proposed to help deal with manure emissions, including ideas from start-up companies. Some involve processing manure into a more concentrated dry or liquid fertilizer, although economical efforts to do so today require a high price for organic fertilizer. Some technologies would use manure as a source of protein for animal feed by feeding the manure either to insects or single-celled organisms, such as bacteria (Patthawaro and Saejung 2019; Roffeis et al. 2015). None of these ideas today would be cheap enough for implementation, but they are worth continued exploration.

H. Estimated potential reductions and recommendations for moving forward

Based on these analyses, we believe the realistic potential exists to cost-effectively reduce methane emissions from managed manure by 90 percent, direct nitrous oxide emissions by 90 percent, and indirect nitrous oxide emissions by 50 percent (Table 4.6). These reductions should also have large collateral benefits for odor and water quality. Costs should be substantially less than the money now spent on digesters. Under some scenarios, the costs might be modest; for example, if modest use of sulfate turns out to greatly reduce methane. Financial benefits to the farmer could also offset costs; for example, if there are crop yield gains from using acidified manure.

Our analysis here has focused on liquid slurry storage of manure—the dominant source of emissions—and has ignored so far the roughly 15 percent of these total methane emissions reported by Denmark from manure that result from calves who are raised for several months with deep straw bedding because it is better for animal welfare. The combination of straw and compacted manure creates the wet conditions with little oxygen

Table 4.6 | Potential Reduction in Emissions from Manure Management

SCENARIO	METHANE	DIRECT NITROUS OXIDE	INDIRECT NITROUS OXIDE
Existing management	2,208.8	508.6	566.2
FCE gain mitigation alone	1690.7	370.7	509.1
FCE + other mitigation	253.6	55.6	296.0
TOTAL % REDUCTION DUE TO MITIGATION	**-89%**	**-89%**	**-48%**

Note: FCE = food conversion efficiency.

Source: Author's calculations.

that generate methane, particularly because the manure/straw material is not removed for months. According to the Danish national report, removing the material once per month would reduce emissions by more than 80 percent. Our analysis here assumes that these emissions can also be economically managed, but because the data used to estimate these emissions are weak, we believe the first effort should be to properly measure emissions.

Overall, the first need is to do the science better by properly characterizing emission factors for manure management in general and by testing the most promising manure management options we have discussed. We offer the following recommendations:

- Denmark should start requiring to the maximum extent practicable that dairy and pork farms remove their manure far more frequently. It should explore the best means possible using a range of different farm types to design reasonable requirements. For new barns the requirement should be to remove manure twice per day unless the farmer prefers to use some other technique, such as in-barn acidification, that delivers the same results.
- Denmark should immediately fund an effort to better characterize manure management emissions. There are very wide-ranging uncertainties in the emission estimates for different parts of manure management. For example, there is support for emission estimates that range from 3 percent to 21 percent (or even more) of potential methane production from slurry tanks. Denmark's analyses are not based on any tests of operational slurry tanks in Denmark, and only one study of emissions in the barn. It would be foolish to spend large sums of money on mitigation approaches until Denmark has properly quantified these numbers. Based on our consultations with researchers engaged in this work, we estimate that a budget from $7 million to $11 million over four years would be enough to monitor 20 dairies and 20 pig farms.
- As noted above, Denmark should place a moratorium funding new biogas manure digesters and should quickly require that existing digesters cease using agricultural crops and substitute some form of waste. Denmark should do further analysis to confirm the cost-effectiveness of mitigation presented in this report and should phase out digesters as they age if our estimates are confirmed.
- Denmark should immediately and ambitiously test the various options for acidification at scale. Tests with limited quantities of sulfate should be a top priority. These tests should be done in the next three years so that Denmark can implement these remedies, if they work as anticipated, by the middle of the decade.

Reducing Emissions from Nitrogen Use on Agricultural Soils

Denmark's domestic nitrogen use in agriculture causes 4.3 million tons of emissions, roughly 25 percent of its domestic production emissions (excluding offsets). Nitrous oxide from all the various forms of nitrogen applied to farm fields generates an estimated 3.55 million tons, and emissions from the production of nitrogen fertilizer constitute the remainder at roughly 0.78 million tons. Of these 3.55 million tons of nitrous oxide emissions from farm fields, roughly 3 million are direct and 0.55 million are indirect and occur after nitrogen is lost from farm fields through air or leaching of water (NIR 2020, Supplement, Table 3.D).

Nitrogen losses are also major water quality concerns primarily because of the nitrate leached or deposited by air, which causes pollution of ground- and sea water. Nitrogen pollution is therefore an economic concern as well because the European Union imposes limits on this pollution, which leads the Danish government to place limits on farmers' use of nitrogen.

Nitrogen use efficiency (NUE) of crop production provides a good measure of a country's achievement in using nitrogen. As we use the term, NUE is the percentage of nitrogen applied to a farm field from all sources that is absorbed by the edible portion of the crop. We estimate Denmark's NUE at 47 percent. Table 4.7 provides our estimates of the NUE of each crop used for feed, crops that occupy around 90 percent of Danish agricultural land.

Table 4.7 | Nitrogen Use Efficiencies by Crop

CROP TYPE	AREA (HECTARES)	TONS OF N APPLIED PER CROP	NITROGEN CONTENT PER CROP (TONS)	NITROGEN USE EFFICIENCY
Grain maize	6,400	1,312	476	36%
Triticale	10,300	1,905	669	35%
Spring wheat	20,000	4,042	1,285	32%
Pulses	20,050	7,278	2,254	31%
Oats and dredge corn	64,575	10,798	3,499	32%
Rye	106,375	17,787	6,495	37%
Winter barley	109,350	23,955	9,016	38%
Rapeseed	169,150	34,333	17,928	52%
Maize for green fodder	176,325	36,144	26,266	73%
Permanent grassland out of rotation	238,450	44,935	18,549	41%
Grass and clover in rotation	269,500	111,235	58,413	53%
Winter wheat	536,950	125,549	57,708	46%
Spring barley	590,375	101,754	40,692	40%
Fodder beets	4,000	993	686	69%
NATIONAL TOTAL	**2,321,800**	**522,021**	**243,936**	**47%**

Note: Authors' estimate is based on the average nitrogen requirements for an average of soil types set forth in LBST (2019). This estimate could be refined using national, farm-by-farm data on nitrogen application by field. Some crops use a higher share of manure than others. Crops using manure will use more nitrogen because Danish law allows additional nitrogen application with manure based on the assumption that some of it is not available to the crop that year. In our analysis, we assume manure to be spread proportionately across crops based on nitrogen demand. If we did not make this assumption, some crops would appear to be less nitrogen-efficient based simply on whether they are grown near farms with abundant manure supply. Increasing that share of crops would therefore appear to reduce national nitrogen efficiency. But that would not actually increase the manure used in the country. Because any crop can be fertilized with manure, allocating manure proportionately makes it possible to assess more accurately the consequences of changes in production of any one crop.

Source: Authors' calculations, assuming equal shares of manure.

Denmark's cropland NUE is low relative to some other countries, such as the United States and Canada, which are achieving an overall NUE of 68 percent (data underlying Zhang et al. 2015). Some of that is probably due to crop mix; for example, the United States produces a great deal of soybeans with very high nitrogen use efficiency while Denmark only produces a limited quantity of oilseeds. And overall, the reason for low NUE is probably not a lack of farmer care. To our understanding, no country more closely tracks and controls the application of nitrogen. The low NUE probably results, first, from the large quantity of nitrogen that is applied in the form of manure. Because manure nitrogen is not as readily available to crops and tends to have more losses to the air (as ammonia), Denmark allows farmers to apply 20–25 percent more nitrogen when applying manure than when applying synthetic nitrogen fertilizer (farmers everywhere tend to follow a similar practice). A second reason is that Denmark has many sandy soils in the west, which tend to leach water, and nitrogen with it. Meanwhile, much agricultural land in eastern Denmark has drainage channels to avoid excess water, and they also cause considerable water and nitrogen loss.

Another major contributing factor is the extensive rainfall Denmark receives in the winter, often without frozen soils. Much of the nitrogen lost from soils occurs because nitrogen is transformed by microorganisms from an organic form where it is bound in effect in dead biomass into inorganic nitrogen that can be lost from soils. This process, called mineralization, is increased by temperature and continues to occur throughout summer and fall months after many crops stop taking up nitrogen through their roots. Heavy late autumn and winter rainfall, when plants are not growing, then causes large quantities of water to leach this nitrogen away (Askegaard et al. 2005).

These are the physical conditions Denmark must deal with and will require a series of ambitious efforts to reduce the nitrogen losses.

As with other benefits, the improvements in feed conversion efficiency contribute to nitrogen reductions by reducing feed requirements. We estimate reductions in applied nitrogen at 19 percent.

The additional ways of reducing emissions from nitrogen application can be usefully separated into four categories:

- Changing application methods, including both manure and fertilizer, so that less is applied without decreasing yields. According to present estimation methods, the quantities of nitrous oxide emitted are proportional to the quantity of nitrogen applied (and it is possible that increasing NUE may even provide disproportionate benefits) (Searchinger et al. 2019). More efficient fertilizer application would reduce emissions from nitrous oxide and would reduce emissions involved in fertilizer production.
- Reducing the share of nitrogen in soils that transforms into nitrous oxide (and nitrogen oxides).
- Reducing the leaching and air losses of applied nitrogen.
- Reducing the emissions involved in the production of nitrogen fertilizer.

Although most potential solutions contribute to reductions in more than one of these ways, we group our discussion of solutions based on the primary pathway for each mitigation type. For emissions from the production of fertilizer, we discuss them primarily in the energy section.

A. Reducing nitrogen application without reducing yields

Several potential methods exist for reducing nitrogen application without reducing yields.

Precision agriculture

Application of nitrogen using precision agriculture involves linking information technology with nitrogen application to vary nitrogen application rates based either on a particular part of a field or on the timing of application.

The standard methods, which focus on varying where nitrogen is applied, are evaluated in a recent report commissioned by the Danish government on strategies for reducing nitrogen leaching (Eriksen et al. 2020). The theory is that, by varying nitrogen application rates across a farm field, less nitrogen can be applied to those areas that need nitrogen less, for example, because the soils have other limitations. One U.S. study found that one-quarter of U.S. maize fields have consistently low yields relative to other fields, and that matching nitrogen application rates to those yields would reduce nitrogen losses from all midwestern maize fields by 15 percent.[23] Danish researchers have expressed doubts about the potential savings from this approach in Denmark due to more consistent yields across fields, but there may be some nitrogen savings from a variety of more careful application techniques or even separate fertilization of grass and clovers.

Varying the timing of fertilizer application holds even greater promise and was not discussed in the recent report on precision agriculture. Major crops, such as maize, wheat, and barley, need differing quantities of nitrogen at different times and tend to have their primary needs several weeks after spring planting or during spring "green-up" for winter wheat. Much of the nitrogen available to crops mineralizes from soils in the course of the spring. Yet because the quantity that does so varies by soil and year, farmers cannot rely on it fully and apply more nitrogen themselves than is needed in those years when mineralization rates are high.

Two methods seem practical for better estimating the quantity of nitrogen really needed. One is to use some kind of satellite or drone photography to estimate the nitrogen status of the young wheat plant, which can be used to estimate available soil nitrogen. To illustrate the potential, research tests on winter wheat in Switzerland over two years found 5–40 percent reductions in nitrogen application with the same yields using drone-based photographs to vary application rates (Argento et al. 2020). Another possibility is illustrated by a soil-based model for maize in the United States, which combines information on soils, yields, and each year's weather to inform farmers how much nitrogen to apply during the growing season. Papers have estimated potential reductions in nitrogen application using this model of 20–40 percent (Sela et al. 2019, 2018). This model is commercially available to farmers in the United States today. Farmers only need to insert some information about their fields; the software system accesses weather data and runs the model to provide in-season nitrogen recommendations. No such tool is available in Denmark, however, or for wheat or barley in the United States.

None of these methods are likely to be ultimately expensive. Already farmers managing 59 percent of cultivated area in Denmark use global positioning systems, 40 percent of farm area is cultivated with controlled spraying technology, and 15 percent of farms use drones.[24] Some financial savings should result from using these systems for reduced fertilizer. Over time, there should be abundant opportunities to improve any system as the quantity of data increases and the systems are better able to predict nitrogen needs. The potential financial savings in nitrogen, however, may not be large enough to motivate farmers to take full advantage of these opportunities. Public policies should encourage their development and widespread use.

Microorganisms to enable crops to fix nitrogen

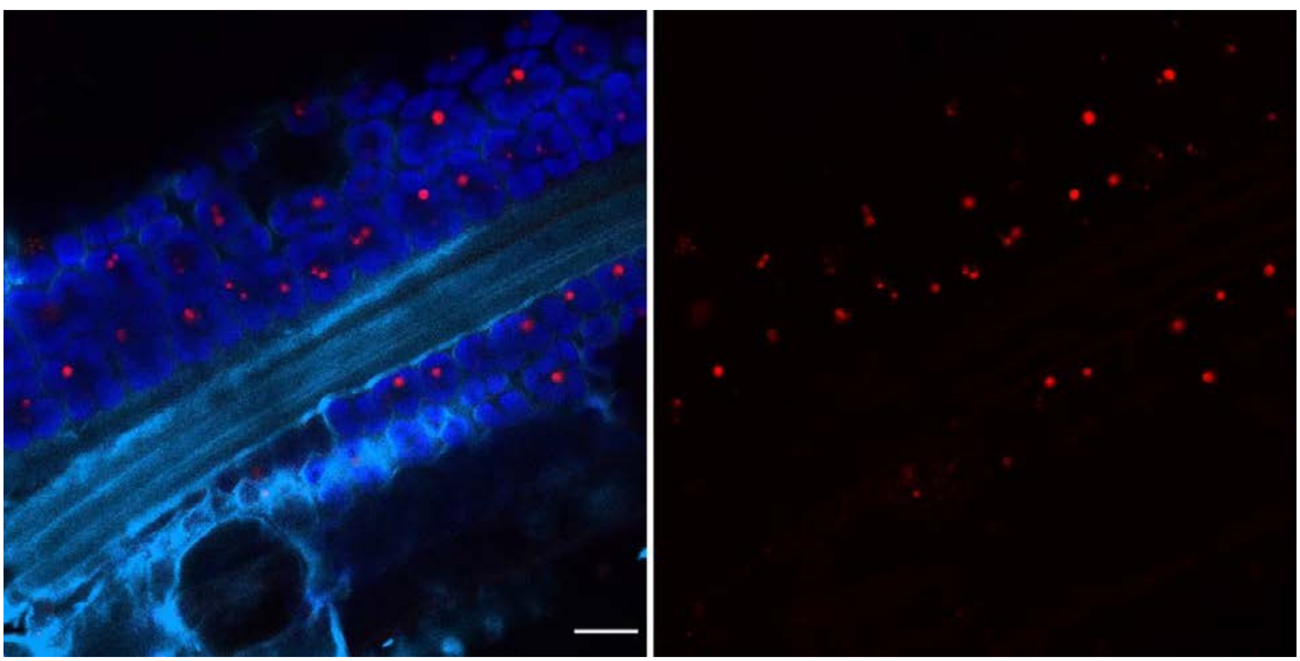
By far the most nitrogen-efficient crops in the world are legumes because they interact with a group of bacteria (known as rhizobia) to obtain most or all of their own nitrogen from the air. Soybeans, a prominent example, are estimated to have an 80 percent NUE globally (Zhang et al. 2015). That high NUE reduces losses to the environment. Climate benefits are also high because an estimated 1 percent of fertilizer or manure nitrogen applied to crops turns into nitrous oxide, but the nitrogen directly taken up by legumes does not turn into nitrous oxide in the process of being used by that crop (IPCC 2006). In addition, no emissions are generated in producing that nitrogen in the form of fertilizer. Unfortunately, almost no significant crops fix much nitrogen except legumes, which have special cellular structures called nodules. Sugarcane is the most significant exception because it interacts with select bacteria in different ways to fix some of its nitrogen (Cocking et al. 2006).

In the last few years, a few companies have been trying to develop bacteria that will interact with other crops to fix at least some of the nitrogen for them. Start-up companies including Pivot Bio and Indigo Agriculture are in this business and have received extensive venture capital funding. The massive agricultural company Bayer has joined with a start-up company to do this kind of work. Pivot Bio reports yield gains with its nitrogen-replacing product in several field tests in the United States. Yet it is difficult to evaluate these products' success at the time of writing because these companies have not made available underlying data for their claims, and the companies have offered limited explanations about how their products work. Because this is a novel and challenging field, some skepticism is appropriate.

Despite this reason for skepticism, at least one company, Azotic, based in Sheffield, England, has provided sufficient information about its product to justify active exploration of this category of solution in general and its product in particular. Its product is an outgrowth of work by the plant scientist Edward Cocking at the University of Nottingham, identifying a specific strain of the major bacterium that fixes nitrogen in sugarcane, known as Gd (*Gluconaaecetobacter diazotrophicus*) (Cocking et al. 2006). The company has demonstrated that it can get a wide variety of crops to use this bacterium to fix nitrogen abundantly in laboratory studies. (The company also reports success in the laboratory on maize, wheat, barley, oats, rapeseed, soybeans, white clover, grasses, tomatoes, and common beans.) This strain of Gd is reportedly able to colonize not only roots but cells on the leaves of a wide variety of crops, where it is closely associated with the chloroplasts (Figure 4.3). There it receives energy from the crop to function and in return fixes nitrogen into ammonium, making it directly available for use in the leaf. Key results have been published in the peer-reviewed literature (Dent and Cocking 2017), and the company has made available to us reports of other studies it has funded.

In the peer-reviewed article, the company's founding scientist cites field studies that generate the same yield as normal nitrogen application for both wheat and maize with 50 percent less fertilizer applied along with this strain of Gd (Dent and Cocking 2017). A company brochure claims similar results for these crops in more studies and increases in yields with only 25 percent less fertilizer. Experiments with rice in Thailand found 18 percent yield increases replacing 40–50 percent of nitrogen application with the product ("Evaluation on Efficacy" 2019).

Figure 4.3 | Colonization of Leaves with Nitrogen-Fixing Bacterium



Source: Cocking et al. (2006).

Note: Maize leaf: stained with safranin, showing long pleomorphic bacteria and extensive intracellular colonization of leaf cells with bacteria closely associated with chloroplasts. Scale bar 10 ɥm.

Price also does not appear to be a significant barrier. The price being offered for commercial use in the United States on maize, $9 per acre,[25] is by our calculations lower than the cost savings from replacing 25 percent of the nitrogen. The product has also involved no genetic engineering and is simply an identified strain of Gd naturally produced. It therefore avoids regulatory concerns and can be used for organic production. The company also reports that its product has already been used on more than 40,000 hectares of maize in the United States in 2019.

One major issue with use of Gd is that each crop may require a different mechanism for ensuring that Gd establishes itself in the crop. The product is immediately available for growing maize by disbursing a small amount of liquid with the seed in furrows at planting and, if it works, would be commercially viable now. For wheat, according to the company, there have been two issues. One, for winter wheat, is that the Gd microbe does not last the winter, so some new solution will be required to apply it in the spring. The company reports now that it has developed a dry seed coating that may be more effective and cheaper on maize and would also work and be cheap on spring-planted wheat and barley, potentially solving the challenge for spring-planted cereals.[26]

This type of product might contribute even more to improved yields with associated breeding. This product generates ammonium directly in cells that plants can use directly, and for reasons we explain more below, many crops benefit from a greater mix of ammonium with nitrate.

Like other innovative technologies, the success of this and related products is far from certain. The company has shared promising results conducted by agricultural testing companies it has hired, but there are only limited results from fully independent researchers. However, the idea is sufficiently promising to merit Danish collaboration with the company and possibly with other companies and researchers pursuing similar products. The first step would be a series of pilot tests. If such a product could supply one-quarter of a crop's nitrogen needs, it would dramatically help to address climate and broader environmental challenges in Denmark and the world.

Changing to more nitrogen-efficient crops

A third way of improving nitrogen use efficiency is to shift to more nitrogen-efficient crops. Fodder beets are a good example. We estimate fodder beet nitrogen use efficiency in Denmark at 66 percent. By contrast, we estimate winter wheat at 49 percent, spring wheat at 33 percent, and spring barley at 41 percent.

Another option might be shifting to grasses. The NUE for grass/clover mixes is roughly 50 percent, but some of that nitrogen not going into the crop is probably helping to build soil carbon, making the real losses low. According to a recent long-term experiment at Aarhus University, grass/clover mixes build soil carbon by 0.8 tons of carbon per hectare per year,[27] which implies that they are fixing around 66 kg of nitrogen per year. There is also experimental evidence of potential to achieve much higher efficiencies with grasses (Manevski et al. 2018). In addition, there is good evidence that less nitrogen leaches from these grasses as their roots are extensive and active enough throughout the year (Manevski et al. 2018).

In our land use discussions below, we encourage some shifts from barley or wheat to fodder beets and from silage maize to grasses. Such measures could also reduce emissions related to nitrogen.

B. Reducing direct and indirect nitrous oxide from soils

Although more efficient nitrogen application is one valuable strategy for reducing losses and emissions, nitrogen application will continue through manure, synthetic fertilizer, cover crops, and crop residues. It is necessary to reduce the emissions of nitrous oxide (N_2O) and nitrogen oxides (NOx) that occur from the nitrogen that will still be applied.

Nitrous oxide emissions will also continue, regardless of the level of nitrogen application, because much of the nitrogen that contributes to direct and indirect nitrous oxide is inorganic nitrogen that microbes release from organic nitrogen in the soils. (That is true even as much of the nitrogen applied that year by farmers goes into soils and comes out only in later years.) This nitrogen may be the majority of the nitrogen that leaches out of the soils, creating water pollution in general and leading to nitrous oxide indirectly (Dourado-Neto et al. 2010; Ladha et al. 2005; Zhao et al. 2016; Askegaard et al. 2015). Overall, Denmark estimates that nitrogen leaching from Danish soils each year equals 25 percent of all nitrogen applied to agricultural soils (NIR 2020).

Nitrification and urease inhibitors

Both the direct and most indirect emissions of nitrous oxide occur once nitrogen is in soils in the form of nitrate. Nitrate losses occur because nitrate (as an anion) does not adhere to most soil particles and so leaches away easily with water. By contrast, when inorganic nitrogen in soils is in the form of ammonium, it adheres well to soil particles. In addition, nitrous oxide is produced in small amounts in the microbial transformation of ammonium to nitrate (a process called "nitrification") and in larger amounts in the breakdown of nitrate. Nitrogen in the soils in the form of ammonium therefore does not contribute to nitrous oxide until it turns into nitrate.

One challenge, however, is that "nitrifying" microbes (both bacteria and archaea) are widely present and normally transform ammonium into nitrate within a few days in agricultural soils. A related issue in Denmark is that nearly all synthetic fertilizer—roughly half of total applied nitrogen—is applied as nitrate anyway and so is available to run off. (The other half of total applied nitrogen results from manure and air deposition and so must go through the process of transforming into nitrate before it will contribute to nitrous oxide or run off significantly with water.)

Nitrification inhibitors are one recognized method for reducing both nitrous oxide and leaching losses of nitrogen. These are chemicals that inhibit the enzymes in microbes necessary to turn ammonium into nitrate. Existing inhibitors tend to last only a few weeks. However, by applying them in the spring when nitrogen is first applied, they can keep more nitrogen from running off before crops need them. They can also have a disproportionate effect in reducing nitrous oxide because (a) inorganic nitrogen concentrations in soils (the form of nitrogen that can generate nitrous oxide) is highest after applications of manure or synthetic fertilizer, and (b) this earlier period often has the combination of dry and wet soil conditions that generate the most nitrous oxide (Sadeghpour et al. 2018).

Although nitrification inhibitors have long been identified for climate mitigation, in a 2018 study researchers at the University of Copenhagen estimated a very high mitigation cost, at around DKK 1,300 ($193) per ton of CO_2 mitigated (Dubgaard and Ståhl 2018, Figure 1.1). If that estimate turns out to be valid, we consider this cost too high for implementation. However, that estimate is based on several conservative estimates by researchers at Aarhus University: (1) nitrification inhibitors (NIs) reduce nitrous oxide only by 40 percent, (2) they do not increase yields, and (3) because of higher fertilizer prices, farmers reduce their fertilizer application and lower yields. (The analysis also assumed that farmers would be required to shift from nitrate-based fertilizers to an ammonium-based fertilizer, which would also be necessary.) The focus of this analysis was 2030, so a conservative approach was justified. We think there are reasons to be more optimistic over the period toward 2050.

- Although meta-analyses typically find nitrous oxide reductions of 40–50 percent on average (Akiyama et al. 2010; Yang et al. 2016), those averages hide wide variations, with many individual results at the 80 percent level or more. Much of that variation is likely due to weather conditions. For example, if the wet conditions that lead to nitrous oxide occur after the early spring, nitrification inhibitors will have little effect. But some variation is probably due to controllable, knowable factors if more carefully analyzed, such as variations in soils, consistent weather patterns, and crop types that might respond better to some kinds of inhibitors rather than others or to different doses or methods of application. Today, studies of inhibitor effects are too sporadic to yield this kind of consistent, management knowledge.
- It is possible to combine an inhibitor with coatings that delay release of the inhibitor and of the nitrogen and therefore can reduce nitrous oxide emissions for a longer period.

- Although results are extremely variable, one meta-analysis found increases in yield, by an average of 7.5 percent (Akiyama et al. 2010), and another by 9 percent for grains, 5 percent for vegetables, and 14 percent for hays (Yang et al. 2016). The result of such yield gains would be a large economic gain. 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 (Yang et al. 2016). The variability in results, however, is large, and many individual studies have found no yield gains, but even a small increase in yield for some crops can pay for the added cost of an inhibitor for that crop.
- These same meta-analyses have also found small increases in nitrogen use efficiency. Again, there is high variability, but few studies have deliberately tested a combination of using nitrification inhibitors and reduced fertilizer. Those kinds of tests are needed to determine if using inhibitors can achieve a higher nitrogen use efficiency.
- Finally, we do not agree that the costs of nitrification inhibitors should be evaluated by assuming that their costs will lead farmers to apply less fertilizer and lower yields. If higher fertilizer costs would lead farmers to reduce fertilizer but are otherwise justified as cost-effective ways of mitigating emissions, those added costs can be assumed by the government.

The opportunity to improve NI utilization and development is based on the underdevelopment of NIs to date. Because nitrogen fertilizer is relatively cheap, farmers have had little incentive to purchase NIs, and fertilizer companies have accordingly devoted few resources to developing better NIs or even to improving knowledge about how to use existing NIs. Climate and broader environmental considerations warrant a much stronger effort.

One way to improve NI use is to more systematically study their effects on yield and nitrogen use with different crops, with different crop varieties, in different soils, and over many years around Denmark. Variability in response is partially due to changing weather conditions but is also likely due to different microbial communities and interactions in different soils. As just one example of the controllable factors that are not well understood, one paper showed that both the method of storing inhibitors and the types of fertilizer they were used in greatly altered their effectiveness (Sha et al. 2020). Measuring nitrous oxide is important but difficult and expensive, so financial considerations will require carefully targeting those studies. But evaluating the effects of NI on yields and nitrogen use efficiency would be relatively cheap and would provide one measure of the effectiveness of inhibitors (and should be done with variable nitrogen rates). This work could yield quick results and could also be done in coordination with researchers in other countries.

A second way to improve NI utilization is to quickly test even existing NIs with different coatings that might prolong their use or to combine them with urease inhibitors. One limitation of existing NIs is that their effect diminishes rapidly (for some the effect is mostly absent after three weeks). But some portion of NIs might be coated to prolong effects. A variety of companies are offering different combinations of inhibitors, and it may even be possible to do these combinations and coatings in ways tailored to individual farm fields. This exploratory work could also be done quickly.

A third way is to develop better NIs. Only three nitrification inhibitors are in common use (Trenkel 2010)—the last released more than 25 years ago—and only in the last two years have fertilizer companies released two new variations, both chemical extensions of existing compounds. Soil microorganism communities are highly complex and are as likely to respond to different NIs in different places as bacteria are to respond to different antibiotics. Existing NIs also have limited effects. They likely inhibit the enzyme that catalyzes the first part of the nitrification reaction but not the second. Existing NIs also work on bacteria but do not appear to work on nitrifying archaea. Developing better NIs that are not toxic is a big effort that would probably require Denmark to coordinate with other countries.

Both public research and private regulatory incentives could be used to develop better NIs. To our knowledge, there is virtually no public research

Figure 4.4 | Researchers discovered that *brachiaria humidicola*, a planted grass commonly used in Latin America, releases biological nitrification inhibitors from its roots.

Source: CIAT

funding to develop new NIs or even to develop precommercial information that private companies might use to develop better products. In *Creating a Sustainable Food Future*, we also recommend regulations that would require fertilizer providers to increase their share of nitrogen fertilizer sold in combination with NIs over time—further elaborated in Kanter and Searchinger (2018). Doing so would provide strong private incentives both to develop better NIs and to identify which farms are likely to benefit from them.

We recommend an ambitious joint program between researchers and farmers to test out NIs in different combinations and with different coatings across Denmark. Research and regulatory programs, preferably in coordination with other countries, would also be appropriate to push their development. The results are uncertain, but we believe it is possible that nitrification inhibitors could become a cost-effective means of reducing nitrous oxide emissions by 50 percent from the nitrogen applied to agricultural fields.

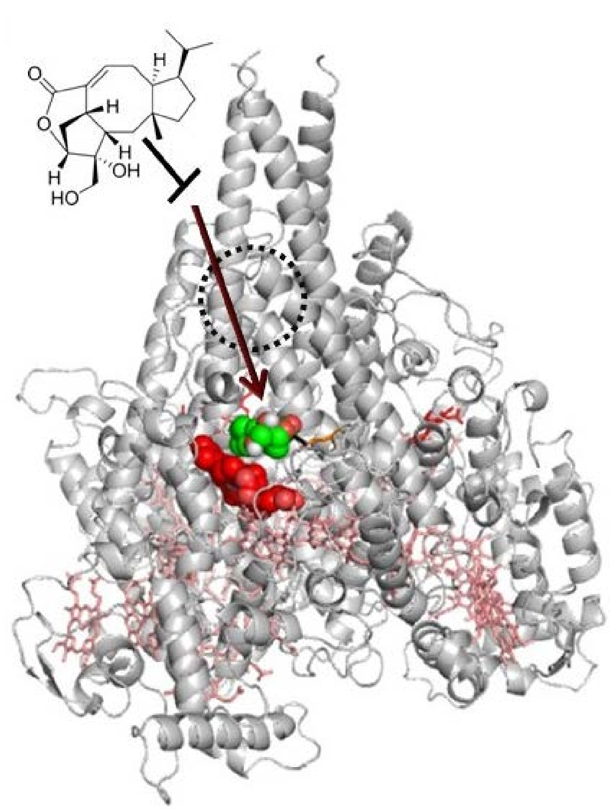
Acidification and other nitrification inhibition of manure spread on soils

Denmark already uses manure for half of its intentional nitrogen additions. Feed conversion efficiency improvements would reduce the total nitrogen in manure by 50 percent. But manure still causes nitrous oxide, and while the IPCC estimates that emissions per ton of nitrogen are the same from manure and synthetic fertilizer, there is some reason to believe they could be higher. Nitrification inhibitors can work on manure, and there are some test results, but there is far less analysis of inhibitors with manure than with synthetic fertilizer. Testing inhibitors with manure is therefore a priority.

Another possibility is that the acidification that provides one means of addressing ammonia will also reduce nitrous oxide. There is a limited literature, but one study found a 78 percent reduction in nitrous oxide emissions over a period of almost two months (Park et al. 2018), and other studies have also found large reductions although not necessarily as large (Fangueiro et al. 2015; Owusu-Twum et al. 2017). If acidification becomes a broadly utilized technique, either alone or possibly in combination with inhibitors, it might greatly reduce emissions. Testing these results in Denmark is a high priority.

Assuming that NIs can be as effective with manure as with synthetic fertilizer, we assume that a 50 percent reduction in nitrous oxide emissions from the manure ultimately applied to soils is possible.

Figure 4.5 | Nitrification inhibitors attach to parts of the first enzyme that enables bacteria to turn ammonium into nitrate, inhibiting nitrification.



Source: G.V.S. Subbarao (JIRCAS)

Biological nitrification inhibition

Ecologists have long recognized that little nitrogen is transformed into nitrate in certain tropical grass and forest ecosystems, but this phenomenon was long ignored by agronomists. Around 2005, researchers working in Colombia discovered low N_2O emission rates from tropical pastures of a commonly planted grass called *Brachiaria humidicola* (Figure 4.4). They subsequently traced these low rates of nitrification to chemicals exuded from the roots that worked to block nitrification (Subbarao et al. 2015). This property is known as biological nitrification inhibition (BNI).

Subsequent work by a loose, global coalition of plant scientists has been able to identify domestic or wild strains of sorghum, wheat, maize, and rice that also exude phytochemicals from roots with BNI (Subbarao et al. 2015; Tesfamariam et al. 2014; O'Sullivan et al. 2016). These discoveries create potential for breeding to strengthen the BNI effect and to incorporate the BNI trait into high-yielding varieties (using classical and molecular breeding tools and therefore without genetic engineering). Among cereals, sorghum and wheat BNI are the most developed, with several promising varieties identified and with some progress already made in breeding this property into high-yielding wheat varieties.

BNI has the potential to work not just more cheaply but substantially more effectively than synthetic nitrification inhibitors. Chemicals exuded by crops appear capable of blocking more of the enzymatic steps that turn ammonium into nitrate and are often released directly into soil microsites where nitrification most occurs. BNI might also be able to persist in soils well into subsequent years. For example, the residual BNI effect from *Brachiaria* pastures has substantially reduced soil nitrification rates and improved maize grain yields for three subsequent years in a *Brachiaria*-maize rotation (Subbarao et al. 2015). That would be particularly advantageous in Denmark in helping to control leaching.

At this time, the main prospect for BNI in Denmark is through wheat because high-yielding wheat varieties with BNI traits are farthest along in development. No significant BNI work has been done on barley, Denmark's second major crop, and maize is farther behind than wheat, although BNI properties have been identified in some maize germplasm.

The critical need for BNI is funding. The research has been undertaken in small amounts by a number of research institutions, with loose coordination by the Japan International Research Center for Agricultural Sciences (JIRCAS), without significant additional funding. Denmark by itself could increase the funding dramatically and could ideally work with other countries to do so as well.

Achieving yield benefits from nitrification inhibition

One way both chemical and biological nitrification inhibition can boost yields is by assuring that nitrogen remains in the soil until a crop is needed. That is more likely for sandy soils or when farmers apply nitrogen well before crops need it. The benefit would be influenced by rainfall patterns, which can explain some of the variability in results of using NI, but any such benefit could also be achieved by adding yet more nitrogen fertilizer.

Another way nitrification inhibition might boost yields is broadly unappreciated. Crops can absorb nitrogen in soils both in the form of ammonium and in the form of nitrate, but plants have dramatically different systems for absorbing, storing, transporting, and ultimately metabolizing each form of nitrogen. In cropland soils (other than rice), ammonium levels are extremely low because ammonium is converted quickly into nitrate. Crops therefore absorb nearly all of their nitrogen in the form of nitrate, and too much ammonium is toxic. But carefully controlled studies back to the 1970s have found that increasing the share of ammonium tends to increase crop yields substantially, often by levels of 40–70 percent (Britto and Kronzucker 2002). One recent paper found that even when adding nitrate had no more effect on maize growth, adding ammonium increased ear growth by 50 percent in the period after silking (Loussaert et al. 2018). Overall, because there are a variety of relative advantages or disadvantages for each form of nitrogen and different pathways for crops to use them, it makes sense that crops could often benefit from both.

There is also evidence, and it is intuitively likely, that different crop varieties have different capacities to benefit from higher ammonium.[28] Without some form of NI there has been no incentive to select or breed for this quality in crops because ammonium will not be available. But this property suggests a potential to select crop varieties (and breed others) that would have higher yields when combined with either chemical or nitrification inhibitors.

This experience suggests the opportunity to realize significant yield gains with either chemical or biological nitrification inhibition. For synthetic nitrification inhibitors, benefits might depend in part on prolonging the effect as in maize until well after planting. Even a quick variety selection program might help to identify these opportunities. We preliminarily recommend an active crop selection program with synthetic NIs, and that Denmark support breeding efforts to develop crops that respond even better to NI, BNI, and higher ammonium.

Limiting ammonia and nitrous oxide losses from land-applied nitrogen

One way of achieving higher nitrogen use efficiency is to reduce losses from soils to the air. The 2020 NIR (Table 5.27) estimates that roughly 20,000 tons of nitrogen are lost to the air through ammonia emissions from manure. Denmark estimates that roughly another 17,000 tons of nitrogen are emitted in ammonia from fertilizers, NOx from manure, and NOx from fertilizers. (NOx is a separate form of nitrogen from nitrous oxide but also occurs through nitrification and denitrification processes, and quantities are uncertain [NIR 2020, Table 5.27].) Overall, therefore, Denmark estimates that around 9 percent of the total quantity of nitrogen applied to soils is lost to the air.

Reducing these losses would reduce the roughly 200,000 tons of GHGs (CO_2e) that result from indirect nitrous oxide created when the nitrogen that escapes to the air from croplands falls back to the earth (NIR 2020). Reducing these losses would also contribute to a higher nitrogen use efficiency, and thereby both reduce emissions from manufacturing nitrogen fertilizer (discussed below) and potentially help to reduce direct nitrous oxide emissions because of lower application of nitrogen.

The first category of measures to reduce these losses are those that apply to ammonia losses during the application of manure. The feed conversion efficiencies we project reduce nitrogen from manure application by roughly 30 percent.

Acidifying manure in storage prior to field application can also reduce emissions from typical field application by two-thirds (SEGES 2017). Other alternatives for field application include injecting manure beneath the surface and the use of at least some kinds of urease inhibitors, both of which can probably reduce ammonia emissions by around 50 percent (Mikkelsen et al. 2006; Sigurdarson et al. 2018). As of 2015, 77 percent of cattle slurry and 37 percent of swine slurry is injected, so roughly half of manure is already partially controlled.

To control ammonia, it seems likely that there will be requirements in the future that all manure be applied in some way to control ammonia losses. The exact mix of solutions remains to be explored. Injection, for example, sometimes seems to enhance yields modestly, compared with surface application, but in some circumstances it can also increase nitrous oxide emissions. Because we believe such forms of application will need to be applied to reduce nitrogen pollution, we do not consider the GHG benefits of these controls to have an additional cost. Overall, we estimate that ammonia losses from manure that is already injected can be reduced an additional 10 percent and that the remainder can be reduced by two-thirds, for a total reduction from present conditions of slightly more than 40 percent.

The only realistic way to reduce much nitrogen leaching is for plant roots to intercept the water and take up much of the nitrogen.

A second category of measures are those that apply to NOx. NOx emissions result from the same processes of nitrification and denitrification as direct emissions of nitrous oxide. Although NOx emissions are far less studied, we assume here that the same measures that would reduce nitrous oxide emissions by 50 percent by reducing nitrification would proportionately reduce NOx emissions.

Some other measures we recommend to reduce direct nitrous oxide emissions from soils could increase ammonia emissions. Ammonia emissions from the use of synthetic fertilizer in Denmark are low because roughly half of the synthetic fertilizer applied is in the form of nitrate, which does not release ammonia (NIR 2020, Table 5.17). A substantial majority of the ammonia lost occurs from the roughly 25 percent of fertilizer applied as NPK (a combination of nitrogen, phosphorous, and potassium). The nitrate does, however, lead to high leaching losses and cannot be used with nitrification inhibitors to reduce nitrous oxide. To reduce losses of nitrous oxide, synthetic fertilizer needs to shift to some other nitrogen that could release more ammonia.

Despite this potential, we here assume that two measures would keep ammonia losses from synthetic fertilizer at present levels. First, our estimates of potential increases in nitrogen use efficiency from the present level of 47 percent to 63 percent (discussed overall below) would result in a reduction of synthetic fertilizer application by roughly 45 percent.[29] Second, we assume that synthetic fertilizer can be applied with a urease inhibitor. We here assume that these emission increases can be kept down through urease inhibitors. We assume that the effects balance each other out, so we assume that the ammonia emissions from synthetic fertilizer do not change.

The NIR also estimates that 13 percent of nitrogen losses to the air result from crops themselves or small nitrogen sources such as sewage sludge. We do not estimate any mitigation of these emissions.

Overall, these measures would reduce nitrogen losses to the air and therefore indirect nitrous oxide emissions by roughly 50 percent in addition to the reductions due to feed conversion efficiency. They would also modestly contribute to higher nitrogen use efficiency by 4–5 percent.

Reduced leaching nitrogen losses: Cover crops, earlier winter wheat planting

The 20–25 percent of applied nitrogen that leaches out of the root zone is officially a source of roughly 330 million tons of greenhouse gas emissions using IPCC default factors (NIR 2019). There is a reasonable chance that these emissions are underestimated. Much of Danish agriculture is drained, and studies using indirect measurements suggest that similar drained areas in the United States have higher emission rates (Turner et al. 2015). This leaching also contributes to emissions by requiring more fertilizer to replace it, leading to both higher direct nitrous oxide emissions and emissions from manufacturing. If nitrogen use efficiencies could increase to 65 percent from 47 percent, surpluses would be reduced by around one-third, which would help to reduce leaching.

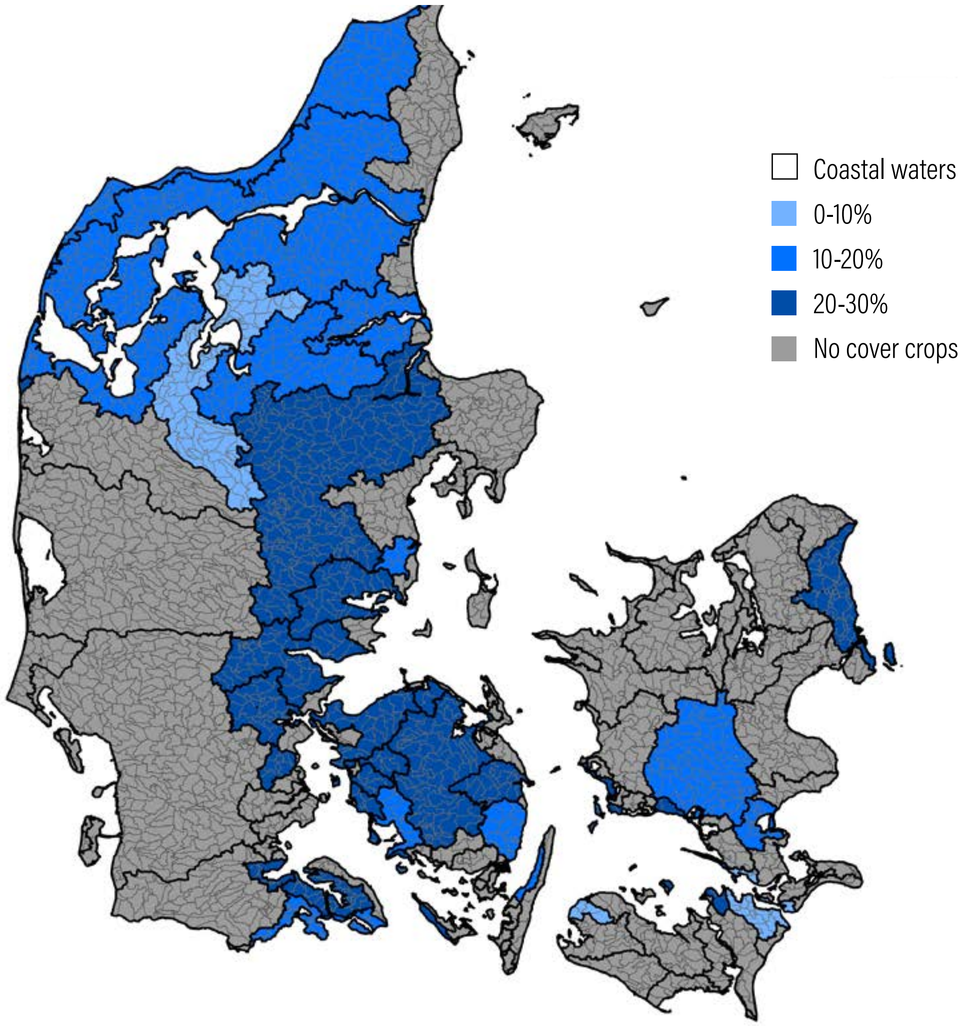
Yet even with low nitrogen application, most leaching would still remain—as found in Danish field tests with very low nitrogen surpluses (De Notaris et al. 2018, Table 2).[30] Studies have repeatedly shown that much of the nitrogen that becomes available in soils is mineralized that year from soil organic matter (even as new nitrogen goes into soils), which means nitrogen becomes available even when crops cannot use it and so can leach out of the soils in late fall and early winter (Askegaard et al. 2005). The only realistic way to reduce this leaching is for plant roots to intercept the water and take up much of the nitrogen.

One option is to plant winter wheat two weeks earlier than normal, which has been estimated to reduce nitrogen leaching from wheat fields by roughly 25 percent (Munkholm et al. 2017; Thiel et al. 2019).[31] Earlier planting is inhibited by potential increased weed pressures. Weed problems are serious, but we assume here that these problems can be solved, allowing earlier wheat planting. (There is far less winter barley and rye, but we assume the same for both crops.) Overall, in our 2050 scenario, these winter cereals occupy roughly one-third of all cropland that is not in grass production.

Another benefit could result from the "biorefinery" option discussed in Part 5. We include a scenario in which grasses replace roughly 120,000 hectares of silage maize or cereal crops. There is evidence that such grasses would reduce nitrogen leaching by roughly 70 percent from those lands (Manevski et al. 2018).

Cover crops provide another alternative. If established relatively early, cover crops in Denmark reduce nitrate leaching by roughly 50 percent compared with no cover crops (Aronsson et al. 2016; De Notaris et al. 2018). That result is consistent with results more generally (Abdalla et al. 2019; Kaye and Quemada 2017).

Figure 4.6 | Use of Cover Crops in Denmark



Source: LBST (2020).

Although cover crops are a valuable practice, cover crops today are already used on roughly 20 percent of Danish agriculture (Figure 4.6),[32] and we calculate that the maximum potential use is 45 percent because cover crops cannot be used on winter-planted crops such as winter wheat or on grasslands or other perennial crops. In addition, expanding cover crop use is challenging because both the practicalities and benefits of cover crops depend heavily on when they can be planted. Cover crops can be planted early after winter wheat, but they must be planted later after spring barley because of a later harvest and there is little time for cover crops to grow after late-harvested crops such as sugar beets.

Another issue is that cover crops may increase direct nitrous oxide emissions when plowed under in the spring. There is uncertainty about this result, but the evidence is strongest for this effect in climates such as Denmark's (Basche et al. 2014). Aarhus researchers report finding this result. Even if nitrous oxide rates are similar for cover crops and fertilizer, controlling their contributions to nitrous oxide through nitrification inhibitors will be important.

The costs of cover crops are today variable. Denmark has so far found the cost fairly modest if using a cheap seed source (spring radish) and cover crops are paid for by yield gains on sandy soils when planting spring barley (but not after rye) (Kristensen et al. 2019). In the United States, one study estimated that cover crops are on average profitable when grown for three years but not (absent special conditions) when used only for one (Myers et al. n.d.). This study, however, also found wide variability and was based on those farmers who used cover crops, which may not be representative of other farmers. Another U.S. study found that cover crops were profitable for growing vegetables but not for use with grains and oilseeds (Chahal et al. 2020). Because of differing conditions, these studies only suggest that the potential for cover crops to be more cost-effective if continued for several years should be studied in Denmark.

Because of the complexity of leaching, a sophisticated nitrogen leaching model is necessary to provide a proper estimate of both future leaching and potential reductions. Most of the nitrogen leached is unrelated to that year's nitrogen application or even many years' nitrogen application. Different watersheds will have different leaching rates, and drained peatlands may be a significant source of nitrogen leaching (Vassiljev et al. 2018). We here offer a rough estimate that the combination of earlier planting of nearly all winter cereals and expansion of cover crops to 40 percent of Danish agricultural land would reduce overall leaching by 25 percent.[33] We estimate that conversion of silage maize and cereals for fodder to grasslands as part of the biorefinery could reduce leaching by roughly 4 percent. We elsewhere contemplate restoring 400,000 hectares of cropland to peatland vegetation or forest, roughly 20 percent of cropland that is not in some kind of grass or other permanent crop, and we assume that would reduce leaching by at least another 20 percent. Overall, these measures would reduce leaching by 50 percent.

Because leaching is not proportionate to nitrogen application and is more related to land area in crops, we also assume that the increase in nitrogen use efficiency would be adequate to prevent any increases in leaching from added production. The component of leaching related to nitrogen application appears to be based on nitrogen surplus (the excess of nitrogen per hectare not absorbed and removed by the crop). Our projected increase in NUE cancels out the effect of even a 45 percent increase in production, so the surplus remains largely unchanged. We therefore apply our 50 percent reduction in leaching to 2017 leaching levels.

Aarhus researchers have been developing improved nitrogen leaching models. It should be possible to develop improved estimates of potential reductions. Such reductions are important not merely to reduce indirect nitrous oxide emissions but also to avoid nitrogen pollution. Beyond such analysis, we recommend the following:

- To make it easier to plant winter wheat earlier, develop methods for better addressing the increased weed exposure.
- To address the nitrous oxide from cover crops, test nitrification inhibitors at plowing.
- Continue to work on a variety of application methods and systems that could reduce costs and increase the success of cover crops.
- Seek to develop cover crops with higher yields. At present, cover crops sometimes generate only around one ton of dry matter above-ground yield per hectare per year, but they can generate two to three tons on well-manured soils with high nitrogen loads. In theory, it could be economical to harvest cover crops with such yields, but that is apparently not done. In the United States, some farmers graze cover crops. Research and projects should focus on boosting yields and economically utilizing cover crops.
- Test the yield and economic effects of sustained cover crop use over multiple years by establishing a set of test farms.
- Develop better cover crops. Research efforts to breed better cover crops are extremely limited. Desirable qualities to breed into cover crops include more rapid fall growth and good performance when planted as an underseeding in the spring.

C. Overall possible reductions in field-applied nitrogen and recommendations

These various strategies could possibly work together to achieve a two-thirds reduction in direct nitrous oxide emissions from applied nitrogen. That represents the combined effect of improvements in feed conversion efficiency, which reduces nitrogen by reducing the need for crops and reducing the nitrogen content of manure, increased nitrogen use efficiency, and nitrification inhibition, which reduces nitrous oxide by 50 percent from applied nitrogen. The improvement in nitrogen use efficiency itself can result from the combined effects of many changes: precision agriculture, nitrification inhibition, crop shifts, a nitrogen-fixing microbe, and reduced ammonia losses.

Based on this analysis, the basic recommendation is for well-funded, ambitious, coordinated efforts at research, development, and real farm experimentation.

- One effort that could be expanded most quickly is the use of nitrification inhibitors, which should be tested broadly on a range of nitrogen sources, using different inhibitors, coating differing percentages of NIs for delayed release. Researchers should measure nitrous oxide levels in some areas, but because doing so is expensive, researchers should even more broadly test NIs just for effects on yields and nitrogen use efficiency, which can be done cheaply. Participating farmers should establish test strips and be guaranteed compensation for any reduced yields.
- The work with nitrification inhibitors should proceed in parallel with efforts to identify crop varieties suitable for Denmark that achieve higher yields with an increased share of ammonium.
- Another effort that has potential for rapid scale-up is acidification of manure in tanks before application. This application should be tested for effects on both ammonia losses and nitrous oxide formation. Testing should be done with a range of different lowered pH levels on a range of soils to determine the right balance of acidification. Yields should also be tested at different application levels.
- Nitrogen-fixing microbes, if they work, might not only address Denmark's nitrogen challenges but also help to transform global agriculture. Although results are uncertain, the Azotic product in particular has a published, understandable scientific foundation rooted in the special qualities of sugarcane, and the company has shared test results that although paid for by the company have been carried out by independent companies. Broad success in Denmark depends not only on proving its success but also on developing a cost-effective mechanism for introducing it into each separate crop. Given the promise, Denmark should do some immediate, independent tests. If those are successful, Denmark should then explore a development partnership.

Reducing Emissions from Enteric Methane

Enteric emissions in Denmark amount to roughly 4.6 million tons, roughly 90 percent from cattle. Cattle produce these emissions through the digestion process. Denmark has already achieved a low emission rate per kg of milk relative to cattle globally because highly digestible feed leads to high milk production and cattle growth rates per kg of feed, and the quantity of methane decreases with less feed. Feeding additional fats to cattle can likely reduce enteric methane modestly, but in *Creating a Sustainable Food Future*, we found that doing so is likely not cost-effective.

The main opportunities to reduce enteric methane probably result from a feed additive plus cattle breeding. Extensive testing has identified many compounds that very briefly reduce methane but that then cease to be effective, presumably because the microbial community adapts. Here we discuss options that might work.

A. 3-NOP

In 2015, the first study was published indicating that one small molecule developed by the Dutch company DSM had a persistent ability to suppress methane production in cattle rumens (Hristov et al. 2015). Since then, multiple studies of cattle have shown that this small molecule, called 3-nitrooxypropan (3-NOP), generates sustained methane reductions. Several studies have found reductions of 30 percent or more in both cattle and sheep over at least several weeks (Jayanegara et al. 2018). Some studies have found reductions of only 20–25 percent (Melgar et al. 2020a), but the response appears dose-related. A recent study found that a medium dose (0.1 grams per kg of feed) achieved a 36 percent reduction in methane but a 46 percent reduction in methane corrected for energy in milk (Melgar et al. 2020b). Higher doses did not obtain more reduction. DSM reports that initial studies in Denmark have found reductions of 20–28 percent in methane per kg of feed but 28–40 percent reductions based on energy value in milk.[34]

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. Based on existing research, the chemical appears to have no adverse effects on animal health. Evidence of studies from 3-NOP and other studies of algae (discussed below) so far find that reducing methane harms neither animals nor their productivity. This testing alleviates concerns that methane inhibition might cause a dangerous build-up of hydrogen in the rumen. Toxicity testing also appears to be finding no toxicity (Thiel et al. 2019).

The science remains unclear as to whether 3-NOP increases production. Because ruminants lose up to 12 percent of the gross energy in feed as a result of the rumen's methane production, reduced methane production in theory has the potential to increase productivity or reduce the quantity of feed needed. Several studies of 3-NOP in dairy cows have not found any increased production of milk (Hristov et al. 2015; Melgar et al. 2021), and studies have not found increased weight gain in beef cattle (Jayanegara et al. 2018). Nevertheless, DSM is claiming results in Denmark, and at least one other study has found increased energy content due to higher milk fat (Melgar et al. 2020b), while another study hints at an improvement in feed conversion efficiency (Schilde et al. 2021).

Cost will also be an issue. DSM has not released its proposed pricing information, and we are not aware of the production costs. Assuming it is approved, 3-NOP would become the only additive with proven effectiveness at anything approaching this level. That at least temporarily gives DSM a monopoly position. There is, however, a mainly environmental market for 3-NOP, and this market therefore largely depends on government policy or voluntary industry agreement. These conditions suggest the opportunity for a negotiated price that would be reasonable to both producer and Danish agriculture.

Although DSM tests have occurred for three months without losing inhibitory effects, the tests have generally not been for longer periods. There was some hint in a recent paper of possibly declining effects over a longer period. There is therefore some risk that microbes could adapt to 3-NOP over longer periods. Yet results so far have been hopeful, and the maker of 3-NOP is working with researchers to develop models for optimizing its use.

DSM is still undergoing approval by European authorities. DSM expects final approval soon. Denmark should now be testing 3-NOP over longer periods. To make that more feasible, it does not need to undertake methane testing continuously, but it does need to compare methane results with controlled animals many more months after starting 3-NOP feeding.

B. Seaweed (algae)

Seaweeds made up of the red algae *Asparagopsis* contain compounds that suppress methane formation. For years, there were mainly studies of the effect of red algae in ruminant fluid in test tubes (Blain 2016), but there have now been successful tests at least for a few weeks in dairy and beef cattle. One paper found 45–80 percent reductions from beef depending on the feed ration (Roque et al. 2020), while another found methane reductions up to 98 percent using an algae with a higher level of active ingredient (Kinley et al. 2020). Another recent paper found that feeding cattle with 1 percent of dry matter from a red seaweed achieved 60–70 percent reductions in methane in dairy cattle (Roque et al. 2020).

Studies are also hinting at large reductions in feed conversion efficiency from feeding of algae. One beef study discussed above found 7–14 percent gains in feed conversion efficiency (Roque et al. 2020). Another beef study found an average 35 percent improvement in feed conversion efficiency, although the change was not statistically significant given a high level of variation. The dairy found 5 percent higher milk yield at this dose, even with 25 percent less total feed (Roque et al. 2020). Some of these gains exceed the potential energy savings from reduced methane but might be explained by a shift in the type of fatty acids produced in the rumen (with a higher proportion of propionate).[35]

It is now clear that the active ingredient that achieves this reduction is a form of bromoform called bromochloroform (BCM) (Machado et al. 2016). BCM also works to reduce emissions if given directly to cattle without the algae (Tomkins et al. 2009). This effective ingredient raises two concerns.

One issue is whether it poses a danger to the cattle or to people because BCM itself is toxic. However, the quantities in seaweed needed for cattle are small. Testing to date has found both no adverse health effects on cattle and no increased bromoform levels in milk or meat (Roque et al. 2019a, 2020; Kinley et al. 2020). One likely contributing factor is that bromoform is broken down by microorganisms in anaerobic conditions, the type that prevails in the rumen. Yet the quantity and length of tests run are limited, so more tests need to be run for longer periods to guarantee a lack of effects.

The other concern with BCM is that it is an ozone-depleting substance and growing red algae could release significant quantities to the atmosphere (Tegtmeier et al. 2015). Because previous research has provided no quantitative estimates of the potential risk even while raising this concern, we did our own rough quantitative analysis. Despite high uncertainties, our analysis indicates this issue is meaningful. Producing enough red algae to feed to all the world's cattle at the most likely needed application rates could possibly generate a level of ozone-depleting emissions that ranges from 5 to 50 percent of all present human emissions of ozone-depleting substances (Appendix D). We therefore believe that the only safe way to produce red algae would be to do so indoors, in controlled tanks, where air emissions could be filtered.

The practicality of doing that depends on the concentration of BCM in algae. In the concentrations used in some studies, such as Roque et al. (2020), 1 percent of the organic

Figure 4.7 | Red algae are showing high potential to reduce enteric methane emissions in cattle.

Source: Alexander Hristov

matter in feed would be required, which is unrealistic. But in Kinley et al. (2020), the researchers had access to algae with five times the concentration of BCM, which required an inclusion rate of only 0.2 percent. That also suggests a potential to generate even more concentrated algae to further reduce the inclusion rate. At these higher concentrations, the costs of producing the algae might be reasonable,[36] and there might be substantial cost savings if there are any meaningful gains in feed conversion efficiency.

Another solution might be to produce BCM synthetically and to feed it to cattle incorporated into some feed other than algae. Producing BCM separately is not a large technical challenge. However, if fed directly to cattle, BCM is toxic and therefore its use is broadly prohibited. But if BCM is not toxic to cattle when incorporated into algae in the amounts being fed, it seems likely that BCM could be added to another feed to achieve the same effect. There might be added public relations concerns with feeding BCM directly, but if it is acceptable to feed BCM to cattle through algae, there is no reason it should be worse to feed it to cattle in another form.

The potential ozone-depletion issues are a real concern, and the best evidence of BCM/red algae benefits are recent. But the potential benefits from the use of BCM are too high to ignore. Research should continue on algae and should expand to include alternative methods of delivering BCM. The research should study both the costs of producing algae in closed loop systems and ways to ensure that BCM is not released from the facility. Potential BCM releases from the storage of algae should also be investigated. Because public relations challenges could result if only one country used BCM, Denmark should take a leadership role in pushing research into this option at the European level.

C. Other methane inhibiting feed additives

Researchers at Aarhus University have identified a compound that reduces methane almost completely in laboratory test tubes. In the first feeding experiments with cattle in the fall of 2019, such a compound reduced emissions by either one-third or one-half in the two cows tested over four and six hours.[37] According to researchers, the compound could be produced cheaply. Yet far more research is needed to determine its effectiveness. Some additional testing is underway, but no details are available.

Another company has developed a compound based on extracts from garlic and bitter orange that achieved 38 percent and 20 percent reductions in methane in a dairy cattle study of two different breeds while boosting yields (Vrancken et al. 2019). One concern is that doing so required this supplement at 3 percent of total feed, which would require unrealistically large quantities of garlic and orange relative to present global production levels if this approach were used universally.

Nitrate is another compound that has been found to reduce methane emissions in several studies, typically by around 10 percent (Henderson et al. 2017). In one study, at a very high inclusion rate of 2 percent of nitrate per kg of dry matter, a Danish study found methane reductions of 23 percent (Olijhoek et al. 2016). We did not analyze this option more closely because the costs were estimated to start at around \$100 per ton of CO_2e and rise quickly (Henderson et al. 2017). It would be worthwhile to explore combination options that combine some nitrate with 3-NOP to determine if the effects are cumulative and whether nitrate can prove cost-effective at some level.

D. Breeding for reduced enteric methane

One hope has been to breed cattle that produce lower quantities of methane. Studies have found that some cattle produce less methane than others and that a portion of those differences appear to be inherited. The genetics appear to affect the microbiome (the precise mixes of different microorganisms) in the stomach of cattle in ways that influence methane emissions (Wallace et al. 2019). But there also appear to be influences on the methane emissions by genetics separate from the influence on the microbiome (Difford et al. 2018; López-Paredes et al. 2020). That suggests both that reductions could be obtained by breeding and that some of those reductions could be additional to those obtained by influencing the microbiome through feed additives.

Exactly how much reduction is achievable is unclear. One estimate suggests that breeding could achieve an additional reduction of 15 percent beyond that just achievable by increased output per cow within a decade (González-Recio et al. 2020).

Genetic improvement of livestock is a continuous project. There are different ways of measuring gains, which must be sorted out. As feed additives become available to reduce methane, it will also be important to favor those forms of genetic selection that generate additional reductions even when combined with those feed additives. Much of the breeding effort is international. Denmark should adopt a specific, quantitative policy for incorporating methane reduction into selection.

E. Possible enteric reductions and recommendations

The improvements in feed conversion efficiency discussed above would likely have major effects on enteric methane, and for our cattle scenario, we estimate a reduction of 34 percent.

The main opportunity to reduce methane in the near term, and beyond the effects of feed conversion efficiency, is 3-NOP. The best evidence now is that it can achieve 25–40 percent reductions in methane from milk on an energy-corrected basis. Pricing by DSM, the producer, has not been announced, but it seems likely to be based at least initially less on costs of production than on a negotiation between purchasers and DSM. Like any other developer of a new technology, DSM will have a temporary monopoly. We assume that such pricing will be reasonable and enable Denmark to start using 3-NOP soon. Regardless, patents only last so long, so we also assume that the costs of its production will allow for highly cost-effective mitigation in 2050. That is particularly likely given the emerging evidence that it increases energy content in milk, which means it could result in net savings. At this time, 3-NOP requires regular ingestion over the day, which limits its use in grazing cattle, but developing a delayed release format for grazing cattle seems possible. Overall, we assume modest improvements over time and that 3-NOP or some other feed additive could cost-effectively achieve a 45 percent reduction in emissions for cattle by 2050. (We also assume 50 percent reductions in the much smaller enteric methane emissions of pigs.)

Additional reductions also seem possible. Achieving an additional 10 percent reduction through breeding by 2030 seems a reasonable, although uncertain, estimate based on current projections, although these are based on only limited real experimentation. BCM can deliver even higher reductions, although it faces the issues we discuss above. Other compounds may emerge.

There is also some risk over time that archaea will develop resistance to 3-NOP or any alternative inhibitor. Rumen digestion produces hydrogen gas, which is an energy source that archaea can exploit. Archaea therefore have an evolutionary advantage if they can evolve defenses to any inhibitor and fully exploit this source of energy. The long-term, sustained inhibition of enteric methane is therefore not guaranteed.

Even so, based on our plausibility test, we assume a cost-effective reduction of 55 percent of enteric methane for 2050 based on both feed additives and breeding. If BCM could be successfully utilized, the initial evidence suggests the achievements could be even greater.

Based on these analyses, we offer the following recommendations:

- Denmark should negotiate with the producer of 3-NOP as soon as it is approved to test large-scale implementation within Denmark. If successful over one or two years, full-scale utilization should then occur, subject to a reasonable negotiation of price with the producer.
- We recommend increased funding for tests of effects on emissions of other alternatives, including combinations of 3-NOP with algae.
- We recommend that Denmark work with other countries to explore alternative mechanisms for delivering the small quantities of BCM, for longer tests of red algae in cattle, and for closed-loop methods of production.
- Finally, we urge enhanced efforts to breed cattle that emit less enteric methane.

Reducing Danish Agriculture's Domestic Energy Emissions

Denmark has roughly 1.7 million tons of CO_2e emissions from the use of energy for domestic agricultural production, of which roughly 700,000 result from nitrogen production, 600,000 from tractors and related fieldwork, 300,000 from energy used in the barn, and 100,000 from energy used in producing other fertilizers through heavy equipment.

Measures already described, if achieved, would cut roughly in half the requirements for synthetic fertilizer and therefore the emissions from their production. Nitrogen production would be reduced by 50 percent in our mitigation scenarios, depending on the production levels due to increased feed conversion efficiency (10 percent), decreased ammonia losses from manure (roughly 10 percent), and increased nitrogen use efficiency (30 percent). The feed conversion efficiency gains reduce crop requirements and therefore fertilization requirements by 10 percent. The reduction of ammonia losses by half from all the manure management measures described would cut the loss of roughly 20 percent of nitrogen in manure to 10 percent, which would reduce the need for synthetic fertilizer by roughly 6 percent in these scenarios. Because increases in nitrogen use efficiency do not alter the quantity of nitrogen in manure available, the 17 percent improvement our scenario contemplates in nitrogen use efficiency reduces fertilizer requirements by 31 percent. All the reductions in nitrogen requirements lead to reductions in synthetic fertilizer use. These measures are therefore valuable energy-saving measures as well.

Reducing emissions from nitrogen production further requires a different method of synthesizing ammonia used in fertilizer. As discussed in *Creating a Sustainable Food Future*, 85 percent of the energy involved in producing synthetic fertilizer, and therefore the vast majority of the emissions, results from the production of hydrogen gas (H2). Hydrogen today is produced mainly from natural gas, but it can be produced using electricity, and there are also direct methods under investigation to produce hydrogen directly from solar radiation without first producing electricity. Today, use of electricity to produce hydrogen is done at only a limited scale. But the synthesis of hydrogen using solar or wind power is a major focus of research and development in the energy sector because of its potential use as a fuel. A massive facility is being built in Saudi Arabia, and the European Union has been developing a green hydrogen development plan (Robbins n.d.). Projects are underway to synthesize hydrogen and from that ammonia in Australia. One key to the successful deployment of this process is likely the development of ways to economically produce ammonia using intermittent power sources, so that excess wind and solar power can be utilized when not needed for direct electricity use.

Cost-effective hydrogen production also faces great challenges. The large fertilizer company Yara is building a plant to use hydroelectric power to make hydrogen, but that option is not scalable. Hydroelectric power is limited and enormously valuable to balance out future electricity supplies from the intermittent sources of solar and wind, and any use of hydroelectric power for hydrogen production will come at the expense of other valuable uses. More promising is a proposed project by Yara and Ørsted to use offshore wind power to produce ammonia.[38]

Although these options are challenging, we ambitiously assume that no-carbon sources will replace 85 percent of the emissions from nitrogen fertilizer production by 2050. Combined with our other measures, that translates into a 90 percent reduction in this emissions source. (In part because this achievement is uncertain, reducing energy emissions by reducing fertilizer use also remains important in the ways discussed elsewhere in this report.)

The development of hydrogen fuels from wind or solar could also address the challenge of replacing fossil fuels in heavy equipment and tractors. The development of electric tractors is in the early stages and is more likely to be economical for small rather than large farm equipment (*Future Farming* 2020). Hybrid tractors also seem feasible as a mechanism for increasing tractor efficiency (Moreda et al. 2016).

In-barn energy use can be reduced by using solar and wind to decarbonize the overall electric grid and by using heat pumps. Uses that rely on intensive heat may require hydrogen or the use of the limited, bioenergy resources that are truly low carbon (as discussed below).

In general, there are also opportunities to increase energy efficiency in agriculture. They include more ideally sizing tractors, improved drying facilities, and more efficient heating systems in barns (Visser et al. 2012). We have not studied these opportunities in Denmark, however.

Overall, in addition to the different benefits generated by feed conversion efficiency gains, we assume 90 percent reductions in energy emissions that are easiest to switch to alternative energy sources, which are barn operations and pesticide manufacture. We also assume 85 percent reductions from field operations, nitrogen fertilizer production, and phosphorus and potassium fertilizer production due to its reliance on heavy mining machinery. Overall, these changes result in a 90 percent reduction in energy emissions.

Achieving these emissions is challenging and mostly out of the control of the agricultural sector as most are based on developing a cost-effective, carbon neutral energy source such as hydrogen from wind and solar that can power heavy machinery and nitrogen fertilizer production. The agricultural sector can push for this work in the energy sector to proceed and to focus on agricultural uses.

Reducing Production Emissions for Feed Imports

According to our estimates, of the roughly 2 million tons of production emissions for growing feeds imported into Denmark, roughly half are involved in the production of sugar beet pulp, and the vast majority of the rest are for oilseed cakes from soybeans, rapeseed, or other oilseeds. As with crops within Denmark, the major emissions are from nitrogen use and energy use on farms.

Overall, the tools available to reduce these emissions are similar to those for reducing Denmark's crop emissions. One challenge is that roughly one-quarter of these production emissions come from soybeans, which are already efficient nitrogen users because they are legumes.

The mechanisms for Danish agriculture to reduce these emissions are to work with suppliers to help them to use some of the same techniques recommended for production in Denmark. Because these are commodity imports, Denmark will not know the precise sources of its supplies. But Denmark could work with groups of suppliers that produce the quantities of crops that match Denmark's imports and take credit for their reductions. We have not generally investigated these issues in depth. Because Denmark will have less control, we will assume "only" 50 percent reductions in these production emissions.

Overall Possible Production Emissions Reduction Potential

Our overall finding is that it is possible to reduce Denmark's domestic production emissions by roughly 80 percent per kg of food prior to factoring in offsets (Table 4.8). Doing so depends on the successful development and deployment of many technologies, although not all of the technologies we have described need to work. The successful approval of 3-NOP for enteric methane inhibition and the success of manure acidification are particularly significant, but we consider them likely at this time. The success of a bacteria that could fix a large fraction of nitrogen would have huge significance for nitrogen mitigation, but we consider it substantially less certain at this time.

Our estimate of an 80 percent reduction in emissions per unit of food remains similar regardless of Denmark's level of production. (The main exception is that peatland restoration could occur at any production level.) The total emissions would change with the level of production (and would therefore be roughly 45 percent higher with a 45 percent higher production). Based on the level of production, our projected emissions in 2050 with our mitigation scenario—prior to factoring in any offsets—vary from 4.4 million to 6.1 million tons depending on the level of production increase.

These emissions must be offset in some way. Bioenergy from straw and soil carbon gains can make a small but meaningful contribution. Most of the offsets can come from forest restoration if combined with appropriate gains in land use efficiency so agricultural production does not simply shift to other locations.

Table 4.8 | Summary of Mitigation Potential of Production Emissions (Excluding Soil Carbon and Bioenergy Offsets)

CATEGORY	2017 PRODUCTION BASELINE	AFTER MITIGATION	25% HIGHER PRODUCTION BASELINE	AFTER MITIGATION	45% HIGH PRODUCTION BASELINE	AFTER MITIGATION
Nitrous oxide from fertilizer	1.14	0.30	1.42	0.38	1.65	0.44
Nitrous oxide from manure	1.01	0.36	1.27	0.45	1.47	0.52
Nitrous oxide from residues	0.61	0.25	0.76	0.31	0.88	0.36
Other	0.05	0.03	0.07	0.03	0.08	0.04
Grazing manure	0.18	0.05	0.22	0.06	0.25	0.07
Indirect: leaching	0.19	0.10	0.24	0.12	0.28	0.14
Indirect: atmospheric deposition	0.38	0.20	0.47	0.25	0.54	0.29
NITROGEN APPLICATION TOTAL	**3.55**	**1.28**	**4.44**	**1.60**	**5.15**	**1.86**
Enteric dairy	2.77	0.82	3.46	1.03	4.01	1.20
Enteric cattle nondairy	1.26	0.37	1.58	0.47	1.83	0.54
Enteric pigs	0.42	0.18	0.53	0.23	0.61	0.27
Enteric other	0.16	0.08	0.20	0.10	0.23	0.11
ENTERIC TOTAL	**4.60**	**1.46**	**5.75**	**1.83**	**6.67**	**2.12**
Energy emissions field operations	0.52	0.05	0.65	0.06	0.75	0.07
Energy barn operations	0.29	0.02	0.36	0.03	0.42	0.03
Production of nitrogen fertilizer	0.72	0.10	0.90	0.12	1.04	0.14
Production of phosphorus and potassium fertilizer	0.04	0.00	0.04	0.01	0.05	0.01
Production of pesticides	0.08	0.01	0.10	0.01	0.12	0.01
TOTAL ENERGY USE	**1.64**	**0.18**	**2.05**	**0.22**	**2.38**	**0.26**
Manure management dairy	-	-	-	-	-	-
METHANE	0.85	0.07	1.06	0.09	1.23	0.11
Nitrous oxide	0.29	0.03	0.36	0.04	0.42	0.04
Manure management pigs	-	-	-	-	-	-
METHANE	1.36	0.18	1.70	0.22	1.97	0.26
Nitrous oxide	0.22	0.03	0.28	0.03	0.32	0.04
TOTAL MANURE MANAGEMENT	**2.72**	**0.31**	**3.40**	**0.39**	**3.94**	**0.45**
Peatlands	4.80	0.24	4.80	0.24	4.80	0.24
Liming	0.21	0.21	0.21	0.21	0.21	0.21
Other (residue burning CO_2 from urea)	0.01	0.01	0.01	0.01	0.01	0.01
International production emissions	**1.35**	**0.67**	**1.68**	**0.83**	**1.95**	**0.97**
TOTAL PRODUCTION EMISSIONS, DOMESTIC AND INTERNATIONAL WITHOUT OFFSETS	**18.88**	**4.35**	**22.35**	**5.33**	**25.12**	**6.11**

Source: Author's calculations.

PART 5

Achieving Land Area Carbon Neutrality and Generating Offsets

Critical contributions to solving climate change include increases in output of food per hectare, first, to avoid increasing agricultural area and, second, if possible, to reduce land area and utilize that available land to restore peatlands and forests.

Our measure of Denmark's "hidden" land use costs using COCs counts the annualized carbon costs of devoting land for Danish agricultural production, but carbon neutral land use—land use that neither adds nor reduces CO_2 emissions—cannot require eliminating COCs. If agriculture were to avoid all COCs, it would have to stop using land altogether. The typical meaning of carbon neutrality is to avoid adding carbon to the atmosphere. For land use, we believe that requires changes to avoid increasing Denmark's land area carbon footprint. By the same reasoning, meeting rising food needs while reducing agricultural land use area should provide carbon reductions.

The challenge is factoring these common-sense global needs into ways of properly analyzing Denmark's change in emissions from land use between now and 2050. Typical ways of counting greenhouse gas emissions and reductions on a national basis do not factor in changes in food production at all. If Denmark were to eliminate its agricultural production and reforest all of its land, the gains in carbon sequestration would be counted regardless of whether doing so increased overall land use demands and carbon losses. That is why our approach has used COCs.

The test is to be "land area carbon neutral." Our approach to that test starts with the mathematical principle that to achieve "carbon neutral land area use," the land use efficiency of global agriculture—the output of "food" per hectare—must grow at the same rate as production. Land use efficiency here refers to the combined effects of increases in crop yields and livestock feeding efficiencies. If production rises 10 percent, land use efficiency must rise 10 percent.

To be land area carbon neutral, land use efficiency should increase at the same percentage as global increases in food production.

This increase in global land use efficiency could be achieved with high growth rates by some countries and less by others, so countries could claim that they are entitled to do so less than others and still be considered carbon neutral. For example, Denmark could claim that because its agriculture is already land-efficient, due to high crop yields and feed conversion efficiencies for dairy and pork, it should be considered land area carbon neutral even if its efficiency gains are lower than the global average need. In contrast, many poorer countries may face greater economic and logistical challenges in increasing yields and claim that it is they who should have to increase efficiency less while richer countries do more. An ideal global economic response would assign the burden and resources to increase land use efficiency wherever it is cheapest.

Another perspective might be that countries should increase their land use efficiency only to the extent they increase their production; for example, a 10 percent increase in production requires a 10 percent increase in land use efficiency. Although that sounds reasonable, it basically means that existing farms that happen to be in a country with expanding food consumption and production can only be considered carbon neutral if they vastly increase their land use efficiency—far more than the global average need. Identical farms in countries that are not expanding production would not need to increase their land use efficiency at all.

Although we recognize possible different arguments, we adopt as the basic rule that to be counted as achieving carbon neutral land use, agriculture everywhere should share equally in this global burden. That means agricultural production will only be counted as land area carbon neutral if it increases its land use efficiency at the same percentage as global increases in production. The starting date counts, and here we use 2017, which is our base year.

This rule then raises the question of how to calculate a percentage increase in "food," as "food" consists in fact of vastly different foods with different yields. There is a mathematically correct answer that derives from the need to avoid land use change. Each food must be weighted by its different land use requirements and different levels of production increase so that the gains in all foods are sufficient to avoid land expansion. COCs provide just such a weighting. As we describe in Appendix A, we have used COCs and the food projections of the GlobAgri-WRR model to estimate the likely average increase in land use efficiencies for all foods globally necessary to avoid land expansion in 2050. Using this measure, we estimate that production will expand by 45 percent between 2017 and 2050, which means land use efficiencies must also grow by 45 percent.

Over time, it is not our projection but actual increases in global production that will define this obligation. For example, if massive and unlikely dietary change were to hold the growth in food demand to 25 percent, then the global land use efficiency target for agriculture would be only 25 percent. We describe briefly in Appendix A how these calculations can be made over time.

For planning purposes, we use this 45 percent scenario, the "proportionate global growth" scenario, to estimate what levels of land use efficiencies Denmark needs to achieve to be counted as having carbon neutral land use. Mathematically, also, if we use for analysis a scenario in which Denmark increases its production by 45 percent, we can measure whether land use efficiencies are growing sufficiently by just counting the changes in hectares to meet this added production. In other words, if hectares required for this production increase, then Denmark has not met this land use efficiency target, but if hectares decrease, then Denmark can restore land and count the carbon gained as carbon sequestration offsets.

Denmark has 2,465 million hectares of cropland in our baseline. With a 45 percent increase in food production, this cropland would grow precisely by 45 percent, an increase of 1.109 million hectares.

Using this scenario, land use efficiency gains must increase sufficiently to avoid this expansion to achieve land area carbon neutrality. Because Denmark's pledge for carbon reductions applies to emissions within Denmark, we separately identify land use efficiency targets and related measures for achieving carbon neutrality from agricultural activities within Denmark and from production of feed imported into Denmark.

We emphasize that using this 45 percent increase scenario for analysis does not mean Denmark has to increase its production by 45 percent to be carbon neutral. Instead, it is a mathematical tool that we can use to estimate the gains in land use efficiency as a percentage to achieve carbon neutral land use at any level of production. Denmark could choose to produce less and reforest more land for reasons other than climate. To be considered land area carbon neutral, however, whatever agriculture Denmark continues to produce must occur with this increase in land use efficiency.[39]

We divide the land use discussion into three sections:

- First, we analyze the potential for Denmark to achieve land area carbon neutrality in Denmark alone and to achieve sufficient feed efficiency and yield gains to free up lands for reforestation in Denmark to generate further carbon reductions.
- Second, we analyze the potential for such land use efficiency gains abroad to make Denmark's international feed use land area carbon neutral and to allow reforestation and offset production emissions for production emissions for imported feed.
- Finally, we put these different components together to describe how Danish agriculture could become a net source of global reforestation sufficiently to offset production emissions.

Increasing Agricultural Land Use Efficiency in Denmark

We examine several ways of increasing land use efficiency in Denmark. The first goal is to be able to produce 45 percent more food without expanding land area. The second goal is to produce this much food on less land, allowing land to be reforested, to sequester carbon and to offset Denmark's remaining production emissions from agriculture.[40]

A reasonable estimate is that each hectare of land no longer needed for agriculture can through reforestation on average sequester 3 tons of carbon per year for many decades, which equals 11 tons of CO_2.[41] This estimate is based on average forest carbon uptake rates, which include plantation forests that grow in early years more rapidly than natural forests. Plantation forests will not, however, store more carbon in the long run, and they provide a fraction of the biodiversity of natural forests.

However, researchers have also identified ways of transitioning older, highly managed forests into more natural forests that would more rapidly support biodiversity than starting from agricultural land (Møller et al. 2018). One possibility would be to plant more rapidly growing species for wood production and then simultaneously transition existing forests into more natural vegetation. Although this potential requires further analysis, we use 11 tons of CO_2 per hectare per year as our estimate of average carbon gain.

A. Increasing feed conversion efficiency

In the first part of the discussion of production emissions, we estimate the potential to increase feed conversion efficiency. These same increases would also reduce the agricultural area needed for any level of production. When we factor livestock efficiency gains into our 45 percent production growth scenarios, we find that the combination of these gains and the crop yield gains in our baseline are sufficient to limit 30,000 hectares even at the higher level of production. Additional land-saving measures are necessary to achieve domestic land area carbon neutrality, to offset the carbon opportunity costs of eliminating crop production on restored peatlands, and to allow sufficient reforestation to offset remaining production emissions.

B. Higher crop yield gains

One way to save additional land for reforestation would be to increase yields. We start by assuming that yields can continue to grow in Denmark based on recent trends. Our trend line estimates assume Denmark's wheat yields grow at the average growth rate of Danish and European yield gains, which adds up to a yield gain of 14 percent between 2017 and 2050. For barley, yield growth rates in Denmark and Europe as a whole are almost identical, and we use a rate of an additional 42 kg per hectare per year, which adds up to a 24 percent increase in that period. For rapeseed, yield growth in Denmark has been spectacular in recent years, and because that is hard to imagine continuing, we use an average of growth rates between Denmark and Europe as a whole, which would increase yields by 34 percent by 2050. (Table 5.1 shows our estimated yield gains and their relationship to Danish and European trend lines.)

What are the prospects for higher yields? A little more than half of Denmark's agricultural land is in wheat and barley, with rye developing as an alternative to barley, so we focus here primarily on them.

For wheat, there has been high concern that yields in the high-yielding countries of Western Europe have not been growing significantly in recent years (Brisson et al. 2010; Le Gouis et al. 2020). Yet genetic progress in yield potential has still been growing (Brisson et al. 2010; Petersen et al. 2010). European problems have been attributed to climate change, possibly reduced fertilization, and shifts away from legumes to rapeseed as an alternating crop. In Denmark, researchers have blamed increased use of manure for reduced fertilization and soil compaction (Petersen et al. 2010).

Another limitation is that Denmark already has some of the highest wheat yields in Europe and the world and changes in management alone may have limited capacity to boost yields. Researchers evaluate this potential by estimating a rainfed cropping "yield gap." That represents the difference between the yield farmers achieve and the yield researchers estimate they could achieve with ideal management given an area's rainfall patterns, soils, and other climate characteristics. Using a crop model to estimate maximum potential yields, one study found substantial yield gaps for wheat across much of Europe, but Denmark had the lowest gap, less than 10 percent (Schils et al. 2018). The implication is that management changes alone have little potential to boost Denmark's wheat yields.

Addressing soil compaction, however, provides one example of management changes that might boost yields even for wheat. Restricting heavy machinery to permanent lanes, called "controlled traffic farming," provides one option that might be increasingly used (Hefner et al. 2019).

Researchers have also demonstrated that breeders continue to increase wheat's potential yield—its yield with perfect management—through the time-honored practice of steadily selecting for higher-producer varieties. Even without major breakthroughs, one analysis estimated that just

Table 5.1 | Yields in 2050 Based on Danish or European Trend Lines

CROP YIELD (T/HA)	2017 YIELD	2050 YIELD (DENMARK TRENDLINE)	YIELD GAIN	2050 YIELD (EU TRENDLINE)	YIELD GAIN	USED YIELD GAIN
Barley	5.81	7.19	24%	7.25	25%	**24%**
Wheat	7.67	8.45	10%	9.07	18%	**14%**
Rapeseed	3.81	5.97	57%	4.23	11%	**34%**
Maize	7.80	*	*	10.24	31%	**31%**
Rye	6	9.12	52%	**	**	**24%**
Other						**15%**

Notes: * Insufficient years of data for maize trend line in Denmark.
** Europe-wide rye yields are too low to provide basis for Danish yield growth estimates.

Source: Danish Statistics and FAOSTAT for existing yields and future yields authors' estimates.

selecting for the best pattern of ideal traits could increase yield potential by between three and five tons per hectare per year (roughly 40–60 percent above present Denmark yields) (Senapati and Semenov 2020).

There is also no shortage of breeding ideas for breakthroughs to increase yields. They include breeding strategies to increase wheat's heat tolerance (Stratonovitch and Semenov 2015), although that is unlikely to be a problem in Denmark, and its efficiency in use of nitrogen (Zörb et al. 2018). A bigger change would be a move to "hybrid" wheat. Wheat, like most other grains, is self-pollinating, which means its offspring's genes come only from the parent. Hybrid crops use human interventions to ensure that seeds are the offspring of two separate parents. Hybrid maize has resulted in substantially higher yields since the 1930s, but hybridization has not been able to consistently and significantly increase wheat yields enough to justify the added expense. Yet scientific developments, using modern biological methods for identifying beneficial genes, suggest potentially higher yields through hybrid wheat (Zhao et al. 2015). Even more dramatically, scientists in Illinois have started to make breakthroughs that for the first time are dramatically improving photosynthesis and that could allow for substantially higher yields in a broad range of crops by 2050, including wheat (Ort et al. 2015). As discussed above, nitrification inhibition, including biological nitrification inhibitions, may also be able to significantly increase yields if combined with crops selected to take advantage of higher ammonium shares of soil nitrogen.

Breeding opportunities for barley in general match these kinds of opportunities in wheat (Senapati and Semenov 2020; Mühleisen et al. 2013). In addition, the crop yield gap analysis cited above found a barley yield gap in Denmark of 30–40 percent (Schils et al. 2018). Although all yield gap analyses have substantial levels of uncertainty (as discussed in *Creating a Sustainable Food Future*), this analysis provides at least some evidence of a significant potential to increase barley yields in Denmark through management changes alone.

After wheat and barley, the dominant crops in Denmark (occupying one-third of all cropland) are some kind of grass, grass-legume mix, or other fodder crop. Although data are limited, our "trend line" estimates their yield gain at roughly 15 percent.[42] In our discussion of biorefineries, below, we find high potential to increase forage yields, for example, by shifting to festulolium.

Although uncertain, we believe there are scenarios in which yields would grow not at trend line estimates over the last 20 years but at 50 percent higher rates. Table 5.1 shows the yields that would have to be achieved, and the yields seem achievable.

How can Denmark pursue these higher yield gains? In the past, many yields gains were achieved by adding synthetic fertilizer, draining wet fields, and in other countries, adding irrigation. But precision agriculture provides a set of tools for improved management. And the revolution in microbiology, even without genetic engineering, provides a wide variety of new tools for identifying and quickly selecting different plants to breed improved crop varieties. WRI discusses these new tools in *Creating a Sustainable Food Future*.

The policy need is to increase resources for crop-breeding and target them at the range of promising opportunities. That is not a project Denmark should undertake on its own, but it is also not a task Denmark should leave to others: Denmark's crop selections, such as heavy use of barley, and climate give it priorities shared by a limited number of other countries. Denmark should work with other governments, private companies, and international breeding institutions to expand coordinated efforts to achieve the key breeding breakthroughs.

C. Reduced fallow land

Danish statistics identify roughly 50,000 hectares of agricultural land left fallow on average. Some of that fallow probably represents different agronomic challenges that make it impossible to plant or harvest land. But some of these lands probably are the result of public policy. EU policy provides incentives to devote land to environmental focus areas that can include leaving lands fallow but

Table 5.2 | Yields at Present, in the 2050 Trend-Line and in the Higher Yield Scenario

CROP	2017 YIELDS IN UNITS t/ha	2050 ASSUMED YIELDS IN UNITS t/ha	2050 HIGHER YIELDS IN UNITS t/ha
Winter wheat	7.59	8.50	8.96
Spring wheat	4.79	5.36	5.65
Rye	5.92	8.58	8.58
Triticale	6.02	7.83	8.73
Winter barley	6.316	7.28	8.31
Spring barley	5.444	6.59	7.16
Oats and dredge corn	4.71	5.42	5.77
Grain maize	6.97	9.34	10.52
Winter rapeseed	3.78	4.88	5.42
Beets for sugar production	67.95	78.14	97.51
Fodder beets	69.35	79.75	84.95
Lucerne	49.822	57.30	61.03
Maize for green fodder	37.29	42.88	45.68
Cereals for green fodder	17.446	20.06	21.37
Grass and clover in rotation	46.436	53.40	56.88
Permanent grassland out of rotation	15.668	18.02	19.19
Aftermath, cereals silage and silage	5.628	6.47	6.89

Source: Authors' calculations using yields from FAOSAT and Statistics Denmark.

does not include reforestation. Danish rules on cover crops to reduce nitrogen loadings also allow farmers to reduce cover crop areas by allowing some lands to remain fallow.

Some of these lands probably already provide valuable habitat without being reforested. But we assume that reforming policies to credit reforestation in place of environmental focus areas or cover crop requirements would allow for the reforestation of 15,000 hectares, roughly one-third of these lands.

D. Grasses and biorefineries in Denmark for protein feed

One way to increase food production on existing agricultural land in Denmark is to use some land to generate feeds that substitute for feed imports, which for Denmark are mostly high-protein oilseed cakes, particularly those from soybeans. Others have looked at options for increasing food production considering that any production in Europe that replaces soybeans reduces global deforestation and saves land. Our approach is different, but we still believe the "biorefinery" idea has significant potential to save land globally, although doing so requires achieving high grass yields.

The biorefinery approach seeks to replace some of Denmark's imported protein cake by producing a high-protein grass or a grass and clover mixture and refining much of the protein into a substitute for soybean cake. Overall, 19 percent of the dry matter in the crop would replace soybean cake as a high-protein feed for any livestock (Jørgensen and Lærke 2016; Manevski et al. 2018, 2016).[43] Most of the remainder, 56 percent overall, would still have good protein levels and could substitute for maize silage or any other silage as a cattle feed. The remaining 25 percent waste would be suitable for bioenergy use. In addition to these feed uses, such a system could have environmental benefits over maize silage in lower leaching of nitrogen, less soil erosion, potentially higher habitat values for insects and birds, and soil carbon gains.

Much of the interest in this concept is based on a too-simplistic goal of avoiding the import of soybeans. The theory is that demand for soybeans is causing deforestation in Latin America. In fact, as we discuss above, some life-cycle analyses, including those by the Food and Agriculture Organization of the United Nations (FAO), assign land use costs only if soybeans are purchased from Latin America. With such an "accounting" approach, to the extent Denmark replaces soybeans with biorefinery protein feeds, it eliminates all emissions from land use change even if doing so replaced wheat and required importing more wheat from elsewhere in Europe.

We disagree with that simple conceptualization of the challenge. Although it is true that soybeans are a globally expanding crop, that is being driven not by any particular "evil" of the soybean but by growing global demand for meat and dairy. Given the global demand, an important reason that soybeans are expanding is that they—like rapeseed—have high yields relative to alternatives (such as peas) for supplying this feed. It would be a mistake to produce more protein meal in Europe at the expense of requiring more agricultural land globally.

The first question is whether a biorefinery system provides a net increase or decrease in Denmark's land carbon footprint. Fortunately, carbon opportunity costs provide a means of evaluating this question based on different yields and uses of grass-based, biorefinery outputs. They recognize, for example, that globally (and within Europe), more carbon is lost from vegetation and soils on average to produce a ton of soybean meal than to produce a ton of wheat or a ton of silage maize. The calculation generates a number for "carbon benefits per hectare," for example, for wheat production in Denmark. These carbon benefits represent the annualized average amount of carbon dioxide that would be emitted from land use change if these crops had to be produced on other land. The difference between use of a Danish hectare of agricultural land for the biorefinery and its use as present for wheat, silage maize, or barley, for example, represents the net land use carbon advantage or disadvantage of using the land for the biorefinery.

Overall, as Table 5.3 shows, the benefits depend heavily on the yield.[44] At present average dry matter yields for grass clover of almost 9 tons, the benefit of 16.3 tons of CO_2 per hectare per year from biorefining is sufficiently close to silage maize of 14.6 tons that it is not reliably better. But if grass or legumes could achieve the same yields as silage maize, 11.2 tons of dry matter (DM) per hectare per year, the benefits of 21.9 tons of CO_2 per hectare per year would exceed the benefits of silage maize by 50 percent.

If grass yields could be higher, the land use benefits of a biorefinery would be much greater. For example, if grass yields could achieve 20 tons of dry matter per hectare per year, the savings in COCs from protein meal would reach 18.2 tons of CO_2 without any reduction in fodder produced per hectare for cattle and therefore no requirement for more land devoted to fodder production in Denmark. It is also possible, perhaps likely, that the fiber produced by biorefineries will turn out to be of higher quality than silage maize, as studies so far have found higher energy uptake and milk yield (Jørgensen and Lærke 2016). That could increase the benefits meaningfully.

One option that might generate these higher yields would be to use festulolium, a cross between rye grass and fescue. In a controlled experiment, Aarhus researchers were able to obtain festulolium yields of 20 tons of dry matter per hectare per year at one site and 15 tons in another (Manevski et al. 2018). Because of the resources that researchers can devote to small research plots, researcher yields are typically higher than the yields farmers will achieve on average in the real world. But there is also potential to breed festulolium to achieve higher yields (Manevski et al. 2018), particularly because breeding efforts have been modest.

Production emissions from the use of festuololium with high nitrogen inputs could be higher, but the overall effects are uncertain and the potential for mitigation substantial. At the nitrogen uses that have generated 20 tons DM per year of festulolium, production emissions associated with fertilizer would reach 3.9 tons of CO_2e per year at standard IPCC nitrous oxide emission rates. This rate is more than twice that of silage maize but only modestly higher per ton of dry matter, which is what matters.

In addition, the protein cake production would save 1.1 tons of CO_2e from being generated abroad in the production of soybeans.[45] Overall, production emissions per kg of feed would decline.

In addition, there is evidence that nitrous oxide emission rates on these grasslands may be half or lower than IPCC emission factors would suggest, which would lower the production emissions from using festulolium substantially (Baral et al. 2019). Because it absorbs so much nitrogen, festulolium would have other benefits in substantially reduced nitrogen leaching, reducing indirect emissions (and other nitrogen pollution). And any perennial grass would also be a candidate for a nitrogen-fixing microbe, which might reduce its need for synthetic fertilizer. Given all these uncertainties' potential positive and negative effects, we are not factoring in any changes in production emissions due to a biorefinery shift at this time, but we believe the opportunity exists for reductions.

Table 5.3 | Potential Carbon Benefits per Hectare of Different Biorefinery Products Based on Grass Yield

GRASSLAND YIELD FOR BIOREFINERY DM	PROTEIN MEAL SUBSTITUTE PRODUCED (TONS/HA/Y)	COCS FOR PROTEIN MEAL SUBSTITUTE	SILAGE MAIZE SUBSTITUTE PRODUCED T/HA/Y)	SILEAGE MAIZE SUBSTITUTION COCS (TCO_2/HA/Y)	BIOMASS FOR ENERGY USE (TONS/HA/Y)	POTENTIAL CO_2 SAVINGS FROM BIOENERGY USE OF ENERGY MATERIAL	TOTAL CARBON BENEFITS PER YEAR (TONS CO_2/HA/Y)
8.82	1.7	9.0	4.9	6.4	0.25	1.2	16.6
10	1.9	10.17	5.6	7.28	0.25	1.4	18.8
12	2.3	12.2	6.7	8.7	0.25	1.9	21.1
14	2.7	14.2	7.8	10.2	0.25	2.2	26.3
16	3.0	16.3	9.0	11.6	0.25	2.2	30.1
18	3.4	18.3	10.1	13.1	0.25	2.5	32.0
20	3.8	20.3	11.2	14.6	0.25	2.8	33.9

Source: Authors' calculations.

Another question is the economics. There is one full-scale biorefinery system in place today, and researchers at Aarhus University estimate that the costs of the soybean equivalent protein cake would have to be roughly double those of present soybean cakes to make the system economical with present technologies. But these are early days in the development of these processes and assume today's grass yields. Precisely because the technology is very new, the prospect for bringing these costs down is likely significant. Although its economics are uncertain, we believe development of a biorefinery process meets our standards for inclusion in our 2050 scenario.

Ideally, grass-based agriculture would be able to replace not merely fodder crops but cereals used for feed like wheat and barley. Doing so, however, would require a process for making the cellulose in grasses equivalently digestible to the carbohydrates in cereals. Such processing is possible, and studies have proved capable of doing so, but the cost estimates at this time are far too high, and we do not factor this possibility into our mitigation scenarios. This fact means that application of the biorefinery as described here is limited by the demand for fiber feed by Denmark's dairy and beef production. For this reason, even though we calculate that biorefineries at high grass yields produce more carbon benefits per hectare per year than even wheat and barley production in Denmark, grasses used with a biorefinery cannot replace wheat and barley area.

Biorefineries with high grass yields could save 200,000 to 300,000 hectares of global agricultural land and mitigate up to 2.8 million tons of grenhouse gas emissions.

We constructed scenarios for biorefineries for our different future production levels using our assumptions of improved feed conversion efficiencies. In these scenarios, we assume improved feed conversion efficiency and higher crop yields, an assumption that reduces the potential area for biorefineries but that is significantly offset by the need for fodder to meet increased overall production. In these scenarios, we assume an average grass yield of 16 tons of dry matter per hectare and that biorefineries are established on 80 percent of land otherwise devoted to maize, cereals for fodder, and "aftermath"[46] and on 50 percent of the land devoted to clover and grass mixes in rotation. The result is that roughly 200,000 hectares would be devoted to biorefineries in the 25 percent production growth scenario and 230,000 hectares in the 45 percent production growth scenario.

Under these scenarios, the fodder produced by the biorefinery would almost completely replace the fodder otherwise produced on the land it replaces. Due to the replacement of soybean cake, as shown in Table 5.5, there would be net land savings of 3.1 or 3.6 million tons of carbon dioxide per year (depending on the production increase scenario).

These calculations assume that a biorefinery with 16 tons of dry matter per hectare per year replaces silage maize, other fodders, and soybeans in Latin America at their present yields. If these other feed crops were to increase as other scenarios contemplate, the 16 tons of dry matter for the biorefinery would replace fewer hectares devoted to fodder and soybeans, and the net land savings would decline. For an average 25 percent increase in the yields of these other crops, and still assuming the same yield of grasses for the biorefinery, the net land use savings as measured by carbon opportunities costs would decline 35 percent. To avoid double-counting, this area of potential land savings needs to be used when combining the potential land savings from biorefineries with the potential land savings from yield gains.

This increase in carbon opportunity costs represents an increase in Denmark's contribution to food production, generating more feed on the same land and replacing imported soybeans. This increased production could be used to save land in different ways. One way would be just to reduce the land use requirements for imported feed. However, doing so would not provide a mechanism within Denmark for offsetting Denmark's remaining production mechanisms.

We also believe there are other good ways discussed below of reducing the land use carbon footprint of imported feeds. Another way to use the increased production from biorefineries would be to produce fewer other crops in Denmark, in other words, to increase their production less than otherwise required to meet food growth targets. Doing so would use the biorefineries to free agricultural land or reforestation, which would provide carbon sequestration that could be used to offset Denmark's domestic emissions.[47] We incorporate that method into our carbon neutral agriculture projection.

Because 25 percent of the grass would be devoted to bioenergy use, that bioenergy production also provides an offset. For reasons discussed below, we assign half of the potential displacement of fossil fuels to the energy sector, and credit half to agriculture.

Table 5.5 | Biorefinery Benefits in Our 2050 Scenarios (at 16 Tons DM Grass/Hectare)

	25% INCREASED FOOD PRODUCTION	45% INCREASED FOOD PRODUCTION
Area devoted to biorefinery (ha)	197,400	229,000
% substitution of imported oilseed cakes	26%	26%
COCs saved (tCO_2e) (existing crop yields)	3,108,500	3,605,000
Potential land area saved for reforestation	259,000	300,500
COCs saved (tCO_2e) (high crop yields)	2,006,300	2,327,300
Potential land area saved for reforestation (higher crop yields)	167,000	194,000
Bioenergy savings	435,000	505,000

Source: Authors' calculations.

Based on this analysis, our recommendation is to proceed actively with developing the biorefinery process. Part of that effort should focus on increasing yields with grasses such as festulolium in all of the different types of lands that today produce fodder.

E. Increased use of fodder beets

Fodder beets have a long tradition as animal feed both for dairy and pigs but are little used in Denmark. They occupy only around 4,300 hectares compared with 683,000 for barley, 534,000 thousand for wheat, and 176,000 for silage maize.

Fodder beets are roughly as digestible as wheat, more digestible than barley, and more energy-rich than silage maize. They also have two potential climate advantages over these other crops. First, fodder beet yields are much higher. We estimate Danish yields in dry matter at 14.6 tons per hectare over the last three years (assuming 21 percent dry matter, which is uncertain). By contrast, wheat dry matter yields were 6.7 tons per hectare, and spring barley 4.4 tons per hectare. Although fodder beets have lower protein content than wheat, they have higher energy content and digestibility than barley, and their protein content is comparable to silage maize and more digestible (Evans 2019).[48] These differences could save large quantities of land if fodder beets replace some of these other crops.

Second, fodder beets use nitrogen very efficiently. We estimate their nitrogen use efficiency at 66 percent. By contrast, we estimate winter wheat nitrogen use efficiency at 49 percent, and spring barley at 41 percent.

There are many practical challenges with fodder beets. They need their own specialized equipment. Dairy cattle, after eating other feeds much of the year, need to be transitioned to fodder beets with some care to ensure continued milk yields and to avoid illness because of their extremely high energy content. Fodder beets face their own set of plant diseases, have their own weed problems, and present harvesting challenges if conditions become wet in the late autumn. Most problematically, fodder beets are wet and bulky and therefore harder to handle than grains. Fodder beets are mainly fed to cattle for a few months over the winter before they spoil. Fodder beets are virtually never fed to pigs in modern production because they are difficult to manage. Too much water content may also limit the quantity of fodder beets that can be used.

Yet there are practical strategies to increase fodder beet usage for dairy cattle. Modern equipment makes it possible to harvest fodder beets more easily and convert them into a more manageable form. One way to preserve fodder beets longer is to silage them in combination with maize to produce a concentrate that substitutes for feed concentrates year-round rather than just forages (Evans and Messerschmidt 2017). In New Zealand, fodder beets are being used for grazing systems that lead to several times the yield of other crops and grasses and provide the energy content to allow weight gains similar to those from feeding cereals (Gibbs 2020). That would be particularly valuable for Denmark's organic farms.

If 200,000 hectares of spring barley could be replaced with fodder beets, the more than doubling of yield would allow reforesting of an additional 150,000 hectares with the same feed production. (This is true even compared to the higher spring barley yields we consider possible for 2050.) At 3 tons of carbon sequestration per hectare per year, that would mitigate for decades an additional 2.2 million tons of carbon dioxide. We believe Denmark should adopt a specific project to increase the use of fodder beets, with a minimum goal of 200,000 hectares.

F. Summary of potential savings in land in Denmark, resulting mitigation, and costs and benefits

If all these land-saving options were realized, total land saved for reforestation and rewetting peatlands would rise to 600,000 hectares in the 45 percent proportionate global growth scenario: 195,000 hectares as a result of feed conversion efficiency improvements and high rates of yield gains, 15,000 hectares from existing fallow lands, 200,000 hectares from using fodder beets, and 195,000 hectares from the successful employment of the biorefinery. This level of land savings would require high success in many different areas. For our carbon neutral scenario, we assume not that all are successful but instead that together the strategies free up 450,000 hectares for peatland restoration or reforestation while meeting the food production target.

Of this 450,000, roughly 140,000 is required to save land for peatland restoration, which leaves 310,000 hectares for reforestation. If each of those hectares could sequester 11 tons of CO_2 per hectare per year, the GHG mitigation would be roughly 3.4 million tons. That would offset almost 80 percent of Denmark's remaining production emissions (and we describe possible ways bioenergy and soil carbon gains could offset the remainder).

How much land Denmark should restore should reflect broader social judgments. Reforesting agricultural land requires up-front payments for the value of the land and potentially some relatively modest planting costs while mitigation occurs over the following decades. The cost of mitigation through reforestation at the present average price of Danish farmland could approach $90 per ton of CO_2 if the only value were mitigation based on a present discount value calculation.[49] That price would exceed our maximum mitigation planning price of $50 per ton, but two factors lower these costs.

One factor is that Danish farmland values in part reflect the value of public support, which is incorporated into land values, including land rental values (Swinnen et al. 2013). We have not estimated this effect, but this part of the value is likely significant and should not count as a true economic cost. If policy is reformed to allow farmers to continue to receive this income, or alternatively, if Denmark is allowed to use money saved from this support toward reforestation, the costs to the Danish government would be less and would match those of the true economic costs.

The second factor is co-benefits. The value of the nitrogen savings may depend on the level of nitrogen otherwise emitted at the time, but at present prices paid for nitrogen might reduce costs by half or more (Klimarådet 2020).

If managed properly, this restoration could also have enormous value for Denmark's biodiversity. Denmark's biodiversity is extremely low because most of its land is dedicated to agriculture, and even most of its small areas of remaining forests are highly managed for production. "A majority of the country's more than 30,000 species by nature are adapted to the forest as living place, and many endangered species are found only in the forest" (A. Petersen et al. 2016). As a summary report for the Nordic Council of Ministers states, "For biodiversity, the basic assumption is that natural undisturbed old growth forest (i.e., unmanaged forest) with its broad array of natural habitats host the highest and most important biodiversity including the highest richness of rare species. For biodiversity at species level, this is well documented in the field" (Dinesen et al. 2021).

Making Denmark's Feed Imports Land Use Carbon Neutral or Net Sources of Mitigation

By our calculation, the import of feed used in Denmark has 11.7 million tons in implicit land use greenhouse costs measured by carbon opportunity costs. Without any increases in land use efficiency, the 45 percent increase in production scenario implies that these costs would rise to 17 million tons. By our accounting, we would then assign greenhouse gas costs equal to the increase, or 5.25 million tons. Denmark would need increases in the land use efficiency of imported feeds by 45 percent to avoid these emission charges. Larger increases could lead to offsets.

Of the imports, oilseed cakes, used as a protein feed for livestock, account for 85 percent of the land use costs (measured by COCs), and 78 percent of those are from soybeans. Crops other than oilseed cakes are mostly sugar beet pulp and a modest quantity of wheat and barley. We therefore focus here primarily on reducing the land use costs of oilseed cakes. If all the 2.2 million tons of oilseed cakes used were imported as soybeans from Latin America, that would require roughly 585,000 hectares of soybeans (allocating the portion of soybeans to soybean cake by weight). With a 45 percent increase in production but without any changes in yield, the area requirement would grow to roughly 850,000 hectares, an increase of 265,000 hectares.

The first goal is to avoid this increase in COCs; a second goal would be to reduce agricultural land enough to also offset the agricultural production

emissions from imports of 1.35 million tons. Here we focus exclusively on oilseed cakes and assume for purposes of simplicity that they will all come in 2050 from soybean cakes from South America.

A third possibility might be to use land restoration abroad to offset emissions from domestic agricultural production, but that is less desirable because these kinds of offsets, if achievable, could be used by other sectors as well. These offsets are not merely offsets as we use the term—activities of Danish agriculture that remove carbon from the air or reduce emissions by others—but rather activities by others for which Danish agriculture would seek credits. Such offsets are no more available to Danish agriculture than to any other sector, and mitigation should avoid them to the extent practicable because a limited quantity of such potential offsets are available to the world.

A. Feed conversion efficiency gains

The feed conversion efficiency gains we describe above would also reduce the quantities of imported feed and thereby reduce carbon opportunity costs.

In our analysis, in the 45 percent proportionate global production increase scenario, the feed conversion efficiency gains reduce the 5.25 million ton increase in carbon opportunity costs by 11 percent to 4.67 million. In effect, these feed efficiency gains would save roughly 83,000 hectares of the 263,000 hectare increase in soybean area.

B. Increasing yields

One way to reduce land use demands is to increase soybean yields. Denmark's soybeans originate overwhelmingly in South America, where yields have been growing at a healthy rate. If the current trend continues, soybean yields in South America will grow by roughly 33 percent between 2017 and 2050, which would increase yields from roughly 3 tons per hectare per year to 4. In the proportionate global growth scenario (45 percent), these yield increases would supply 32 percent more soybeans on the same land and therefore reduce soybean COCs by that same percentage. When combined with feed conversion efficiency gains, this increase almost exactly avoids the remaining increase in COCs and avoids any expansion of soybean area.

Continuing this trend line, however, is not easy. Analysis of potential improvements in soybean yields in Brazil from management improvements alone are likely less than 500 kg per year (Sentelhas et al. 2015). Like other crops, however, there are significant opportunities for improvements through breeding (Liu et al. 2020; Ainsworth et al. 2012).

Because Denmark is not a soybean producer itself, we cannot recommend that Denmark invest resources to further drive soybean yields. We assume that the trend line in South America increases in our scenarios but believe Denmark should explore additional measures to ensure that its international feed imports are land area carbon neutral. Additional gains would also allow for offsets to Denmark's 1.35 million tons of international production emissions.

C. Increasing pasture yields in Latin America

The great majority of agricultural land in Latin America is pasture (Aide et al. 2013), and while some of that pasture was historically dry, hundreds of millions of hectares were wet enough that they were naturally forested or covered by woody savanna (Griscom 2017; Searchinger et al. 2018). Yet most of this land is poorly utilized for grazing, with low stocking rates and low growth rates (Searchinger et al. 2019). The potential to double or even quadruple output on much of this land is well accepted (Strassburg et al. 2014). The mechanisms for doing so typically generate many related benefits in addition to reducing land area, including lower production emissions such as methane per kg of beef (Cardoso et al. 2016). Some systems can generate improved habitat and increased stores of carbon in vegetation (Montagnini et al. 2013).

The basic requirements to improve output are both known and proven. They include properly fertilizing pastures or incorporating legumes, rotating cattle rapidly around different fields to ensure that they eat the forage available, having supplemental feeds or hays for dry seasons, providing health care and minerals, timing calve births to reflect food availability, and selecting faster growing cattle within a herd for reproduction (Cardoso et al. 2016). Advanced silvo-pastoral systems incorporate trees and nitrogen-fixing shrubs that provide shade and temperature control, a high level of protein, and fertilization for grasses (Montagnini et al. 2013).

Danish agricultural production does not import meat or milk from pastures, but pasture areas often are near lands in Latin America that produce soybeans (Imbach et al. 2015). As soybeans expand, they often occupy pasture, which in turn expands into forested areas (Arima et al. 2011; Barreto 2010). One option to avoid clearing of forests is to increase yields of adjacent pastures as cropland expands, particularly as part of integrated projects.

In general, studies have found that abundant pasture intensification efforts are economical in themselves or certainly economical as a means of addressing climate change (Strassburg et al. 2014; Spera et al. 2014; Cohn et al. 2014). Much of the challenge relates to the need for up-front investments and training, and sometimes there are nonmarket barriers such as uncertain property ownership.

It would be feasible for Danish agriculture, collectively and in collaboration with the government, to develop projects in which it saves overall land in South America by boosting pasture intensification in areas adjacent to soybean production and using these gains either to avoid continued deforestation or to reforest lands.

D. Replacing soybeans with tree-based oilseeds

Another option could be to work with farms supplying soybeans to switch to higher-yielding sources of protein cake. Part of our work on this project has been to identify whether such options exist. There are at least two possibilities.

The macauba tree provides one option that is already the subject of a small test in Brazil (Colombo et al. 2018). Macauba is a palm tree that produces a large oilseed, but, unlike oil palm, it does not rely on areas that are native wet tropical forest to grow best. Researchers promoting macauba claim that it can produce three tons of vegetable oil per hectare and seven tons of protein cakes, although only one of these tons is equivalent in feed value to soybean cakes. Measured only by its yield of high-value protein cakes, the yield is less than soybeans. But because only a portion of the hectare is attributable to this type of cake, the effective yield is higher. A pilot project is underway in Brazil.

Another option that we consider sufficiently promising to justify exploration is the use of the oilseed pongamia tree (*Pongamia pibnata*) (Figure 5.1). Pongamia is native to eastern Asia, Australia, and the Pacific Islands. It has long been used ornamentally and harvested for medical purposes, but it has not been used for food. It is known to tolerate tough conditions (including high salinity, heat, flooding, and drought). It also fixes its own nitrogen. When crushed, the seed produces 64 percent oil by weight and 35 percent high-protein meal. The key reason it has not been used for food or feed is that that its oil includes bioactive qualities that have a bad smell and need to be removed.

Beginning around 2010, TerViva, a start-up company, began experimenting with pongamia as a replacement for soybeans and palm oil. It gathered plants from a variety of countries, including Austria, that had high-yielding varieties. It claims now to have come up with a cheap process for removing the unpleasant smell and has started selling the oil, which it claims has many health advantages, such as high oleic acid. It also reports that feeding tests have found that 1 kg of pongamia cake can replace 1 kg of soybean cake with ruminants and achieve close to that ratio for pigs.

Most important, the company claims that pongamia has enormous yield potential that could rise even up to 12 tons per hectare of total oilseeds, roughly four times the yield of soybeans. (The yield of oilseed meal would be almost eight times that of soybeans because a higher proportion of pongamia seed is protein feed rather than vegetable oil.)[50] The evidence is promising but limited. Most of the pongamia plantings have occurred so far in Florida on lands with sandy soils and a high water table. Yield projections are based primarily on analysis of individual test trees after six years, with an average yield that translates at expected tree density to 3.8 tons per hectare, and higher-yielding varieties achieving 4.9 tons. The much-higher yields are projections based on the way yields increase with tree age in these plantings and also yields produced from individual, older trees in Australia with even much higher yields. In 2018, the first true commercial plantings occurred on only 40 hectares, and more plantings were planned for 2020 on 400 hectares. (All this information was provided by the company in materials and two interviews.)

Another claimed advantage is the quantity of carbon that would be stored directly in vegetation, estimated by the company at 31 tons of carbon per hectare at an age of 25 years.

The trials with pongamia are at an early stage, and there are both historical failures and success stories with oilseed trees. Several years ago, there was great global enthusiasm for jatropha, which turned out to grow much less successfully than anticipated. In contrast, the oil palm tree has turned out to be a staggering agronomic success. Its limitation is not its yield, which is high for vegetable oil, but the fact that it grows well mainly in areas otherwise dominated by wet, tropical forests.

From a purely agricultural perspective, the proper approach at this early stage would probably be to “wait and see,” but the urgency of addressing climate change suggests a far more active approach. If pongamia works at high yields, it holds out the promise of dramatically reducing the footprint required to meet the world’s rapidly growing demand for both high-protein cake and vegetable oil.

Even so, a new crop that grows well in the tropics, while it should reduce overall the global demand for land, can often increase deforestation in the tropics. For this reason, efforts to promote pongamia should be linked to “produce and protect” plans as we discuss below. We initially recommend an active program by Denmark to work with the company to test this approach in Latin America while providing feed for Danish agriculture.

Figure 5.1 | Pongamia Trees Growing in Florida

Source: TerViva Inc.

E. Overall potential of international land restoration carbon offsets

Options to reduce the Danish land carbon footprint from feed imports include increases in soybean yields, a shift to higher-yielding, tree-based oilseeds in Latin America, and pasture intensification on adjacent lands. Trend yield gains for soybeans in Latin America and a successful implementation of the biorefinery would by themselves eliminate any expansion of international land area (and therefore COCs).

Some other options require innovations in oilseed trees, but the potential for pasture intensification is today proven and sufficiently high that it alone could greatly reduce Denmark's land carbon footprint. For example, assuming that pasture yields need to double in Brazil to meet rising demand for beef and dairy, Denmark could help farmers avail themselves of known management technologies to enable them to triple yields on some hectares. Without any other gains in feed conversion efficiency or crop yield gains, Denmark would need to triple yields on 263,000 hectares to offset net land area conversion for increased soybean production in the proportionate growth scenario. With trend line yield gains for soybeans, Denmark would only need to do so on roughly 100,000 hectares of pasture. If Denmark then did so on another 68,000 hectares, for a total of 168,000 hectares of pasture improvement, and reforested that many hectares at four tons of carbon per hectare per year (Cook-Patton et al. 2020), Denmark could offset the 1 million tons of remaining production emissions we estimate from imported feed.

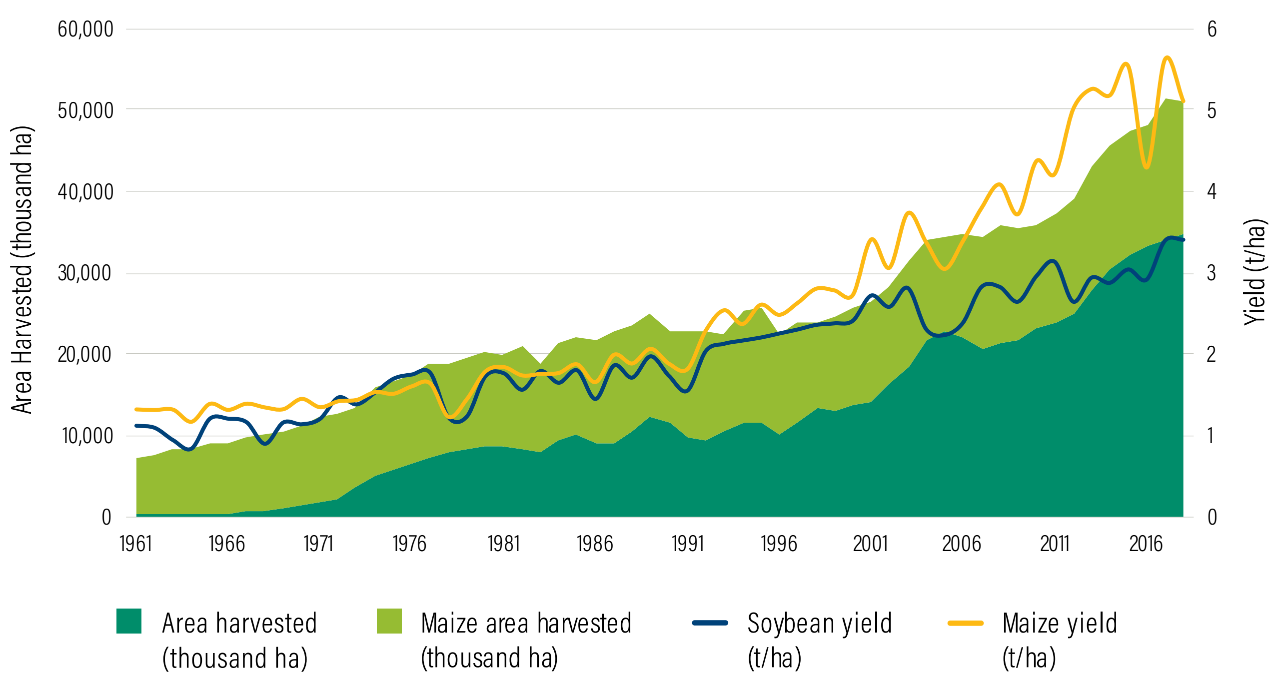
Overall, the combination of options give Denmark a high capacity not only to be land area carbon neutral with its imported feeds but also to offset its remaining international production emissions.

Transforming Yield Gains into Greenhouse Gas Offsets

Although increasing yields increases the capacity to store carbon while meeting the same global food demands, it does not guarantee increasing carbon storage. As explained in *Creating a Sustainable Food Future*, the main reason is that increases in yields may encourage changes in the location of agricultural land, leading to more deforestation locally and often in the tropics. For example, as soybean yields in Brazil have grown, so has the area dedicated to soybeans (Figure 5.2). A likely reason is that higher yields have helped Brazilian soybeans to become a more cost-competitive source of vegetable oil and protein cake for livestock throughout the world. Through market forces, these production increases in Brazil have probably contributed to saving or restoring forests elsewhere, but the costs in carbon and biodiversity from losing Brazilian forests and savannas are high. These carbon losses occur quickly, while carbon recovery elsewhere is slow; and Brazilian forests and savannas have unparalleled biodiversity (Searchinger et al. 2015b).

What yield gains on some lands do achieve is an increase in the global capacity to save forests and their carbon while meeting food needs. The same is true of reductions in consumption of land-intensive foods, such as beef. In this way, yield gains are not different from increased productivity of any other good. For example, increases in energy efficiency, such as more efficient cars, increase the capacity to

Figure 5.2 | Yield Growth for Soybeans and Maize in Brazil Did Not Reduce Agricultural Area Due to Increased Global Market Share



Source: FAOSTAT (2020).

reduce oil consumption, but they do not guarantee that consumption will decline because people could also use more energy.

Based on this result, we believe that increases in yields should count fully in determining whether Danish agriculture is land area carbon neutral. Yield increases spare land precisely in the opposite but otherwise same way that increases in consumption and production of food cause land clearing. Yield gains should cancel out production increases in their effects on land use.

To fully offset production emissions, however, we believe that further land-sparing increases in land use efficiency should be combined with measures that either "protect" or "restore" lands. This combination ensures that the land-sparing does in fact result in more carbon stored in land and soils and less carbon in the air.

There are two ways to do so. One is to physically restore the spared land. For example, we have counted the full carbon benefits of restoring forests on agricultural land in Denmark that could be freed by increases in yield even with 45 percent increases in production. In South America, Danish agriculture could similarly support forest restoration projects enabled by increases in yields of pasture or oilseeds.

Another possibility is to support productivity gains in "produce and protect," sometimes called "produce and conserve," projects in South America. The REDD+ program is trying to move in this direction. These programs estimate future deforestation without new efforts, and then reward reductions in this deforestation. An example is the "produce, conserve, and include" project in the Brazilian state of Mato Grosso that seeks to increase agricultural output while not just protecting but reforesting forest land.[51]

Our basic proposal is therefore that land-sparing at a higher rate than necessary to achieve land area carbon neutrality should receive a credit for 50 percent of the typical carbon saved just by itself. In other words, productivity gains that reduce the need for one hectare of land would by themselves count as saving the carbon in half a hectare of land. (The precise calculation can be done using carbon opportunity costs.) This assumption of a 50 percent credit is not a precise calculation but recognizes that part of the challenge is to reduce the need for agricultural land and the other part is to ensure that this reduction results in more forest or other native habitat. When land efficiency gains are combined with restoration or with participation in a "produce and protect" plan that otherwise meets standards for a successful REDD+ project,[52] the carbon stored by each hectare saved or restored should count 100 percent as an offset of agricultural production emissions.

We also recommend that these offsets for production emissions occur separately for domestic agricultural production and for imported feed, for reasons we set forth in Box 5.1.

Box 5.1 | How Interchangeable Should Credit Be for Domestic and International Land Savings and Forest Protection and Restoration?

Our approach in this report has been to focus separately on achieving carbon neutrality for agricultural production within Denmark and for imported feeds. In theory, yield gains and forest protection and restoration in other countries could also provide offsets for Danish agricultural production emissions, which would require less reforestation in Denmark. One reason to develop separate solutions for domestic production and imported feed is to avoid double-counting. Gains in land use efficiency in other countries and reforestation will likely be claimed by agricultural sectors in those countries for reducing emissions. If their reforestation is also claimed by Danish agriculture, that would occur in a way that cannot be counted as reductions by Denmark. By contrast, so long as feed produced in other countries is counted by them as well as by Denmark as part of a life-cycle analysis, which by definition goes beyond domestic emissions, there is no inherent accounting problem if agricultural industries in both countries count their mitigation.

PART 6

Soil Carbon and Bioenergy

In addition to land use, other possible mechanisms for offsetting emissions include soil carbon gains and bioenergy, which we explore in this part.

Soil Carbon Gains

Denmark's present national inventory report estimates that Danish agricultural land sequesters roughly 0.7 tons of carbon dioxide per hectare per year. *Creating a Sustainable Food Future* includes a chapter explaining our skepticism about the potential to sequester soil carbon on working agricultural lands, but soil carbon gains in Denmark are possible. Because of its vast livestock industry, Denmark imports large quantities of carbon and nutrients and deposits them on its soils through manure. These are the additions needed to build soil carbon. Soil carbon gains are a kind of natural, although only partial, benefit of Denmark's high emissions from livestock production and use of imported feed.

The question is whether these gains can continue at this level or grow. We are somewhat skeptical. One reason is that soil carbon gains are believed to slow and eventually stop as soil carbon increases because higher soil carbon leads to greater microbial activity that returns carbon to the atmosphere. Another reason is that soil carbon gains have not been consistent in Denmark. Soil carbon declined from 1987 to 2009 (Taghizadeh-Toosi et al. 2014), which means there was a net emission from soils in those years. Increased use of cover crops might be able to increase soil carbon, although the quantities are unclear (Searchinger and Ranganathan 2020). Even factoring in cover crops, modeling studies using the soil carbon model used for the NIR also estimate limited potential to build soil carbon in Denmark (Taghizadeh-Toosi and Olesen 2016).

Shifts of land toward a biorefinery might be able to sequester soil carbon. Evidence discussed in Part 5 suggests grass production increases soil carbon by 0.8 tons of carbon per hectare per year. Our largest biorefinery scenario contemplates a shift of roughly 135,000 hectares from silage crops to grasses, and that could build soil carbon at this rate equal to 400,000 tons of carbon dioxide per year. But the ability of such soil carbon gains to persist over time in unclear, particularly the quantity of soil carbon that will remain in soils after years in which these same lands are rotated into crop production.

There is enormous scientific uncertainty about soil carbon changes. Based on this analysis, we compromise and assume soil carbon uptake will continue even in the years around 2050 at a rate of half the recent gain claimed by Denmark, or 350,000 tons of carbon dioxide per year, and we add another 50,000 tons of carbon dioxide to reflect potential gains from the biorefinery system for a total of 400,000 tons in our scenarios in which food production grows by 25 percent or 45 percent.

Bioenergy

One potential source of mitigation would result from increases in bioenergy, reducing emissions from the energy sector and in effect reducing the "net emissions" attributable to agriculture as an offset. In *Creating a Sustainable Food Future* (chap. 7), WRI concluded that dedicating land to the production of bioenergy was not good for the climate. "Dedicating land" means any use of land that diverts its capacity to produce plants to energy use and away from other purposes, most obviously by growing either food or energy crops directly to turn into biofuels. The climate savings from reduced fossil emissions would generally be less than the carbon opportunity cost of devoting land to bioenergy rather than to storing carbon in forests or producing food so other lands can be used as forests. That is the same reason that the use of crops in digesters is costly from a carbon perspective.

The report explains that most estimates of climate benefits of dedicating land to produce bioenergy—nearly all, in effect—assume that land is "free" from a climate perspective; that is, that land has no opportunity to store carbon if not used for bioenergy. In a world that desperately needs to use productive land to produce more food and carbon storage, that assumption is untenable. This error is reflected in the incorrect assumption that biomass is "carbon neutral," based on an error in the interpretation of IPCC national reporting guidance.

Biomass that could provide net benefits, however, includes waste materials, to some extent crop residues, and "additional" plant production otherwise not produced or used, such as cover (catch) crops. Using "straw," although it probably sacrifices some soil carbon, can generate climate savings because 85 and 90 percent of the carbon in the straw would likely otherwise be emitted to the air by soil microorganisms during decomposition within a few years (Liska et al. 2014). If only 15 percent of the carbon in straw would build soil carbon while use of the straw for energy could save 50 percent of its level of carbon in fossil fuel use, then bioenergy use would have a higher net gain.

This use of straw for bioenergy must also avoid adverse effects on soil productivity that reduce yields. Global meta-analyses find that soil organic carbon does not generally affect crop yield so long as it exceeds 2 percent (Oldfield et al. 2019). But analyses at this global scale do not necessarily capture effects within Denmark. Some science suggests that higher soil organic matter helps Danish farms maintain valuable soil structures that could contribute to crop yields through a variety of effects, including resistance to soil compaction from use of heavy machinery (Schjønning et al. 2009). In our analysis, we therefore assume that only the same percentage of straw could continue to be removed.

In our analysis in this report, we credit the use of straw for bioenergy with roughly 0.96 million tons of offsets against Danish agriculture's climate emissions in 2017. This straw is presently used to support district heating facilities that supply mainly residential heat. This national figure does not need to deduct lost carbon in soils due to the use of straw because changes in soil carbon are already accounted for elsewhere. This estimate also fully credits bioenergy with avoided fossil emissions because at this time fossil fuels are likely the alternative energy source.

Here we briefly explore (1) what additional mitigation might be achieved by alternative use of straw, and (2) whether energy crops, in particular fast-growing willow planted on cropland, might also contribute to reducing Denmark's emissions.

A. Straw

Danish Statistics reports an annual average use of straw for bioenergy from 2016 to 2018 (primarily from wheat and barley) of 1.514 million tons. These are "wet tons," and are roughly 15 percent water, so the dry matter is 1.289 million tons. This straw contains about 0.6 million tons of carbon (assuming 47 percent carbon), which is equivalent to roughly 2.2 million tons of carbon dioxide. This straw is now nearly all used for district plants to supply residential heat. One helpful but simple way of evaluating mitigation potential is by estimating whether and by how much additional fossil emissions might be avoided using this roughly 0.6 tons of carbon in straw (worth about 2.2 million tons of carbon dioxide) in a different way. These savings can be summarized by a percentage; for example, for each ton of carbon dioxide released by using straw, how much carbon dioxide is saved by not using fossil fuels.

To estimate the net gains of bioenergy, the analysis should start by deducting 10 percent for lost soil carbon, reducing this figure to roughly 2 million tons. However, because we are using soil carbon changes overall for Denmark that are separately estimated, such effects should already be reflected in the national emissions figures.

Use of biomass for heating, as presently used in Denmark, is generally an efficient use of biomass compared to other bioenergy uses, such as cellulosic ethanol or electricity. Unlike these other uses, the efficiency of conversion of energy in biomass to heat can be similar to the efficiency of converting energy in fossil fuels to heat. However, biomass has less energy per kg of carbon than natural gas and oil due to the structure of its carbon molecules. Estimates vary modestly, but, in general, biomass has slightly more carbon per unit of energy than coal and therefore roughly twice the carbon of natural gas.

Assuming that district heating plants are today 80 percent efficient, and natural gas alternatives would be 90 percent efficient, we estimate that each ton of carbon dioxide in straw today saves 43 percent of the carbon dioxide that would otherwise be released by use of natural gas. That already involves an efficient use of biomass relative to other bioenergy uses and generates the 0.96 million tons of CO_2 credits we build into our 2017 baseline. According to correspondence with the Danish Energy Agency, new heating plants can achieve the same heat conversion efficiency as natural gas,[53] and if all plants achieved this conversion efficiency, the carbon dioxide saved would rise only modestly to 47 percent.

We assign 100 percent of these carbon savings in 2010 to the agriculture sector because the use of straw in Denmark for heating now is cheap. Future uses of straw for district heat, however, are poor options. Home heating can be generated efficiently using heat pumps and electricity. This kind of heating is therefore not a sector that is hard to "decarbonize." Like others, we assume that biomass in 2050 will not be employed for such heating uses and must be utilized in alternative ways (Venturini et al. 2019).

One option would be to turn the biomass into some kind of liquid biofuel. Even so, because biomass has more carbon per unit of energy than oil or natural gas, some of this carbon must be lost in the conversion process to a liquid fuel. Energy is also needed to power the conversion. Typical cellulosic ethanol conversion estimates, even assuming significant efficiency improvements from current technology, are lower than 50 percent (Searchinger et al. 2015b) (using conversion efficiencies from the GREET life-cycle model for cellulosic ethanol).

Another option that has been discussed would divert straw from present heating uses into a process that would generate two products: jet fuel and biochar (Stiesdal 2019). Jet fuel would, of course, displace kerosene derived from fuel oil for airplane travel, while biochar would be returned to the soil based on the expectation that carbon in biochar would resist microbial decomposition, remain longer in the soils, and build soil carbon. Other proposals would similarly try to produce an alternative fuel for heavy equipment plus biochar (Venturini et al. 2019). Even in these approaches, however, one ton of carbon in straw will not replace one ton of carbon in fossil fuels because some of the carbon is lost in the pyrolysis. Even after being turned into biochar, some carbon is likely to decompose in the soil. We here assume that 60 percent of the original carbon will either replace fossil carbon or persist in soils for at least 30 years.[54] That would increase the carbon value of the straw by 17 percent, or roughly 400,000 tons of CO_2.

Making any of these technical approaches reasonably cost-effective remains to be proved. However, we assume here that some method will be found to do so by 2050.

Unfortunately, any likely method that achieves these reductions will probably be substantially more expensive than using fossil fuels. These costs will be paid for by energy users, and they will expect to be credited with at least much of the greenhouse gas reductions. Put another way, if all these reductions were credited to the agricultural sector, use by the energy sector could not count toward its effort to achieve carbon neutrality. Here we assume that 50 percent would be credited to each sector.

Another change that could occur would be increased production of straw due to higher yields. In our land use scenario for a 45 percent increase in overall food production but with feed conversion efficiency gains, wheat and barley production increase by 32 percent, and straw production should increase almost as much. We deduct modestly on the assumption that 15 percent of this yield gain results from improvements to the "harvest index." (Increases in the harvest index increase grain but at the expense of straw.) In other scenarios, the increase in straw production is lower. It grows by 8 percent in our 25 percent growth scenario; in our scenario with no increase in food production, it declines by 9 percent.

Overall, the use of straw in 2050 for bioenergy in our calculation would save 0.6 million tons of CO_2 in our existing production scenario, 0.71 million tons in our 25 percent growth scenario, and 0.81 million tons in our proportionate growth scenario.

B. Willow

Analysis in *Creating a Sustainable Food Future*, among other publications, illustrates why dedicating productive land to energy crops is not a good climate strategy considering the opportunity cost of land either to produce food or to store carbon in forests. Denmark has been modestly exploring the use of fast-growing willow trees as an energy source. Here we intentionally use simple numbers to explore this calculation for Danish willow.

According to the best study available, willow today achieves an average yield of 7.35 tons of dry matter per hectare per year (Nord-Larsen et al. 2014). At a minimum, at least 10 percent of this biomass is likely to be lost during the decomposition process (Whittaker et al. 2016), bringing these effective yields down to 6.6 tons of dry matter per hectare per year (equal to 24.2 tons of carbon dioxide).

If used for cellulosic ethanol, each ton of carbon in the willow would displace 0.45 tons of carbon in fossil fuels based on the analysis above. The result would be savings of roughly 5.5 tons of carbon dioxide per hectare per year in the form of displaced fossil fuels. But doing so would sacrifice food production, which needs to be replaced. COCs calculate the cost of replacing this food production elsewhere in the world. Measured this way, the principal crops in Denmark generate an amount of each crop that would cost 12 to more than 14 tons of CO_2 per hectare per year to replace elsewhere.[55] In other words, this use of land for willow would cause a net loss in global carbon storage on average while producing the same quantity of food.

There are modeling projections that willow could achieve yields of 12 tons of dry matter per hectare per year. That would raise the savings from displaced fossil fuels to about 10 tons of CO_2 per hectare per year, but that is still less than the carbon lost around the world to replace the crops Denmark would no longer produce.

Using wood for electricity production, even with cogeneration of heat, would be no better. The above estimates for cellulosic ethanol assume displacement of oil. The fossil alternative to electricity and heat would be natural gas. Even if we assume optimistically that this wood would be converted to useable energy with the same efficiency as natural gas (and counting only a 10 percent loss of dry matter in drying the wood), the results would be the same as expressed above: savings of 5.5 tons CO_2 per hectare per year at present willow yields and about 10 tons CO_2 per hectare per year at 12-ton yields. These savings remain lower than the land use costs of replacing most Danish crops that could be displaced by willow. These uses also assume that the alternative even in 2050 would be natural gas, when the likely (and necessary) alternative for electricity would be solar and wind.[56]

We also are skeptical of the potential to achieve the same efficiency as natural gas without turning wood into wood pellets. Producing wood pellets today requires that 20 percent of wood be used to generate heat for drying (Sterman et al. 2018; Röder et al. 2015). That would reduce the fossil savings by roughly an additional 20 percent compared with our calculations above.

The potential percentage savings relative to fossil fuels would be low even if biomass could be generated at much higher yields. That is because the percentage of greenhouse gas savings in replacing fossil fuels should properly be based on the “net savings.” For example, if willow could achieve a yield of 20 tons of dry matter per hectare and even if it had no production emissions and no loss of carbon in drying, the carbon opportunity cost of the land it used would still reduce the total savings. We estimate that even with these yields, willow would generate an 18 percent savings compared with fossil fuels if that willow replaced winter wheat. Solving climate change requires virtually 100 percent reductions in energy emissions, and these “net savings” would fall far short. (Similar calculations could be done for our other scenarios.)

Based on this analysis, we recommend against any effort to expand willow production for bioenergy in Denmark.

C. Potential additional bioenergy mitigation

Based on our analysis, we estimate the potential for savings from bioenergy in the future based both on straw and on the potential additional supply of biomass from the biorefinery option. As discussed above, our full-scale biorefinery implementation in the proportionate growth (45 percent increase) scenario would save 0.5 million tons, and the 25 percent scenario would save 0.41 million tons. The combined bioenergy mitigation with straw would reach 1.3 or 1.1 million tons in the two scenarios.

These offsets can only occur if the alternative is the use of fossil fuels, not some low-carbon energy source such as solar power or wind. However, we do believe that hard-to-abate sectors will remain that even by 2050 will probably not be carbon-free. That is one reason these benefits by 2050 will depend on the development of alternative bioenergy uses.

We do caution, however, that our assumption of a 50 percent credit for agriculture is generous. Following economic principles, the emission reduction should be credited to the sector based on its share of the overall additional costs to achieve the mitigation. It is possible that the energy sector will need higher costs to transform this biomass into useable forms of energy than the agriculture sector incurs to provide it.

PART 7

Overall Potential for Carbon Neutrality and Recommendations

Our analysis sets forth a challenging but possible path for Danish agriculture to achieve carbon neutrality on a life-cycle basis. This mix of measures should be viewed only as a starting strategy to initially guide efforts.

This mixture is not random. It reflects our effort to identify solutions based on their likelihood of success, their potential for actually mitigating emissions, and their chance of being cost-effective. Yet none is implemented on a large scale today. Nearly all require some additional development. As a result, some measures described will not work as expected, others may work better, and still additional measures may emerge.

In this part, we summarize the technical path described. Because this path relies heavily on innovation, we offer several policy principles for guiding innovation. Finally, we offer a series of specific recommendations for moving forward.

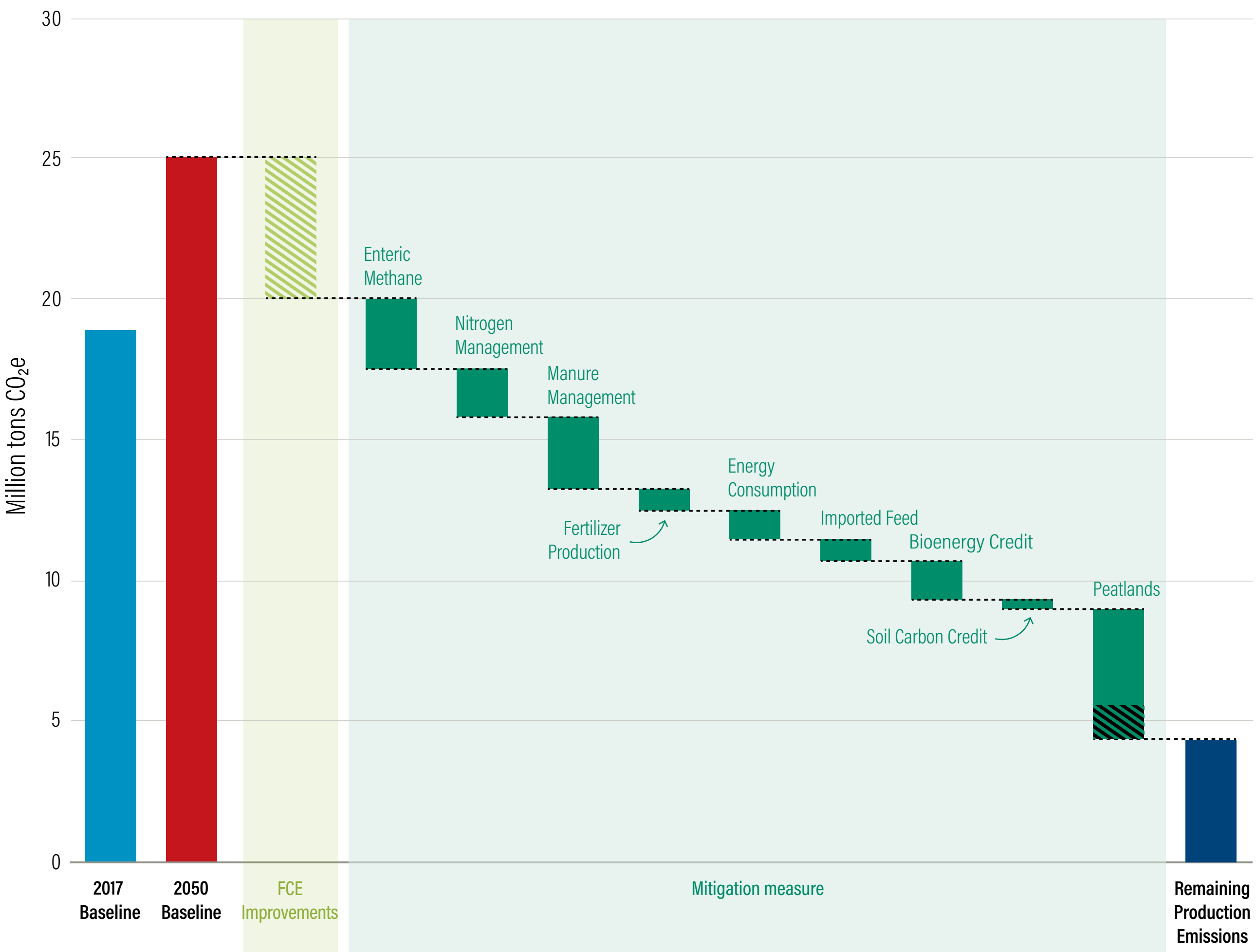
Summary of Carbon Neutrality Path Presented

We outline a possible path to achieve a carbon neutral agriculture sector even with a 45 percent "globally proportionate" increase in food production. Without any changes in agricultural production, Denmark's production emissions before counting offsets would increase to 25.1 million tons without offsets, but in our mitigation scenario, these emissions could plausibly be reduced to 6.2 million tons, roughly a 75 percent decrease (Table 7.1 and Figure 7.1). Of these, 5.2 million would be domestic and 1 million would be international for imported feed. Reduction in domestic production emissions alone without offsets would be 80 percent. This level of reduction would exceed the level of reduction in production emissions required in the scenarios for meeting climate targets in *Creating a Sustainable Food Future*. Improvements in feed conversion efficiency and crop yields could also freeze Denmark's land carbon footprint even with this increase in production, making Denmark land area carbon neutral.

Figure 7.2 outlines the contributions of different factors for Denmark to become land area carbon neutral. To become fully carbon neutral, Danish agriculture would need offsets for its production emissions, and we favor separate offsets for remaining domestic and international production emissions. Doing so avoids the risk of double-counting and avoids suggestions that Denmark is favoring its production at the expense of agriculture in other countries. Domestically, roughly 2 million tons of offsets would come from soil carbon gains (20 percent) and bioenergy (80 percent) through uses of straw and the biorefinery system. The remaining offsets would require reforestation of 310,000 hectares of land, which would offset the roughly 3.4 million tons of remaining production emissions.

Overall, in this scenario, Denmark would reduce agricultural land area by 450,000 hectares because that would include 140,000 hectares of rewetted peatlands. That would take roughly 17 percent of Danish agricultural land out of production. In general, this land would be less-productive agricultural land.

Figure 7.1 | Carbon Neutral Mitigation Scenarios for Denmark's Production Emissions with a 45 Percent Increase in Production



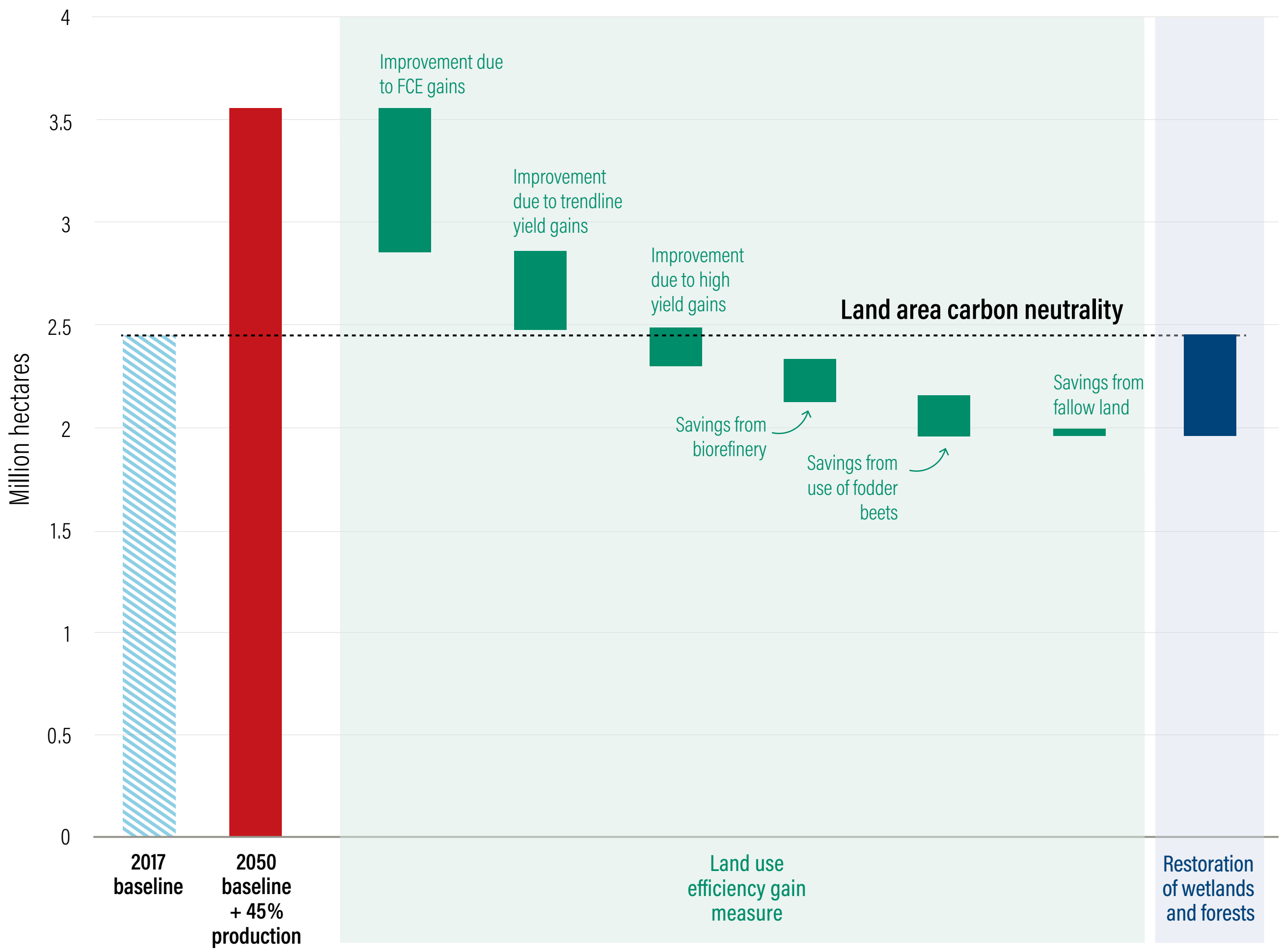
Note: The red bar shows emissions in 2050 in proportionate growth scenario and other bars show potential reductions from the different mitigation measures. Reductions are sequential. Reductions other than peatlands would all be larger without food conversion efficiency (FCE) improvements. The dark green striped portion of the peatlands bar represents the carbon cost of replacing the food now produced on peatlands without additional Danish yield gains. Bioenergy credit and soil carbon credit are absolute values to show their role. Bioenergy credit and soil carbon credit in 2017 and 2050 are left out of those baselines to avoid double-counting.

Source: Authors' calculations.

Focusing on international emissions, we anticipate remaining production emissions of almost 1 million tons after mitigation. We find multiple opportunities for Denmark to increase the land use efficiency of its imported feeds enough not only to be land area carbon neutral but also to offset these remaining production emissions through forest protection and restoration.

The reforestation offsets would not be perpetual. Eventually, restored forests would either cease to sequester carbon or would sequester carbon much more slowly. However, climate stabilization strategies do not require the elimination of all nitrous oxide and methane; they require lowering these emissions combined with some reforestation or other land-based negative emissions in coming decades to reduce atmospheric carbon. By the later part of this century, the world will hopefully be able to use other methods to remove carbon from the air, such as direct air capture. Relying on these offsets, generated by Danish agriculture's own increases in land use efficiency, is an appropriate way of achieving carbon neutrality in 2050.

Figure 7.2 | Contributions to Land Area Carbon Neutrality and Land Sparing to Allow Offsets of Remaining Production Scenarios with 45 Percent Increase in Production



Note: Y-axis shows hectares of cropland used (counting all land used for animal feed). Each gray bar shows the contribution of the measure to saving land while meeting the 45 percent food growth target, as discussed in report. The light part of some bars is the part of that reduction not necessary to achieve the 450,000 hectare target for restoration. The green bar shows the area that would be rewetted or reforested to offset remaining production emissions.

Source: Authors' calculations.

Table 7.1 | Greenhouse Gas Emissions in 2050 with and without Mitigation with Different Future Levels of Food Production (Billion Tons of CO_2e)

CATEGORY	MITIGATION MEASURES	2017 PRODUCTION BASELINE	AFTER MITIGATION	25% HIGHER PRODUCTION BASELINE	AFTER MITIGATION	45% HIGHER PRODUCTION BASELINE	AFTER MITIGATION
Nitrous oxide from fertilizer	FCE improvements; improved nitirification inhibitors, precision nitrogen timing, nitrogen-fixing microbes, biological nitrification inhibition, early winter wheat planting, improved cover crops	1.14	0.30	1.42	0.38	1.65	0.44
Nitrous oxide from manure		1.01	0.36	1.27	0.45	1.47	0.52
Nitrous oxide from residues		0.61	0.25	0.76	0.31	0.88	0.36
Other		0.05	0.03	0.07	0.03	0.08	0.04
Grazing manure		0.18	0.05	0.22	0.06	0.25	0.07
Indirect–leaching		0.19	0.10	0.24	0.12	0.28	0.14
Indirect–atmospheric deposition		0.38	0.20	0.47	0.25	0.54	0.29
NITROGEN EMISSIONS TOTAL		**3.55**	**1.28**	**4.44**	**1.60**	**5.15**	**1.86**
Enteric dairy	FCE improvement; 3-NOP, Breeding, BCM, Compound X	2.77	0.82	3.46	1.03	4.01	1.20
Enteric cattle non-dairy		1.26	0.37	1.58	0.47	1.83	0.54
Enteric pigs		0.42	0.18	0.53	0.23	0.61	0.27
Enteric other		0.16	0.08	0.20	0.10	0.23	0.11
ENTERIC TOTAL		**4.60**	**1.46**	**5.75**	**1.83**	**6.67**	**2.12**
Energy emissions field operations	Energy efficiency, low carbon electricity from grid; electrified farm equipment, hydrogen tractors	0.52	0.05	0.65	0.06	0.75	0.07
Energy barn operations		0.29	0.02	0.36	0.03	0.42	0.03
Production of nitrogen fertilizer		0.72	0.10	0.90	0.12	1.04	0.14
Production of phosphorus & potassium fertilizer		0.04	0.00	0.04	0.01	0.05	0.01
Production of pesticides		0.08	0.01	0.10	0.01	0.12	0.01
TOTAL ENERGY USE		**1.64**	**0.18**	**2.05**	**0.22**	**2.38**	**0.26**
Manure management dairy	Daily evacuation of manure from barns, slurry storage acidification sulfate addition; slurry tank covers; simple aerobic storage; high value manure options; low carbon fertilizer production	-	-	-	-	-	-
Methane		0.85	0.07	1.06	0.09	1.23	0.11
Nitrous oxide		0.29	0.03	0.36	0.04	0.42	0.04
Manure mangement pigs		-	-	-	-	-	-
Methane		1.36	0.18	1.70	0.22	1.97	0.26
Nitrous oxide		0.22	0.03	0.28	0.03	0.32	0.04
TOTAL MANURE MANAGEMENT		**2.72**	**0.31**	**3.40**	**0.39**	**3.94**	**0.45**
Peatlands	Restoration	4.80	0.24	4.80	0.24	4.80	0.24
Liming	None explored	0.21	0.21	0.21	0.21	0.21	0.21
Other (residue burning CO_2 from urea)		0.01	0.01	0.01	0.01	0.01	0.01
Bioenergy	Increased straw, higher value uses	(0.48)	(0.95)	(0.48)	(1.14)	(0.48)	(1.31)
Soil carbon (including land conversion)	Increased cover crops, but reduced gains as soils saturate	(0.30)	(0.35)	(0.35)	(0.40)	(0.35)	(0.40)
International production emissions	Similar to domestic crop options; tree-based oilseed	1.35	0.67	1.68	0.83	1.95	0.97
TOTAL PRODUCTION EMISSIONS DOMESTIC & INTERNATIONAL		**18.10**	**3.13**	**21.52**	**3.78**	**24.29**	**4.39**

Source: Authors' calculations.

Table 7.2 | Timing of Possible Large-Scale Implementation of Mitigation Measures

MITIGATION TYPE	COMMENT
Ongoing	
Feed conversion efficiency gains	Steady gains through management and breeding, new breeding emphasis on residual feed intake.
Yield gains	Steady annual gains and some opportunities for major breakthroughs.
Cover crop use	Continued implementation with steady innovations in management and breeding to reduce costs and increase cover crop growth.
Earlier winter crop planting	Start now but management and innovations needed to reduce pest problems with earlier planting to allow broader scale-up.
Immediate Start and Available Now	
Peatland restoration	Projects have started and can expand with more relaxed criteria. Trial methods needed to address phosphorus releases.
Remove barn manure daily	Can be mostly done immediately with added labor, and new barn design for replacement barns can make removal easier over time.
Expanded fodder beet use	Technologies available today.
"Produce and protect" projects in South America	Doable with pasture improvement today, while tree-based oilseeds need pilot projects.
Eliminate use of crops in digester, and stop subsidizing new digesters	Possible now.
Almost Immediate Start—Still Some Uncertainty	
Feed 3-NOP enteric methane inhibitor	Still awaiting EU regulatory approval, likely to come soon. Must prove that effect is sustained year-on-year. Adjustments over time may enhance benefits.
Acidified manure storage	Available now but first steps should be a variety of full-scale pilots of acid in storage, including tests with only limited sulfate and to assess yield effects on crops. Also, need for two-year project to better quantify manure emissions. Then scale up quickly.
~4–6 Year Time Horizon before Scale-Up	
Large-scale use of nitrification inhibitors	Although available now, large-scale pilot projects and assessments needed, including inhibitors with coatings, to maximize benefits and to ensure no water quality effects. Longer-term effort needed to develop better inhibitors.
Precision agriculture guidance for delayed nitrogen application	Development of model and/or remote testing to guide nitrogen application in-season for wheat and barley.
Nitrogen-fixing microbe	Work on maize can be tested immediately; methods to use on wheat and barley need to be developed.
BCM enteric methane inhibition	Large-scale pilots of red algae use and closed-loop production warranted. Approvals needed to test bromochloroform (BCM) with feeds other than algae and then testing required.
Biorefinery	Expanded pilot projects needed along with expanded efforts to breed and grow high-yielding, perennial grasses, such as festulolium.

Table 7.2 | Timing of Possible Large-Scale Implementation of Mitigation Measures (cont.)

MITIGATION TYPE	COMMENT
Time Horizon of 10+ Years	
Biological nitrification inhibition	Merits intensive research.
High-value uses of manure	Creative proposals but none is cost-effective yet.
Shift bioenergy uses of straw to harder to abate fossil fuel uses	Alternatives required because electrification is possible to replace present residential heat uses; alternatives could include industrial heat or airplane fuels but require development.
Tree-based oilseeds at scale	Might be able to replace soybeans at a fraction of land but need pilots to move first.
Hydrogen or electric or other alternative energy farm equipment	Depends on broader progress in the energy sector.
Nitrogen fertilizer from low-carbon energy	Likely depends on progress in making low-carbon hydrogen, but some ideas exist for alternative methods.

Source: Authors' analysis.

This path to carbon neutrality requires that Denmark increase its land use efficiency by more than 45 percent, but it does not require that Denmark increase its food production by 45 percent. However, reducing production increases or even keeping food production at present levels does not make the task proportionately easier. The changes in agriculture required to achieve a 75 percent reduction in Danish agriculture production emissions with higher production levels are roughly the same as those required to reduce its emissions by 75 percent at present production levels.[57] Denmark could choose to boost its land use efficiency, keep production at present levels rather than at 45 percent higher levels, and restore habitat on more than 450,000 hectares. Under our accounting system, however, Denmark would still need to increase the land use efficiency of whatever production level by more than 45 percent for this reforestation to count as an offset. Merely reforesting land without also boosting food production on remaining lands to offset the losses in food production would benefit Danish wildlife and could generate other benefits. But it would not merit offset credits in our accounting system because it would mainly transfer food production abroad.

The measures we have described would also have large additional water quality, wildlife, and social benefits (although in some cases, we are assuming additional costs assigned for these benefits). They could reduce Denmark's nitrogen pollution. We recommend that restoration be used to devote additional lands not to commercial forestry but to wildlife and biodiversity, which would increase true natural habitat in Denmark almost 20-fold. That is partially true because reforesting some of these lands will not be cheap, and social benefits related to meeting Denmark's goals to improve biodiversity are one way of paying for them. Such efforts would also generate larger, long-term carbon storage. This focus on natural forests, however, could be achieved on a net basis. As described above, Danish researchers have identified strategies for transitioning existing, older production forests to more natural, biologically diverse forests. Newly forested areas could be used for plantations to replace the wood from these transitioned natural forests.

Improvements in dairy and pork feeding efficiency would make the largest contributions to mitigation of any single mitigation measure as we have described them. Some ways of increasing feed efficiency compromise the humane treatment of animals, but others could benefit animal welfare, such as through improved healthcare and reduced mortality. Breeding that focuses on reducing "residual feed intake," the amount of energy in feed not used by the animal, rather than merely output per animal, is also a method of increasing feed efficiency in ways that should at least preserve animal welfare.

Overall, we find that achieving a carbon neutral future for Danish agriculture may be possible and highly beneficial in multiple ways, but it will also be hard. This difficulty should be no surprise. Reducing energy emissions requires multiple, successful efforts to develop new technologies to achieve the goals. Mitigation analyses in the agricultural sector have placed far less emphasis on innovation, and innovation has received even fewer resources, but the challenge is similar.

Policy Principles for Advancing the Necessary Innovations

This strategy relies heavily on continued innovations. We offer four strategies to spur and guide innovation.

Approach agricultural mitigation like product development not just research. When a company seeks to develop a fundamentally new product, it establishes a product development team. That team identifies a range of big and small technological obstacles and implementation challenges. It then assigns each challenge to different subteams, to solve them systematically, reporting back and asking for appropriate budget authority over time. The teams and subteams may be organized in different ways, and there is a business literature about the best strategies for organizing teams and identifying priorities. Regardless, some form of product development process is the model Denmark should follow in systematically addressing each of the challenges identified here.

Today, Denmark and other countries mostly follow a different model. In this model, researchers propose research projects, which are typically modestly funded. Results are completed and written up; researchers bid on new projects and start a new cycle to pursue the most promising results. Eventually, once rounds of research have made satisfactory progress, governments may require or incentivize implementation of successful measures. Even then, researcher projects may primarily be used to assess whether and how to adjust a new technology to generate improvements rather than a systematic effort to continue the innovations.

This system is far too slow and occurs at too small a scale. For example, for nearly 10 years, Danish researchers have identified the possibility that modest levels of sulfate might cheaply reduce methane emissions from manure, and only now expect to receive modest research funds to test this option. It may not work, but its promise of a cheap, effective solution should have motivated immediate funding first at a smaller scale, and then quickly at a larger scale if the small-scale tests proved successful.

This system is also not the way agriculture generates continuous improvements in its productivity. Farmers, interacting with agricultural suppliers, are continuously adjusting production techniques to boost yields and economic returns year after year. Advancing innovations for agricultural greenhouse gas mitigation would benefit from an approach that creates the same sense of urgency as product development.

Properly account for greenhouse gas effects, including land use effects. The easiest way to pursue the wrong measures is to count their greenhouse gas effects incorrectly. To count them correctly, we have identified types of emissions for which Denmark needs better data, such as emissions from manure management. To guide future work, Denmark also needs to be able to estimate likely benefits and assess progress. Although the model developed for Denmark's NIR is a good start, many of its estimates appropriately use national data, while planning efforts need to characterize farms by type and estimate their emissions. There are also interactive effects on emissions that need to be factored into planning, such as the multiple effects of improved feed conversion or nitrogen use efficiency.

The biggest potential distortion can result from failing to properly factor the greenhouse gas costs of land use into climate accounting. Failing to do so leads to one basic mistake: claiming reductions in greenhouse gas emissions for reducing food production.

This is a major issue faced by Denmark and all other countries in counting national emissions to meet national climate goals. Denmark has announced goals to reduce its emissions by 70 percent by 2030, in part based on its own pledges, but substantial reductions are also required by

EU law. The accounting Denmark and most other countries use to measure their emissions is primarily based on guidance from the IPCC for national inventory reporting. These guidelines were intended to generate an accurate picture of global emissions and do not necessarily reflect a country's own contribution to reducing global emissions. Used to assess national mitigation efforts, the guidelines have many strengths but also limitations that can distort Denmark's and other countries' incentives.

For example, if a country enacts policies that reduce food (or factory) production in its own country and if that production is replaced somewhere else, global emissions reported to the United Nations by all countries will be accurate, but the country's claim to have reduced global emissions will be inaccurate. Another limitation is that this approach provides no incentive for a country to reduce the emissions associated with its consumption unless this also changes that country's production. One of the most prominent accounting problems results from the treatment of bioenergy as carbon neutral, in that the very real carbon emitted by burning biomass is ignored. As a result, countries that switch land from food production to bioenergy can count reductions in energy emissions, and sometimes reductions in agricultural production emissions, while ignoring the global consequences of reducing food production.

To properly assess actions that reduce emissions, Denmark needs to factor land use properly into its system for planning and assessing progress. It should do so by either by using the carbon opportunity cost of land method used in this report or some other method that factors in that opportunity cost.

Create incentives for the private sector to innovate. Innovation can come from the public sector, from public-private partnerships, and from the private sector. In *Creating a Sustainable Food Future*, we recommended providing guarantees to the private sector in advance that if they develop technologies that would reduce emissions at a specified price of less, those technologies would be required. We also suggested technology forcing strategies that increase the burden on private industry to innovate. For example, we recommended establishing a requirement that fertilizer companies sell increasing percentages of their fertilizer over time with inhibitors or other technologies that reduce emissions (further developed in Kanter and Searchinger 2018). Doing so would encourage fertilizer companies to develop better products and better ways of using their products.

Denmark could develop such policy approaches by itself but would be most effective in doing so in collaboration with other countries and with the European Union.

Reduce disincentives for agriculture to innovate. The regulatory process can discourage private industry from developing new approaches to reducing environmental problems. If requirements to control pollution are based on what has proved to be cost-effective, industry may have an incentive to prove pollution controls are ineffective or too expensive. There are two possible ways to avoid these disincentives. One is to set requirements in advance regardless of cost so industry has reasons to innovate to meet those standards. That is the approach taken, for example, in setting future fuel efficiency standards for automobiles. Another approach is to fix the cost to industry so that added costs will be at the expense of the government. That does not provide incentives to innovate but avoids disincentives. Combining the two is also possible and might be most effective.

Recommendations

Our discussion of each technological option includes separate recommendations, but here we set forth a number of cross-cutting recommendations.

Technology development and implementation

1. Move forward quickly and comprehensively to try out, develop, and implement the various mitigation technologies on their own appropriate schedules. We recommend that Denmark establish a budget in the range of $250 million per year, comparable to its present budget for digesters, to be spent on coordinated efforts that combine testing on farms with research and assessment for some technologies, and just research for others. Even once implemented, continuous processes should be put in place to test and try various improvements. Table 7.2 categorizes mitigation measures by different timelines for large-scale adoption. A few technologies illustrate the different opportunities over time.

- Almost immediate: Evacuating manure from barns more frequently is a measure that can at least in part be implemented immediately. The analysis required is basic cost-engineering of physical methods of removing manure given existing barn structures. The enteric methane inhibitor 3-NOP seems likely to be approved next year and if so, can proceed on a similar immediate scale, albeit with some initial testing.
- Within a few years: Acidification of manure requires a little testing and development but merits immediate, full-scale pilot projects, including efforts to test if a modest quantity of sulfate can achieve the same methane-reduction goals. Acidified manure should be applied carefully in test strips to assess yield effects along with tests of possible effects on phosphorus losses from soils. If successful over three years, large-scale adoption could start. Nitrification inhibitor use should proceed similarly.
- Within a decade: Nitrogen-fixing microbes can be tested immediately on maize, and, if successful, implemented immediately thereafter, while Denmark can test products and work with the most promising companies to quickly develop the science to use any successful microbes on other crops. Biorefining is a technology that might be able to proceed on a similar schedule, although it may take time to reduce costs sufficiently and to increase perennial grass yields enough to make biorefineries highly beneficial.
- Longer term: Biological nitrification inhibition is a longer-term technology for which Denmark should work with other countries to expand the research.

2. Establish a technical team, with subteams to be responsible for the development and implementation of solutions for each major source of emissions. Each subteam should have mitigation targets and should compete for funding. As discussed, Denmark should shift from a model of public research followed by implementation to a "product development" model that establishes government, research, agriculture, and other stakeholder teams to pursue each type of solution. For example, one team might pursue enteric methane solutions; another team might pursue manure management solutions. One model would be to establish an oversight team with government appointees but with a separate budget while maintaining a government agricultural climate group to oversee progress. Subteams could compete on regular basis for funding, making the case for the opportunities in their work and for the benefits that funding would bring. Each team can more thoroughly evaluate the arguments for each mitigation measure identified in this report and consider alternative technologies, particularly as new ideas emerge over time.

3. Eliminate use of crops from digesters, impose a moratorium on funding new manure digesters, and assess a phase-out of digesters as they age. The elimination of crop use is critical to ensuring that digesters are producing new climate gains. The additional recommendations are worth emphasizing because digester subsidies are costing Denmark around $250 million per year. We recommend additional analytic work to confirm or dispute our estimates, including work to better assess emissions from manure today. If this analysis confirms our assessment that digesters are not cost-effective, digesters should be allowed to retire as they age. This funding might support many of the other measures set forth in this report.

Assessing, planning, and tracking emissions reductions

4. Quickly resolve key uncertainties about emission factors. Denmark has spent billions of dollars on digesters that have proved to be not cost-effective, expense that could have been avoided if Denmark had had better information on manure storage emission rates. With a budget of probably $7 million, Denmark could clearly establish emission rates for manure management within three years.

5. Establish an emissions planning and tracking accounting system that also factors in carbon opportunity costs. Such a system can start with Denmark's national inventory report

(NIR) system, but that system should be modified to make it more useful for planning agricultural mitigation. For example, estimates of emissions from the NIR system often start with end use data, such as fertilizer used nationally, or feed consumed per animal. A system that plans mitigation needs to incorporate farm management features that determine the end data, such as how much fertilizer will be used for each crop. To develop effective policies for different farms, it is also often helpful to group farms into representative farm types, such as dairy farms of a certain size using a certain manure management system. We developed a relatively simple representation of Danish agriculture for the analyses in this paper for these purposes. It could provide some insights for adapting the national inventory system and database into a better tool than we developed.

For all the reasons explained in this report, such a system also needs to track the land area carbon footprint and how it changes over time. And it should use some kind of carbon opportunity cost method to incorporate the effects on greenhouse gas emissions through land use.

Ensuring broad social support

6. Seek a social compact linking agricultural production increases, land restoration, and climate mitigation. Although increased food production in Denmark has the potential to contribute to solving climate change, doing so imposes an environmental burden on those who live in Denmark. Without steady mitigation of agricultural emissions, it also burdens other sectors in Denmark under present EU laws and global treaties. Our scenarios suggest a potential to increase food production, reduce emissions, and restore habitat, but social and political support for such joint efforts will likely depend on parallel progress in achieving each goal. We therefore suggest that the different Danish stakeholders reach an agreement about 2050 and interim targets for (a) increases in Danish food production, (b) peatland and forest restoration, and (c) emissions mitigation. Progress in each should be tied to progress in the others, giving all stakeholders an incentive to pursue all three objectives.

7. Seek agreement about which costs of mitigation are borne by agriculture and which by the government in a way that provides incentives for agriculture to advance mitigation technologies.

8. Devote land taken out of agriculture production to achieving carbon and biodiversity values rather than uses for forestry, bioenergy, or low-level agriculture. Some new production forests may be planted in return for transitioning older production forests to maximize habitat. Doing so not only contributes to those environmental goals but also creates shared incentives among agricultural and environmental organizations to support increases in agricultural land use efficiency.

International cooperation

9. Develop partnerships in South America to increase land use efficiency of Danish feed imports through "produce and protect" efforts. Our report describes a variety of measures that could increase the land use efficiency of feeds imported from South America, both directly or in combination with pasture improvements. Using these increases to protect and restore forests would provide offsets. Because of this international component, it makes sense for Danish agriculture and the government to work together to make these measures happen.

10. Seek to revise international carbon accounting standards. Denmark should work to reform global carbon accounting rules so they avoid incentives that primarily result in shifting emissions abroad. Better rules should recognize the greenhouse gas benefits of consumption changes, and properly factor in land use. As discussed above, present EU laws and IPCC guidance have created distorted incentives for agricultural climate mitigation by encouraging changes that just reduce food production. Denmark should seek to revise these accounting standards.

11. Seek international partners for expanded collaboration and funding of several research objectives. Two should be biological nitrification inhibition and the potential to select for and enhance varieties that can most increase yields with an increased share of soil nitrogen in the form of ammonium. Breeding for improved wheat, barley, and grass yields are others.

APPENDIX A: DETERMINING GROWTH IN FOOD DEMAND FOR ESTIMATING LAND AREA CARBON NEUTRALITY AND POTENTIAL OFFSETS

Because consumption and production of food are rising and are expected to keep rising at least through 2050, agricultural area must expand unless the amount of food produced per hectare increases at the same rate as total production does globally. In other words, to avoid agricultural land expansion, the global average rate of increase in food production must be matched by the same global rate of increase in land use efficiency of food production.

As we discuss in the main text, any one country could make an argument that it should be considered land area carbon neutral with a lower rate of land use efficiency increase (versus the global rate), which would implicitly require that other countries increase their land use efficiency at a higher rate than the global average, that they already have high yields and thus should not be expected to further increase yields, or that the obstacles facing them are greater because of economic or biophysical impediments. Countries could also argue that they should only have to increase yields to the extent they increase food production. Any of these arguments would in effect place a higher obligation on other countries. We start with the assumption, however, that each country should share the same obligation to increase land use efficiency and apply that to Denmark. We therefore estimate what the global rate of food production increase will be from 2017, our base year, to 2050.

To provide such an estimate, the relevant growth in "food" must be defined. Rather than one product, food consists of a variety of products, each supplying differing quantities of calories, protein, and other nutrients—and each meeting different subjective desires and aspirations. Each food will have its own level of production increase. For example, the GlobAgri-WRR model used in *Creating a Sustainable Food Future* projects that between 2010 and 2050, global dairy production will rise 58 percent, which implies a 44 percent increase from 2017 to 2050. The implied rise in pork production between 2017 and 2050 is 31 percent, but because poultry increases are much larger, the overall rise in monogastric meat (pork and poultry) is 69 percent. Soybean production is projected to rise 49 percent from 2017 to 2050 (although actual increases in soybean production have been occurring at a faster rate than predicted by the model).

We do not believe it is appropriate or practical to make producers of each food responsible for increasing that food's land use efficiency at the rate of its own growth. What matters to avoid land use change is the overall rate of growth across many foods. In addition, some foods, such as soybeans, are growing faster precisely because their high yields relative to most other high-protein crops such as pulses make them the least-costly source of high-protein animal feed. Implicitly assigning land use emissions to soybean producers unless their yields grow at a higher rate would not accurately measure the relative contribution of their yield increases to avoiding overall agricultural land expansion.

To generate a single number for food production growth, each food has to be weighted by an appropriate factor. From a land use and carbon perspective, the first two factors that matter are the amount of land used to produce each different type of food and the density of carbon on those lands. For example, if soybean yields are half those of maize but both use the same types of land, then an increase of one ton of soybeans is equivalent from a land use and land carbon opportunity cost perspective to an increase of two tons of maize. Conversely, if wheat and maize yields are similar, but wheat on average uses drier land that would store half as much carbon, then an increase of one ton of maize is equivalent to an increase of half a ton of wheat. This approach is precisely the formula for deriving carbon opportunity costs, and the result is that a ton of increase of each food has a corresponding quantity of carbon lost on average from vegetation and soils to produce that food.

We used these carbon opportunity costs to estimate the growth in "food" demand from 2017 to 2050 projected by GlobAgri-WRR measured by its carbon cost. That growth equals the increase in the quantity of each food multiplied by the carbon opportunity cost of each food. Applying that analysis just to crops, we estimate a 44 percent increase in food demand between 2017 and 2050. We also estimate the growth in carbon opportunity costs due to the growth in demand for the major livestock categories that rely heavily on crops: dairy, pork, poultry, and eggs. The aggregate increase in carbon opportunity costs for these categories is 47 percent. We use 45 percent as our overall estimate of food demand growth because it is a rough compromise average of these increases.

We do not incorporate into this analysis projected increases in the demand for ruminant meat, particularly meat from cattle, sheep, and goats. The primary source of feed for these animals globally is grass from grazing, a variety of fodders often gathered locally, crop residues, and various other food wastes (Herrero et al. 2013). Data on pasture area are particularly challenging (Fetzel et al. 2017), which means that accurately counting increases in land use efficiencies required for ruminant meats is challenging. We therefore believe it is best to separately calculate the need for land use efficiency gains for ruminant meat production when it is independent of dairy. That will require separate analysis that we have not undertaken for this report. As Denmark produces ruminant meat principally as a by-product of its dairy production, its increase is incorporated into our dairy projection.

Our 45 percent estimated food increase is only for planning purposes. To determine if Danish agriculture is truly land area carbon neutral in coming decades, the actual global rate of increase in food production is what matters. For example, if food production were to only increase by 35 percent by 2050 (measured by carbon opportunity costs [COCs]), then Denmark would only need to increase its land use efficiencies by 35 percent to be carbon neutral. Extra increases could count toward offset credits.[a]

Note: a. COCs will change over time because, as yields grow, the carbon loss per ton of each crop or meat or milk will decline (unless that food production expands onto more carbon-rich land, which would pull the COC back upward). For estimating growth in food demand, what matters is the growth from the base year used. The use of COCs is therefore similar to the use of a consumer price index to measure inflation. To determine if wages have grown at the same rate as inflation, one would need to measure the growth from the same base year.

APPENDIX B: METHODOLOGICAL NOTE

The analysis of national greenhouse gas emissions in this report and potential mitigation are based primarily on emissions reported in the various national emission inventory reports (NIRs) submitted by Denmark to the United Nations. These emissions are reported both in long written reports and in spreadsheets submitted as appendixes. We used both sources, as the results are sometimes reported in different ways in the different sources.

To calculate mitigation potential, we developed separate spreadsheet models to estimate drivers of emissions from the different categories and to estimate potential reductions. For example, to estimate emissions from manure digesters and costs, we used the ClimAg model to analyze them with different assumptions. To estimate implications for land use, we developed a spreadsheet with area and yields for different crops and examined the implications for crop area of changes in feed conversion efficiency, yield gains, and crop shifting, and how those changes alter carbon opportunity costs. These spreadsheets generated what can be called "bottom-up" estimates of emissions that do not necessarily rely on national data sources, such as quantity of fertilizer sold. We ensured that these bottom-up estimates did a reasonable job of approximating national emissions categories reported in the NIR. We used our bottom-up estimates of percentage reductions in emissions. For those categories of emissions reflected in the NIR which did not include carbon opportunity costs, we then applied these percentage reductions to the NIR category estimates.

This two-step method ensured consistency with national emission reports. We employed this practice because there are national sources of data, such as data on fertilizer sales, that can be used and are used for national emissions estimates but do not depend on more precise estimates of individual activities, such as fertilizer use per type of crop. The national methods also by themselves do not always allow for mitigation analysis. For example, these methods cannot themselves estimate changes in methane and feed demands due to improvements in livestock feeding efficiencies. But there is also significant uncertainty in all ways of estimating many agricultural emissions. Because we determined that the NIR estimates are reasonable, we chose to tie our emissions and mitigation estimates to the absolute levels of emissions reported in the NIR.

Several parts of our analysis relied on more complex models. Our estimates of the emissions intensity of Danish pork and dairy and those of other countries used the ClimAg model developed by one of our authors, Stefan Wirsenius. This model is described in more detail in Wirsenius et al. (2020), including its appendixes. Estimates of future food demands, weighted by land use requirements, were based on applying carbon opportunity costs per type of crop or livestock product from Searchinger et al. (2018). These carbon opportunity costs were applied to projected global increases for each type of food production using the GlobAgri-WRR model, developed primarily by another coauthor, Patrice Dumas. This model is described in some detail in Appendix A of *Creating a Sustainable Food Future*. Future per capita diets are based on FAO projections underlying Alexandratos and Bruinsma (2012), except they were adjusted modestly to ensure adequate food availability in sub-Saharan Africa and South Asia. Future populations by country are based on midlevel population projections from the United Nations.

The analysis of opportunities for mitigation potential and the remaining discussion are based on the expertise of the authors, and the eight years of research that went into the formulation of *Creating a Sustainable Food Future*. That work included a massive review of the literature and consultations with dozens of researchers around the world. These researchers contributed to reports that underlie the final full report. For this Denmark report, we did additional extensive review of the peer-reviewed and informal literature and engaged in additional consultations with subject experts in such fields as enteric methane inhibition, nitrogen use, and manure management. The work was also based on extensive personal interviews, phone calls, and emails with agricultural and land use experts in Denmark, particularly those associated with the Agroecology Department at Aarhus University, with SEGES, and with various departments at the University of Copenhagen.

APPENDIX C: ATTRIBUTIONAL VERSUS CONSEQUENTIAL LIFE-CYCLE ANALYSIS AND SIGNIFICANCE FOR COUNTING EMISSIONS FROM LAND USE

The field of life-cycle analysis (LCA) often distinguishes "attributional" from "consequential" LCAs, but the methodologies of each vary and the methods are not fully distinguishable. "Attributional" analysis, in some sense, tries to identify the observed emissions generated in producing a specific product. "Consequential" analysis attempts to analyze the consequences of increasing or decreasing consumption and therefore production of that product.

Either approach can use a purely biophysical analysis. For example, an attributional analysis might try to identify the source of the specific electrons that a factory uses, and determine the emissions from that particular source, with higher emissions for electricity from natural gas than for electricity from wind. A "consequential analysis" might try to estimate what the "marginal" source of electrons is likely to be. For example, even if that factory itself buys electricity from a wind producer, if there is only so much wind power, the marginal source of electricity might be natural gas anyway, which could be used by a consequential LCA. An "attributional" LCA, however, could also attribute emissions from the average sources of electricity in a country, or even a continent, rather than the specific wind power supplying the factory. There are no clearly fixed rules.

Moreover, the only real purpose of an LCA is to determine the consequences of doing something differently, of changing production methods or quantities or consumption. In that sense, all LCAs try to be "consequential." Overall, the biggest distinction between attributional and consequential LCAs is that attributional LCAs typically use an average emission for inputs, while consequential LCAs try to determine the emissions from the "marginal" source. But as the electricity example above suggests, it is often hard to determine the marginal source, and the average emissions may often be the best guide. And even using average emissions, the analyst must choose what to average. Choices must be made, and they should be guided by some notion of what the likely consequences of changing consumption or production would be.

One way of doing consequential life-cycle analysis is to use economic models, but economic models introduce into the analysis a range of changes by other people. For example, one consequence of almost any additional consumption by one person is that it makes a product, whether food or oil, more expensive, and reduced consumption makes it cheaper. One consequence of additional consumption by one person is likely to be less consumption by others. Changing consumption could also change production methods. Applied to consumption of oil, an economic analysis might estimate that increased consumption by one person will cause other people to consume less oil because of higher prices, and perhaps even trigger long-term declines in oil use by making electric cars more competitive. Should the LCA therefore claim that consuming oil causes fewer emissions than generated directly by burning it?

Energy LCAs almost never use economic models, and neither do LCAs that analyze the production emissions from agriculture, but economic models are occasionally used in counting emissions from land use from agriculture, particularly as indirect land use change for bioenergy. A "consequential" LCA of "indirect land use change" may use an economic model to analyze the effects of bioenergy or increased meat consumption and claim fewer emissions by claiming that either the change in consumption of bioenergy or meat will increase prices. As a result of higher prices, some people may consume less food. Other farmers may add more fertilizer or make other changes to increase yields, and production may shift from one country to another. We do not follow this approach for multiple related reasons described in the main text.

One reason these economic models have been used to count "indirect" land use costs is that the alternative has often been to view the ongoing use of existing (previously cleared) agricultural land as emissions-free. However, the ongoing use of land by agriculture cannot be considered carbon-free because not using land for agriculture will typically allow trees and other native vegetation to regrow, storing more carbon. Carbon opportunity costs are a somewhat more elaborate way of estimating this opportunity cost of devoting land to agriculture and are based on the global or regional average quantities of carbon that could be stored if that food were not consumed. We use carbon opportunity costs in this analysis. They are a kind of "attributional" way of measuring the greenhouse gas costs of agriculture because they are based on the average carbon lost to generate a food product.

In other respects, our LCA approach shares characteristics of an attributional analysis in that we generally focus on average emissions to generate a product, but when analyzing potential mitigation, we attempt to analyze the biophysical consequences. For example, we would not assign a greenhouse gas credit just for shifting soybean purchases from one country to another.

APPENDIX D. POTENTIAL BROMOFORM EMISSIONS FROM SEAWEED RELATIVE TO GLOBAL, ANTHROPOGENIC EMISSIONS OF OZONE-DEPLETING CHEMICALS

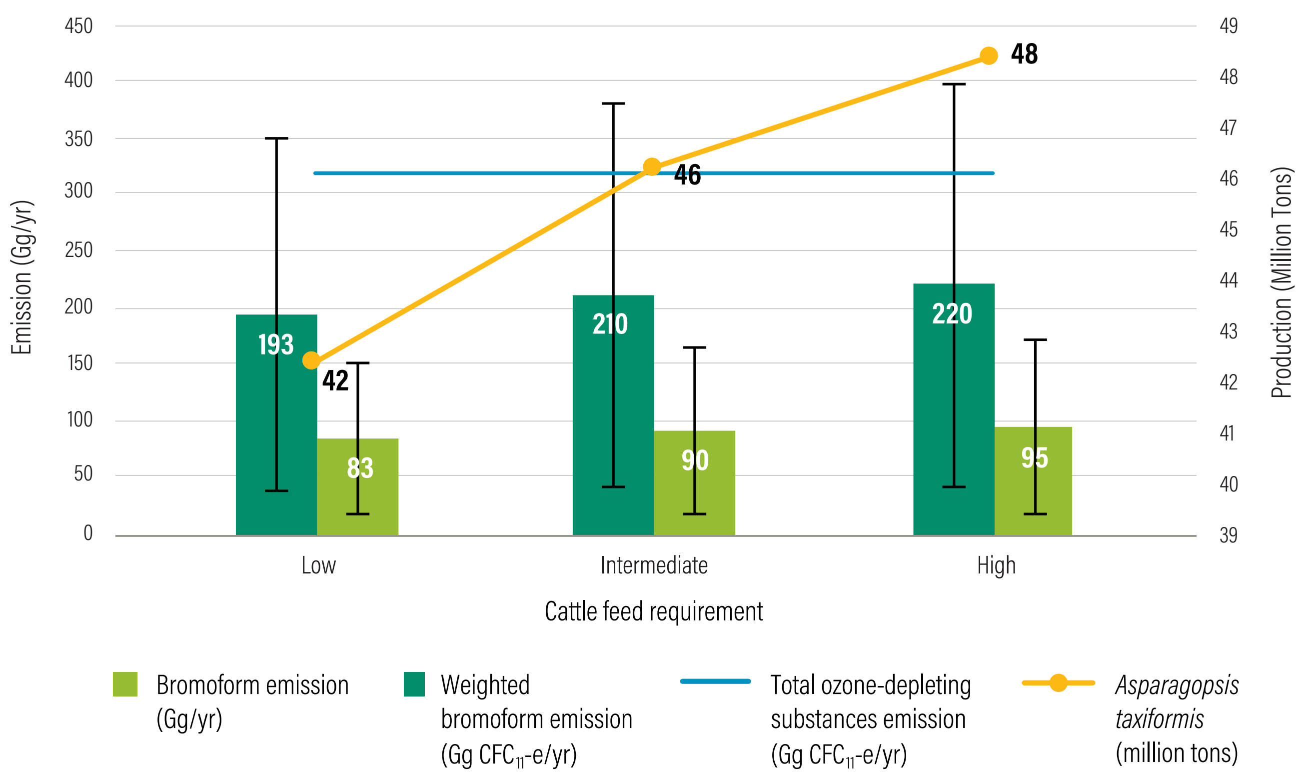
Asparagopsis taxiformis can reduce enteric methane production from dairy cattle effectively by large percentages when added at a 1 percent level of organic matter (OM) inclusion rate (Roque et al. 2019). This mixing of *Asparagopsis* 1 percent OM and Rhodes grass 99 percent OM is equivalent to 1.01 percent dry weight biomass replacement of normal grass (Machado et al. 2016). According to FAO, the world had 1.468 billion head of cattle in 2013, and the feed requirements for the low, intermediate, and high technology cattle systems were 7.8, 8.5, and 8.9 kilograms dry weight per day per head, respectively (Kassam and Fischer 1991). Assuming a 1 percent OM inclusion rate and that all the cattle are fed seaweed to reduce methane, the annual quantity of seaweed required will be 46.2 million tons (42.4 for low, 48.4 for high) dry weight.

Naturally, red seaweeds are strong oceanic emitters of bromoform, although the range of emission estimates is large. One study estimated emissions to the stratosphere at the rate of 29.1 to 274.2 micrograms per gram dry weight per day for red seaweeds (Keng et al. 2020). If we assume that on average each ton of seaweed needs 30 days to grow in the ocean, the 46.2 million tons seaweed per year requested for cattle will release 40.3 to 379.9 gigagrams (Gg) bromoform annually to the stratosphere. The global ocean fluxes of bromoform range between 379.1 Gg/yr to 631.8 Gg/yr (Ziska et al. 2013), with mean fluxes at 505.5 Gg/yr. Therefore, the 46.2 million tons of seaweed can lead to an additional 8–75 percent emission.

Global total emissions of ozone-depleting substances reduced from 1.46 million tons per year (1,460 Gg/yr) to 0.32 million tons (320 Gg/yr) due to the Montreal Protocol, measured in tons of chlorofluorocarbon-11 equivalent (CFC_{11}-equivalent) per year (Hegglin et al. 2015). Weighted by the ozone-depleting potential of 0.43 (average of spring, summer, and fall seasons) (Papanastasiou et al. 2014), the average of our range of 40.3 to 379.9 Gg bromoform emission is equivalent to 90.4 Gg CFC_{11}-equivalents. That would be 28 percent of the 2014 global total emissions of ozone-depleting substances, with a range from 5 percent to 51 percent. Figure D1 shows our estimates.

Because of these potential concerns, we recommend focusing on production of red algae in controlled factories where any emissions can be filtered.

Figure D1 | Potential Emissions of Ozone-Depleting Substances from Production of Red Algae in the Ocean



Source: Authors' calculations.

ENDNOTES

1. These calculations are based on the value added of Danish agriculture as estimated by the World Bank, https://data.worldbank.org/indicator/NV.AGR.TOTL.KD?locations=DK.

2. The arable land and forest area numbers and animal density come from FAO at either the 2020 FAOSTAT Land Use domain, http://www.fao.org/faostat/en/#data/RL, or the live animals domain, http://www.fao.org/faostat/en/#data/QA.

3. Wollenberg et al. (2016) summarizes least-cost mitigation analyses by three integrated assessment models, which call for only 11–18 percent reductions in emissions by 2030 relative to the baseline, reductions it summarizes of only one gigaton of CO_2e. However, these integrated assessment models did not find limited need for agricultural mitigation because of other good alternatives; they were programmed to assume limited potential for agricultural mitigation. One consequence of this limited mitigation potential is that the models require expensive and challenging "negative emissions" later in the 21st century to achieve climate targets. In Smith et al. (2008), only 11 percent of the estimated emission reduction potential in agriculture is from reductions in core agricultural emissions, such as nitrous oxide and methane; the remainder results from some kind of carbon sequestration or avoided peatland carbon loss.

4. For example, analyses have shown that increased mitigation of methane in the next two decades significantly increases the amount of carbon dioxide that can be emitted in the next few decades before temperatures exceed targets of 2 degrees of warming (Collins et al. 2018).

5. Statistics Denmark, Table BDF11.

6. Statistics Denmark, Tables AFG5 and HST77.

7. Statistics Denmark, Table HST77.

8. Technically there are two ways to justify a discount rate. One is to assume that the cost of carbon emissions in each future year is constant, but to value earlier mitigation based on the time-value of money using a long-term return to capital. That is the assumption discussed in Searchinger et al. (2018). Another approach is to use 4 percent as the value of earlier mitigation based both on the added cost of immediate mitigation and the added value of avoiding both short-term and permanent damage, including risks of crossing various climate thresholds (Daniel et al. 2019). Either way, this discounting approach is roughly consistent with global bioenergy policies, which in the United States amortize emissions from land use change over 30 years as discussed in Searchinger et al. (2018).

9. Carbon opportunity costs can be calculated in two ways: the carbon loss method or the carbon gain method. The carbon loss method estimates the average quantity of carbon lost to produce a ton of a crop. The carbon gain method estimates the potential quantity of carbon that could be sequestered by reforesting cropland if there were less production of a crop. At a 4 percent discount rate, the carbon opportunity costs of each were surprisingly similar for most crops (Searchinger et al. 2018).

10. Global carbon opportunity costs are based on the average carbon released from land conversion to produce a type of food. Regional opportunity costs are based on that number just in a region, which for Denmark is Europe.

11. AnimalChange (2012), Figure 7. This analysis focused on efficiencies based on protein (kg of protein in output, e.g., meat, divided by kg of protein in feed).

12. Email to T. Searchinger from Maike Brask, Arla Foods, September 2, 2020.

13. These improvements in herd management were based on a slightly reduced age at first calving (from 25 to 23 months) and a somewhat higher calving rate (0.95 instead of 0.86).

14. Based on extrapolation of those trends, we assumed an increase in number of liveborn piglets per litter, from 17.3 to 21.7, and an increase in liveweight gain rates of slaughter pigs (in the finishing phase), from 0.97 to 1.22 kg per day.

15. Arguably, agricultural emissions should be adjusted downward to count just the difference in emissions between drained peatlands and natural peatlands. We follow this approach to ensure avoid confusion between our peatland emissions estimates and those now in use within Denmark.

16. "Agricultural Land Prices and Rents: Land Prices Vary Considerably between and within Member States," Eurostat press release, March 21, 2018, https://ec.europa.eu/eurostat/documents/2995521/8756523/5-21032018-AP-EN.pdf/b1d0ffd3-f75b-40cc-b53f-f22f68d541df.

17. According to the NIR, roughly 20 percent of this nitrous oxide is due to indirect emissions of nitrous oxide that originate with ammonia releases from manure and 80 percent occurs directly from the management of the manure (NIR 2019).

18. We use a range here because the time of typical storage is unclear, with estimates ranging from 17 to 30 days. In addition, more extensive testing will undoubtedly lead to adjustments in estimates of the relationship between emissions and time of storage.

19. The University of Copenhagen study assigns the mitigation through fossil energy savings a "shadow price" that reduces the overall cost to the mitigation of methane in the agricultural sector, but because that shadow price is lower than the cost of the agricultural mitigation, this approach has the effect of increasing the portion of digester costs assigned to agricultural mitigation. This approach is a useful way of comparing the costs of one form of agricultural mitigation with

another. If we assume that mitigation in the energy sector is cheaper than mitigation in the agricultural sector, it therefore assigns to agricultural mitigation the additional costs of achieving energy mitigation through a digester relative to another energy mitigation measure. Although we believe that approach also has merit, it does not by itself reveal the overall cost-benefit ratio of all mitigation achieved through a digester, and it is also subject to the uncertainty of what future mitigation costs are likely to be in the energy sector. We therefore instead count all the fossil energy savings from a digester assuming that biogas will be cleaned and will replace natural gas and divide the overall costs of the digester by all the climate mitigation (from both fossil energy substitution and reduction in agricultural methane) to determine an average cost per overall ton of CO_2e mitigation.

20. The University of Copenhagen study projects costs for in-barn systems from the ground up. We use SEGES estimates of existing system costs for in-storage application, costs that may be high due to limited competition and opportunities for learning at this time. These systems are not designed to maintain low pH for extended periods. We start with their 3 liters of sulfuric acid assumption, 5.5 kg, and then, based on the total acid needs estimated by the University of Copenhagen and their costs, we add 2 additional kg of sulfuric acid for cattle manure and 5 additional kg for pig manure, at a cost of DKK 1/kg.

21. In doing this analysis, we assume that the public policy decision has been made that it is cost-effective to pay for the reduced ammonia emissions from acidification prior to field application because such efforts are already underway. That defines a cost per ton of ammonia abated. If it is considered cost-effective, that cost can be viewed as a minimum benefit per ton of ammonia abated. We then count that benefit per ton of additional ammonia reduction using in-storage acidification.

22. Albrektsen et al. (2017, Appendix J and Table 5.3) provides different emission factors for in-barn versus external storage that illustrate these numbers.

23. Calculations by authors based on Basso et al. (2019).

24. For more information see https://www.ispag.org/Leadership/CountryRep/Denmark.

25. This cost is based on information provided by Azotic.

26. Email to T. Searchinger from A. Botes, chief scientist at Azotic, March 8, 2021.

27. These are new results reported to us in an email from Uffe Jørgensen, January 16, 2021.

28. Controlled experiments at JIRCAS have tested differing shares of ammonium with different sorghum varieties and have found that a large yield response from higher ammonium with one variety but none with another (unpublished data provided by Guntur Subbarao, JIRCAS).

29. The increased nitrogen use efficiency results in an overall reduction of nitrogen application by 28 percent, but because all manure will be used, these reductions all occur through reductions in synthetic fertilizer.

30. As specified in the 2020 NIR, part 5.7 (pp. 402–3), the NIR technically estimates indirect N_2O emissions from leaching based on a percentage of nitrogen applied to soils that is estimated to leach. But this percentage is not fixed. It is based on actual estimates of nitrogen leaching, and then this nitrogen leaching is divided by total applied nitrogen to obtain a percentage leached. The result mathematically depends on the estimate of nitrogen leached and is the same result as just estimating the quantity of nitrogen leached.

31. This report does not provide a precise figure, but this estimate has also been provided by Aarhus researchers orally to us.

32. Personal communication from Nanna Hellum Kristensen, December 2021. Cover crop use has been increasing and was only 8 percent of Danish cropland a few years ago (Aronsson et al. 2016).

33. Roughly 25 percent of Danish cropland has no cover during the winter. We assume here that cropland leaches 50 percent more nitrogen per hectare than average Danish cropland. If cover crops could reduce that leaching by 50 percent, the total reduction in leaching would be 19 percent. Winter wheat, barley, and rye occupy roughly one-third of Danish cropland that is not in grassland. We will assume it is responsible for one-third of the nitrogen leaching and that earlier planting could reduce these losses by 25 percent, reducing overall leaching another 8 percent. We round the total of 27 percent to 25 percent.

34. Email from Mark van-Nieuwland (DSM) to T. Searchinger, September 11, 2020.

35. Personal communications from Ermias Kebreab, January 2021.

36. Although not focused on red algae, a study by the U.S. Department of Energy estimated a cost of $1,137 per dry ton of algae in a closed loop system (Zhu et al. 2018). At that cost, and a 0.2 percent inclusion rate, algae would be only around 1 percent of the feed costs. The algal cost estimate may be low, but a fourfold higher cost would raise feed costs to roughly 4 percent. If algae result in a significant improvement in feed conversion efficiency, the result would be net savings.

37. This paragraph is based on email communications between Searchinger and Mette Olaf Nielsen in 2020.

38. Press announcement from Ørsted, https://orsted.com/en/media/newsroom/news/2020/10/143404185982536 (last accessed March 6, 2021).

39. In these examples, we assume that carbon sequestration from reforestation benefits would match but not exceed carbon costs of reduced food production. If Danish land use efficiency grows by 45 percent, Denmark could also keep agricultural production at its current level and use these gains to liberate even more lands for reforestation than would be possible with the increased production. However, we would not assign this reforestation greenhouse gas savings because Denmark would not have contributed to increases in global land use efficiency that allow more land to be reforested on a net basis while meeting food demands. Denmark could choose to follow this path for legitimate social and local environmental reasons, but the climate results from land use would be the same as if it increased its production by 45 percent. If Denmark increased its land use efficiency by 55 percent, and reforested 45 percent of its agricultural land, our system would recognize carbon credits for 10 percent of that reforestation.

40. In our baseline we assume that yields in 2050 will be higher than those in 2017 by 21 percent for barley, 12 percent for wheat, 29 percent for rapeseed, 34 percent for maize, and 15 percent for grasses and all other crops. We explain how we develop these numbers in Appendix A.

41. Calculations by researchers at the University of Copenhagen for Danish national reporting estimate an average gross gain in carbon stock (excluding losses due to harvest or other conversions) of 2.96 tons of carbon per hectare in above-ground and below-ground biomass, dead wood, and soils. (Estimate based on data provided in Johannsen et al. [2019] and with advice communicated by Searchinger in four email exchanges, October 9, 2020).

42. Limited years of data have precluded us from estimating clear trend lines for grass fodders, but the average yields of legume/grass mixes in rotation from the three years 2016–18 were roughly 8 percent higher than those from 2006 to 2008. Permanent grass yields do not show the same gains. If we take an average of these two over 33 years, the gain would be 13.2 percent, which we round up to 15 percent.

43. This section also reflects multiple conversations and email exchanges with Uffe Jørgensen, Søren Jensen, and Morten Ambye-Jensen, all with Aarhus University.

44. Our calculation of carbon benefits from biorefining is based on estimates from researchers at Aarhus University that 19 percent of the dry matter in the grass (or grass/legume mix) will be turned into protein meal with an equivalent protein value as soybeans, that 56 percent will be an equivalent feed to silage maize, and that 25 percent will be used for energy use. Achieving these goals assumes that 20 percent of the grass biomass is nitrogen, although that may not be fully required. (These numbers assume that each ton of carbon in biomass used for energy is able to save 0.45 tons of carbon from fossil fuels through bioenergy use, which is a common estimated number for liquid biofuels.)

45. There is also some evidence that the regular use of grasses in Denmark, at least on sandy soils, contribute more than 1 ton of carbon per hectare per year soil carbon gains (over 3.67 tons of CO_2). Those increases may occur, but we do not factor them in because we consider them less likely at the high nitrogen-removal rates of festololium as building soil carbon also requires nitrogen.

46. "Aftermath" is areas that are planted mostly in grasses but with a portion in cereals that are harvested together for fodder.

47. Doing so would require increased imports of other feeds, such as cereals, but their land use costs are offset by the biorefineries' production of high-protein feeds that replace soybeans.

48. Although not identical, fodder beets have advantages generally similar to those of sugar beets, which are increasingly recognized as an excellent cattle feed (Evans and Messerschmidt 2017).

49. In 2018, the average sale price of Danish agricultural land was roughly $21,000 per hectare based on reports to EUROSTAT (https://ec.europa.eu/eurostat/databrowser/view/apri_lprc/default/table?lang=en). Assuming carbon sequestration rates of 3 tons of carbon per hectare per year, roughly 11 tons of CO_2, for 50 years, the present discount value of this carbon at a 4 percent discount rate, the rate used for carbon opportunity costs, would be equivalent to an immediate mitigation of 246 tons of carbon. Assuming $1,000 for site-preparation and planting costs, the cost would be $89 per ton of CO_2.

50. Information for this discussion comes from materials provided by TerViva, which has Pongamia plantings of several thousand hectares in Florida, and from email and telephone conversations conducted in 2019 and 2020 with its chief executive and chief scientist.

51. Sustainable Trade initiative, Mato Grosso, https://www.idhsustainabletrade.com/landscapes/mato-grosso-brazil/.

52. The criteria for a sound forest protection offset project are generally set forth well in the Architecture for REDD+ Transitions (ART) standards available at https://www.artredd.org/. We impose here additional requirements for rising yields to achieve land area carbon neutrality.

53. The absolute number provided is 103 percent of lower heating value energy for both biomass and natural gas. For the purpose of estimating saved fossil emissions, the absolute efficiency does not matter, only the relative conversion efficiencies.

54. A typical, even optimistic estimate for the loss of carbon from pyrolysis is 35 percent (Pröll et al. 2017). For the carbon included in the biochar, there are conflicting results regarding the percentage that is still lost over a few decades. Data in

one meta-analysis (Wang et al. 2016), for example, include losses as high as 13 percent in a single year and as low as half a percent in five years. This meta-analysis developed a curve to explain the studies, which would suggest a mean decomposition rate of 5 percent after nine years (although there were fewer data from long-term than short-term studies), with a much slower decomposition rate overall after one year. A wide variety of biochar and receiving properties have been suggested to influence these different decomposition rates (Jiang et al. 2016). That presents a challenge because it will be difficult to maximize biochar properties for long-term soil retention while also producing jet fuel. Additions of biochar also have complex effects on other soil carbon, sometimes increasing decomposition rates and sometimes decreasing them (Fatima et al. 2020). Here we assume that an additional 5 percent of the original carbon would be lost to decomposition by 30 years, which typically approximates our use of a 4 percent discount rate.

55. These numbers are generated by multiplying the average yields and the global or regional carbon opportunity costs for a ton of each crop.

56. Even with our optimistic assumptions for the jet fuel/biochar combination above, the savings would not be much different. Because our calculations above assumed straw, they assumed no production emissions to generate the crop (or to transfer it to the processing plant or to redistribute the biochar). If we assume that producing willow requires energy use equivalent to 10 percent of the energy gained from the willow, and a 10 percent loss of carbon in original drying of the willow, the net savings from carbon dioxide in this example would still only reach 10 tons of carbon dioxide per hectare at a yield of 12 tons dry matter of willow per hectare. (There is high potential for much higher drying losses and also releases of methane during that process.)

57. Few forms of mitigation do not increase and decrease in proportion to increases and decreases in production. For example, rewetting peatlands is highly beneficial and could be fully achieved at existing production levels. Changes in soil carbon and bioenergy are also not linearly related to changes in production. Nearly all other forms of mitigation do scale linearly with production levels.

NOTES

All unreferenced numbers are results of the authors' modeling.

All dollars are U.S. dollars unless otherwise indicated.

All tons are metric tons unless otherwise indicated.

All general references to greenhouse gas emissions are in carbon dioxide equivalents using a 100-year global warming potential unless otherwise indicated.

"Kcal" = kilocalorie, also referred to as simply "calorie."

REFERENCES

Abdalla, Mohamed, Astley Hastings, Jaak Truu, Mikk Espenberg, Ülo Mander, and Pete Smith. 2016. "Emissions of Methane from Northern Peatlands: A Review of Management Impacts and Implications for Future Management Options." *Ecology and Evolution* 6 (19): 7080–102. https://doi.org/10.1002/ece3.2469.

Abdalla, Mohamed, Astley Hastings, Kun Cheng, Qian Yue, Dave Chadwick, Mikk Espenberg, Jaak Truu, et al. 2019. "A Critical Review of the Impacts of Cover Crops on Nitrogen Leaching, Net Greenhouse Gas Balance and Crop Productivity." *Global Change Biology* 25 (8): 2530–43. https://doi.org/10.1111/gcb.14644.

Aide, T. Mitchell, Matthew L. Clark, H. Ricardo Grau, David López-Carr, Marc A. Levy, Daniel Redo, Martha Bonilla-Moheno, et al. 2013. "Deforestation and Reforestation of Latin America and the Caribbean (2001–2010)." *Biotropica* 45 (2): 262–71. https://doi.org/10.1111/j.1744-7429.2012.00908.x.

Ainsworth, Elizabeth A., Craig R. Yendrek, Jeffrey A. Skoneczka, and Stephen P. Long. 2012. "Accelerating Yield Potential in Soybean: Potential Targets for Biotechnological Improvement." *Plant, Cell & Environment* 35 (1): 38–52. https://doi.org/10.1111/j.1365-3040.2011.02378.x.

Akiyama, Hiroko, Xiaoyuan Yan, and Kazuyuki Yagi. 2010. "Evaluation of Effectiveness of Enhanced-Efficiency Fertilizers as Mitigation Options for N_2O and NO Emissions from Agricultural Soils: Meta-analysis." *Global Change Biology* 16 (6): 1837–46. https://doi.org/10.1111/j.1365-2486.2009.02031.x.

Albrektsen, Rikke, Mette Hjorth Mikkelsen, and Steen Glydenoerne. 2017. "Danish Emission Inventories for Agriculture: Inventories, 1985–2015." 250. Aarhus: Danish Center for Environment & Energy, Aarhus University.

Alexandratos, N., and J. Bruinsma. 2012. "World Agriculture towards 2030/2050: The 2012 Revision." ESA Working Paper no. 12-03. Rome: Food and Agriculture Organization of the United Nations.

AnimalChange. 2012. "Seventh Framework Programme, Theme 2: Food, Agriculture and Fisheries, and Biotechnologies, Deliverable 2.2: Preliminary Scenarios of the Developments in Agricultural Commodity Markets, Livestock Production Systems, and Land Use and Land Cover." Brussels: AnimalChange.

Anson, Sam, and Karen Turner. 2009. "Rebound and Disinvestment Effects in Refined Oil Consumption and Supply Resulting from an Increase in Energy Efficiency in the Scottish Commercial Transport Sector." *Energy Policy* (New Zealand Energy Strategy) 37 (9): 3608–20. https://doi.org/10.1016/j.enpol.2009.04.035.

Argento, F., T. Anken, F. Abt, E. Vogelsanger, A. Walter, and F. Liebisch. 2020. "Site-Specific Nitrogen Management in Winter Wheat Supported by Low-Altitude Remote Sensing and Soil Data." *Precision Agriculture*, June. https://doi.org/10.1007/s11119-020-09733-3.

Arima, Eugenio Y., Peter Richards, Robert Walker, and Marcellus M. Caldas. 2011. "Statistical Confirmation of Indirect Land Use Change in the Brazilian Amazon." *Environmental Research Letters* 6 (2): 024010. https://doi.org/10.1088/1748-9326/6/2/024010.

Arneth, A., S. Sitch, J. Pongratz, B.D. Stocker, P. Ciais, B. Poulter, A.D. Bayer, et al. 2017. "Historical Carbon Dioxide Emissions Caused by Land-Use Changes Are Possibly Larger than Assumed." *Nature Geoscience* 10 (2): 79–84. https://doi.org/10.1038/ngeo2882.

Aronsson, H., E. M. Hansen, I.K. Thomsen, J. Liu, A. F. Øgaard, H. Känkänen, and B. Ulén. 2016. "The Ability of Cover Crops to Reduce Nitrogen and Phosphorus Losses from Arable Land in Southern Scandinavia and Finland." *Journal of Soil and Water Conservation* 71 (1): 41–55. https://doi.org/10.2489/jswc.71.1.41.

Askegaard, M., J.E. Olesen, and K. Kristensen. 2005. "Nitrate Leaching from Organic Arable Crop Rotations: Effects of Location, Manure and Catch Crop." *Soil Use and Management* 21 (2): 181–88. https://doi.org/10.1111/j.1475-2743.2005.tb00123.x.

Attwood, Sophie, Paula Voorheis, Cecelia Mercer, Karen Davies, and Daniel Vennard. 2020. "Playbook for Guiding Diners toward Plant-Rich Dishes in Food Service," July. https://www.wri.org/publication/playbook-guiding-diners-toward-plant-rich-dishes-food-service.

Baral, Khagendra R., Poul E. Lærke, and Søren O. Petersen. 2019. "Nitrous Oxide Emissions from Cropping Systems Producing Biomass for Future Bio-refineries." *Agriculture, Ecosystems & Environment*. https://agris.fao.org/agris-search/search.do?recordID=US201900371826.

Barreto, Paulo. 2010. "Will Cattle Ranching Continue to Drive Deforestation in the Brazilian Amazon?" Imazon.

Basche, A.D., F.E. Miguez, T.C. Kaspar, and M.J. Castellano. 2014. "Do Cover Crops Increase or Decrease Nitrous Oxide Emissions? A Meta-analysis." *Journal of Soil and Water Conservation* 69 (6): 471–82. https://doi.org/10.2489/jswc.69.6.471.

Basso, Bruno, Guanyuan Shuai, Jinshui Zhang, and G. Philip Robertson. 2019. "Yield Stability Analysis Reveals Sources of Large-Scale Nitrogen Loss from the US Midwest." *Scientific Reports* 9 (1): 5774. https://doi.org/10.1038/s41598-019-42271-1.

Bastami, Mohd Saufi B., Davey L. Jones, and David R. Chadwick. 2016. "Reduction of Methane Emission during Slurry Storage by the Addition of Effective Microorganisms and Excessive Carbon Source from Brewing Sugar." *Journal of Environmental Quality* 45 (6): 2016–22. https://doi.org/10.2134/jeq2015.11.0568.

Bastami, M.S., D.L. Jones, and D.R. Chadwick. 2019. "Microbial Diversity Dynamics during the Self-Acidification of Dairy Slurry." *Environmental Technology* 0 (0): 1–11. https://doi.org/10.1080/09593330.2019.1706644.

Blain, Loz. 2016. "Australian Seaweed Found to Eliminate More than 90% of Cow Burb Methane." *New Atlas*, October 20. https://newatlas.com/csiro-seaweed-cow-methane-emissions/46021/.

Blicher-Mathiesen, Gitte, Hans Estrup Andersen, and Søren Erik Larsen. 2014. "Nitrogen Field Balances and Suction Cup-Measured N Leaching in Danish Catchments." *Agriculture, Ecosystems & Environment* 196 (October): 69–75. https://doi.org/10.1016/j.agee.2014.06.022.

Boesgard, Knud 2019. "The Danish Example." In *Biogas and Biomethane in Europe: Lessons from Denmark, Germany and Italy*, edited by M. Eyl-Mazzega and C. Mathieu, 19–33. Paris: IFRI Centre for Energy.

Brisson, Nadine, Philippe Gate, David Gouache, Gilles Charmet, François-Xavier Oury, and Frédéric Huard. 2010. "Why Are Wheat Yields Stagnating in Europe? A Comprehensive Data Analysis for France." *Field Crops Research* 119 (1): 201–12. https://doi.org/10.1016/j.fcr.2010.07.012.

Britto, Dev T., and Herbert J. Kronzucker. 2002. "NH_4+ Toxicity in Higher Plants: A Critical Review." *Journal of Plant Physiology* 159 (6): 567–84. https://doi.org/10.1078/0176-1617-0774.

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

Chahal, Inderjot, Richard J. Vyn, Danielle Mayers, and Laura L. Van Eerd. 2020. "Cumulative Impact of Cover Crops on Soil Carbon Sequestration and Profitability in a Temperate Humid Climate." *Scientific Reports* 10 (1): 13381. https://doi.org/10.1038/s41598-020-70224-6.

Ciais, P., C. Sabine, G. Bala, V. Bopp, J. Brovkin, J. Canadell, R. Chhara, et al. 2013. "Carbon and Other Biogeochemical Cycles." In *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge: Cambridge University Press.

Cocking, Edward C., Philip J. Stone, and Michael R. Davey. 2006. "Intracellular Colonization of Roots of Arabidopsis and Crop Plants by *Gluconacetobacter Diazotrophicus." In Vitro Cellular & Developmental Biology: Plant* 42 (1): 74–82. https://doi.org/10.1079/IVP2005716.

Cohn, Avery S., Aline Mosnier, Petr Havlík, Hugo Valin, Mario Herrero, Erwin Schmid, Michael O'Hare, and Michael Obersteiner. 2014. "Cattle Ranching Intensification in Brazil Can Reduce Global Greenhouse Gas Emissions by Sparing Land from Deforestation." *Proceedings of the National Academy of Sciences* 111 (20): 7236–41. https://doi.org/10.1073/pnas.1307163111.

Collins, William J., Christopher P. Webber, Peter M. Cox, Chris Huntingford, Jason Lowe, Stephen Sitch, Sarah E. Chadburn, et al. 2018. "Increased Importance of Methane Reduction for a 1.5 Degree Target." *Environmental Research Letters* 13 (5): 054003. https://doi.org/10.1088/1748-9326/aab89c.

Colombo, Carlos Augusto, Luiz Henrique Chorfi Berton, Brenda Gabriela Diaz, and Roseli Aparecida Ferrari. 2018. "Macauba: A Promising Tropical Palm for the Production of Vegetable Oil." OCL 25 (1): D108. https://doi.org/10.1051/ocl/2017038.

Cook-Patton, Susan C., Sara M. Leavitt, David Gibbs, Nancy L. Harris, Kristine Lister, Kristina J. Anderson-Teixeira, Russell D. Briggs, et al. 2020. "Mapping Carbon Accumulation Potential from Global Natural Forest Regrowth." *Nature* 585 (7826): 545–50. https://doi.org/10.1038/s41586-020-2686-x.

Daniel, Kent D., Robert B. Litterman, and Gernot Wagner. 2019. "Declining CO_2 Price Paths." *Proceedings of the National Academy of Sciences* 116 (42): 20886–91. https://doi.org/10.1073/pnas.1817444116.

Danish Ministry of Environment and Food. 2018. "Fact Sheet: Food Waste in Denmark."

Dean, Joshua F., Jack J. Middelburg, Thomas Röckmann, Rien Aerts, Luke G. Blauw, Matthias Egger, Mike S.M. Jetten, et al. 2018. "Methane Feedbacks to the Global Climate System in a Warmer World." *Reviews of Geophysics* 56 (1): 207–50. https://doi.org/10.1002/2017RG000559.

De Notaris, Chiara, Jim Rasmussen, Peter Sørensen, and Jørgen Olesen. 2018. "Nitrogen Leaching: A Crop Rotation Perspective on the Effect of N Surplus, Field Management and Use of Catch Crops." *Agriculture, Ecosystems & Environment* 255 (March): 1–11. https://doi.org/10.1016/j.agee.2017.12.009.

Dent, David, and Edward Cocking. 2017. "Establishing Symbiotic Nitrogen Fixation in Cereals and Other Non-legume Crops: The Greener Nitrogen Revolution." *Agriculture & Food Security* 6 (1): 7. https://doi.org/10.1186/s40066-016-0084-2.

Difford, Gareth Frank, Damian Rafal Plichta, Peter Løvendahl, Jan Lassen, Samantha Joan Noel, Ole Højberg, André-Denis G. Wright, et al. 2018. "Host Genetics and the Rumen Microbiome Jointly Associate with Methane Emissions in Dairy Cows." *PLOS Genetics* 14 (10): e1007580. https://doi.org/10.1371/journal.pgen.1007580.

Dinesen, Lars, Anders Petersen, and Carsten Rahbek. 2021. "Synergy in Conservation of Biodiversity and Climate Change Mitigation in Nordic Peatlands and Forests: Eight Case Studies." TemaNord, no. 510. Copenhagen: Nordic Council of Ministers.

Dourado-Neto, D., D. Powlson, R. Abu Bakar, O.O.S. Bacchi, M.V. Basanta, P. thi Cong, G. Keerthisinghe, et al. 2010. "Multiseason Recoveries of Organic and Inorganic Nitrogen-15 in Tropical Cropping Systems." *Soil Science Society of America Journal* 74 (1): 139–52. https://doi.org/10.2136/sssaj2009.0192.

Dubgaard, Alex, and Lisa Ståhl. 2018. "Omkostninger ved virkemidler til reduktion af landbrugets drivhusgasemissioner: Opgjort i relation til EU's 2030-målsætning for det ikke-kvotebelagte område." IFRO 271. Copenhagen: University of Copenhagen.

Dumont, M., L. Luning, I. Yildiz, and K. Koop. 2013. "Methane Emission in Biogas Production." In *The Biogas Handbook: Science, Production, and Applications*. Oxford, UK: Woodhead.

EIA (U.S. Energy Information Administration). 2012. *Annual Energy Outlook 2012: With Projections to 2035*. Washington, DC: EIA.

Eriksen, Jørgen, Ingrid K. Thomsen, Carl Christian Hoffmann, Berit Hasler, and Brian H. Jacobsen. 2020. "Virkemidler til reduktion af kvælstofbelastningen af vandmiljøet." Tjele, Denmark: Aarhus University, University of Copenhagen.

"Evaluation on Efficacy of N-Fix on Nitrogen Needs and Agronomic Performance of Rice in Central Area 2 Sites in Thailand." 2019. Nakohn Swan, Thailand: Eurofins Agroscience Services.

Evans, Essi. 2019. "Fodder Beets: An Economical Substitute for Grains." *Progressive Dairy*, September 30. https://www.progressivedairycanada.com/topics/feed-nutrition/feed-beets-an-economical-substitute-for-grains.

Evans, Essi, and Ulrike Messerschmidt. 2017. "Review: Sugar Beets as a Substitute for Grain for Lactating Dairy Cattle." *Journal of Animal Science and Biotechnology* 8 (March). https://doi.org/10.1186/s40104-017-0154-8.

Fangueiro, David, José Pereira, André Bichana, Sónia Surgy, Fernanda Cabral, and João Coutinho. 2015. "Effects of Cattle-Slurry Treatment by Acidification and Separation on Nitrogen Dynamics and Global Warming Potential after Surface Application to an Acidic Soil." *Journal of Environmental Management* 162 (October): 1–8. https://doi.org/10.1016/j.jenvman.2015.07.032.

Fatima, Samar, Muhammad Riaz, Mohammad I. Al-Wabel, Muhammad Saleem Arif, Tahira Yasmeen, Qaiser Hussain, Mahnaz Roohi, et al. 2020. "Higher Biochar Rate Strongly Reduced Decomposition of Soil Organic Matter to Enhance C and N Sequestration in Nutrient-Poor Alkaline Calcareous Soil." *Journal of Soils and Sediments*, August. https://doi.org/10.1007/s11368-020-02753-6.

Fetzel, T., P. Havlik, M. Herrero, J.O. Kaplan, T. Kastner, C. Kroisleitner, S. Rolinski, et al. 2017. "Quantification of Uncertainties in Global Grazing Systems Assessment." *Global Biogeochemical Cycles* 31 (7): 1089–102. https://doi.org/10.1002/2016GB005601.

Filso, Stina Susgaard. 2019. "Erfaringer fra lavbundsordningen: Udtagning af kulstofrige jorde som klimavirkemiddel." Aarhus, Denmark: SEGES.

Flanagan, Katie, Kai Robertson, and Craig Hanson. 2019. *Reducing Food Loss and Waste: Setting a Global Action Agenda*. World Resources Institute. https://doi.org/10.46830/wrirpt.18.00130.

Future Farming. 2020. "John Deere: We Believe in Electric Tractors." March 12. https://www.futurefarming.com/Machinery/Articles/2020/3/John-Deere-We-believe-in-electric-tractors-100-552869E/.

Gibbs, Jim. 2020. "Kiwis Find It's Hard to Beat the Beet." https://hayandforage.com/article-2885-kiwis-find-it%E2%80%99s-hard-to-beat-the-beet.html.

González-Recio, O., J. López-Paredes, L. Ouatahar, N. Charfeddine, E. Ugarte, R. Alenda, and J. A. Jiménez-Montero. 2020. "Mitigation of Greenhouse Gases in Dairy Cattle via Genetic Selection: 2. Incorporating Methane Emissions into the Breeding Goal." *Journal of Dairy Science* 103 (8): 7210–21. https://doi.org/10.3168/jds.2019-17598.

Griscom, B.W. 2017. "Natural Climate Solutions." *Proceedings of the National Academy of Sciences* 114 (44): 11645–50.

Gyldenkærne, Steen. 2019. "Bestilling til AU vedr. fejl om udbredelse af organiske jorde af 28-08-2019." DCE—Nationalt Center Miljo og Energi, Aarhus University.

Harpenslager, Sarah F., Eva van den Elzen, Martine A.R. Kox, Alfons J.P. Smolders, Katharina F. Ettwig, and Leon P.M. Lamers. 2015. "Rewetting Former Agricultural Peatlands: Topsoil Removal as a Prerequisite to Avoid Strong Nutrient and Greenhouse Gas Emissions." *Ecological Engineering* 84 (November): 159–68. https://doi.org/10.1016/j.ecoleng.2015.08.002.

Heber, Al, Don Jones, and Al Sutton. n.d. "Controlling Ammonia Gas in Swine Buildings." Purdue University and U.S. Department of Agriculture.

Hefner, Margita, Rodrigo Labouriau, Michael Nørremark, and Hanne Lakkenborg Kristensen. 2019. "Controlled Traffic Farming Increased Crop Yield, Root Growth, and Nitrogen Supply at Two Organic Vegetable Farms." *Soil and Tillage Research* 191 (August): 117–30. https://doi.org/10.1016/j.still.2019.03.011.

Hegglin, Michaela I., David W. Fahey, Mark McFarland, Stephen A. Montzka, and Eric R. Nash. 2015. *Twenty Questions and Answers about the Ozone Layer: 2014 Update-Scientific Assessment of Ozone Depletion.*

Henderson, B., A. Falcucci, A. Mottet, L. Early, B. Werner, H. Steinfeld, and P. Gerber. 2017. "Marginal Costs of Abating Greenhouse Gases in the Global Ruminant Livestock Sector." *Mitigation and Adaptation Strategies for Global Change* 22 (1): 199–224. https://doi.org/10.1007/s11027-015-9673-9.

Herrero, M., P. Havlík, H. Valin, A. Notenbaert, M.C. Rufino, P.K. Thornton, M. Blummel, et al. 2013. "Biomass Use, Production, Feed Efficiencies, and Greenhouse Gas Emissions from Global Livestock Systems." *Proceedings of the National Academy of Sciences* 110 (52): 20888–93. https://doi.org/10.1073/pnas.1308149110.

Hertel, Thomas W., Alla A. Golub, Andrew D. Jones, Michael O'Hare, Richard J. Plevin, and Daniel M. Kammen. 2010. "Effects of US Maize Ethanol on Global Land Use and Greenhouse Gas Emissions: Estimating Market-Mediated Responses." *BioScience* 60 (3): 223–31. https://doi.org/10.1525/bio.2010.60.3.8.

Houghton, R.E. 2008. "Carbon Flux to the Atmosphere from Land-Use Changes: 1850–2005." In *TRENDS: A Compendium of Data on Global Change*. Oak Ridge, TN: Carbon Dioxide Information Analysis Center, Oak Ridge National Laboratory.

Hristov, Alexander N., Joonpyo Oh, Fabio Giallongo, Tyler W. Frederick, Michael T. Harper, Holley L. Weeks, Antonio F. Branco, et al. 2015. "An Inhibitor Persistently Decreased Enteric Methane Emission from Dairy Cows with No Negative Effect on Milk Production." *Proceedings of the National Academy of Sciences* 112 (34): 10663–68. https://doi.org/10.1073/pnas.1504124112.

IEA (International Energy Agency). 2012. *World Energy Outlook 2012*. Paris: IEA.

IEA Bioenergy. 2017. *Denmark Country Report 2015, Energy from Biomass*. Esbjerg, Denmark: IEA Bioenergy.

Imbach, P., M. Manrow, E. Barona, A. Barretto, G. Hyman, and P. Ciais. 2015. "Spatial and Temporal Contrasts in the Distribution of Crops and Pastures across Amazonia: A New Agricultural Land Use Data Set from Census Data since 1950." *Global Biogeochemical Cycles* 29 (6): 2014GB004999. https://doi.org/10.1002/2014GB004999.

IPCC. 2006. *IPCC Guidelines for National Greenhouse Gas Inventories*. Prepared by the National Greenhouse Gas Inventories Programme. Published: IGES.

IPCC. 2018. *Global Warming of 1.5°C*. http://www.ipcc.ch/report/sr15/.

IPCC. 2019. *2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories*. Geneva: IPCC.

Jacobsen, Brian H. 2019. "Omkostninger ved virkemidler der kan bidrage til reduktion af ammoniakemission i 2020 og 2030." IFRO Idrening 2019/05. Institut for Fødevare- og Ressourceøkonomi, University of Copenhagen.

Jacobsen, B.H., and L. Ståhl. 2018. *Economic Analysis of the Ammonia Regulation in Denmark in Relation to the Habitat Directive*. Report no. 274. Institute of Food and Resource Economics, University of Copenhagen. https://www.cabdirect.org/cabdirect/abstract/20183230166.

Jayanegara, Anuraga, Ki Ageng Sarwono, Makoto Kondo, Hiroki Matsui, Muhammad Ridla, Erika B. Laconi, and Nahrowi. 2018. "Use of 3-Nitrooxypropanol as Feed Additive for Mitigating Enteric Methane Emissions from Ruminants: A Meta-analysis." *Italian Journal of Animal Science* 17 (3): 650–56. https://doi.org/10.1080/1828051X.2017.1404945.

Jiang, Xinyu, Karolien Denef, Catherine E. Stewart, and M. Francesca Cotrufo. 2016. "Controls and Dynamics of Biochar Decomposition and Soil Microbial Abundance, Composition, and Carbon Use Efficiency during Long-Term Biochar-Amended Soil Incubations." *Biology and Fertility of Soils* 52 (1): 1–14. https://doi.org/10.1007/s00374-015-1047-7.

Johannsen, V.K., Thomas Nord-Larsen, Niclas Scott Bentsen, and Lars Versterdahl. 2019. "Danish National Forest Accounting Plan 2021–2030, Resubmission 2019." Frederiksberg, Denmark: University of Copenhagen. https://research.ku.dk/search/result/?pure=en/publications/danish-national-forest-accounting-plan-20212030--resubmission-2019(44a9601f-35e7-4f33-8bc6-1df736d97d1d).html.

Jørgensen, Uffe, and Poul Lærke. 2016. "Perennial Grasses for Sustainable European Protein Production." In *Perennial Biomass Crops for a Resource-Constrained World*, ed. Susanne Barth, Donal Murphy-Bokern, Olena Kalinina, Gail Taylor, and Michael Jones, 33–41. Berlin: Springer. https://doi.org/10.1007/978-3-319-44530-4_3.

Kanter, David R., and Timothy D. Searchinger. 2018. "A Technology-Forcing Approach to Reduce Nitrogen Pollution." *Nature Sustainability* 1 (10): 544. https://doi.org/10.1038/s41893-018-0143-8.

Kassam, A.H., and G.W. Fischer. 1991. *Agro-ecological Land Resources Assessment for Agricultural Development Planning: A Case Study of Kenya: Resources Data Base and Land Productivity*. Rome: Food and Agriculture Organization of the United Nations.

Kavanagh, I., W. Burchill, M.G. Healy, O. Fenton, D.J. Krol, and G.J. Lanigan. 2019. "Mitigation of Ammonia and Greenhouse Gas Emissions from Stored Cattle Slurry Using Acidifiers and Chemical Amendments." *Journal of Cleaner Production* 237 (November): 117822. https://doi.org/10.1016/j.jclepro.2019.117822.

Kaye, Jason P., and Miguel Quemada. 2017. "Using Cover Crops to Mitigate and Adapt to Climate Change: A Review." *Agronomy for Sustainable Development* 37 (1). https://doi.org/10.1007/s13593-016-0410-x.

Keng, Fiona Seh-Lin, Siew-Moi Phang, Noorsaadah Abd Rahman, Emma C. Leedham Elvidge, Gill Malin, and William T. Sturges. 2020. "The Emission of Volatile Halocarbons by Seaweeds and Their Response towards Environmental Changes." *Journal of Applied Phycology* 32 (2): 1377–94. https://doi.org/10.1007/s10811-019-02026-x.

Klimarådet. 2000. "Kendte veje og nye spor til 70 procents reduction: Retning og tiltag for de næste ti års klimaindsats i Danmark." https://klimaraadet.dk/da/rapporter/kendte-veje-og-nye-spor-til-70-procents-reduktion.

Kinley, Robert D., Gonzalo Martinez-Fernandez, Melissa K. Matthews, Rocky de Nys, Marie Magnusson, and Nigel W. Tomkins. 2020. "Mitigating the Carbon Footprint and Improving Productivity of Ruminant Livestock Agriculture Using a Red Seaweed." *Journal of Cleaner Production* 259 (June): 120836. https://doi.org/10.1016/j.jclepro.2020.120836.

Kristensen, Troels, Jesper Overgard, Jesper Og, and Lisbeth Mogensen. 2019. *Fremtidens helhedsorienterede og balancerede kvægproduktion: Visioner og udfordringer for malkvægsbedriften frem mod år 2040*. DACA Report 146. Aarhus, Denmark: Aarhus University.

Ladha, Jagdish, Surendra Pathak, Timothy Krupnik, J. Six, and Chris Kessel. 2005. "Efficiency of Fertilizer Nitrogen in Cereal Production: Retrospects and Prospects." *Advances in Agronomy* 87 (December): 85–156. https://doi.org/10.1016/S0065-2113(05)87003-8.

Lamb, Anthony, Rhys Green, Ian Bateman, Mark Broadmeadow, Toby Bruce, Jennifer Burney, Pete Carey, et al. 2016. "The Potential for Land Sparing to Offset Greenhouse Gas Emissions from Agriculture." *Nature Climate Change* 6 (5): 488–92. https://doi.org/10.1038/nclimate2910.

Lantz, M., and B. Björnsson. 2016. "Emission of Greenhouse Gases in Production and Use of Biogass from Manure." Lund, Sweden: Lund University.

LBST (Landbrugsstyrelsen). 2019. "Vejledning om gødsknings- og harmoniregler." Copenhagen: Miljø- og Fødevareministeriet.

LBST. 2020. "Målrettet kvælstofregulering: Se kort over kystvandoplande med krav om obligatoriske efterafgrøder." June 19. https://lbst.dk/nyheder/nyhed/nyhed/maalrettet-kvaelstofregulering-se-kort-over-kystvandoplande-med-krav-om-obligatoriske-efterafgroeder/.

Le Gouis, Jacques, François-Xavier Oury, and Gilles Charmet. 2020. "How Changes in Climate and Agricultural Practices Influenced Wheat Production in Western Europe." *Journal of Cereal Science* 93 (May): 102960. https://doi.org/10.1016/j.jcs.2020.102960.

Lesschen, J.P., M. van den Berg, H.J. Westhoek, H.P. Witzke, and O. Oenema. 2011. "Greenhouse Gas Emission Profiles of European Livestock Sectors." *Animal Feed Science and Technology* 166–167 (June): 16–28. https://doi.org/10.1016/j.anifeedsci.2011.04.058.

Liska, Adam J., Haishun Yang, Maribeth Milner, Steve Goddard, Humberto Blanco-Canqui, Matthew P. Pelton, Xiao X. Fang, et al. 2014. "Biofuels from Crop Residue Can Reduce Soil Carbon and Increase CO_2 Emissions." *Nature Climate Change* 4 (5): 398–401. https://doi.org/10.1038/nclimate2187.

Liu, Shulin, Min Zhang, Feng Feng, and Zhixi Tian. 2020. "Toward a 'Green Revolution' for Soybean." *Molecular Plant* 13 (5): 688–97. https://doi.org/10.1016/j.molp.2020.03.002.

Loide, Valli. 2019. "The Effect of Acidified Slurry on Soil Based on Leaching Test Data (2017–2018)." Interreg, Baltic Sea Region and European Regional Development Fund.

López-Paredes, J., I. Goiri, R. Atxaerandio, A. García-Rodríguez, E. Ugarte, J.A. Jiménez-Montero, R. Alenda, and O. González-Recio. 2020. "Mitigation of Greenhouse Gases in Dairy Cattle via Genetic Selection: 1. Genetic Parameters of Direct Methane Using Noninvasive Methods and Proxies of Methane." *Journal of Dairy Science* 103 (8): 7199–209. https://doi.org/10.3168/jds.2019-17597.

Loussaert, Dale, Josh Clapp, Nick Mongar, Dennis P. O'Neill, and Bo Shen. 2018. "Nitrate Assimilation Limits Nitrogen Use Efficiency (NUE) in Maize (*Zea mays L.*)." *Agronomy* 8 (7): 110. https://doi.org/10.3390/agronomy8070110.

Lyngso, Henning. 2019. "Baltic Slurry Acidification: Policy Recommendations for Supporting SAT Implementation." Organe Institute, Interreg Baltic Sea Region, and European Union.

Machado, Lorenna, Marie Magnusson, Nicholas A. Paul, Robert Kinley, Rocky de Nys, and Nigel Tomkins. 2016. "Identification of Bioactives from the Red Seaweed *Asparagopsis Taxiformis* That Promote Antimethanogenic Activity in Vitro." *Journal of Applied Phycology* 28 (October): 3117–26. http://dx.doi.org/10.1007/s10811-016-0830-7.

Manevski, Kiril, Poul Lærke, Xiurong Jiao, Sanmohan Santhome, and Uffe Jørgensen. 2016. "Biomass Productivity and Radiation Utilisation of Innovative Cropping Systems for Biorefinery." *Agricultural and Forest Meteorology* 233 (December): 250–64. https://doi.org/10.1016/j.agrformet.2016.11.245.

Manevski, Kiril, Poul E. Lærke, Jørgen E. Olesen, and Uffe Jørgensen. 2018. "Nitrogen Balances of Innovative Cropping Systems for Feedstock Production to Future Biorefineries." *Science of the Total Environment* 633 (August): 372–90. https://doi.org/10.1016/j.scitotenv.2018.03.155.

Melgar, A., M.T. Harper, J. Oh, F. Giallongo, M.E. Young, T.L. Ott, S. Duval, and A.N. Hristov. 2020a. "Effects of 3-Nitrooxypropanol on Rumen Fermentation, Lactational Performance, and Resumption of Ovarian Cyclicity in Dairy Cows." *Journal of Dairy Science* 103 (1): 410–32. https://doi.org/10.3168/jds.2019-17085.

Melgar, A., K.C. Welter, K. Nedelkov, C.M.M.R. Martins, M.T. Harper, J. Oh, S.E. Räisänen, et al. 2020b. "Dose-Response Effect of 3-Nitrooxypropanol on Enteric Methane Emissions in Dairy Cows." *Journal of Dairy Science* 103 (7): 6145–56. https://doi.org/10.3168/jds.2019-17840.

Melgar, A., C.F.A. Lage, K. Nedelkov, S.E. Räisänen, H. Stefenoni, M.E. Fetter, X. Chen, et al. 2021. "Enteric Methane Emission, Milk Production, and Composition of Dairy Cows Fed 3-Nitrooxypropanol." *Journal of Dairy Science* 104 (1): 357–66. https://doi.org/10.3168/jds.2020-18908.

Michigan State University. n.d. "The Same for Less: Genetic Science Holds the Key to Better Feed Efficiency in Dairy Cattle." AgBioResearch. https://www.canr.msu.edu/news/the_same_for_less_genetic_science_holds_the_key_to_better_feed_efficiency_i. Accessed September 1, 2020.

Mikkelsen, Mette Hjorth, Steen Gyldenkaerne, Hanne Poulsen, and Sven Sommer. 2006. "Emissions of Ammonia, Nitrous Oxide and Methane from Danish Agriculture, 1985–2002: Methodology and Estimates." Department of Policy Analysis, National Environmental Research Institute, Danish Institute of Agricultural Sciences.

Møller, Peter Friis, Jacob Heilmann-Clausen, Rita Merete Buttenschøn, Inger Kappel Schmidt, Carsten Rahbek, Hans Henrik Bruun, and Rasmus Ejrn. 2018. "Anbefalinger vedrørende omstilling og forvaltning af skov til biodiversitetsformål." Copenhagen: GEUS.

Montagnini, Florencia, I. Ibrahim, and E. Murgueitio. 2013. "Silvopastoral Systems and Climate Change Mitigation in Latin America." *Bois et Forêts des Tropiques* 316 (2): 3–16.

Moreda, G.P., M.A. Muñoz-García, and P. Barreiro. 2016. "High Voltage Electrification of Tractor and Agricultural Machinery: A Review." *Energy Conversion and Management* 115 (May): 117–31. https://doi.org/10.1016/j.enconman.2016.02.018.

Mrotzek, Almut, Dierk Michaelis, Anke Günther, Nicole Wrage-Mönnig, and John Couwenberg. 2020. "Mass Balances of a Drained and a Rewetted Peatland: On Former Losses and Recent Gains." *Soil Systems* 4 (March). https://doi.org/10.3390/soilsystems4010016.

Mühleisen, Jonathan, Hans Peter Maurer, Gunther Stiewe, Paul Bury, and Jochen Reif. 2013. "Hybrid Breeding in Barley." *Crop Science* 53 (May): 819. https://doi.org/10.2135/cropsci2012.07.0411.

Munkholm, L.J., E.M. Hansen, I.K. Thomsen, E.M. Wahlström, and H.S. Østergaard. 2017. "Nitrogen Uptake, Nitrate Leaching and Root Development in Winter-Grown Wheat and Fodder Radish." *Soil Use and Management* 33 (2): 233–42. https://doi.org/10.1111/sum.12337.

Myers, R., A. Weber, and S. Tellatin. n.d. "Cover Crop Economics." Sustainable Agriculture Research and Education. https://www.sare.org/resources/cover-crop-economics/. Accessed October 12, 2020.

NIR (National Inventory Report). 2019. *Denmark's National Inventory Report 2019: Emission Inventories, 1990–2017*. By O. Nielsen et al. Submitted under the United Nations Framework Convention on Climate Change and the Kyoto Protocol. Aarhus University, DCE (Danish Centre for Environment and Energy). Scientific Report no. 318. http://Dce2.Au.Dk/Pub/SR318.pdf.

NIR. 2020. *Denmark's National Inventory Report 2019: Emission Inventories, 1990–2018*. By O. Nielsen et al. Submitted under the United Nations Framework Convention on Climate Change and the Kyoto Protocol. Aarhus University, DCE (Danish Centre for Environment and Energy).

Nord-Larsen, Thomas, Lisbeth Sevel, and Karsten Raulund-Rasmussen. 2014. "Commercially Grown Short Rotation Coppice Willow in Denmark: Biomass Production and Factors Affecting Production." *BioEnergy Research* 8 (March). https://doi.org/10.1007/s12155-014-9517-6.

Oldfield, Emily E., Mark A. Bradford, and Stephen A. Wood. 2019. "Global Meta-analysis of the Relationship between Soil Organic Matter and Crop Yields." *SOIL* 5 (1): 15–32. https://doi.org/10.5194/soil-5-15-2019.

Olesen, Jørgen, Søren Petersen, Peter Lund, Uffe Jørgensen, Troels Kristensen, Lars Elsgaard, Peter Sørensen, and Jan Lassen. 2018. "Virkemidler til reduktion af klimagasser i landbruget." DCA 130. Aarhus, Denmark: Aarhus University.

Olijhoek, D.W., A.L.F. Hellwing, M. Brask, M.R. Weisbjerg, O. Højberg, M.K. Larsen, J. Dijkstra, et al. 2016. "Effect of Dietary Nitrate Level on Enteric Methane Production, Hydrogen Emission, Rumen Fermentation, and Nutrient Digestibility in Dairy Cows." *Journal of Dairy Science* 99 (8): 6191–205. https://www.journalofdairyscience.org/article/S0022-0302(16)30301-0/fulltext.

OECD (Organisation for Economic Co-operation and Development). 2012. *OECD Environmental Outlook to 2050: The Consequences of Inaction*. Paris: OECD.

Ort, Donald R., Sabeeha S. Merchant, Jean Alric, Alice Barkan, Robert E. Blankenship, Ralph Bock, Roberta Croce, et al. 2015. "Redesigning Photosynthesis to Sustainably Meet Global Food and Bioenergy Demand." *Proceedings of the National Academy of Sciences* 112 (28): 8529–36. https://doi.org/10.1073/pnas.1424031112.

O'Sullivan, Cathryn A., Ian R.P. Fillery, Margaret M. Roper, and Richard A. Richards. 2016. "Identification of Several Wheat Landraces with Biological Nitrification Inhibition Capacity." *Plant and Soil* 404 (1): 61–74. https://doi.org/10.1007/s11104-016-2822-4.

Owen, Justine J., and Whendee L. Silver. 2015. "Greenhouse Gas Emissions from Dairy Manure Management: A Review of Field-Based Studies." *Global Change Biology* 21 (2): 550–65. https://doi.org/10.1111/gcb.12687.

Owusu-Twum, M.Y., N. Loick, L.M. Cardenas, J. Coutinho, H. Trindade, and D. Fangueiro. 2017. "Nitrogen Dynamics in Soils Amended with Slurry Treated by Acid or DMPP Addition." *Biology and Fertility of Soils* 53 (3): 339–47. https://doi.org/10.1007/s00374-017-1178-0.

Papanastasiou, D.K., S.A. McKeen, and J.B. Burkholder. 2014. "The Very Short-Lived Ozone Depleting Substance $CHBr_3$ (Bromoform): Revised UV Absorption Spectrum, Atmospheric Lifetime and Ozone Depletion Potential." *Atmospheric Chemistry and Physics* 14 (6): 3017–25. https://doi.org/10.5194/acp-14-3017-2014.

Park, Sang Hyun, Bok Rye Lee, Kwang Hwa Jung, and Tae Hwan Kim. 2018. "Acidification of Pig Slurry Effects on Ammonia and Nitrous Oxide Emissions, Nitrate Leaching, and Perennial Ryegrass Regrowth as Estimated by 15N-Urea Flux." *Asian-Australasian Journal of Animal Sciences* 31 (3): 457–66. https://doi.org/10.5713/ajas.17.0556.

Patience, John F., Mariana C. Rossoni-Serão, and Néstor A. Gutiérrez. 2015. "A Review of Feed Efficiency in Swine: Biology and Application." *Journal of Animal Science and Biotechnology* 6 (1). https://doi.org/10.1186/s40104-015-0031-2.

Patthawaro, Sirada, and Chewapat Saejung. 2019. "Production of Single Cell Protein from Manure as Animal Feed by Using Photosynthetic Bacteria." *MicrobiologyOpen* 8 (12): e913. https://doi.org/10.1002/mbo3.913.

Petersen, Anders, Thomas Lundhede, Hans Brrun, Jacob Heilmann-Clausen, Bo Thorsen, Strange Strange, and Carsten Rahbek. 2016. "Bevarelse af biodiversiteten i de danske skove; En analyse af den nødvendige indsats, og hvad den betyder for skovens andre samfundsgoder." Copenhagen: Center for Macroecology, University of Denmark.

Petersen, J., M. Haastrup, L. Kundsen, and J. Olesen. 2010. "Causes of Yield Stagnation in Winter Wheat in Denmark." *DJF Report Plant Science* 147. Aarhus, Denmark: Aarhus University.

Petersen, Søren O., Astrid J. Andersen, and Jørgen Eriksen. 2012. "Effects of Cattle Slurry Acidification on Ammonia and Methane Evolution during Storage." *Journal of Environmental Quality* 41 (1): 88–94. https://doi.org/10.2134/jeq2011.0184.

Petersen, S.O., O. Højberg, M. Poulsen, C. Schwab, and J. Eriksen. 2014. "Methanogenic Community Changes, and Emissions of Methane and Other Gases, during Storage of Acidified and Untreated Pig Slurry." *Journal of Applied Microbiology* 117 (1): 160–72. https://doi.org/10.1111/jam.12498.

Petersen, Søren O., Anne B. Olsen, Lars Elsgaard, Jin Mi Triolo, and Sven G. Sommer. 2016. "Estimation of Methane Emissions from Slurry Pits below Pig and Cattle Confinements." *PLoS ONE 11* (8). https://doi.org/10.1371/journal.pone.0160968.

Prag, Adam A., and Christian B. Henriksen. 2020. "Transition from Animal-Based to Plant-Based Food Production to Reduce Greenhouse Gas Emissions from Agriculture: The Case of Denmark." *Sustainability* 12 (19): 8228. https://doi.org/10.3390/su12198228.

Pröll, Tobias, Rafat Al Afif, Sebastian Schaffer, and Christoph Pfeifer. 2017. "Reduced Local Emissions and Long-Term Carbon Storage through Pyrolysis of Agricultural Waste and Application of Pyrolysis Char for Soil Improvement." *Energy Procedia* 114 (July): 6057–66. https://doi.org/10.1016/j.egypro.2017.03.1742.

Robbins, Jim. n.d. "Green Hydrogen: Could It Be Key to a Carbon-Free Economy?" Yale E360. https://e360.yale.edu/features/green-hydrogen-could-it-be-key-to-a-carbon-free-economy. Accessed November 5, 2020.

Röder, Mirjam, Carly Whittaker, and Patricia Thornley. 2015. "How Certain Are Greenhouse Gas Reductions from Bioenergy? Life Cycle Assessment and Uncertainty Analysis of Wood Pellet-to-Electricity Supply Chains from Forest Residues." Biomass and Bioenergy 79 (August): 50–63. https://doi.org/10.1016/j.biombioe.2015.03.030.

Rodhe, Lena K.K., Jamal Abubaker, Johnny Ascue, Mikael Pell, and Åke Nordberg. 2012. "Greenhouse Gas Emissions from Pig Slurry during Storage and after Field Application in Northern European Conditions." *Biosystems Engineering* 113 (4): 379–94. https://doi.org/10.1016/j.biosystemseng.2012.09.010.

Rodhe, Lena, Johnny Ascue, Agnes Willén, Birgitta Persson, and Ake Nordberg. 2015. "Greenhouse Gas Emissions from Storage and Field Application of Anaerobically Digested and Non-digested Cattle Slurry." *Agriculture, Ecosystems & Environment* 199. https://doi.org/10.1016/j.agee.2014.10.004.

Rodhe, Lena, Johnny Ascue, Marianne Termeden, and Leticia Pizzul. 2019. "Ammonia Emissions from Storage: Non-digested and Digested Cattle Slurry with and without Acid." Interreg Baltic Sea Region, European Union.

Roffeis, M., B. Muys, J. Almeida, E. Mathijs, W.M.J. Achten, B. Pastor, Y. Velásquez, A.I. Martinez-Sanchez, and S. Rojo. 2015. "Pig Manure Treatment with Housefly (*Musca domestica*) Rearing: An Environmental Life Cycle Assessment." *Journal of Insects as Food and Feed* 1 (3): 195–214. https://doi.org/10.3920/JIFF2014.0021.

Roque, Breanna M., Joan K. Salwen, Rob Kinley, and Ermias Kebreab. 2019a. "Inclusion of *Asparagopsis armata* in Lactating Dairy Cows' Diet Reduces Enteric Methane Emission by over 50 Percent." *Journal of Cleaner Production* 234 (October): 132–38. https://doi.org/10.1016/j.jclepro.2019.06.193.

Roque, Breanna Michell, Charles Garrett Brooke, Joshua Ladau, Tamsen Polley, Lyndsey Jean Marsh, Negeen Najafi, Pramod Pandey, et al. 2019b. "Effect of the Macroalgae *Asparagopsis taxiformis* on Methane Production and Rumen Microbiome Assemblage." *Animal Microbiome* 1 (1): 3. https://doi.org/10.1186/s42523-019-0004-4.

Roque, B.M., M. Venegas, R. Kinley, R. deNys, T.L. Neoh, T.L. Duarte, X. Yang, et al. 2020. "Red Seaweed (*Asparagopsis taxiformis*) Supplementation Reduces Enteric Methane by over 80 Percent in Beef Steers." BioRxiv, July. https://doi.org/10.1101/2020.07.15.204958.

Sadeghpour, Amir, Quirine M. Ketterings, Françoise Vermeylen, Gregory S. Godwin, and Karl J. Czymmek. 2018. "Nitrous Oxide Emissions from Surface versus Injected Manure in Perennial Hay Crops." *Soil Science Society of America Journal* 82 (1): 156–66. https://doi.org/10.2136/sssaj2017.06.0208.

Sanderson, Benjamin M., Brian C. O'Neill, and Claudia Tebaldi. 2016. "What Would It Take to Achieve the Paris Temperature Targets?" *Geophysical Research Letters* 43 (13): 7133–42. https://doi.org/10.1002/2016GL069563.

Schilde, Matthias, Dirk von Soosten, Liane Hüther, Ulrich Meyer, Annette Zeyner, and Sven Dänicke. 2021. "Effects of 3-Nitrooxypropanol and Varying Concentrate Feed Proportions in the Ration on Methane Emission, Rumen Fermentation and Performance of Periparturient Dairy Cows." *Archives of Animal Nutrition* 0 (0): 1–26. https://doi.org/10.1080/1745039X.2021.1877986.

Schils, René, Jørgen E. Olesen, Kurt-Christian Kersebaum, Bert Rijk, Michael Oberforster, Valery Kalyada, Maksim Khitrykau, et al. 2018. "Cereal Yield Gaps across Europe." *European Journal of Agronomy* 101 (November): 109–20. https://doi.org/10.1016/j.eja.2018.09.003.

Schjønning, P., Goswin Johann Heckrath, and B.T. Christensen. 2009. *Threats to Soil Quality in Denmark: A Review of Existing Knowledge in the Context of the EU Soil Thematic Strategy*. Tjele, Denmark: Dept. of Agroecology and Environment, Faculty of Agricultural Science, Aarhus University.

Searchinger, Timothy, and Janet Ranganathan. 2020. "INSIDER: Further Explanation on the Potential Contribution of Soil Carbon Sequestration on Working Agricultural Lands to Climate Change Mitigation." World Resources Institute. August 24. https://www.wri.org/blog/2020/08/insider-further-explanation-potential-contribution-soil-carbon-sequestration-working.

Searchinger, T.D., R. Edwards, D. Mulligan, R. Heimlich, and R. Plevin. 2015a. "Do Biofuel Policies Seek to Cut Emissions by Cutting Food?" *Science* 347 (6229): 1420–22. https://doi.org/10.1126/science.1261221.

Searchinger, T.D., L. Estes, P.K. Thornton, T. Beringer, A. Notenbaert, D. Rubenstein, R. Heimlich, et al. 2015b. "High Carbon and Biodiversity Costs from Converting Africa's Wet Savannahs to Cropland." *Nature Climate Change* 5: 481–86. https://doi.org/10.1038/nclimate2584.

Searchinger, Timothy D., Stefan Wirsenius, Tim Beringer, and Patrice Dumas. 2018. "Assessing the Efficiency of Changes in Land Use for Mitigating Climate Change." *Nature* 564 (7735): 249. https://doi.org/10.1038/s41586-018-0757-z.

Searchinger, Tim, Richard Waite, Craig Hanson, Janet Ranganathan, Patrice Dumas, and Emily Matthews. 2019. *World Resources Report: Creating a Sustainable Food Future—a Menu of Solutions to Feed Nearly 10 Billion People by 2050.* Final report. Washington, DC: World Resources Institute, World Bank, UN Development Programme, and UN Environment Programme. http://www.sustainablefoodfuture.org.

SEGES. 2017. "Baltic Slurry Acidification: Status, Economy and Consideration by Acidification of Slurry." Interreg Baltic Sea Region, European Union.

Sela, S., H.M. van Es, B.N. Moebius-Clune, R. Marjerison, and G. Kneubuhler. 2018. "Dynamic Model-Based Recommendations Increase the Precision and Sustainability of N Fertilization in Midwestern US Maize Production." *Computers and Electronics in Agriculture* 153 (October): 256–65. https://doi.org/10.1016/j.compag.2018.08.010.

Sela, S., P.B. Woodbury, R. Marjerison, and H.M. van Es. 2019. "Towards Applying N Balance as a Sustainability Indicator for the US Corn Belt: Realistic Achievable Targets, Spatio-temporal Variability and Policy Implications." *Environmental Research Letters* 14 (6): 064015. https://doi.org/10.1088/1748-9326/ab1219.

Senapati, Nimai, and Mikhail A. Semenov. 2020. "Large Genetic Yield Potential and Genetic Yield Gap Estimated for Wheat in Europe." *Global Food Security* 24 (March): 100340. https://doi.org/10.1016/j.gfs.2019.100340.

Sentelhas, P.C., R. Battisti, G.M.S. Câmara, J.R.B. Farias, A.C. Hampf, and C. Nendel. 2015. "The Soybean Yield Gap in Brazil: Magnitude, Causes and Possible Solutions for Sustainable Production." *Journal of Agricultural Science* 153 (8): 1394–411. https://doi.org/10.1017/S0021859615000313.

Sha, Zhipeng, Tiantian Lv, Maarten Staal, Xin Ma, Zhang Wen, Qianqian Li, Gregor Pasda, et al. 2020. "Effect of Combining Urea Fertilizer with P and K Fertilizers on the Efficacy of Urease Inhibitors under Different Storage Conditions." *Journal of Soils and Sediments* 20 (4): 2130–40. https://doi.org/10.1007/s11368-019-02534-w.

Sigurdarson, Jens Jakob, Simon Svane, and Henrik Karring. 2018. "The Molecular Processes of Urea Hydrolysis in Relation to Ammonia Emissions from Agriculture." *Reviews in Environmental Science and Bio/Technology* 17 (2): 241–58. https://doi.org/10.1007/s11157-018-9466-1.

"Sire Evaluations for Feed Efficiency to Be Released in 2020." n.d. *Dairyherd*. https://www.dairyherd.com/article/sire-evaluations-feed-efficiency-be-released-2020. Accessed September 1, 2020.

Smith, P., D. Martino, Z. Cai, D. Gwary, H. Janzen, P. Kumar, B. McCarl, et al. 2008. "Greenhouse Gas Mitigation in Agriculture." *Philosophical Transactions of the Royal Society B: Biological Sciences* 363 (1492): 789–813. https://doi.org/10.1098/rstb.2007.2184.

Sokolov, Vera, Andrew VanderZaag, Jermaneh Habtewold, Kari Dunfield, Claudia Wagner-Riddle, Jason J. Venkiteswaran, and Robert Gordon. 2019. "Greenhouse Gas Mitigation through Dairy Manure Acidification." *Journal of Environmental Quality* 48 (5): 1435–43. https://doi.org/10.2134/jeq2018.10.0355.

Sommer, Sven G., J. Webb, and Nicholas D. Hutchings. 2019. "New Emission Factors for Calculation of Ammonia Volatilization from European Livestock Manure Management Systems." *Frontiers in Sustainable Food Systems* 3. https://doi.org/10.3389/fsufs.2019.00101.

Spera, Stephanie A., Avery S. Cohn, Leah K. VanWey, Jack F. Mustard, Bernardo F. Rudorff, Joel Risso, and Marcos Adami. 2014. "Recent Cropping Frequency, Expansion, and Abandonment in Mato Grosso, Brazil Had Selective Land Characteristics." *Environmental Research Letters* 9 (6): 064010. https://doi.org/10.1088/1748-9326/9/6/064010.

Springmann, Marco, H. Charles J. Godfray, Mike Rayner, and Peter Scarborough. 2016. "Analysis and Valuation of the Health and Climate Change Cobenefits of Dietary Change." *Proceedings of the National Academy of Sciences* 113 (15): 4146–51. https://doi.org/10.1073/pnas.1523119113.

Sterman, John D., Lori Siegel, and Juliette N. Rooney-Varga. 2018. "Does Replacing Coal with Wood Lower CO_2 Emissions? Dynamic Lifecycle Analysis of Wood Bioenergy." *Environmental Research Letters* 13 (1): 015007. https://doi.org/10.1088/1748-9326/aaa512.

Stiesdal, Henrik. 2019. "SkyClean: Carbon Negative Fuel Concept." Stiesdal Fuel Technologies, January 1.

Strassburg, Bernardo B.N., Agnieszka E. Latawiec, Luis G. Barioni, Carlos A. Nobre, Vanderley P. da Silva, Judson F. Valentim, Murilo Vianna, and Eduardo D. Assad. 2014. "When Enough Should Be Enough: Improving the Use of Current Agricultural Lands Could Meet Production Demands and Spare Natural Habitats in Brazil." *Global Environmental Change* 28 (September): 84–97. https://doi.org/10.1016/j.gloenvcha.2014.06.001.

Stratonovitch, Pierre, and Mikhail A. Semenov. 2015. "Heat Tolerance around Flowering in Wheat Identified as a Key Trait for Increased Yield Potential in Europe under Climate Change." *Journal of Experimental Botany* 66 (12): 3599–609. https://doi.org/10.1093/jxb/erv070.

Subbarao, Guntur Venkata, Tadashi Yoshihashi, Margaret Worthington, Kazuhiko Nakahara, Yasuo Ando, Kanwar Lal Sahrawat, Idupulapati Madhusudhana Rao, et al. 2015. "Suppression of Soil Nitrification by Plants." *Plant Science* 233 (April): 155–64. https://doi.org/10.1016/j.plantsci.2015.01.012.

Swinnen, Johan, Pavel Ciaian, d'Artis Kancs, Kristine van Herck, and Liesbet Vranken. 2013. *Possible Effects on EU Land Markets of New Cap Direct Payments*. European Parliament, Directorate-General for Internal Policies.

Taghizadeh-Toosi, Arezoo, and Jørgen E. Olesen. 2016. "Modelling Soil Organic Carbon in Danish Agricultural Soils Suggests Low Potential for Future Carbon Sequestration." *Agricultural Systems* 145 (June): 83–89. https://doi.org/10.1016/j.agsy.2016.03.004.

Taghizadeh-Toosi, Arezoo, Jørgen Olesen, Kristian Kristensen, Lars Elsgaard, H. Østergaard, Mette Lægdsmand, Mogens Greve, and B. Christensen. 2014. "Changes in Carbon Stocks of Danish Agricultural Mineral Soils between 1986 and 2009." *European Journal of Soil Science* 65 (September). https://doi.org/10.1111/ejss.12169.

Tegtmeier, S., F. Ziska, I. Pisso, B. Quack, G.J.M. Velders, X. Yang, and K. Krüger. 2015. "Oceanic Bromoform Emissions Weighted by Their Ozone Depletion Potential." *Atmospheric Chemistry and Physics* 15 (23): 13647–63. https://doi.org/10.5194/acp-15-13647-2015.

Temme, Elisabeth H.M., Reina E. Vellinga, Henri de Ruiter, Susanna Kugelberg, Mirjam van de Kamp, Anna Milford, Roberta Alessandrini, et al. 2020. "Demand-Side Food Policies for Public and Planetary Health." *Sustainability* 12 (15): 5924. https://doi.org/10.3390/su12155924.

Tesfamariam, Tsehaye, H. Yoshinaga, S.P. Deshpande, P. Srinivasa Rao, K.L. Sahrawat, Y. Ando, K. Nakahara, et al. 2014. "Biological Nitrification Inhibition in Sorghum: The Role of Sorgoleone Production." *Plant and Soil* 379 (1): 325–35. https://doi.org/10.1007/s11104-014-2075-z.

Thiel, A., A.C.M. Schoenmakers, I.A.J. Verbaan, E. Chenal, S. Etheve, and P. Beilstein. 2019. "3-NOP: Mutagenicity and Genotoxicity Assessment—ScienceDirect." 2019. *Food and Chemical Toxicology* 123: 566–73. https://www.sciencedirect.com/science/article/pii/S0278691518308123.

Tilman, David, and Michael Clark. 2014. "Global Diets Link Environmental Sustainability and Human Health." *Nature* 515 (7528): 518–22. https://doi.org/10.1038/nature13959.

Tomkins, N.W., S.M. Colegate, and R.A. Hunter. 2009. "A Bromochloromethane Formulation Reduces Enteric Methanogenesis in Cattle Fed Grain-Based Diets." *Animal Production Science* 49 (12): 1053–58. https://doi.org/10.1071/EA08223.

Tooley, William. 2013. "Aerobic Treatment of Manure Lagoons Showing Environmental and Economic Benefits with Eco-system Service Paybacks." NRCS 69-3A75-0-123. Natural Resources Conservation Service.

Trenkel, M.E. 2010. *Slow- and Controlled-Release and Stabilized Fertilizers: An Option for Enhancing Nutrient Use Efficiency in Agriculture*. Paris: International Fertilizer Industry Association.

Turner, Peter A., Timothy J. Griffis, Xuhui Lee, John M. Baker, Rodney T. Venterea, and Jeffrey D. Wood. 2015. "Indirect Nitrous Oxide Emissions from Streams within the US Corn Belt Scale with Stream Order." *Proceedings of the National Academy of Sciences* 112 (32): 9839–43. https://doi.org/10.1073/pnas.1503598112.

UNEP (UN Environment Programme). 2013. *The Emissions Gap Report 2013*. Nairobi: UNEP.

UNEP. 2017. *The Emissions Gap Report 2017*. Nairobi: UNEP.

VandeHaar, M.J., L.E. Armentano, K. Weigel, D.M. Spurlock, R.J. Tempelman, and R. Veerkamp. 2016. "Harnessing the Genetics of the Modern Dairy Cow to Continue Improvements in Feed Efficiency." *Journal of Dairy Science* 99 (6): 4941–54. https://doi.org/10.3168/jds.2015-10352.

van Vuuren, Detlef P., Elke Stehfest, Michel G.J. den Elzen, Jasper van Vliet, and Morna Isaac. 2010. "Exploring IMAGE Model Scenarios That Keep Greenhouse Gas Radiative Forcing below $3W/M_2$ in 2100." *Energy Economics* 32 (5): 1105–20. https://doi.org/10.1016/j.eneco.2010.03.001.

van Vuuren, Detlef P., Elke Stehfest, David E.H.J. Gernaat, Jonathan C. Doelman, Maarten van den Berg, Mathijs Harmsen, Harmen Sytze de Boer, et al. 2017. "Energy, Land-Use and Greenhouse Gas Emissions Trajectories under a Green Growth Paradigm." *Global Environmental Change* 42 (January): 237–50. https://doi.org/10.1016/j.gloenvcha.2016.05.008.

Vassiljev, Anatoli, Katrin Kaur, and Ivar Annus. 2018. "Modelling of Nitrogen Leaching from Watersheds with Large Drained Peat Areas." *Advances in Engineering Software* 125 (November): 94–100. https://doi.org/10.1016/j.advengsoft.2018.03.007.

Venturini, Giada, Amalia Pizarro-Alonso, and Marie Münster. 2019. "How to Maximise the Value of Residual Biomass Resources: The Case of Straw in Denmark." *Applied Energy* 250 (September): 369–88. https://doi.org/10.1016/j.apenergy.2019.04.166.

Visser, C.L.M de., F.E. de Buisonjé, H.H. Ellen, C. Stanghellini, and M.P.J. van der Voort. 2012. "Energy Savings Measures in Agriculture: Overview on the Basis of National Reports." Wageningen University and Research, January.

Vrancken, Hilde, Maria Suenkel, Paul R. Hargreaves, Lynette Chew, and Edward Towers. 2019. "Reduction of Enteric Methane Emission in a Commercial Dairy Farm by a Novel Feed Supplement." *Open Journal of Animal Sciences* 9 (3): 286–96. https://doi.org/10.4236/ojas.2019.93024.

Wallace, R. John, Goor Sasson, Philip C. Garnsworthy, Ilma Tapio, Emma Gregson, Paolo Bani, Pekka Huhtanen, et al. 2019. "A Heritable Subset of the Core Rumen Microbiome Dictates Dairy Cow Productivity and Emissions." *Science Advances* 5 (7): eaav8391. https://doi.org/10.1126/sciadv.aav8391.

Wang, Jinyang, Zhengqin Xiong, and Yakov Kuzyakov. 2016. "Biochar Stability in Soil: Meta-analysis of Decomposition and Priming Effects." *GCB Bioenergy* 8 (3): 512–23. https://doi.org/10.1111/gcbb.12266.

Weiss, Franz, and Adrian Leip. 2012. "Greenhouse Gas Emissions from the EU Livestock Sector: A Life Cycle Assessment Carried Out with the CAPRI Model." *Agriculture, Ecosystems & Environment* 149 (March): 124–34. https://doi.org/10.1016/j.agee.2011.12.015.

Wenzel, Henrik, Jin Mi Triolo, Lars Toft, and Niels Ostergaard. 2020. "Energiafgrødeanalysen." Syddans University, SEGES.

Whittaker, Carly, Nicola E. Yates, Stephen J. Powers, Tom Misselbrook, and Ian Shield. 2016. "Dry Matter Losses and Greenhouse Gas Emissions from Outside Storage of Short Rotation Coppice Willow Chip." *Bioenergy Research* 9: 288–302. https://doi.org/10.1007/s12155-015-9686-y.

Wirsenius, Stefan, Timothy Searchinger, Jessica Zionts, Liqing Peng, Tim Beringer, and Patrice Dumas. 2020. "Comparing the Life Cycle Greenhouse Gas Emissions of Dairy and Pork Systems across Countries Using Land-Use Carbon Opportunity Costs." Working paper. World Resources Institute. https://www.wri.org/publication/comparing-life-cycle-greenhouse-gas-emissions-dairy-pork-systems.

Wollenberg, Eva, Meryl Richards, Pete Smith, Petr Havlík, Michael Obersteiner, Francesco N. Tubiello, Martin Herold, et al. 2016. "Reducing Emissions from Agriculture to Meet the 2°C Target." *Global Change Biology* 22 (12): 3859–64. https://doi.org/10.1111/gcb.13340.

Yang, Ming, Yunting Fang, Di Sun, and Yuanliang Shi. 2016. "Efficiency of Two Nitrification Inhibitors (Dicyandiamide and 3, 4-Dimethypyrazole Phosphate) on Soil Nitrogen Transformations and Plant Productivity: A Meta-analysis." *Scientific Reports* 6 (1): 22075. https://doi.org/10.1038/srep22075.

Zhang, Xin, Eric A. Davidson, Denise L. Mauzerall, Timothy D. Searchinger, Patrice Dumas, and Ye Shen. 2015. "Managing Nitrogen for Sustainable Development." *Nature* 528 (7580): 51–59. https://doi.org/10.1038/nature15743.

Zhao, Yusheng, Zuo Li, Guozheng Liu, Yong Jiang, Hans Peter Maurer, Tobias Würschum, Hans-Peter Mock, et al. 2015. "Genome-Based Establishment of a High-Yielding Heterotic Pattern for Hybrid Wheat Breeding." *Proceedings of the National Academy of Sciences* 112 (51): 15624–29. https://doi.org/10.1073/pnas.1514547112.

Zhu, Y., S.B. Jones, and D.B. Anderson. 2018. "Algae Farm Cost Model: Consideration for Photobioreactors." Richland, WA: Pacific Northwest National Laboratory.

Ziska, F., B. Quack, K. Abrahamsson, S.D. Archer, E. Atlas, T. Bell, J.H. Butler, et al. 2013. "Global Sea-to-Air Flux Climatology for Bromoform, Dibromomethane and Methyl Iodide." *Atmospheric Chemistry and Physics* 13 (17): 8915–34. https://doi.org/10.5194/acp-13-8915-2013.

Zörb, Christian, Uwe Ludewig, and Malcolm J. Hawkesford. 2018. "Perspective on Wheat Yield and Quality with Reduced Nitrogen Supply." *Trends in Plant Science* 23 (11): 1029–37. https://doi.org/10.1016/j.tplants.2018.08.012.

ABOUT WRI

World Resources Institute is a global research organization that turns big ideas into action at the nexus of environment, economic opportunity, and human well-being.

Our Challenge

Natural resources are at the foundation of economic opportunity and human well-being. But today, we are depleting Earth's resources at rates that are not sustainable, endangering economies and people's lives. People depend on clean water, fertile land, healthy forests, and a stable climate. Livable cities and clean energy are essential for a sustainable planet. We must address these urgent, global challenges this decade.

Our Vision

We envision an equitable and prosperous planet driven by the wise management of natural resources. We aspire to create a world where the actions of government, business, and communities combine to eliminate poverty and sustain the natural environment for all people.

Our Approach

COUNT IT

We start with data. We conduct independent research and draw on the latest technology to develop new insights and recommendations. Our rigorous analysis identifies risks, unveils opportunities, and informs smart strategies. We focus our efforts on influential and emerging economies where the future of sustainability will be determined.

CHANGE IT

We use our research to influence government policies, business strategies, and civil society action. We test projects with communities, companies, and government agencies to build a strong evidence base. Then, we work with partners to deliver change on the ground that alleviates poverty and strengthens society. We hold ourselves accountable to ensure our outcomes will be bold and enduring.

SCALE IT

We don't think small. Once tested, we work with partners to adopt and expand our efforts regionally and globally. We engage with decision-makers to carry out our ideas and elevate our impact. We measure success through government and business actions that improve people's lives and sustain a healthy environment.

ABOUT RESOURCE EQUITY

Resource Equity believes empowered women change the world. We advocate for legal, policy, and social change with the goal of advancing women's land and resource rights, and we serve as a global source for research, best practices, and policymaking. We are committed to collaborating with partners around the world in our focus on women, land, and resources.

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