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WORKING PAPER

COMPARING THE LIFE CYCLE GREENHOUSE GAS EMISSIONS OF DAIRY AND PORK SYSTEMS ACROSS COUNTRIES USING LAND-USE CARBON OPPORTUNITY COSTS

STEFAN WIRSENIUS, TIM SEARCHINGER, JESSICA ZIONTS, LIQING PENG, TIM BERINGER, AND PATRICE DUMAS

HIGHLIGHTS

- This paper compares the life cycle greenhouse gas emissions of average dairy production from 13 countries and pork production for 10 countries, incorporating a carbon opportunity cost (COC) for land use that essentially assigns emissions for the carbon lost on agricultural land used to produce a crop.
- Factoring in COCs greatly increases the total emissions assigned to both pork and dairy, particularly for pork, for which COCs tend to be around 75 percent of total carbon costs.
- In general, we find that emissions from economically developed countries are more similar than those found by other analyses. For example, total emissions per kilogram of pork from 8 countries differ by only 9 percent, and for dairy production in 11 of 13 countries, by 25 percent, at most.
- More concentrated dairy systems tend to have lower carbon costs than more grazing-based systems. Two grazing systems have much higher emissions than concentrated systems, but New Zealand shows that it is possible to have similar carbon costs to concentrated dairy systems even with all grazing.
- Denmark is in the lowest carbon cost tier of countries analyzed for both pork and dairy, which differs from some other analyses, but differences are not large. Denmark has high feed efficiency for both pork and dairy, which lowers both production emissions and COCs, and it also benefits from cooler temperatures that reduce emissions from manure management.

CONTENTS

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EXECUTIVE SUMMARY

Comparisons of the greenhouse gas (GHG) emissions of livestock production in different countries using life cycle analyses (LCAs) can provide insights into the changes in farm practices that would reduce global emissions. Such comparisons can indicate whether adopting the methods of other countries would significantly reduce emissions. This paper provides such an analysis. It originated with a request from the Danish Agriculture and Food Council to benchmark Danish pork and dairy emissions against other countries, which could inform a strategy for achieving the council's announced goal of carbon neutrality by 2050.

One key issue is how analyses of this type factor in the GHG costs of devoting land to agricultural use. Some LCAs do not factor in any land costs, and others, in effect, only factor in costs for crops originating from countries that have ongoing expansion of agricultural land. As a result, the livestock systems of some countries can be assigned higher emissions than those of other countries because of the origin of their crops, even if their production uses less land overall.

This paper uses a different land-use approach to compare the GHG emissions per kilogram of output across 13 countries for dairy, all of which are European, except for Brazil, New Zealand, and the United States; and across 10 countries for pork, 8 of which are European. In some cases, the analysis includes more recent data than other studies to estimate production emissions, which are all emissions other than land use GHG costs. This paper uses a model that can help overcome data uncertainties by incorporating processes that govern relationships between feed and output per cow and pig.

This analysis also counts land-use carbon costs using carbon opportunity costs. This approach recognizes that when more agricultural land is used to generate food, less land is available to store carbon in native vegetation, which represents a true GHG cost.

Using this method, we have the following general findings:

- We find that land-use carbon costs, with some exceptions, tend to range roughly from one and a half to two times the production emissions for dairy and from two to three times the production emissions for pork. These figures are much higher than in other estimates, which use different methods to estimate land-use costs, and they highlight the importance of limiting land requirements to achieve GHG goals.
- To a large extent, both land-use costs and production emissions estimates reflect the feed efficiency of production, which is the amount of feed consumed per kilogram of milk or pork produced.
- Our method of estimating land-use carbon costs results in smaller differences in emissions for the most concentrated dairy and pork systems than in some other analyses that assess land-use carbon costs using some form of direct land-use change. Because these other analyses assign emissions from land-use change only to some expanding crops, or only to soybeans from Latin America, emissions can vary substantially due to which country supplies the soybeans.
- For modern concentrated pork and dairy systems, we find differences, but they are not particularly large. For concentrated dairy operations in seven different countries, the emissions vary by at most 25 percent. For pork production, in each country other than Brazil, the maximum variation in emissions is 14 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.
- In dairy systems, the big contrasts are between systems that rely on concentrated feeds and those that rely more heavily on grazing. Although grazing systems will have less soil erosion, require fewer pesticides, and can increase animal welfare, they have higher emissions because they have lower feed efficiency, which leads to higher enteric methane and more land-use requirements per kilogram of milk.
- Production emissions differences in concentrated dairy systems reflect some differences in feed efficiency, but they also reflect temperature differences because warmer temperatures have higher manure management emissions. Land-use differences are also heavily influenced by forage yields.
- The two big factors that alter production emissions in pork systems are the manure management system and the climate, which strongly influences methane losses from stored manure. European countries increase manure management emissions the farther south they are located. The United States also has high manure management emissions because of its use of lagoons.
- Denmark ranks in the lowest emitting tier of dairy and pork producers. According to our estimate details, Denmark is lowest among pork producers and is third lowest among dairy producers, but because the differences are very small and the uncertainties are

substantial, emissions among all countries in this tier should be considered equal. Despite a variety of uncertainties, Denmark's ranking in the lowest-emitting tier makes sense because of Denmark's high feed efficiency for both pork and dairy and also because the country's cooler temperatures hold down manure management emissions.

- From a policy perspective, these results suggest that reducing Denmark's livestock production just to reduce its reported emissions is unlikely to be a good global strategy for reducing GHG emissions from the food sector as long as the world demands equal or growing quantities of milk and pork. Yet the similarity in performance among many developed economies also means that just shifting their pork production to Denmark is also unlikely to have significant GHG benefits. To reduce its emissions substantially, Danish agriculture cannot merely imitate practices in other countries but will instead need to employ innovative approaches.

INTRODUCTION

Comparisons between the greenhouse gas (GHG) emissions of agricultural production systems in different countries can provide useful information for the development of country strategies to reduce those emissions. An analysis of livestock systems is particularly important because these systems generate around two-thirds of global agricultural emissions and utilize around three-quarters of global agricultural land (Searchinger et al. 2019). In previous publications, the World Resources Institute (WRI) has recommended both some shifts in diets by the world's large meat consumers to plant-based foods because of their lower emissions and reductions in emissions from the production of meat (Searchinger et al. 2019). The goals of this kind of analysis include a better understanding of the sources of differences in emissions for livestock production and the extent to which these differences reflect management versus environmental features.

This kind of analysis is also challenging due to uncertainties in data about farm management. Likewise, there are uncertainties in emission factors for agriculture because agricultural emissions, unlike energy emissions, cannot be measured directly and therefore always need to be estimated indirectly from data about inputs and management practices. This working paper seeks to explore the level of confidence that reasonably can be achieved today in these estimates and to identify key uncertainties.

This paper presents a new analysis of pork and dairy emissions in multiple countries. The work originated as an effort to benchmark Danish agriculture against other countries to develop a strategy for how Danish agriculture could become carbon neutral by 2050. However, the analysis is interesting for the broader purposes described above. (Minority funding for the report was provided by the Danish Agriculture and Food Council, but the lead author was not paid from this source or by WRI for this work and the intellectual independence of the institute and the authors was guaranteed.)

Although several international comparisons exist that include emissions from different European countries (Gerber et al. 2010; Lesschen et al. 2011; MacLeod et al. 2013; Weiss and Leip 2012), this analysis differs in three ways. 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 assure the consistency of data assumptions as well as to fill in for some missing date. Third, we incorporate a different way of accounting for the GHG costs of devoting land to producing pork and dairy. This carbon opportunity cost (COC) method recognizes that most land devoted to food production has an opportunity cost in the form of less carbon storage in vegetation and soils compared to forests and other native vegetation.

Appendix C lists the key parameters and data sets used in our model for pork and dairy systems in different countries, and each has uncertainties in various degrees. We hope this analysis and list will encourage other researchers and those with good information (e.g., industry analysts) to come forward with improved evidence for the different parameters in each country.

Because our analysis originally focused on comparing Danish pork and dairy emissions with those of other countries, this paper also concentrates on that comparison. One advantage of this focus is the high quality of Danish data, which we believe is based on the most extensive reporting system for agriculture of any country in the world. Among other data, Danish farmers must keep track of and report every animal, all feed quantities purchased, and all fertilizers used. Although a major agricultural producer for its size, Denmark is a small country, so its agricultural systems are more homogeneous than those in other countries. Our estimates for Danish emissions are therefore firmer than our estimates for those of other countries. Even so, there are important uncertainties, including the emissions from manure management.

The countries we selected for comparison are designed to be representative of different major producing countries, with two additional considerations. First, data was too poor to attempt our method of analysis with equivalent detail in some key countries, including India for dairy and China for pork. Other analyses that have used less detailed methods have included these countries in international comparisons, but those analyses did not require some of the data needed for our methods. In addition, because of Denmark's interest in comparing its emissions with those of other European countries, we included a disproportionate number of European countries.

Critically, our analysis of national emissions to some extent separates the livestock farm from the cropland used to produce concentrated feeds. Pasture must be local, and dairy farms will nearly always rely on their own or at least locally generated forage, so our emissions calculations for forage are based on locally generated forage. But dairy or pig producers do not need to have their own cropland; many do not, and others produce some of their own crops and buy others. There are examples of concentrated dairy and pork production that rely on large imports of feed from far away, including California for dairy and North Carolina for pork. In addition, where pork or dairy production is co-located in areas with abundant feed, it is at least equally and probably more likely that the abundance of feed with little transportation cost attracts the pork and dairy production rather than the other way around. As a result, even if pork and dairy moved elsewhere, the feed would still be produced in these areas and shipped elsewhere to produce pork and dairy products. Our analysis assumes that crops could be imported from off the farm, and while those crop-production emissions are counted in ways we discuss, we focus here on the emissions attributable to the livestock operation. A highly efficient or inefficient pork sector, for example, does not necessarily imply the same country has an efficient or inefficient crop sector.

METHODS

Our analysis of dairy and pork emissions is based on a life cycle analysis (LCA), which counts all of the emissions involved in the production of pork and dairy. Our analysis ends at the farm gate, which means it does not include emissions in food processing or packaging, subsequent transportation and retail, or cooking and consumer waste. It does, however, include emissions "upstream" of the farm, including those involved in producing inputs, such as fertilizer, and emissions from the production of feed regardless of whether it comes from the farm, from another farm, or even from another country. Our analysis also includes land-use costs based on the opportunity cost of land to store carbon.

Categories of Livestock Production Emissions

Production emissions are all of the emissions other than those related to land use. The major categories of emissions from the production process are as follows:

- Methane (CH_4) from feed digestion ("enteric" methane)
- CH_4 and nitrous oxide (N_2O) from the management of manure excreted in housing
- CH_4 and N_2O from manure deposits on pasture
- Carbon dioxide (CO_2) from energy use in the livestock operation
- CO_2 and N_2O from the production of inputs, of which the most significant are the emissions from the production of fertilizer
- A global/regional mixed average of emissions from producing concentrate feed, which are mainly N_2O resulting from nitrogen use and CO_2 released in producing fertilizer and in running farm field equipment
- N_2O and CO_2 emissions from applying nutrients and using energy to produce and harvest forage crops (for dairy), estimated on a national basis
- N_2O from the application of synthetic fertilizer and degradation of grass residues on pasture
- Net additional emissions that result from the use of manure as a fertilizer, which includes a credit for avoided emissions in producing nitrogen fertilizer but an emissions charge for the larger quantities of nitrogen applied when using manure

Land GHG COCs for Livestock Feed

In addition to the above production emissions, we separately show and then include emissions based on the quantity of land used to generate dairy or pork in the different systems. We call this cost the carbon opportunity cost (COC), and although the details can become a little complicated, the basic concept is simple. The more land required to produce agricultural products generally—including dairy and pork—the less carbon is stored on land in vegetation and soils; therefore, more carbon is instead held in the atmosphere, warming the planet. The quantity of carbon displaced from the land to the atmosphere to produce each kilogram of pork or dairy is a measure of the GHG emissions from land use. As a result, if less land is required, then the land carbon "footprint," as measured by COCs, will be lower.

Life cycle analyses have struggled with how to assign emissions related to land use: some assign no GHG costs to land use, some only so-called direct land-use change, some a modified form of direct land-use change that involves shared responsibility, and some use economic models to estimate indirect land-use change. The World Resources Institute has previously discussed the limitations of these methods (Ranganathan et al. 2016; Searchinger et al. 2019), and we summarize them in Box 1.

Our approach employs a somewhat modified version of the land-use COC from Searchinger et al. (2018). This approach starts with the basic physical fact that devoting land to agriculture typically means storing less carbon on that land than would be stored if that land were left in its native vegetation. This fact means land has a COC when used for agriculture in the form of forgone carbon storage.

This COC is particularly high because the world is continuing to clear forests and other natural ecosystems (e.g., woody savannas) for agriculture to meet rising food demands, and this clearing releases carbon from vegetation and soils. The quantity of this ongoing conversion is tied to agricultural land area. Holding down that land area needed for agriculture avoids the need to convert more land and saves carbon somewhere, and that can be achieved either by consuming foods that require less land to produce (e.g., beans instead of beef) or by producing more kilograms of a food (e.g., pork or milk) on the same land.

But even if the world were no longer expanding agricultural land, using less land for food production would allow the "liberated" land to be reforested, and reforesting land is also a valuable component of solving climate change (Griscom et al. 2017; Rogelj et al. 2018). For this reason, regardless of whether the world is expanding or contracting agricultural land, land used to produce food still has a COC. A livestock system that uses less land would have a lower COC per kilogram of meat or dairy and therefore would be less costly and more beneficial from a climate perspective.

A major reason this rather obvious concept is overlooked is that the actual physical emissions associated with clearing agricultural land overwhelmingly occurred in the past. As a result, national and global estimates of annual GHG emissions only count the carbon lost from newly converted land that year. This approach makes sense when counting how much additional carbon is added to the air each year globally, but focusing only on new land conversion understates the true GHG costs of agriculture because it treats all existing (previously cleared) agricultural land as if it had no opportunity cost. But if any one hectare of land were not needed by a country's farms to produce the same tons of pork or dairy for feeding one group of people, it could store more carbon through reforestation or could continue to produce food but for additional people, avoiding the need to expand agricultural land and clear more forestland elsewhere.

This conceptual difference can cause great confusion. It means that the full climate costs of agriculture and its land use vastly exceed the annual costs typically assigned to agriculture in global (or national) estimates, even when they include an estimate of recent annual land-use change. The reporting of recent annual emissions is like an accounting system for a company that only includes its annual variable cost of producing cars (the steel and labor required, for example), but not the fixed costs, such as the costs of building the factory or machinery. Such accounting does not reflect the full financial costs of producing cars. The full costs of agriculture should include some way of annualizing these fixed costs (the lost carbon storage).

To quantify this cost for crops, the COC for any individual crop is based on the average amount of carbon that is lost from vegetation and soils to produce a kilogram of that crop. But when native vegetation is cleared for crop production, it is a one-time loss of carbon although crops could be produced indefinitely. As in other systems addressing land-use change, the one-time loss of carbon needs to be amortized. For biofuel policies, Europe has used an amortization period of 20 years and the United States has used 30 years, meaning the annual cost is

Box 1 | Limitations of Some Life Cycle Analysis Approaches to Land Use

Life cycle analysis (LCA) calculations for agricultural production have employed a variety of methods for addressing land use, but they have significant limitations.

- **Some count no greenhouse gas (GHG) cost for land use.** One basic method of many LCAs is to identify hectares of land used but not to attribute GHG emissions to them, so the LCA only counts emissions from the production process. This approach provides no incentive to increase yields and can encourage changes in management that reduce production emissions even a little, even if they reduce yields a great deal. To illustrate with an extreme example, if a farm reduces fertilizer use and therefore emissions per kilogram of wheat even a little, this method would treat that change as beneficial even if that would cause yields to decline by half. (This method is employed in Lesschen et al. [2011], among other papers.)

- **Some count land-use change emissions only if a crop is produced on newly cleared land.** This method has the same limitations as above. As 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, for reducing feed demands. This method also rewards buyers for just changing their suppliers rather than reducing the overall land required to produce pork or dairy. Most fundamentally, in wealthier countries that have cleared their forests for farms only in the past, this method neither penalizes farming systems for using a lot of land for the same output nor rewards highly productive farming systems for using a relatively small amount of land—even though using more land in any country increases the global quantity of agricultural land and decreases the total quantity of carbon stored in vegetation and soils.

- **Some count land-use change if a crop is expanding and is produced in a country that is expanding agricultural land.** This "shared responsibility" method, for example, employed by the Food and Agriculture Organization of the United Nations in MacLeod et al. (2013), assigns no or few GHG emissions to a pork operation that purchased soybeans from the United States, where agricultural land use has not recently expanded, but assigns large emissions to feed purchased from Brazil, where both soybeans and agricultural land overall have recently expanded. 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, such as from Brazil to the United States, even though the total demand for agricultural products would not change and it is likely that the first country's crops would just be sold to another buyer. In addition, as long as a farm avoids purchasing soybeans or another crop from a country where agricultural land has recently expanded, the farm has the same flawed incentives as with the other methods above: it receives no incentive to boost yields and can be rewarded for decreasing yields.

- **Some count land-use change for expanding crops only.** This method, employed by Weiss and Leip (2012), is similar to that above but assigns emissions to a crop wherever it is produced (e.g., all soybeans) if that crop is expanding globally but not to a crop that is not expanding. For this approach, just switching feed suppliers from one country to another does not reduce emissions, but switching from one crop to another does. This system therefore also does not reward or penalize farming systems for the quantity of land they use or the quantity of carbon they displace.

  Each of these methods could actually increase land use requirements. For example, soybeans are used for animal feed rather than pulses because soybean yields globally are roughly three times those of pulses. Partly for that reason, land used to produce pulses is not expanding. According to these accounting methods, however, switching feed ingredients from soybeans to pulses would count as a GHG reduction even though doing so would require three hectares more land in pulses for each hectare saved from soybeans.

- **Some economic models 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, given resultant changes in wheat prices and wheat demand, and what the resulting carbon emissions would be.

  One problem with this approach is that the analysis requires hundreds to thousands of estimates of economic relationships, all of which have high uncertainties and most of which have not been—and could not be—estimated well econometrically if only because of insufficient data. Even if this approach were desirable, it cannot be reliably executed.

  A separate, more fundamental problem is that this approach can reward changes that are counter to public policy goals. 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.) This reduced consumption avoids land-use change and emissions, but at the cost of higher food prices and often lower food consumption by the poor. Yet the public policy of most countries, and the goal of agricultural industries, is to increase agricultural productivity in part to make sure the world is well-fed. It is contradictory to pursue policies for the goal of increasing food prices and reducing food consumption while simultaneously trying to do the opposite.

1/20th or 1/30th of the carbon lost when the land is cleared. The choice of amortization or discounting mechanism is a policy decision that is based on the importance of achieving GHG emissions reductions earlier rather than later, and it is the kind of decision reflected in the Paris Agreement to achieve GHG reduction goals by 2050.

Here, we use the system discussed in more detail in Searchinger et al. (2018) and its supplement, in which we both account for the rate of loss of carbon (as not all vegetative and soil carbon is lost in the first year of conversion), and we discount both the loss of carbon and the production of crops over time by 4 percent. In effect, this system treats both emissions and crops produced in one year as 4 percent more costly or valuable as emissions and crops produced in the next year. The choice of 4 percent has an economic theory (based on the long-term value of capital and a constant social price of carbon over time), but we use it also because its results work out to be similar to the results of U.S. bioenergy policy in that it is roughly equivalent to counting around 1/30th–1/35th of the value of the carbon lost from native vegetation and soils in each year. As a result, the COC of a kilogram of wheat is generally 1/30th–1/35th of the carbon lost to produce that wheat. It can be thought of as an annual carbon rental cost assigned to the use of land to produce that wheat, and like rent, that annual payment continues as long as the land is used to produce that crop.

How much carbon is lost from land to produce a given food depends on where that land is located and its yield. Because of global trade, it is very hard to know where new land will ultimately be converted if pork or dairy production requires additional feed or where new land conversion will be avoided if feed requirements decline. Therefore, we estimate the average carbon loss that would be required to produce a kilogram of crop at both regional and global scales. A *regional* COC in Europe assumes that more demand for a kilogram of wheat will result in more European agricultural land (and a loss of native vegetation), with a carbon loss equal to the European average for wheat. The *global* COC assumes, in effect, that a little bit of each new wheat or other crop will be produced around the world in each place where it is now produced. For our principal results, we use an average of the regional and global COCs for each country's farming. (Below, we discuss the significance of alternatively using only a global or regional COC, and the differences are typically small.)

For grass consumed in pasture and forage crops used by dairy cattle, we estimate and apply a *national* COC in each country. The national COC is the amount of carbon lost in the country to produce that feed. We apply a national approach to pasture and forages because pasture is inherently local and because forages are so bulky that they are virtually all produced near where they are consumed. These national estimates of harvested forages and pasture output have uncertainties and can have significant effects on total COC estimates, and we discuss those uncertainties below.

Estimates of drained peatlands are built into estimates of COCs for feeds used for concentrates. We also include estimates of emissions from drained peatlands in the national COCs we develop for forage crops.

Livestock Feed Production Emissions

The production emissions for livestock feed, such as those that result from fertilizer and energy use in growing crops, follow our approach to COCs. Production emissions of feeds for crops used in feed concentrates—for example, wheat and maize—are based on the average of global and regional production emissions for that crop. (For oilseed meal, which is only a portion of the oilseed, we use an economic allocation method to allocate both production emissions and COCs to the meal.) Production emissions were estimated using GlobAgri-WRR, the model used in the *World Resources Report: Creating a Sustainable Food Future*. (Sources and assumptions are described in that report [Searchinger et al. 2019] and in the methods sections of Searchinger et al. [2018]).

Production emissions for forages, because they must be supplied locally, are based on national data about such factors as nitrogen use.

Livestock Model

The ClimAg model, developed by the lead author of this paper, provided the ultimate basis for estimating emissions. The model calculates the GHG and nitrogen emissions of individual livestock and crop production sectors. By using data on national average sector characteristics, it estimates the average emissions per kilogram of pork or milk in each country. It also incorporates the COCs and crop feed production emissions discussed above and generates the estimates of all the other categories of emissions using data about sector characteristics.

Critical biophysical relationships built into the model can help to assure data consistency. For example, producing a specified quantity of liters of milk per day per lactating cow requires a certain amount of energy and protein in feed. Using data on milk per cow per day, which is generally more reliable, and data on the quality of feed, makes it possible to estimate the quantity of feed consumed. As a result, the model can provide a check on potentially inconsistent or poor data. Without these kinds of process relationships and national aggregate figures, it is possible for LCAs to make estimates that are biophysically impossible or implausible. It is also sometimes possible to make use of these relationships to fill in data gaps with plausible estimates—which is particularly useful for a few parameters that are not independently known, such as the quantity of herbage grazed per animal or per hectare.

ClimAg can either incorporate cropland used to produce feed as part of the farm or assume that the feed comes from outside the farm. To reflect our treatment of land discussed above, we segregate the livestock operation and treat all cropland used for concentrates as separate regardless of whether the cropland is part of the farm. We then separately estimate the COCs producing these concentrated crops based on the global and regional land COCs and production emissions as described above. The model implicitly assumes that sufficient agricultural land is available in the area of the livestock farm to receive the manure. The model is described in more detail in Appendix B.

National Average Farms

When estimating national average emissions and sources per kilogram of milk, one challenge is that farms differ, and in some countries, dairy systems, in particular, vary greatly. In the United States, for example, dairy production in California is entirely confined, but dairy production in New York, Pennsylvania, and Wisconsin can still use significant grazing. Ideally, an analysis could separately analyze large numbers of representative farms in each country and produce a national estimate by taking a national weighted average of their performance. Unfortunately, the information available from the different types of farms is too piecemeal to be able to analyze each separately and then aggregate them to an average. Our method, like those of other studies, is to therefore use the average of the key parameters and put them together to form an average dairy and pork farm.

For countries like the United States, this method should generate something similar to a national real average, but the difference between the theoretical average farm and real farms will be large. Brazil and Ireland also have some more-intensive dairy farms, but the great majority of farms are smaller scale; our analysis is based on these typical smaller farms because we did not find good data showing a percentage of larger farms that could be incorporated into the overall balance. Outside of Brazil, however, pig farms are quite similar in the basic operations that most influence emissions, so although each farm will vary, the average pig farms we model are likely to be more representative of typical farms.

Separation of Livestock Emissions from Cropland Emissions

As discussed in the introduction, our method focuses on the efficiency of the livestock production system, which is not necessarily closely related to the efficiency of national crop production. Many other LCAs calculate the greenhouse gas emissions of crops produced within that country and assign those to the livestock production (at least primarily). For concentrated crop feed, we assume that the crops do not need to come from the country because they can be and often are imported. The separation between livestock systems and local land use is not complete, however, because, as we discuss above, we assign production and land-use COCs for feeds based on an average of global and regional averages. In Europe, there is one regional average, so the emissions per kilogram of wheat, maize, barley, rapeseed meal, and soybean meal are the same for every country in Europe. For the United States, the regional portion of this calculation is based on the North America region, and for Brazil, Latin America. We also apply COCs and production emissions for forages based on national production.

DAIRY RESULTS

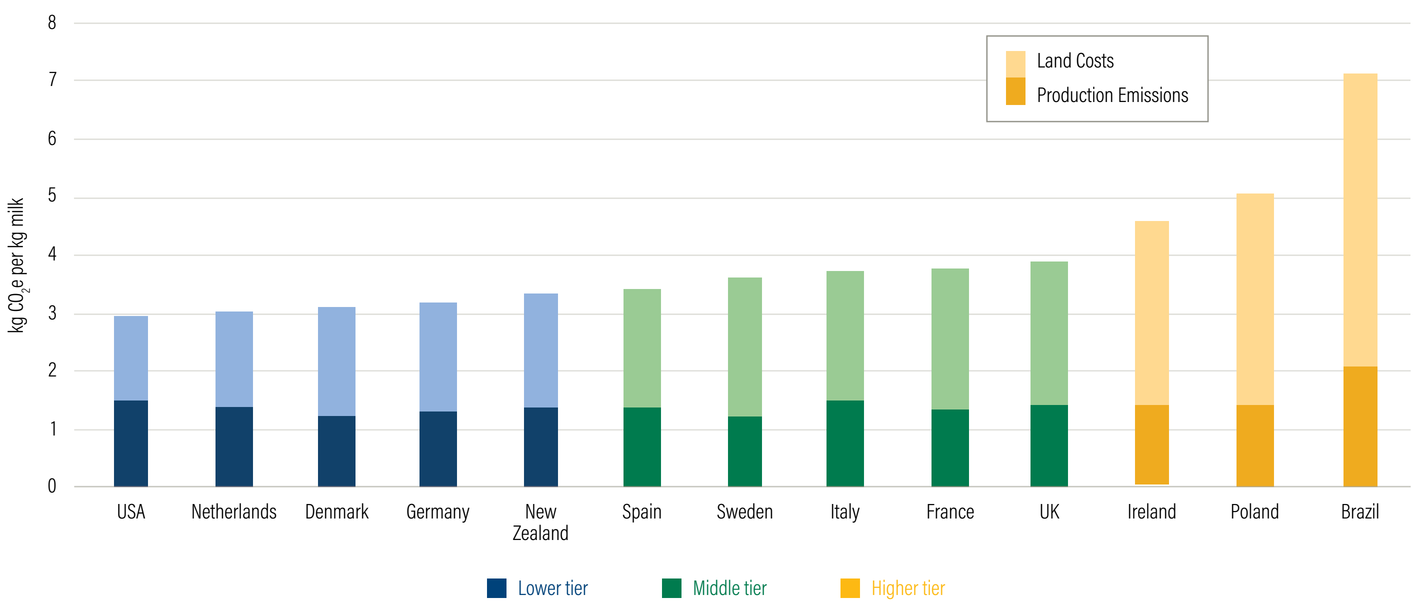
Table 1 and Figure 1 present our principal modeling results for dairy production. We discuss a few of the findings.

Table 1 | **Greenhouse Gas Emissions for Dairy by Country and Emission 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**

Notes: COC = carbon opportunity cost; CO_2 = carbon dioxide; MCF = methane conversion factor; N = nitrogen; NIR = national inventory report; PEM = production emissions.
Source: Authors' calculations.

Figure 1 | **Production and Dairy Emissions by Country**



Notes: CO_2 = carbon dioxide.
Source: Authors' calculations.

The Relative Significance of Different Categories of Production Emissions

In general, enteric fermentation is the largest source of production emissions. For 10 of our countries, enteric emissions range from 40 to 53 percent of total production emissions. In the United States, however, enteric emissions are only roughly one-third of total production emissions. In part, this result is because the country's enteric emissions are low, but it is mostly because its manure management emissions are high. In New Zealand, enteric emissions are high and are roughly 60 percent of total production emissions, and in Brazil, where enteric emissions are extremely high and manure management emissions are extremely low because most dairy uses grazing, enteric emissions constitute 70 percent of total production emissions.

Outside of Brazil, which relies almost entirely on grazing, manure management provides the second-largest source of emissions, but the level depends on three key physical factors: the manure management system, the system's overall feed efficiency, and, quite significantly, the country's typical temperatures (IPCC 2006, 2019). The United States, as noted, has particularly high manure management emissions because it uses many lagoons whereas other countries mainly use slurry pits. Lagoons are large and have high CH_4 emissions; slurry pits are smaller and create fewer emissions. Manure management emissions in Europe tend to increase moving from north to south because warmer temperatures have a large effect on emissions (IPCC 2006, 2019).

A third major category can be considered those emissions related to nitrogen use on cropland and pasture. These emissions include N_2O from manure deposited on grazing land and N_2O and energy production emissions for nitrogen fertilizer used on both forage lands and cropland (nitrogen is the dominant source of emissions for the production of crop feed concentrates). These emissions also include the N_2O from the degradation of grassland residues in grazing lands—the portion of grasses not grazed away—but they are only significant for Brazil.

Concentrated Systems versus Systems with More Grazing

As a general rule, more concentrated and intensive systems have both lower production emissions and land-use requirements (and therefore lower COCs), yet New

Zealand indicates that highly managed grazing systems can have similar emissions as the most efficient concentrated systems.

Virtually all dairy systems raise the heifers (the young female cows) on grass, often on grass grown in rotation with other crops, but the more concentrated systems have little to no other grazing. They rely more heavily both on crops for feed and more digestible forage grasses that are cut and hayed. By contrast, in our country list, Brazil, Ireland, and New Zealand rely overwhelmingly on grazing. In addition, some European countries, such as Poland and France, employ somewhat more grazing in their national dairy herds than others.

For GHGs, more concentrated dairy production results in fewer emissions for the following reasons:

- Both enteric emissions and, to some extent, manure management emissions are tied to feed conversion efficiency, which is the milk output per kilogram of dry matter in feed. The higher feed conversion efficiency using concentrated feeds reflects a number of herd management measures, such as how young a cow is when it has its first calf, but a key factor is the digestibility of feed. Grains and oilseed meals are more digestible than harvested forages and pasture grasses, and some forages are more digestible than others. As a result, as many other LCAs have found, the more confined systems tend to have lower production emissions than those that use more grazing.
- Grazing systems also tend to require more land. When farms use crops or planted and harvested grasses and legumes, they can typically be more consistent in management over an entire field, and they harvest more of the biomass than cattle are able to consume themselves. Grazing systems also often use lands that are less suitable for agricultural production but could still store abundant carbon if left in natural vegetation. These lands are used less intensively primarily because of this reduced suitability. Yet our estimate of COCs in New Zealand are similar to those in Denmark and Germany, which indicates that grazing systems can be intensively managed to achieve high land-use efficiencies.

Although grazing systems still have higher costs overall, one recent recommendation by the Intergovernmental Panel on Climate Change (IPCC) has lowered our original estimates of emissions from grazing systems. The 2006 IPCC guidelines assumed that 2 percent of nitrogen in manure deposited by grazing animals transformed into N_2O, but the panel's 2019 guidelines specify only 0.6 percent for wetter countries and only 0.2 percent in drier, hotter places like Brazil. Prior to these changes, the total GHG emissions from N_2O in grazing lands were similar to those from concentrated manure management in most other dairy systems, which result mostly from CH_4. With the change, these emissions related to manure are now significantly lower in grazing systems. These changes reflect direct measurements in fields, but such measurements are notoriously difficult and may miss some hot spots, so these numbers could change again in the future.

In Brazil, however, the low grazing efficiency leads to another significant source of N_2O emissions: the degradation of grass residues. This degradation makes forage grasslands a significant source of emissions, even though we estimate that Brazil's nitrogen fertilizer application rate is only 25 kilograms (kg) per hectare per year. Brazil's low stocking rate, which results in a large quantity of grazing land per kilogram of milk, leaves much grass to decompose.

Land-Use Emissions

Land-use carbon costs in our system are based on COCs and therefore reflect the quantity and quality (original carbon richness) of land used for each production system.

- The differences among countries in COCs reflect feed conversion efficiencies and the reliance on pasture. The quantity of land required heavily reflects feed conversion efficiency, so the countries with the highest pork and dairy feed conversion efficiencies have lower COCs. Countries that rely on pasture have higher land-use costs both because they have lower feed conversion efficiencies and because feed harvested by grazing cattle per hectare of pasture is typically lower than feed from cropland.
- Among countries with concentrated dairies, those that rely more heavily on maize for feed and maize silage for forages, such as the United States, tend to have lower land-use costs because maize yields are higher overall than yields for wheat, barley, sorghum, and grass forages.
- In the United States, COCs are nearly the same as production emissions, but in other countries, land-use COCs are generally around two-thirds higher than production emissions, and they can be roughly double in grazing systems.

- Among more concentrated systems, Poland stands out with land-use COCs 50 percent to almost double those of other European countries. One reason for this 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.

Overall Differences

Despite the differences cited above, with the exception of Poland, the overall differences in concentrated dairy production systems are not particularly large. For Denmark, Germany, the Netherlands, and the United States, the differences in emissions are negligible and are lower than the associated uncertainties. Their emissions can probably be thought of as roughly 3 kg CO_2e/kg milk or slightly higher. The next group, New Zealand and Spain, are only around 10 percent higher. France, Italy, and the United Kingdom, which generally rely on more grazing than Denmark and the Netherlands, for example, have modestly higher emissions on the order of 3.6–3.9, roughly 20 percent higher than our lowest group.

The difference between the United States and the United Kingdom reaches 33 percent. These differences in totals are explained by the COCs, which in the United States are low due to its heavy reliance on maize and maize silage, and which in the United Kingdom are higher due in part to its higher native carbon stocks and greater reliance on grass forages.

Poland and Ireland are the outliers in Europe particularly because of Poland's low forage yields and the use of extensive grazing lands by both countries. Mostly because of COCs, their emissions are around 2.5 times those of our lowest group. New Zealand is the outlier among grazing systems; according to our estimates, its GHG efficiencies are only around 10 percent higher than the most concentrated countries. Brazil has extremely high emissions due to highly inefficient grazing, which has been noted broadly in many papers.

PORK RESULTS

Fundamental Similarities

Pork systems in the countries we analyzed are quite similar, with the exception of Brazil. Pork is nearly all produced in highly concentrated systems using production techniques that have greatly increased feed conversion efficiencies compared to those of the past. Eight countries have total emissions within 9 percent of each other. Total emissions are similar because feed conversion efficiencies only differ by 12 percent, and most are far closer (excluding Brazil). Although different feed concentrates may be used, such as wheat versus maize or soybean meal versus rapeseed meal, the basic feed rations are similar. With similar feed conversion efficiencies and similar feed rations, COCs vary by only 14 percent (excluding Brazil). Overall, our combined emissions from land-use and production emissions vary by only 15 percent (excluding Brazil), the difference between Spain and the United States and Denmark.

Including or Excluding "Weaners"

Some countries export large quantities of young pigs, called weaners, which are fattened elsewhere; in turn, this means some countries also import large quantities of weaners. For example, 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 is because in addition to the feed that is nourishing the young pig, there must also be feed for the mother sow.

This fact means that for countries that export large quantities of weaners, dividing their total national pork emissions by the weight of pigs sold will generate a much higher emission rate per kilogram of pork than countries that do not export weaners. Similarly, this simple calculation will estimate much lower emissions for countries that import weaners. Neither is a reflection of the true efficiency of pork production but just reflects the different emissions intensity of different parts of the pork production process. The difference is large. If we did not exclude exported weaners (varying slightly with the scenario), Denmark's pork emissions per kilogram of pork would rise roughly 25 percent to more than 13.5 kg CO_2/kg pork, which would be substantially higher than all other country results we have calculated, except for Brazil.

Table 2 | **Pork Emissions by Category and Totals across Countries**

PORK	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	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**

Notes: COC = carbon opportunity cost; CO_2 = carbon dioxide; MCF = methane conversion factor; NIR = national inventory report; PEM = production emissions.
Source: Authors' calculations.

Excluding exported weaners is critical to an accurate analysis. We believe some other analyses failed to do so. That probably explains, for example, why some other studies have estimated that Denmark and the Netherlands have much higher emissions in absolute terms and relative to several other countries, whereas we find that they have among the lowest emissions (see Weiss and Leip [2012, Figure 2] and studies cited in MacLeod et al. [2013, Table 21]). We believe our approach generates a more informative estimate of the climate efficiency of pork production.

The Significance of Temperature and Emission Factors for Manure

Even more than for dairy farms, the big differences in production emissions are the result of manure management and particularly of temperature. For example, U.S. manure management emissions are more than double those of Danish pork, so even though U.S. pork production emissions and COCs are otherwise smaller, the total U.S. emissions are slightly higher. As for dairy, one basic reason is that Denmark is cooler than the United States, and even in the cool parts of the United States, summer temperatures are higher. Another big effect is that some U.S. pig manure is handled by lagoons, which have two to three times the emissions of slurry pits, even at the same temperature. Similarly, Spanish production emissions are 25 percent higher than Denmark's, nearly all due to higher temperatures and their effects on manure management.

Land-Use COCS versus Production Emissions

Largely because pigs generate very little enteric methane, land-use costs measured by COCs are a much higher share of total emissions for pork than for dairy. Overall, COCs tend to be twice to almost three times the size of production emissions. But excluding Brazil, COCs vary by country at most by 16 percent (between the United States and Spain).

The major factor that explains the differences in COCs are the feed conversion efficiencies and the major feed crops relied upon. For example, whereas U.S. pork production relies heavily on maize, European production primarily uses wheat or a combination of wheat and barley, and maize has higher yields.

Figure 2 | Pork Efficiencies by Country

Notes: CO_2 = carbon dioxide.
Source: Authors' calculations.

Brazil

Brazil has higher emissions per kilogram of pork than all other countries because the aggregate feed efficiency is lower. The lower feed efficiency is due to lower reproduction rates, such as fewer piglets per sow and year, and lower liveweight gain rates of fattening pigs. This fact, in turn, means that a larger stock of pigs is needed per unit of pork output. In Denmark, 6 pigs are needed to produce one metric ton of pork per year, whereas in Brazil, 11 pigs are needed.

The substantially higher pork emissions in Brazil relative to all other countries are strongly supported by data from the Food and Agriculture Organization of the United Nations Statistical Division (FAOSTAT), which shows pork production relative to the number of pigs. Because of poor other data, our estimate of Brazilian emissions has a higher uncertainty. As discussed below, our modeling generally relied heavily on a comparison of pork production characteristics put together by an international group of economists united in the InterPig project (discussed in Appendix A). InterPig data for Brazil, however, was sufficiently inconsistent with FAOSTAT data that we decided not to use it. Some of these inconsistencies likely occur because a substantial part of Brazilian pork production uses less modern management and is not included in the InterPig analysis. Instead, we developed plausible estimates of herd characteristics and feed use that would match the FAOSTAT data for the number of pigs and total production.

KEY UNCERTAINTIES

There are substantial uncertainties in these calculations in both the data about farm practices and the emission factors to apply to them. One goal of this working paper is to identify key sources of uncertainty and to encourage industry and researchers to come forward over time with better data. Appendixes A and C provide a comprehensive list of data sources and set forth the key parameters used. We discuss some of the challenges and uncertainties here.

Manure Management

We originally modeled manure management emissions using emission factors from national inventory reports (NIRs) for 2018. In those reports, country governments are supposed to list the percentages of manure managed for pork or dairy with different systems and the emission factors they use to estimate the resulting emissions. We initially used both of those categorizations, but we conducted alternative analyses in a few situations where the information was not adequate or was clearly wrong.

For example, U.S. NIR data were incomplete with respect to the number of animals held in different manure management systems. We found independent data on manure management systems. For these versions, we also used the emission factor provided by each NIR for each type of manure management. These emission factors were primarily derived from the 2006 IPCC national emissions reporting guidelines (IPCC 2006), but countries are allowed to—and did, in some cases—substitute their own values based on local data or more complex calculations. For example, both Denmark and Sweden used extremely low CH_4 emission factors to estimate manure management emissions from slurry stored out of doors, each relying heavily on Swedish studies that found extremely low emissions in stored outdoor manure slurry (Rodhe et al. 2012, 2015). This method has the value of recognizing independent local knowledge, but it may also simply reflect differences in judgment by the different individuals in different countries responsible for preparing the NIRs.

In late 2019, the IPCC revised its guidelines for manure management emissions and some of its emission factors changed substantially (IPCC 2019). In general, the IPCC increased the emission factor for CH_4 from manure storage for all countries, but the increase was particularly large on a percentage basis in cold countries such as Sweden and Denmark, where the default factor doubled. Because these new guidelines are supposed to reflect new knowledge, we also independently applied these new emission factors to the countries in our analysis. We have concerns with using these new estimates alone, however, both because the guidelines still permit—and, in fact, encourage—countries to use their own site-specific data if available and because the reality is that there remain large scientific uncertainties about the scope of emissions. Therefore, we used an average of the two manure methods as our default.

Yet we recognize the substantial uncertainty. Table 3 shows the results of using alternative methods to estimate manure management emissions for pork, for which such emissions are particularly important. As discussed above, nearly all emissions increase, although by different amounts, and some increase significantly. Ultimately, though, the changes are not large enough to alter the individual rankings for either dairy or pork nor to alter the basic characterizations of the results.

The differences do highlight the large uncertainties in these emissions, and we believe the following three deserve particular focus:

- The inconsistency between the new guidelines and the Swedish studies, for example, highlights the uncertainty of CH_4 emissions at the predominantly lower temperatures that prevail in Scandinavia. The effect of low temperatures in particular, and temperature in general, needs to be more thoroughly analyzed empirically.
- Another major issue involves emissions for manure that remains inside the barn rather than outside the barn. A Danish study (Petersen et al. 2016) found large emissions in the barn, particularly for pork, and Denmark included those emissions explicitly in its NIR (even as it used a very low emission factor for outdoor storage). But the 2006 IPCC guidelines did not even discuss indoor emissions, and the 2019 guidelines make no distinction between inside and outside storage. Separating the two sources of emissions makes sense because temperatures are quite different and are generally higher in the barns in many countries. More work is needed to better define emissions.
- Poland's pork emissions are particularly low because the country reports that a large fraction of its manure is handled in dry form after some kind of solid separation. It then uses a very low emission factor for CH_4 for this manure, which is consistent with both 2006 and 2019 IPCC guidance. However, the United Kingdom also manages a substantial fraction of its manure in solid form through deep bedding and uses an emission factor that is eight times higher; this estimate is based on its own estimates that emissions from such systems are similar to liquid slurry. These different conclusions require further analysis, and we consider Poland's low manure management emissions somewhat doubtful.

Differences in manure management emissions also highlight trade-offs between GHGs and other goals. For example, the United Kingdom reports that 15 percent of its pig manure is spread daily instead of stored. Daily spreading means that nutrients are applied to land when crops or grasses do not need them, which increases water pollution and other environmental problems related to nutrients. The goal should be to utilize manure management methods with both low emissions and low environmental effects.

COC Methods and Calculations

As discussed above, calculations of COCs can vary depending on whether one uses global or regional COCs for the crops that go into feed concentrates, such as maize, wheat, and soybean meals. Using global COCs assumes, in effect, that one more kilogram of maize, wheat, or soybean meals will be replaced in the world with the global average carbon loss from vegetation and soils to produce each feed. Regional COCs mean they are replaced only regionally, which is Europe for European countries, North America for the United States, and Latin America for Brazil. For example, for one more kilogram of wheat demand in Europe, the global COC assumes that would be supplied by some fraction of a kilogram in Europe, some fraction in the United States, some fraction in China, and so on, all according to each country's share of production. One rationale for using this global figure is that it is basically impossible to know what specific area of land will be converted in response to an increase in demand for a specific crop. Even if increased European demand for wheat, for example, leads to more production of wheat in Europe, that wheat may replace other European crops that are in turn replaced in other regions. By contrast, the regional COC assumes instead that the crop will be replaced by adding more cropland in Europe alone.

For nearly all countries, the differences between global and regional COCs are not large. For example, for Europe, the difference between the global and regional COC for wheat is only 4 percent, although for barley the difference reaches 17 percent. For maize in the United States, however, the difference is large, as the global number is 80 percent higher than the regional number.

We examined the effect of switching from our use of a global/regional average COC to only a regional or only a global approach, and the choice generally does not alter the relative ranking of the countries we analyzed. For most countries, a global-only COC modestly raises the estimates for dairy by 1.5–4 percent, and a regional-only COC lowers that number by the same. The exceptions are Brazil, which has essentially no change, and the United States, whose

Table 3 | **Differences in Manure Management, Total Production, and Total Emissions for Pork Using Different Manure Emission Factor Methods**

COUNTRY	MANURE MANAGEMENT EMISSIONS (AVERAGE OF NIR AND 2019 IPCC)	MANURE MANAGEMENT EMISSIONS (2019 IPCC)	MANURE MANAGEMENT EMISSIONS NIRS	TOTAL PRODUCTION EMISSIONS USING AVERAGE OF MANURE METHODS	TOTAL PRODUCTION EMISSIONS USING 2019 IPCC	TOTAL PRODUCTION EMISSIONS USING NIR FOR MANURE	TOTAL EMISSIONS USING MANURE AVERAGE	TOTAL EMISSIONS USING 2019 IPCC FOR MANURE	TOTAL EMISSIONS USING NIR FOR MANURE
DENMARK	0.91	1.16	0.66	2.89	3.14	2.64	10.80	11.05	10.55
BRAZIL	3.68	4.59	2.76	6.28	7.20	5.37	19.51	20.42	18.59
FRANCE	1.73	2.17	1.28	3.67	4.12	3.23	11.77	12.22	11.33
GERMANY	1.21	1.18	1.23	3.17	3.14	3.20	11.24	11.21	11.26
ITALY	1.88	2.30	1.46	3.75	4.17	3.34	12.53	12.95	12.11
NETHERLANDS	1.49	1.34	1.63	3.39	3.24	3.54	11.23	11.08	11.38
POLAND	0.75	0.78	0.72	2.81	2.84	2.78	11.39	11.42	11.36
SPAIN	1.97	2.63	1.31	4.00	4.66	3.35	12.83	13.49	12.18
SWEDEN	0.93	1.45	0.42	3.04	3.56	2.52	11.81	12.33	11.29
UK	1.11	1.25	0.96	3.24	3.39	3.09	11.37	11.51	11.22
USA	2.01	2.12	1.90	3.70	3.81	3.59	11.33	11.44	11.22

Notes: IPCC = Intergovernmental Panel on Climate Change; NIR = national inventory report.
Source: Authors' calculations.

change is around 10 percent in either direction, but which still does not alter its rank. For nearly all countries, pork rankings also do not change.

The principal difference is in pork production in the United States, which relies heavily on maize and for which global and regional COCs substantially differ. In the United States, for example, using global COCs increases COCs for pork by 23 percent, enough to raise its COCs to 9.64 kg CO_2/kg pork. That would change its COCs from just slightly lower than the Netherlands and Denmark to more than 13 percent higher. Yet using only a regional COC would make the U.S. COCs more than 20 percent lower than the Netherlands and Denmark.

Another important factor that affects total COCs is the estimation of COCs at the national level for forage and grasslands for dairy, and for which there are also uncertainties. COCs are a function of native carbon stocks and yields. Estimating native carbon stocks becomes more challenging for smaller areas. In the vegetation model, we observe that small changes in climate can cause the models to project different types of dominant vegetation, which lead to quite different carbon stocks. At larger scales, these differences are more likely to average out. For our analysis, we "smoothed" out the differences in northern Europe by employing an average of the national carbon stock and the northern European carbon stock for each type of crop, forage, or pasture. For Italy and Spain, whose native carbon stocks are much lower, we used the national estimates from our vegetation model, which reduces their land-use costs.

To test the sensitivity, we estimated the effect of using the national native carbon stock estimate only for the wetter European countries. The effect is mostly negligible. The second-largest effect is a 5 percent change in COC for the United Kingdom for dairy. The one exception is Ireland, for which COCs would increase by 22 percent. That is due to a very high estimate of native vegetation for Ireland generated by our model.

Yield information is also uncertain. Among the countries we investigated, Denmark and New Zealand had excellent data on forages, and the United States has good data for much but not all forage land. For countries using maize silage, we could also estimate yields from reported yields of maize. For other forages, such as typical grass forages, we relied on data generated by the Common Agricultural Policy Regionalized Impact (CAPRI) modelers, modified by separate information for Poland.

COCs also include the emissions from the ongoing degradation of peatlands used to produce a crop or forage. We estimated peatland emissions for forages and pasture by using NIR data to estimate the percentage of croplands on drained peatlands and applied that percentage also to forage lands. We then applied an emission factor as described in Searchinger et al. (2018). In the United States, the NIR fails to provide data, but farming on peatlands is not as common as in Europe, so we therefore added a number (0.04) that corresponds to a low European number. This is obviously a rough estimate and could be improved with more specific data about forage lands. The effect of this addition ranges from 0.01 to 0.15 kg CO_2e/kg milk.

Data Uncertainties

For all of the countries, with the exception of Denmark, there are large data limitations regarding key farm characteristics. Denmark imposes comprehensive reporting requirements on every farm in the country, which includes, among other factors, the numbers and types of animals, the feed produced and the feed purchased, and the fertilizer used. Although there are uncertainties in other data details, these basic data greatly constrain the results. Furthermore, because the ClimAg model works differently from national statistics, Denmark's data makes it possible to validate the model in important ways. For example, the model relates total pork production per pig to herd characteristics, feed quantity, and feed quality. We found that by using data provided on herd characteristics and feed quality, our model did an excellent job of matching the national statistics and feed information provided by local experts.

The full amount of data needed from many other countries is less available. Example data include the precise feeds and quantities used as well as various herd characteristics, such as the birth rate of pigs or the age of first calving for dairy cows.

Emission Factors Uncertainties

Overall, there remain important uncertainties about the emission factors that determine a wide range of agricultural emissions. Emission factors are formulas for estimating emissions from activities, such as the quantities of CH_4 per kilogram of manure or the quantity of feed energy. In general, we followed IPCC factors, although not always.

For example, CH_4 emissions from feed digestion (enteric fermentation) in ruminants and pigs are calculated as a fraction of gross energy intake. In contrast to many other GHG models for cattle, this fraction is not an exogenous constant but rather an endogenous parameter calculated as a function of feed quality, daily feed intake, and animal liveweight. Those equations were developed by Moraes et al. (2013) using statistical analysis of a data set that contains roughly 2,600 CH_4 energy balance trials. The observed prediction error of these equations is substantially lower than that of the fixed factor of 6.5 percent of CH_4 energy to energy in feed recommended by the IPCC (2006). On balance, CH_4 emissions are lower.

The Overall Confidence Level

Because of these and other uncertainties, precise emissions estimates have a low confidence level. However, results are heavily constrained overall by four pieces of information: (i) productivity per head of pork production, (ii) milk output per dairy cow for milk, (iii) days spent grazing, and (iv) temperature (because of its influence on CH_4 emissions). For pork production, in addition to data on production and pig numbers from FAOSTAT, we relied heavily on data generated from the InterPig network. For dairy, we used FAOSTAT for milk output and the numbers of dairy cows to generate output per cow and cross-checked with national statistics where available. Our analysis therefore heavily depends on their accuracy, but we believe these data are likely to be accurate enough to reveal the major overall differences among countries.

In general, we thus believe that small differences in our results should be disregarded, but the analysis can be used to locate each country generally, for example, among the lower-cost, medium-cost, or high-cost producers. We have marked country categories by color in Figures 1 and 2.

DENMARK

This working paper originated with a request specifically to compare Danish agricultural emissions with those of other countries. Our general finding is that Danish dairy operations are in the lowest emissions tier, but their emissions also are so close to several other countries that they should be viewed as equal given uncertainties. For dairy, estimated emissions are within 3 percent of Germany, the Netherlands, and the United States, which is definitely less than the reliability of our or any estimate achievable with present data and emission factor uncertainties. Five other countries are within 22 percent. There are also many uncertainties when comparing these two tiers. Overall, these distinctions are not large, but some small advantage over this next tier is more probable due to such basic factors as temperature effects on manure and the lower land-use efficiency of the increased use of grazing.

For pork, we again find that Danish production is within the top tier, and it nominally comes in first, but the differences with eight countries are no more than 8 percent. Denmark has two qualities that could explain a top position: a top feed conversion efficiency due primarily to its high rate of breeding piglets per sow and a low temperature. But given the uncertainties, we think it appropriate to consider the emissions as equal.

These findings are a major difference from the results of some previous analyses. Weiss and Leip (2012) ranked Denmark in the half of European countries with higher emissions per kilogram of milk or pork; in each case, more than 50 percent higher emissions than Ireland. Lesschen et al. (2011), by contrast, ranked Denmark with the lowest emissions for milk in Europe and reported that its pork emissions were also relatively low, but the estimated differences with other countries in that paper were much larger than the differences in our estimates. For example, Lesschen et al. (2011) reported that Danish emissions were at least 30 percent lower for dairy and roughly 45 percent lower for pork than the emissions in Netherlands; by contrast, we find these two country results to be very similar. The FAO ranked Denmark somewhat in the middle of some country results presented in Europe, which did not have large differences, but substantially higher than the United States (MacLeod et al. 2013). We cannot explain all the differences, but we believe Weiss and Leip (2012) may have failed to adjust for sales of weaner pigs, and our differences in counting land-use carbon costs helps to explain differences between the FAO result and our result for the United States (Box 1).

DISCUSSION AND CONCLUSIONS

Although a variety of conclusions are possible from our analysis, we emphasize a few here:

Differences between Concentrated and Grazing Operations

In general, emissions from concentrated dairy operations are lower than those that rely on grazing. This difference is consistent with those of the vast majority of other LCAs, and it is even more significant when using COCs as the measure of the carbon costs of land use.

It is also interesting that New Zealand, a grazing system, can achieve emissions that we estimate at only 10 percent higher than the intensive, concentrated dairy countries, and given uncertainties, it could be equal.

At some level, this difference is unfortunate because it highlights trade-offs between climate benefits and other sustainability aspects of livestock production. Grazing lands have reduced soil erosion and pesticide use. Concentrated farming operations are likely to use more antibiotics because of heightened disease risk. They also present additional water quality challenges because they generate large concentrations of nitrogen and phosphorus in fertilizer. Animal welfare is also important, and some people believe cattle are happier when grazing than when in a concentrated operation.

Yet there are also some potential synergies between climate benefits and other aspects of sustainability. Holding down COCs through more intensive land use is not only good for the climate but also increases the potential for protecting or restoring habitat that could provide high biodiversity. If dairy operations use true native grazing lands, their use for dairy will not result in large carbon losses and therefore will not result in large COCs. But the vast majority of grazing lands used for dairy in the countries analyzed are not native grasslands but are pastures converted from areas that were naturally forest or woody savannas. Although extensive (low-productivity) grazing land can provide more habitat than croplands—and, in some altered ecosystems, they can play new, valuable roles for species such as grassland birds—preserving and restoring native vegetation types as a rule is likely to provide greater benefits for biodiversity.

A finding that concentrated systems generally have lower emissions implies that switching to more grazing is unlikely to be a good strategy for reducing global emissions. But that does not imply that concentrated systems should be left alone. They have their own environmental and potential animal welfare issues and still have high emissions, and improving performance across all of these metrics will be important as well.

Land Use

Land use matters, and how it is counted as part of GHG estimates has large consequences for the results and for policy implications.

First, although uncertainties in these calculations caution against overreliance on precise numbers, it is clear that factoring in COCs generally increases the GHG consequences of dairy and pork systems compared to other approaches. For example, in our approach, dairy emissions for European countries are generally around 3 kg CO_2/kg milk, with roughly half due to COCs; in Weiss and Leip (2012), estimates of dairy emissions for almost all countries in Europe are between 1 and 2 kg CO_2/kg milk using its global approach to shared land-use change emissions. Similarly, our estimated emissions for European pork are in the neighborhood of 8 kg CO_2/kg pork, whereas those in the Lesschen et. al. (2011) analysis, which does not assign emissions to land use, are 3.5.

Second, compared to alternative methods of estimating the carbon costs of land use, COCs are more similar across countries. For example, in MacLeod et al. (2013), the FAO only assigns land-use change emissions to countries that import soybeans from Latin America. As a result, the United Kingdom has emissions of 7.17 kg CO_2/kg pork and Denmark, 4.71, but the United States has emissions only of 3.98, which include no emissions from land-use change. Similarly, in Weiss and Leip (2012), Danish milk emissions are roughly one-third higher than those of Italy because of land-use change emissions due to a greater reliance on imported feed.

Third, the differences in land-use change the estimated GHG consequences of relying on grazing. In Weiss and Leip (2012), Irish dairy has no emissions from land-use change because it relies on grazing and does not use imported feed, whereas Denmark has around 0.7 kg CO_2/kg milk from land-use change. By contrast, in our approach, Ireland's COCs are 80 percent higher than those of Denmark, an increase of 1.2 kg CO_2/kg milk.

Uncertainties

Data difficulties and uncertainties reduce the confidence of precise rankings among countries when the differences are small. Yet because of the constraints imposed by key data, we believe the overall patterns among tiers are probably reliable (at least given present estimates of emission factors).

Because of many uncertain parameters, researchers should continue to improve data and to be transparent in their sources and parameters as well. Appendix C provides the list of the key parameters we used, which we encourage other researchers to improve upon and to show transparently as well.

Denmark

From a policy perspective, these results suggest that reducing Danish livestock production just to reduce Denmark's reported GHG emissions is unlikely to be a good global strategy for reducing GHG emissions from the food sector. Yet the similarity in performance among many high-income countries also means that just shifting from those countries to Denmark is also unlikely to have significant GHG benefits.

For a high-performing country like Denmark, our results imply that just adopting production methods and best practices that are broadly used in other countries is unlikely to reduce emissions. Achieving the goal that the Danish agricultural sector has adopted of carbon neutrality will require additional advancements and innovations.

APPENDIX A: DATA SOURCES FOR THE CLIMAG MODEL

In General

The global component of the study analyzes production and land-use COC emissions from pork and dairy. For dairy, we analyze several European production systems along with Brazil, New Zealand, and the United States. For pork, we assess the same European systems as well as Brazil and the United States. To calculate emissions, the model we use, called ClimAg, requires inputs for herd characteristics, feed composition crop yields, and types of manure management. The tables in Appendix C show the specific parameters by country for dairy and pork, respectively.

In limited situations, parameters are not available for certain countries. In these situations, as described below, we default to using the Denmark parameters for any country where more detailed information is not available.

For European countries, we obtained some data from the European Centre for Agricultural, Regional and Environmental Policy Research (EuroCARE). This data was extracted from the CAPRI model developed primarily by the European Union's Joint Research Centre. Information from CAPRI includes data on forage and pasture yields, feed composition, and some information on herd characteristics. FAOSTAT also provided important information for different countries.

For Denmark, we used information provided from a variety of Danish sources, including SEGES, the technical advisory service for Danish agriculture. For Brazil, New Zealand, and the United States, we consulted other sources.

Herd Characteristics for Dairy Production

For all countries, we used FAOSTAT data on milk yield for the most recent year (2017).

For the included European countries, CAPRI provided us with calving intervals and the age of first calving for dairy production.

For Brazil, we obtained the calving interval from a publication by the University of Brazil (McManus et al. 2011).

The New Zealand calving interval comes from an annual publication by the Livestock Improvement Corporation and Dairy New Zealand (LIC and DairyNZ 2018). The New Zealand age of first calving comes from Te Ara, a governmental agricultural organization (Stringleman and Scrimgeour 2008).

For the United States, the calving interval and age of first calving come from a publication by the U.S. Department of Agriculture (USDA) on dairy reproduction (APHIS 2009). Additionally, the U.S. replacement rate can be derived from biannual USDA fact sheets on dairy cow populations (NASS 2020).

Herd Characteristics for Pork Production

InterPig, a consortium of pork economists from different countries, provided almost annual information on pig production in many countries. SEGES participated in this effort and summarized the 2018 information for multiple countries in a 2019 publication (Groes Christiansen and Udesen 2019). This InterPig report provides data on all countries included in our study.

We checked the accuracy of the InterPig data by cross-checking the meat productivity per animal and year against FAOSTAT data on annual meat production and animal stocks. When comparing the FAOSTAT data, we controlled for the trade of live pigs since such trade influences the country averages of meat productivity per animal stock. For all countries except Brazil, InterPig data agreed well with FAOSTAT. For Brazil, InterPig data implied an overestimate by a factor of almost two. To correct for this, we assumed a lower rate of piglets born per sow and lower liveweight gain rates for slaughter pigs compared to the InterPig data.

Feed Composition

For both pork and dairy, CAPRI provided some information about European feed baskets. For each animal and age group, the data included the kilograms per head per year consumed for a number of categories. These categories included cereals, grass, and protein-rich feed (e.g., oilseed cakes), among others.

For the makeup of the cereal basket (i.e., which cereals supplied the cereal portion of feeds in each country), we based it on the share of cereal consumption in FAOSTAT feed consumption data. These estimates of the makeup were used for both dairy and pork.

However, where more detailed information was available, we integrated that. We used a supplemental source for Ireland's dairy feed (Horan and Patton 2019; Humphreys et al. n.d.).

Additionally, the percentages of protein concentrates—and, therefore, the protein contents of feed rations—reported in the CAPRI data for pig feed were unrealistically high. As a result, we consulted other data sets. Thus, for pork, the percentages of energy-rich and protein-rich feed used quantities obtained from Denmark feed data.

In Brazil, we assumed a pasture-based feed basket for dairy with a grain supplement consisting of about 3 percent by dry weight, based on publications from the Brazilian agricultural research institute Embrapa.

Due to a lack of information on U.S. dairy, we assumed the same feed basket as Denmark, but with a higher proportion of pasture feeding.

For New Zealand dairy feed baskets, we used a government document from the Ministry of Primary Industries (2016).

Crop and Grazing Yields

Whole-maize yields were estimated using FAOSTAT, with a harvest index (share of harvested crop relative to total plant growth) of 55 percent for grains and 85 percent for whole maize.

For grass-legume harvested and grazed yields in the European countries (except Ireland), we used data from the CAPRI model except that we adjusted the yield for Poland based on input to match the yield of forages in Statistics Poland.

In most countries, there is little data on consumption of forage per hectare on grazing lands. To differentiate output from grazing land rather than forages, we needed to adjust output because above-ground productivity is normally lower for grazed grass than harvested grass due to such factors as trampling and repeated defoliation. For Sweden and Denmark, whose grazing utilizes almost entirely grasses planted in rotation on cropland, we assumed grazed areas have 15 percent lower yields than harvested forage grasses based on Swedish data. For the United States and other European countries (except for Ireland), where much grazing occurs on permanent grasslands, we assumed a 40 percent lower yield than forage crops. For all grazing land, we also assumed grass consumption by cattle is 60 pecent of the above-ground grass yield.

Pasture yield and grazing efficiency for dairy in Ireland came from Humphreys et al. (n.d.) as well as Horan and Patton (2019).

New Zealand values also came from the Ministry of Primary Industries (2016).

Forage yields in the United States are based on data from the USDA.

For Brazil, grazed intake per hectare was estimated using data on stocking rates from a paper by the International Institute for Sustainability in Brazil (Strassburg et al. 2014).

Manure Management

For the purpose of this study, all European countries as well as New Zealand and the United States have submitted NIRs to the United Nations Framework Convention on Climate Change (UNFCCC) detailing their emissions across several categories. Alongside these reports, countries also submitted spreadsheets detailing the information behind their emissions accounting. These supplements, called the common reporting format (CRF), have important information on manure management.

In particular, these reports have the distribution of manure across both management systems and climates within a country. The spreadsheets also provide methane conversion factors (MCFs) for each system and climate, and N_2O emissions per livestock head.

The CRF was available for all countries except Brazil. For Brazil's manure management, we used two Brazilian LCAs (Cherubini et al. 2015; Higarashi et al. 2013).

We worked with individuals at the U.S. Environmental Protection Agency and the USDA to obtain the distribution of manure in different management systems at the state level. To create a proxy for a national manure management structure, we took a weighted average of the manure distribution and pork and dairy production. In other words, for pork, we averaged the manure distribution proportions in the top five pork-producing states with the total pork produced in those states. We repeated the method for dairy.

Enteric Methane

Methane emissions from feed digestion (enteric fermentation) in ruminants and pigs were calculated as a fraction of gross energy intake.

For cattle, the CH_4 fractions were calculated as a function of feed quality, daily feed intake, and animal liveweight, based on equations developed by Moraes et al. (2013).

For pigs, the CH_4 fractions were adjusted according to data in the NIRs to the UNFCCC.

Energy Use

We included CO_2 emissions from on-farm energy use for tractor work and barn operations. Energy-use assumptions were based mainly on Danish and Swedish data (Hörndahl and Neuman 2012; Nguyen et al. 2011).

APPENDIX B: CLIMAG MODEL DESCRIPTION

The ClimAg model is an agro-industry system model that calculates the use of resources (e.g., land and energy) and emissions of GHGs and nitrogen pollutants from food production and agricultural land use. Its main purpose is to calculate the climate impact of different food and biofuel production systems. In addition to recurring GHG emissions, the model calculates the climate impact of carbon stock changes in plants and soils caused by land use.

The model includes all major supply steps related to production and use of food and biofuels, including (i) production of agricultural inputs; (ii) crop, livestock, and fish production; (iii) processing into end-use-ready items; and (iv) transportation between production nodes. The food consumption step includes calculating food waste production but not energy use for food preparation.

The model includes all major GHG emission sources, including the following:

- N_2O from agricultural soils
- N_2O and CH_4 from manure management
- CH_4 from feed digestion (enteric fermentation) in ruminants and pigs
- N_2O and CO_2 from drained organic soils
- CO_2 from production and use of fuels and electricity in agriculture and related industries
- CO_2 and N_2O from production of mineral fertilizers and other inputs
- CO_2 from transportation of inputs and outputs

The description of nitrogen (N) and carbon (C) flows on a mass balance basis. Mass balance descriptions of N help improve the accuracy of emissions estimates, particularly in crop and livestock production, from which substantial amounts of N can easily escape in the form of different gases and as nitrate. Most of these losses are very expensive to measure and are rarely known with high certainty. Using the mass balance of N ensures physically consistent modeling results and more accurate estimates overall of the N flows in the system.

Endogenous emission factors, calculated using statistically significant and verified formulas. In contrast to the standard in LCAs, in which emission factors are typically constants, this model calculates many as a function of process-specific conditions. For example, emission factors of CH_4 from feed digestion are calculated as a function of feed quality, daily feed intake, and animal liveweight. Endogenous, process-specific emission factors are likely to give more accurate emissions estimates than constant emission factors.

A consistent framework for valuing the climate effect of changes in land carbon stocks. In contrast to most LCAs, which typically ignore lost or forgone C stocks caused by agricultural land use, this model uses the carbon opportunity cost method of attributing carbon costs to land use and for comparing those with recurring GHG emissions. This allows for a much more accurate representation of the full climate cost of land use since the costs of forgone C stocks are typically much higher than that of the recurring GHG emissions.

Endogenous representation of livestock herds such as the number of animals of different functions and ages and the herd output of milk/egg and slaughter animals. The herd size and structure are calculated using herd dynamics parameters, such as reproduction rates and growth rates, and animal cohort descriptions, mainly age and liveweight. This enables the calibration of key herd productivity parameters, such as calving rates and liveweight gain rates, against country statistics on production per number of livestock.

Endogenous estimates of feed energy intake per animal, which are calculated using experiment-based equations that use various herd characteristics parameters as input data—in particular, liveweight, growth rate, and milk/egg production rate. A key feature here is that the liveweights of growing animal cohorts are not exogenous constants, which is the standard in most herd models, but are endogenous parameters calculated using a daily time step. This gives a more accurate estimate of the feed energy intake of the animal because the energy needs for maintenance are nonlinear with respect to liveweight. Endogenous calculations of feed intake ensure reasonably accurate emission estimates even when feed basket data are incomplete. This applies particularly to systems with significant amounts of grazing because the grazed feed quantity is rarely known.

Physically consistent representation of the production and use of by-products generated in crop and livestock systems and related processing industries. Most of these by-products are useful as feedstock in other production. The model calculations of the production of by-products are based on the mass and energy balanced descriptions of the processes in which they originate. This ensures that the availability of by-products is correctly scaled to the production levels in the subsystems that generate the by-products.

Consistent accounting of upstream resource use and emissions of all feedstocks used in production systems. The ClimAg model consistently calculates the land and energy use and the GHG and N emissions that occur in the supply of all categories of feedstocks. Such upstream costs are calculated also for by-products, which typically are considered as free in most other models and analyses. In those analyses, for example, straw used for bioenergy and manure used for organic crop production are typically assigned no upstream cost.

APPENDIX C: SUPPLEMENTARY TABLES ON KEY MODEL PARAMETERS

Table C1 | **Herd Management Parameters Used for Dairy Production by Country**

PARAMETER	DENMARK	GERMANY	SPAIN	FRANCE	UK	POLAND	IRELAND	ITALY	NETHERLANDS	SWEDEN	BRAZIL	USA	NEW ZEALAND
LIVEWEIGHT OF COWS (KG)	650	650	675	677	538	650	535	600	600	650	580	580	460
REPLACEMENT RATE (CULLED %)	37	37	37	37	37	37	37	37	37	37	37	35	37
MILK PRODUCTION (KG/COW/YEAR)	9,683	7,780	8,570	6,722	8,042	6,357	5,220	6,354	8,587	8,628	1,963	10,457	4,237
CALVING INTERVAL (MONTHS)	13.2	14.5	12.9	13.3	14.5	16.1	14.7	14.3	10.7	13.4	13.5	13.2	12.2
AGE OF CALVES WHEN SOLD (MONTHS)	2	1	0.5	0.6	0.6	1.4	2.8	1	0.5	2	2	0.2	0.2
AGE OF FIRST CALVING (MONTHS)	25.0	27.0	30.2	31.7	35.5	35.0	34.8	33.0	25.3	28.0	36.0	25.2	24.0
MORTALITY OF COWS (%)	2	2	2	2	2	2	2	2	2	2	2	2	2
MORTALITY OF CALVES (%)	4	4	4	4	4	4	4	4	4	4	4	4	4
MORTALITY OF HEIFERS (%)	2	2	2	2	2	2	2	2	2	2	2	2	2
LENGTH OF GRAZING SEASON (MONTHS)	6	6.5	7	7	7	5.5	7.7	7	6.5	5	8	6	12

Note: The ClimAg model uses the length of grazing system to segregate feed types consumed by those animals that graze and that differ in and out of the grazing season. This parameter does not show the extent to which the dairy farms rely on grazed forage versus other types of feeds, which is set forth in Table C3. For Brazil, the grazing season means the wetter grazing months when feed quality is higher.
Source: Authors' calculations.

Table C2 | Herd Management Parameters Used for Pork Production by Country

	DENMARK	GERMANY	SPAIN	FRANCE	UK	POLAND	ITALY	NETHERLANDS	SWEDEN	BRAZIL	USA
LIVEWEIGHT OF SOWS (KG)	250	250	250	250	250	250	250	250	250	250	250
REPLACEMENT RATE OF SOWS (%)	54	40	47	46	54	54	40	44	53	45	45
LITTERS OF SOWS PER YEAR	2.26	2.32	2.31	2.34	2.20	2.26	2.24	2.35	2.23	2.33	2.44
LIVE-BORN PIGLETS PER LITTER	17.3	15.3	13.8	14.2	12.1	17.3	12.7	15.1	14.6	13	12.9
AGE AT WEANING OF PIGLETS (DAYS)	31.0	24.5	24.0	24.0	26.5	31.0	26.0	27.0	33.0	27.0	22.0
LWG PER DAY FOR PIGLETS (KG/DAY)	0.18	0.24	0.21	0.24	0.23	0.18	0.23	0.25	0.28	0.13	0.24
AGE AT TRANSFER FOR WEANERS (DAYS)	83.0	77.5	68.0	76.0	87.5	83.0	84.0	74.0	79.0	66.0	64.0
LWG PER DAY FOR WEANERS (KG/DAY)	0.46	0.43	0.30	0.45	0.47	0.46	0.43	0.38	0.47	0.38	0.42
AGE AT SLAUGHTER FOR HOGS (DAYS)	168.0	187.5	197.0	188.0	171.5	168.0	284.0	189.0	176.0	186.0	184.0
LWG PER DAY FOR HOGS (KG/DAY)	0.98	0.84	0.73	0.80	0.87	0.98	0.69	0.83	0.95	0.83	0.86
MORTALITY OF SOWS (%)	10.2	7.0	9.9	6.1	5.0	10.2	2.5	6.0	7.5	6.6	11.7
MORTALITY OF PIGLETS (%)	14.2	15.2	13.8	14.5	12.7	14.2	12.0	13.9	17.6	7.8	14.9
MORTALITY OF WEANERS (%)	3.2	2.9	4.6	2.8	4.1	3.2	4.6	2.6	2.0	2.2	4.1
MORTALITY OF HOGS (%)	3.3	2.5	3.8	3.9	3.2	3.3	2.5	2.5	1.8	2.3	4.5
CARCASS YIELD FOR HOGS (% LIVEWEIGHT)	76	77	75	77	76	76	80	78	73	74	73

Note: LWG = liveweight gain.
Source: Authors' calculations.

Table C3 | Dairy Feed Baskets

PARAMETER	DENMARK	GERMANY	SPAIN	FRANCE	UK	POLAND	IRELAND	ITALY	NETHERLANDS	SWEDEN	BRAZIL	USA	NEW ZEALAND
COWS													
ALL PRODUCTS (%)	**81.5**	**83.4**	**83.3**	**87.4**	**82.4**	**83.4**	**91.6**	**81.2**	**83.8**	**82.6**	**95.0**	**83.2**	**92.0**
CONCENTRATE PRODUCTS (%)	21.4	17.0	24.2	21.6	18.0	10.0	12.0	18.0	20.0	21.5	2.7	21.4	3.5
STALL-FED GRASS-LEGUME FORAGE (%)	24.4	12.8	46.6	38.7	49.2	47.9	31.4	34.0	34.8	49.1	0.0	26.1	0.0
STALL-FED OTHER FORAGE (%)	35.7	47.0	7.6	21.3	5.5	20.0	4.0	22.8	24.2	9.7	0.0	35.7	6.5
GRAZED FORAGE PRODUCTS (LEYS; %)	0.0	6.6	4.9	5.8	9.7	5.5	0.0	6.4	4.8	2.3	0.0	0.0	0.0
PERMANENT AND SEMIPERMANENT PASTURE (%)	0.0	0.0	0.0	0.0	0.0	0.0	44.2	0.0	0.0	0.0	92.3	0.0	82.0
ALL BY-PRODUCTS	**18.5**	**16.7**	**16.7**	**12.6**	**17.6**	**16.6**	**8.4**	**18.8**	**16.2**	**17.4**	**5.0**	**16.8**	**8.0**
PROTEIN SUPPLEMENTAL BY-PRODUCTS (%)	16.0	15.0	15.0	12.5	15.0	12.5	7.5	12.5	16.0	16.0	5.0	16.8	8.0
PURCHASED FIBROUS BY-PRODUCTS (%)	2.5	1.7	1.7	0.1	2.6	4.1	0.9	6.3	0.2	1.4	0.0	0.0	0.0
HEIFERS													
ALL PRODUCTS (%)	**86.5**	**88.5**	**86.5**	**88.5**	**86.5**	**86.4**	**98.0**	**88.5**	**88.5**	**95.7**	**99.9**	**95.5**	**100.0**
CONCENTRATE PRODUCTS (%)	8.7	5.0	8.7	5.0	8.7	5.0	3.0	5.0	5.0	2.0	3.7	8.7	0.0
STALL-FED GRASS-LEGUME FORAGE (%)	44.1	14.0	60.7	3.5	41.1	41.5	42.8	47.1	40.1	66.0	0.0	47.3	0.4
STALL-FED OTHER FORAGE (%)	30.9	46.8	7.6	0.0	3.1	13.3	0.0	30.9	13.0	0.0	0.0	17.0	0.1
GRAZED FORAGE PRODUCTS (LEYS; %)	2.8	22.7	9.5	80.0	33.6	26.6	0.0	5.5	30.4	27.7	0.0	22.5	0.0
PERMANENT AND SEMIPERMANENT PASTURE (%)	0.0	0.0	0.0	0.0	0.0	0.0	52.2	0.0	0.0	0.0	96.2	0.0	99.5
ALL BY-PRODUCTS (%)	**13.5**	**11.5**	**13.5**	**11.5**	**13.5**	**13.5**	**2.0**	**11.5**	**11.5**	**4.4**	**0.0**	**4.5**	**0.0**
PROTEIN SUPPLEMENTAL BY-PRODUCTS (%)	4.5	2.5	4.5	2.5	4.5	4.5	2.0	2.5	2.5	3.0	0.0	4.5	0.0
PURCHASED FIBROUS BY-PRODUCTS (%)	9.0	9.0	9.0	9.0	9.0	9.0	0.0	9.0	9.0	1.4	0.0	0.0	0.0

Source: Authors' calculations.

Table C4 | Pork Feed Baskets

PARAMETER	DENMARK	GERMANY	SPAIN	FRANCE	UK	POLAND	ITALY	NETHERLANDS	SWEDEN	BRAZIL	USA
SOWS											
CONCENTRATE PRODUCTS (%)	84.8	86.3	84.8	84.8	84.8	86.3	84.8	84.8	84.8	84.8	84.8
PROTEIN SUPPLEMENTAL BY-PRODUCTS (%)	15.2	13.7	15.2	15.2	15.2	13.7	15.2	15.2	15.2	15.2	15.2
GILTS											
CONCENTRATE PRODUCTS (%)	78.1	78.1	78.1	78.1	78.1	78.1	78.1	78.1	78.1	78.1	78.1
PROTEIN SUPPLEMENTAL BY-PRODUCTS (%)	21.9	21.9	21.9	21.9	21.9	21.9	21.9	21.9	21.9	21.9	21.9
WEANERS											
CONCENTRATE PRODUCTS (%)	76.8	76.8	76.8	76.8	76.8	76.8	76.8	76.8	76.8	76.8	76.8
PROTEIN SUPPLEMENTAL BY-PRODUCTS (%)	23.2	23.2	23.2	23.2	23.2	23.2	23.2	23.2	23.2	23.2	23.2

Note: Gilts are young female pigs.
Source: Authors' calculations.

Table C5 | Manure Management System Distribution for Pork and Dairy

PARAMETER	DENMARK	GERMANY	SPAIN	FRANCE	UK	POLAND	IRELAND	ITALY	NETHERLANDS	SWEDEN	BRAZIL	USA	NEW ZEALAND
DAIRY													
SLURRY OUTDOOR STORAGE (%)	80	60.0	49.0	31.0	78.0	12.0	100.0	47.0	95.0	89.0	3.9	3.9	0.0
SLURRY INDOOR STORAGE (%)	0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	15.2	15.2	0.0
ANAEROBIC LAGOON (%)	0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	41.6	41.6	100.0
SOLID AND LIQUID STORAGE (%)	0	17.0	51.0	69.0	12.0	88.0	0.0	38.0	2.5	10.0	28.2	28.2	0.0
DEEP BEDDING (%)	0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
DRY LOT (%)	0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	2.9	2.9	0.0
DAILY SPREAD (%)	0	0.0	0.0	0.0	10.0	0.0	0.0	0.0	0.0	0.0	2.9	2.9	0.0
ANAEROBIC DIGESTER (%)	20	23.0	0.0	0.0	0.0	0.0	0.0	15.0	2.5	1.0	5.3	5.3	0.0
PORK													
SLURRY OUTDOOR STORAGE (%)	86	78.0	100.0	93.0	40.0	25.0	n/a	97.0	74.0	87.0	60.0	12.4	n/a
SLURRY INDOOR STORAGE (%)	0	0.0	0.0	0.0	0.0	0.0	n/a	0.0	0.0	0.0	0.0	76.1	n/a
ANAEROBIC LAGOON (%)	0	0.0	0.0	0.0	0.0	0.0	n/a	0.0	0.0	0.0	20.0	11.2	n/a
SOLID AND LIQUID STORAGE (%)	0	6.0	0.0	7.0	44.0	75.0	n/a	0.0	6.5	8.0	0.0	0.0	n/a
DEEP BEDDING (%)	0	0.0	0.0	0.0	0.0	0.0	n/a	0.0	0.0	0.0	0.0	0.0	n/a
DRY LOT (%)	0	0.0	0.0	0.0	0.0	0.0	n/a	0.0	0.0	0.0	0.0	0.0	n/a
DAILY SPREAD (%)	0	0.0	0.0	0.0	16.0	0.0	n/a	0.0	0.0	0.0	0.0	0.0	n/a
ANAEROBIC DIGESTER (%)	14	16.0	0.0	0.0	0.0	0.0	n/a	3.0	19.5	5.0	20.0	0.3	n/a

Source: Authors' calculations.

Table C6 | Forage and Pasture Yields

DAIRY	BRAZIL	DENMARK	FRANCE	GERMANY	IRELAND	ITALY	NETHERLANDS	NEW ZEALAND	POLAND	SPAIN	SWEDEN	UK	USA
WHOLE MAIZE FOR SILAGE (T DM/HA/YR, HARVESTED YIELD)	n/a	11.2	12.1	12.7	10.5	13.1	10.1	15.6	8.8	15.3	10.0	12.2	15.0
GRASS-LEGUMES FOR SILAGE/HAY (T DM/HA/YR, HARVESTED YIELD)	n/a	8.8	8.3	9.2	5.6	4.1	13.2	n/a	4.4	4.2	7.3	7.5	6.5
GRAZED GRASS-LEGUMES ON CROPLAND (T DM/HA/YR, GRAZED YIELD)	n/a	5.9	5.6	6.2	n/a	2.8	8.8	n/a	3.0	2.8	4.9	5.0	4.4
PERMANENT/SEMIPERMANENT GRASSLAND YIELD (T DM/HA/YR, GRAZED YIELD)	4.0	n/a	n/a	n/a	8.2	n/a	n/a	11.7	n/a	n/a	n/a	n/a	n/a

Note: DM = dry matter; ha = hectare; t = tonne; yr = year.
Source: Authors' calculations.

Table C7 | Manure Management and Enteric Methane Emission Factors for Pork and Dairy

	BRAZIL	DENMARK	FRANCE	GERMANY	IRELAND	ITALY	NETHERLANDS	NEW ZEALAND	POLAND	SPAIN	SWEDEN	UK	USA
DAIRY													
CH_4 MANURE MANAGEMENT (% OF MAX CH_4 PRODUCTION, AVERAGE ALL MANURE SYSTEMS)													
NIR	n/a	6.1	8.3	10.0	15.2	8.1	16.4	70.1	5.7	14.1	3.6	15.5	35.0
2019 IPCC	n/a	21.0	18.0	16.0	26.0	23.0	34.0	73.0	7.6	27.0	23.0	30.0	44.0
N_2O MANURE MANAGEMENT (% OF N, AVERAGE ALL MANURE SYSTEMS)	n/a	0.8	0.5	0.6	0.2	0.8	0.4	0.1	0.6	0.4	0.6	0.5	0.5
CH_4 FEED DIGESTION (% OF GE INTAKE, AVERAGE ALL ANIMALS)	6.3	5.7	6.0	5.9	6.0	5.9	5.7	6.0	6.0	5.8	5.8	5.8	5.6
PORK													
CH_4 MANURE MANAGEMENT (% OF MAX CH4 PRODUCTION, AVERAGE ALL MANURE SYSTEMS)													
NIR	36.3	9.4	20.0	18.2	n/a	21.4	27.7	n/a	9.1	18.8	3.8	14.7	30.7
2019 IPCC	67.0	20.0	38.0	19.0	n/a	39.0	24.0	n/a	10.0	42.0	20.0	21.0	38.0
N_2O MANURE MANAGEMENT (% OF N, AVERAGE ALL MANURE SYSTEMS)	0.3	0.5	0.4	0.6	n/a	0.8	0.2	n/a	0.8	0.4	0.6	0.2	0.9

Note: CH_4 = methane; GE = gross energy; IPCC = Intergovernmental Panel on Climate Change; N = nitrogen; NIR = national inventory report; N_2O = nitrous oxide.
Source: Authors' calculations.

Table C8 | Nitrous Oxide Emission Factors

DAIRY	BRAZIL	DENMARK	FRANCE	GERMANY	IRELAND	ITALY	NETHERLANDS	NEW ZEALAND	POLAND	SPAIN	SWEDEN	UK	USA
N_2O SOILS—MANURE APPLICATION (% OF N)	n/a	0.7	0.4	0.7	0.4	0.5	0.6	1.2	0.3	0.4	0.4	0.4	0.5
N_2O SOILS—MANURE EXCRETED AT GRAZING (% OF N)	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.4
N_2O SOILS—FERTILIZER APPLICATION (% OF N)	0.9	1.0	1.1	1.0	1.1	1.0	1.3	1.1	1.0	1.0	1.1	1.1	1.0

Note: N = nitrogen; N_2O = nitrous oxide.
Source: Authors' calculations.

Table C9 | Area per Unit Output for Pork and Dairy

	BRAZIL	DENMARK	FRANCE	GERMANY	IRELAND	ITALY	NETHERLANDS	NEW ZEALAND	POLAND	SPAIN	SWEDEN	UK	USA
AREA USE PER MILK OUTPUT (M^2 PER KG WHOLE MILK)	4.9	1.5	1.7	1.4	2.0	2.1	1.2	1.3	2.9	2.3	1.7	1.7	1.2
AREA USE PER PORK OUTPUT (M^2 PER KG CARCASS)	10.8	8.9	8.1	8.2	n/a	7.3	7.6	n/a	8.2	8.7	9.8	8.9	6.2

Source: Authors' calculations.

ABBREVIATIONS

C	carbon
CAPRI	Common Agricultural Policy Regionalized Impact
CH_4	methane
COC	carbon opportunity cost
CO_2	carbon dioxide
CRF	common reporting format
DM	dry matter
EuroCARE	European Centre for Agricultural, Regional and Environmental Policy Research
FAO	Food and Agriculture Organization of the United Nations
FAOSTAT	FAO Statistical Division
GE	gross energy
GHG	greenhouse gas
IPCC	Intergovernmental Panel on Climate Change
LCA	life cycle analysis
LWG	liveweight gain
MCF	methane conversion factor
N	nitrogen
NIR	national inventory report
N_2O	nitrous oxide
PEM	production emissions
UNFCCC	United Nations Framework Convention on Climate Change
USDA	U.S. Department of Agriculture
WRI	World Resources Institute
yr	year

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ABOUT THE AUTHORS

Stefan Wirsenius is Associate Professor at Chalmers University of Technology.

Tim Searchinger is a Research Scholar at Princeton University and a Senior Fellow at WRI.

Jessica Zionts is a research assistant at WRI

Liqing Peng is a Food and Agriculture Modeler at WRI.

Tim Beringer is a researcher at the Potsdam Institute for Climate Impact Research.

Patrice Dumas is a researcher at the Centre International de Recherche sur l'Environnement et le Développement.

Correspondence should be addressed to tsearchi@princeton.edu, and stefan.wirsenius@chalmers.se.

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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.

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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.