

WHOLE-FARM GREENHOUSE GAS EMISSIONS: A REVIEW WITH APPLICATION TO A PENNSYLVANIA DAIRY FARM

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ABSTRACT. Greenhouse gas (GHG) emissions to the atmosphere and their potential impact on global climate have become important concerns world-wide. Livestock production systems, such as dairy farms, provide both sinks and sources for GHGs. Typical emissions have been quantified in Europe and synthesized to estimate farm-level GHG emissions. However, fewer data are available in the United States, and little has been done to estimate emissions for our farms. Through an extensive literature review, average GHG flows were quantified for each major farm source and sink including the soil, growing crops, animals, and manure storage. These typical gas exchanges were then combined to estimate farm-level net emissions for a representative, 100-cow dairy farm in Pennsylvania. Emissions from animal facilities primarily consisted of animal respiration (532 Mg CO₂ yr⁻¹) and enteric fermentation (16.9 Mg CH₄ yr⁻¹) with a total annual emission of 971 Mg CO₂ equivalent (CO₂e) where each unit of CH₄ is equivalent to 25 units of CO₂ in global warming potential. Manure storage emissions included CO₂, CH₄, and N₂O for a total annual emission of 216 Mg CO₂e with each unit of N₂O equivalent to 298 units of CO₂. Cropland provided a net flux or sink of -784 to -168 Mg CO₂e yr⁻¹ depending upon the amount of manure carbon sequestered in the soil. The estimated whole-farm net annual GHG emission ranged from 2.5 to 5.8 Mg CO₂e per 500 kg livestock unit or 0.50 to 1.2 kg CO₂e kg⁻¹ of milk produced. This review and farm analysis has helped direct modeling efforts by determining the important processes that drive emissions of CO₂, CH₄, and N₂O in dairy production along with expected ranges for these emissions. Such data expand the knowledge base of researchers, farm planners, and policymakers as they work to develop and maintain sustainable farming systems in the United States.

Keywords. Greenhouse gas, Dairy farm, Carbon dioxide, Methane, Nitrous oxide.

The control of greenhouse gas (GHG) emissions has become an important international issue. Although farmland can serve as a sink or storage for carbon sequestered from atmospheric carbon dioxide (CO₂), agriculture is also an important source of emissions. Potential sources of GHGs on dairy farms include the soil, growing crops, animals, and manure. Globally, agriculture contributes approximately 10% of anthropogenic GHG emissions (IPCC, 2007c); similarly, agriculture contributes approximately 6% of U.S. GHG emissions (EPA, 2008). Extensive research in Europe has quantified emissions from individual sources, as well as total farm emissions. Studies have also been performed in the United States to quantify GHG emissions from individual farm sources; however, these data have not been compiled to provide estimates of total farm-level emissions. This research gap needs to be addressed considering that, as a sector, agriculture is reported

to be the greatest contributor of nitrous oxide (N₂O) and the second greatest contributor of methane (CH₄) emissions (EIA, 2007a).

Legislative pressure may necessitate the quantification, and eventual reduction, of GHG emissions. Internationally, the results of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC) has documented that the effects of climate change are already being felt and that these changes are causing negative impacts in many regions of the globe (IPCC, 2007b). On a national level, the U.S. Supreme Court has determined that GHGs are pollutants and, as such, they must be regulated by the EPA (Commonwealth of Massachusetts vs. U.S.E.P.A., Docket No. 05-1120). As of 2009, no legislation has been passed at the federal level. However, the Supreme Court decision is likely to precipitate movement on the national level for either regulation under existing statutes or new legislation to reduce emissions. In fact, there are several bills and initiatives at the regional and state level, which indicates that concern for addressing GHG emissions is increasing within the U.S. Two regional initiatives are the Western Climate Initiative (WCI) and the Regional Greenhouse Gas Initiative (RGGI); both are consortiums of states investigating the potential reduction of GHG emissions. In 2008, RGGI became the first initiative to auction GHG allowances within the United States.

On a state level in 2009, only California had a bill signed into law regulating GHG emissions. Assembly Bill 32 (AB 32) commits California to reducing state-wide GHG emissions to 1990 levels by 2020, approximately a 25% reduction compared to current emissions. Under AB 32, the California Air Resources Board (CARB) is required to

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develop regulations and market-based mechanisms to reach this goal. Mandatory caps on emissions from significant sources will be enacted in 2012 (CARB, 2007). The draft of a scoping plan, released by CARB in 2008, calls for voluntary use of anaerobic digesters on dairy farms. Mandatory regulations will be reconsidered when the scoping plan is updated in 2013. Because of such legislation, it is beneficial for the agricultural sector to voluntarily reduce GHG emissions rather than becoming subject to potentially expensive mandates.

Assuming this evidence continues to develop, concern over GHG emissions will continue to increase at various levels of the government. Policy makers and scientists are thus pursuing methods for quantifying and reducing emissions and mitigating the current atmospheric concentrations of GHGs.

The objective of this review work was to gather GHG emissions data to estimate the average annual GHG emissions from individual sources and sinks on a representative dairy farm in Pennsylvania, and to combine these individual flows to obtain a net farm emission. These data are being used to support whole-farm GHG emission modeling work and to direct research efforts toward farm sources needing better quantification. By comparing emissions from all sources on a dairy farm, researchers and farm planners can focus reduction efforts on the sources with the greatest emissions.

DATA SELECTION AND APPLICATION

Emission mechanisms and typical emission rates from various farm sources and sinks were determined through an extensive review of peer-reviewed articles quantifying GHG emissions. These data were compiled to obtain average fluxes from each source or sink. Finally, these average values were compiled for a representative dairy farm to estimate total annual GHG emissions and to compare the magnitude of individual emission sources.

DATA SOURCES

Dairy farm GHG emissions primarily occur from cropland, animals, and manure handling facilities. A review of field- and laboratory-measured emissions in crop and ruminant livestock production was conducted to determine typical emissions and expected variation in those emissions. An emphasis was given to data most applicable to the environment and production strategies used on dairy farms in the northern United States. Ideally, the studies were performed in the United States; however, because more studies have quantified GHG emissions outside the United States, our review was extended to studies performed in other countries when the conditions of the study were appropriate. In order to be included in the review, the experimental conditions important to the emission source had to represent those that could occur on a northern U.S. dairy farm. For example, the animal's diet was considered when determining whether to include a study reporting CH₄ emissions from animals. Similarly, the type of housing facility was considered when comparing emissions from animal facilities. Therefore, important conditions were: some combination of milking cows, dry cows, heifers, and calves; a diet consisting of a combination of grains, silage, forage

legumes, grasses, and supplements; housing facilities without manure stored under the floor (e.g., tie-stall and free-stall); manure stored as slurries or stacked manure; animals on pasture, dry lots, or in respiration chambers; crops raised either conventionally or organically; and temperate weather patterns. If the conditions of a study were well outside appropriate conditions for our region, the data were excluded. Studies performed over short periods were also eliminated if they were not representative of the entire year (e.g., unusual weather events such as extreme temperature and precipitation patterns). Finally, several studies measured emissions under varied factors such as manure application rate, type of fertilizer, and animal diet. If a factor level did not represent typical farm conditions (e.g., unreasonably high fertilizer application rate), those data were excluded.

The method used to measure emissions was not held as a constraint on acceptable data. A full review of the advantages and disadvantages of each measurement technique was beyond the scope of this review. Instead, all emissions of GHGs reported through peer-review were assumed to be equally valid and they were included in the emission range.

To compile the data, all emissions were converted to consistent units and an average emission factor was determined for each source or sink. Emissions were first reported as total mass of a specific gas (e.g., kg CH₄ or kg N₂O). Using a conversion called the global warming potential (GWP), emissions were also converted to CO₂ equivalents (CO₂e). The GWP is an index developed to standardize GHG emissions to CO₂. GWP factors are calculated based on the radiative efficiency (heat-absorbing capacity) of each gas as compared to CO₂ and the residence time a given mass of gas remains in the atmosphere until it completely decays (IPCC, 2007a). The GWP values used for CO₂, CH₄ and N₂O were 1, 25, and 298 kg CO₂e per kg of each gas, respectively (IPCC, 2007a).

REPRESENTATIVE FARM APPLICATION

The range and average GHG emissions determined through this literature review were specific to individual sources and sinks on a farm. Because of the different units used to quantify each source or sink, the relative contributions of each could not be directly compared or combined. Instead, a representative farm was used as a tool to integrate the different emission factors to estimate GHG emissions from a typical dairy farm in the northeastern United States. This method identified the most important sources of each GHG and the overall net emission from the farm.

Dairy farms in various regions of the United States tend to follow different management practices. The emission factors selected to represent this farm were not specific to the Northeast, but they were selected to generally represent expected emissions occurring in this region. Estimated emissions were not intended to represent a specific farm, but rather to illustrate farm-level GHG emissions for a general farm in the region.

The representative farm was established to represent the herd size, crop area, feed production, and manure management practices typically found on moderately-sized, Pennsylvania dairy farms. Most of the feed required to maintain the dairy herd was produced on the farm using 90 ha of land. The herd consisted of 100 Holstein cows (average mass of 650 kg), 38 heifers over one year in age (average

mass of 470 kg), and 42 heifers under one year of age (average mass of 200 kg). A random calving strategy was assumed where 15% of the cows were dry at any point during the year. This provided a total of 183 LU (500 kg live mass per LU). The average annual milk production for the herd was set at 9,000 kg per cow. Animals were housed in free-stall barns where manure was removed daily, stored as slurry in a 500-m³ storage tank for up to six months, and spread on cropland bi-annually. On average over the year, the storage contained about 1,100 m³ of manure. The farm area included 20 ha of grass, 20 ha of alfalfa, and 50 ha of corn. Corn in this region is normally used for both silage and grain production. The corn land was split with 20 ha used for silage production and 30 ha for high moisture grain. A lower net sequestration (negative emission) was assumed for land in grain production because more CO₂ would be emitted through decomposition of the stover residue left in the field. Emission factors obtained through the review were used with these farm characteristics to provide estimates of total net emissions from individual sources and overall net farm GHG emission in units of CO₂e.

EMISSION SOURCES AND SINKS

Carbon dioxide, CH₄, and N₂O have different pathways of generating emissions from farms. The major environmental factors affecting the rates of many biological reactions, including GHG emission pathways, are temperature, moisture, oxygen concentration, and pH. Many of the emission pathways are controlled by microorganisms, and thus, by the optimum temperature for each specific microorganism involved. Emissions often increase with temperature; however, above some optimum, which varies based on the process, reaction rates decrease or even stop (Richard, 2003). The effect of the substrate (i.e., soil, manure) moisture content is largely determined by whether the pathway is anaerobic or aerobic. At very high moisture contents, or saturation, there is little oxygen diffusion and anaerobic processes (e.g., CH₄ emissions due to anaerobic decomposition) dominate. At somewhat lower moisture contents, aerobic processes, such as CH₄ oxidation, dominate. However, at even lower moisture contents,

microbial activity becomes limited, and reaction rates for all processes are reduced (Paul and Clark, 1989). The effect of oxygen concentration is closely related to the effect of moisture content, as changes in moisture content cause an inverse change in oxygen content. The pH of the substrate affects the activity of microorganisms, and it can cause certain chemical species to be favored over others.

CARBON DIOXIDE PATHWAYS

Carbon dioxide enters an agricultural system through photosynthesis. It is then emitted through respiration of plants (both shoots and roots), animals, and microbial organisms decomposing organic matter from manure and crop residues. Cropland can be a source or sink of GHGs, with the contribution dependent upon the specific gas and the type of cropland. Typically, over the course of a full year, most agro-ecosystems assimilate carbon in the form of CO₂, as shown by an average net emission of -8,345 kg CO₂ ha⁻¹ yr⁻¹ (table 1). This flux is equivalent to net ecosystem production (NEP = photosynthesis – plant respiration – soil respiration). By this definition, a negative value for NEP represents a flux into the system, i.e. plants capture more CO₂ through photosynthesis than they give off through respiration.

Crops producing high amounts of biomass [e.g., corn (*Zea mays* L.) and soybean (*Glycine max* L.)] tend to have a greater carbon input into the system compared to crops producing less biomass (e.g., grassland without added fertilization). This greater input comes through greater growth where more carbon is fixed in both root and shoot dry matter. Annual grain crops [e.g., corn, soybean, and wheat (*Triticum aestivum* L.)] also have less carbon output at harvest when only the grain is removed and the remaining plant biomass stays in the field. With high biomass production and lower biomass harvest, a greater amount of carbon is sequestered, or assimilated in the soil. With more soil carbon and other soil organic matter (SOM), increased microbial respiration in the soil may lead to greater emission of CO₂, offsetting a portion of this potential sequestration of carbon (Bruce et al., 1999; Post et al., 2004).

Average emissions presented in table 1 generally agree with previously published trends. Average net fluxes into corn and wheat crops are greater than that for soybean,

Table 1. Reported CO₂ emission (net ecosystem production, NEP) ranges from croplands.^[a]

Crops	No. of Data	Minimum (kg CO ₂ ha ⁻¹ yr ⁻¹)	Maximum (kg CO ₂ ha ⁻¹ yr ⁻¹)	Average (kg CO ₂ ha ⁻¹ yr ⁻¹)	References ^[b]
All cropland	55	-23,247	1,100	-8,345	---
Grass	28	-14,600	-230	-6,396	a, c, e, g, h, j, l, m
Alfalfa	4	-12,870	-1,283	-6,343	k
Corn ^[c]	10	-23,247	-10,633	-17,745	f, g, o
Soybean	6	-5,133	1,100	-1,794	d, n
Wheat	7	-15,748	-4,220	-9,469	d
Bare soil ^[d]	10	2	522,000	276,000	b, j

^[a] The first data row (in italics) shows values over all croplands, with subsequent rows specific to crop type.

^[b] References: a. Flanagan et al. (2002); b. Flessa and Beese (2000); c. Frank and Dugas (2001); d. Franzluebbers et al. (1995); e. Gilmanov et al. (2003); f. Ginting et al. (2003); g. Kucharik et al. (2001); h. Lee et al. (2007); i. Owensby et al. (2006); j. Reicosky (1997); k. Skinner (2007); l. Sims and Bradford (2001); m. Suyker and Verma (2001); n. Suyker et al. (2005); o. Verma et al. (2005).

^[c] Values for corn generally represent whole-plant (silage) production. Long-term production of grain with residue returned to the soil would increase soil respiration offsetting a portion of the sequestered CO₂. An estimate for grain production is half that noted for whole plant production.

^[d] Emissions from bare soil are due to soil respiration. Emissions on the low end of the range are from respiration with little residue or manure returned to the soil; high emissions result from bare soil with manure application. Farms including a fallow period in crop rotations would likely observe emissions on the lower range.

agreeing with observations by Franzluebbers et al. (1995) and Verma et al. (2005). Perennial forage crops are typically expected to sequester more carbon than annual grain crops, which is shown by the greater negative flux for alfalfa (*Medicago Sativa* L.) and grass as compared to soybean. In addition, little difference has been observed between net emissions from alfalfa and grass (Skinner, 2007).

The data for cropland emissions shown in table 1 were drawn from published studies that utilized various combinations of previous crop history, tillage practices, fertilization strategies, etc. This variety in management strategies explains the great range in net flux found within each crop. Emissions from the same crop can vary due to differences in climate, current management practices, and the management practices used on the field or plot prior to the study. A transition to the use of perennial crops or reduced tillage practices tends to increase carbon sequestration and reduce CO₂ emission. Crops produced using no-tillage systems have sequestered more carbon than crops established using conservation or conventional tillage practices (Bruce et al., 1999; Six et al., 2000). No-till practices slow the decomposition of crop residue and thus reduce emissions and sequester more soil carbon. Corn produced under no-till was found to emit less CO₂ (sequester more carbon) as compared to corn under conservation tillage (Grant et al., 2007). After many years of production in perennial crops or with the use of a given tillage practice, soils reach a steady state where further assimilation of soil carbon diminishes (Bruce et al., 1999).

Crops with a history of field applied manure also sequester less carbon as compared to fields without manure application. Without applied manure, cropland normally has lower soil carbon levels and less CO₂ emission through soil respiration as compared to well-managed fields with high soil carbon levels (Bruce et al., 1999). Most of the studies summarized in table 1 did not provide information on manure application during or prior to the study period; for those that did provide this information, no manure was applied. Since the majority of these studies were not associated with animal production, one can assume that these data do not reflect the influence of a long-term history of manure application. When applying these data to dairy farms, the increased respiration and associated CO₂ emission created through the application of manure must be considered. Assuming a long-term balance in soil carbon on the farm, any carbon applied in manure is ultimately emitted in CO₂.

The reported studies also did not account for removal of biomass. Thus, the net flux reported is different from the net carbon balance for the field. A carbon balance would include

carbon flow into the crop system from manure or other organic material applied to the land and carbon leaving the system in the crop removed. In general, the long term soil carbon level will be in balance, i.e., the carbon inputs will equal carbon outputs. When transitioning to a given crop rotation or perennial pasture system, soil carbon level will increase or decrease over a period of years until a new equilibrium in carbon flow is attained (Bruce et al., 1999; Fang and Moncrieff, 1999). In short-term studies and during the transition of cropping and grazing systems, gains and losses of soil carbon will occur.

Animals and manure handling provide additional sources of CO₂ emission from dairy farms. Animals emit CO₂ through respiration. This respired CO₂ is part of the carbon cycle that initially begins with photosynthetic fixation by plants. When the animals consume the feed produced from the crop, they convert a major portion of the carbon assimilated in the plant material back to CO₂ through respiration (Kirchgeßner et al., 1991; IPCC, 2007a). In the overall farm balance, the CO₂ released offsets the CO₂ sequestered in the plant material. However, some of the feed intake of carbon is converted and released as CH₄. An average CO₂ emission from livestock respiration was found to be about 2,600 kg CO₂ LU⁻¹ yr⁻¹ (table 2). This represents emissions from animals housed in facilities without manure storage. In Europe, housing facilities often contain manure stored in pits under the housing facility. Because this is not common practice on our dairy farms, these data were excluded from this review. However, the data do include minor emissions from manure on the floor of housing facilities.

When long-term manure storage is used on the farm, this also can provide an important source of CO₂ emission. The amount of CO₂ produced and emitted is largely related to the aerobic activity in the manure. Solid manure stored in stacks allows greater infiltration of oxygen which enhances microbial respiration and CO₂ production as compared to manure with a greater moisture content stored in a tank (table 2). For the relatively few data found, emissions of CO₂ from manure storages averaged 59 kg CO₂ m⁻³ yr⁻¹. For the one value found for slurry manure in a tank, the emission was about 30% of this average annual rate.

Another important source of CO₂ emission from farms is that released in the combustion of fuel. Nearly all fuel used on farms today is diesel fuel, which is reported to emit 2.682 kg CO₂ per liter of fuel consumed (EIA, 2007b). Fuel consumption on farms can be estimated based upon typical operations used in the tillage, planting and harvesting of crops, feeding of animals, and handling of manure. Fuel use

Table 2. Reported CO₂ emission ranges from manure storages and animal housing facilities.^[a]

	No. of Data	Minimum	Maximum	Average	References ^[b]
Manure storages (kg CO ₂ m ⁻³ yr ⁻¹)	4	8.6	117	59	a, f, g
Slurry tank	1	17	17	17	f
Stacked	3	8.6	117	72	a, g
Animals and housing (kg CO ₂ LU ⁻¹ yr ⁻¹)	8	1,700	3,800	2,600	b, c, d, e
Lactating cows	3	2,540	3,800	3,120	b, c, d
Dry cows	3	1,700	2,240	2,020	b, c, d
Heifers	2	2,280	3,500	2,800	d, e

^[a] The first data row (in italics) shows values over all types, with subsequent rows specific to type.

^[b] References: a. Hensen et al. (2006); b. Jungbluth et al. (2001); c. Kirchgeßner et al. (1991); d. Pedersen and Sällvik (2002); e. Pinares-Patiño et al. (2007); f. Sneath et al. (2006); g. Sommer and Dahl (1999).

Table 3. Estimated fuel use and the resulting CO₂ emission for machinery operations commonly used on dairy farms.

	Fuel Use (L) ^[a]				CO ₂ Emission ^[b] (kg)
	Tillage	Planting	Harvest	Total	
Crop production (ha ⁻¹)					
Forage	3.3	1.5	130.7	135.5	363
Corn silage	10.2	3.2	62.0	75.4	202
Corn grain	10.2	3.2	30.0	43.4	116
Soybean	10.2	3.2	28.1	41.5	111
Small grain	10.2	6.0	21.4	37.6	101
Manure handling (m ⁻³)				0.58	1.54
Feeding ^[c] (LU ⁻¹ year ⁻¹)				31.6	85.3

[a] Obtained from Lazarus, 2007.

[b] 2.682 kg CO₂ emitted per liter of diesel fuel consumed (EIA, 2007b).

[c] Livestock Unit (LU) is 500 kg of live body mass.

estimates of major machinery operations were reported by Lazarus (2007). Fuel use of individual operations were summed over all operations typically used on dairy farms to obtain representative values for crop production, manure handling, and feeding (table 3). Emissions were then determined as the product of fuel use and the emission factor of 2.682 kg CO₂ per liter of diesel fuel consumed (table 3).

METHANE PATHWAYS

Methane is primarily emitted through anaerobic decomposition of organic matter. Recent research indicates that plants themselves may emit small amounts of CH₄, although the mechanism is not currently known (Keppler and Röckmann, 2007). This implies that croplands could provide an emission of CH₄ under certain circumstances. Because this appears to be a relatively small source and few data are available on this mechanism, this review focuses solely on emissions due to anaerobic decomposition.

Over a long period of time, agricultural lands are typically small sinks for CH₄, as shown by an average net emission over different crops of -1.5 kg CH₄ ha⁻¹ yr⁻¹ (table 4). Soils can emit CH₄ in two ways. First, decomposition of organic matter by microorganisms in poorly aerated soils (e.g., rice paddies, wetlands) can lead to emissions of CH₄ rather than CO₂. Throughout the year, portions of agricultural fields can be saturated with water, creating anaerobic microsites. This may cause minimal amounts of CH₄ to be emitted. However, over an entire year, agricultural soils typically are well-aerated, and CH₄ is oxidized by soil microorganisms. In other words, agricultural soils are small sinks of CH₄.

Manure applied to the surface of cropland may also provide an emission source. In this aerobic environment, CH₄ contained in the manure should quickly dissipate. Thus, the effect of manure application should disappear after a few days with emissions returning to the background levels caused by organic matter decay (Sherlock et al., 2002).

The major source of CH₄ on dairy farms is the animals in their housing facilities. Most of this emission is from enteric fermentation in the ruminant animals, with potentially minor amounts emitted from manure deposited on the barn floor. Like most animals, ruminants cannot digest cellulose found in grasses and leafy plants. However, bacteria in the rumen break down and obtain energy from cellulose in the forage consumed by the animal, producing hydrogen as one by-product. Enteric methanogens, which exist in a symbiotic relationship with other microorganisms in the rumen, prevent the build-up of hydrogen by using it to reduce CO₂ to CH₄, which is then released to the atmosphere through respiration and eructation (Ulyatt et al., 1999). The amount of CH₄ produced is affected by various factors including animal type and size, digestibility of the feed, and the intake of dry matter, total carbohydrates, and digestible carbohydrates (Wilkerson et al., 1995; Monteny et al., 2001).

Reported annual emissions from housing facilities averaged from 58 kg CH₄ LU⁻¹ for dry cows to 106 kg CH₄ LU⁻¹ for lactating cows (table 5). These data primarily represent that emitted through enteric fermentation. As reflected by the data in table 5, there was a range in reported CH₄ emissions. This variation is due to different diets fed, different animal sizes, and differences in measurement procedure among the various studies. The primary difference in emissions is due to the distinction among dry cows, heifers, and lactating cows. Lactating cows emit approximately twice the amount of CH₄ as compared to either dry cows or heifers; this is largely due to their increased feed intake, although ration and animal size also have an effect. These emission factors may include emissions from feces deposited on the barn floor, which would be much less than emissions from enteric fermentation.

During manure storage, CH₄ is generated through a reaction similar to that of enteric fermentation. Cellulose in the manure is degraded by microbes, with products of this process serving as substrates for methanogenesis. Temperature and storage time are the most important factors influencing CH₄ emissions because substrate and microbial growth are generally not limited (Monteny et al., 2001). Reported annual CH₄ emissions from manure storage

Table 4. Reported CH₄ emission ranges from croplands (kg CH₄ ha⁻¹ yr⁻¹),^[a]

Crops	No. of Data	Minimum (kg CH ₄ ha ⁻¹ yr ⁻¹)	Maximum (kg CH ₄ ha ⁻¹ yr ⁻¹)	Average (kg CH ₄ ha ⁻¹ yr ⁻¹)	References ^[b]
All cropland	17	-3.0	-0.4	-1.5	--
Grass	3	-3.0	-0.5	-1.4	b, d, f
Alfalfa	1	-2.6	-2.6	-2.6	e
Corn	6	-2.2	-0.4	-1.5	c, d, e, f
Wheat	1	-1.9	-1.9	-1.9	d, e
Mixed ^[c]	6	-2.2	-1.1	-1.4	f
Bare soil	2	-0.1	0.0	0.0	a

[a] The first data row (in italics) shows the data for all croplands, with subsequent rows specific to a given type of crop.

[b] References: a. Flessa and Beese (2000); b. Flessa et al. (2002); c. Gregorich et al. (2005); d. Kaye et al. (2004); e. Kaye et al. (2005); f. Mosier et al. (2005).

[c] Mixed crop consists of a combination of the following: corn, soybeans, wheat, and/or fallow.

Table 5. Reported CH₄ emission ranges from manure storages and animal housing facilities.^[a]

	No. of Data	Minimum	Maximum	Average	References ^[b]
Manure storages (kg CH ₄ m ⁻³ yr ⁻¹)	15	0.3	15.0	4.5	d, f, i, j, k, l
Slurry, covered ^[c]	2	5.7	7.3	6.5	k, l
Slurry, uncovered	8	1.2	15.0	5.4	f, h, j, k
Stacked	5	0.3	5.8	2.3	d, k
Animals and housing (kg CH ₄ LU ⁻¹ yr ⁻¹)	16	47	121	84	a, b, c, d, f, h, j, m
Dry cows	4	47	71	58	a, e, m
Heifers	3	72	85	77	e, j
Lactating cows	6	94	121	109	c, d, g, h, m

^[a] The first data row (in italics) shows values over all storages and animals, with subsequent rows specific to type.

^[b] References: a. Boadi and Wittenberg (2002); b. Flessa et al. (2002); c. Grainger et al. (2007); d. Hensen et al. (2006); e. Jungbluth et al. (2001); f. Kaharabata et al. (1998); g. Kinsman et al. (1995); h. Kirchgessner et al. (1991); i. Külling et al. (2003); j. Pinares-Patiño et al. (2007); k. Sneath et al. (2006); l. Sommer et al. (2000); m. Wilkerson et al. (1995).

^[c] Cover consists of a natural crust, straw, or similar material on the manure surface.

averaged 4.5 kg CH₄ m⁻³ with stacked storages being about half that from slurry storages (table 5).

NITROUS OXIDE PATHWAYS

Two pathways lead to emissions of N₂O: denitrification and nitrification. Denitrification can serve as either a source or sink of N₂O because N₂O is an intermediate product in the pathway. In wet substrates with little diffusivity, N₂O is the dominant end-product. When substrates have even greater water content and are mostly anaerobic, the N₂O is further reduced to N₂, and N₂O emissions are reduced.

Historically, denitrification was believed to be the primary source of N₂O emissions; however, nitrification has also been established as a contributor (Sahrawat and Keeney, 1986). Nitrification is an aerobic process that oxidizes NH₄⁺ to NO₃, with the production of NO and N₂O as intermediates. The emission of N₂O is thus dependent on both denitrification and nitrification. A conceptual model published by Davidson et al. (2000) illustrates how denitrification and nitrification are connected (fig. 1). This model, known as the “hole-in-the-pipe” (HIP) model, connects the two pathways and thus links the emission of NO and N₂O (Davidson et al., 2000). In this model, oxygen concentration dictates whether the anaerobic or aerobic process dominates, whereas the moisture content determines the size of the holes, or the rate of emission. In addition to these common factors, plant uptake of nitrogen and microbial immobilization of nitrogen also influence N₂O emissions from denitrification and nitrification.

Published data support that farmland is a source of N₂O emission. The review of reported data gave an average net emission of 2.8 kg N₂O ha⁻¹ yr⁻¹ (table 6). A small negative emission (i.e., N₂O sink) reported as the minimum for grassland has two explanations. First, small negative

emissions can be observed from grasslands during short periods in a year. When data are integrated over a full year though, net emissions are typically positive. Second, and most importantly, the observed emission was reported to be below the detection limit of the measurement method used (Wagner-Riddle et al., 1997). As a result, this data point may more accurately represent a zero annual N₂O flux from grasslands. If this negative data point is removed, the minimum observed annual emission is 0 kg N₂O ha⁻¹ yr⁻¹, with a negligible change in the average annual flux.

Emissions of N₂O have been found to correspond with wetting of dry soil (Davidson, 1992) and the application of nitrogen in manure or fertilizer (Mosier et al., 1982). Conversely, negative or zero emissions are observed during dry periods or under management practices with no nitrogen application. The negative observed emission in table 6 occurred during the summer on a grass field with no manure application (Wagner-Riddle et al., 1997). The variability observed in emissions from grassland was due to vastly different management scenarios among production systems. The largest emissions were measured on pasture, which had a large input of manure, and thus nitrogen, deposited by grazing animals. Grass without nitrogen application had emissions at the low end of the range shown in table 6.

All crops exhibited a relatively wide range of measured N₂O emissions (table 6). Crops that showed the greatest variability were those that are normally heavily fertilized (e.g., corn), which suggests that this variability is due in part to different fertilization strategies. Tillage also accounts for some of this variability. Liu et al. (2006) observed that no-tillage systems resulted in greater N₂O emissions as compared to conventional tillage systems.

Nitrous oxide emissions due to livestock were relatively small. Annual emissions of N₂O from manure storage were 0 to 0.1 kg N₂O m⁻³ of manure stored (table 7). These emissions primarily occurred from stacked solid manure or

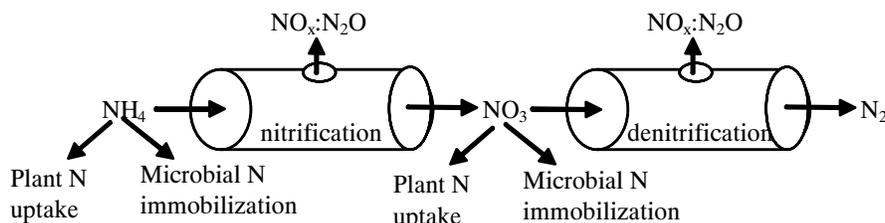


Figure 1. Conceptual model of controls on N gas emissions from soil using the leaky pipe metaphor (Parton et al., 2001).

Table 6. Reported N₂O emission ranges from croplands where negative values are sinks and positive values are sources. ^[a]

Crops	No. of Data	Minimum (kg N ₂ O ha ⁻¹ yr ⁻¹)	Maximum (kg N ₂ O ha ⁻¹ yr ⁻¹)	Average (kg N ₂ O ha ⁻¹ yr ⁻¹)	References ^[b]
All cropland	<i>188</i>	<i>-0.2</i>	<i>28</i>	<i>2.8</i>	--
Grass	81	-0.2	25	1.7	a, c, d, f
Alfalfa	5	1.7	6.6	4.0	a, f, g
Corn	62	0.2	22	4.1	a, d, e, f, g
Soybean	14	0.3	6.2	2.2	g
Wheat	18	0.1	28	2.8	d, e, g
Mixed ^[c]	8	1.1	10	3.4	c, f
Bare soil	2	0.4	5.2	2.8	b

^[a] The first data row (in italics) shows the statistics for all croplands, with subsequent rows specific to crop type.

^[b] References: a. Duxbury et al. (1982); b. Flessa and Beese (2000); c. Flessa et al. (2002); d. Kaye et al. (2004); e. Kaye et al. (2005); f. Mosier et al. (2005); g. Stehfest and Bouwman (2006).

^[c] Mixed crop consists of a combination of corn, soybean, wheat, and/or fallow.

slurry manure with a crust or other material on the surface to enhance aerobic activity. For liquid or slurry manure without a surface crust, reported emissions were generally negligible (table 7). Annual emissions from livestock facilities (presumably manure on the barn floor) averaged 0.3 kg N₂O LU⁻¹ (table 7).

REPRESENTATIVE FARM EMISSIONS

An integration of all important GHG sources and sinks showed that the representative dairy farm was a net emitter. Grass and alfalfa land on the farm had net fluxes of -118 Mg CO₂e yr⁻¹ and -104 Mg CO₂e yr⁻¹, respectively (table 8). Considering the assumptions on corn silage and grain

Table 7. Reported N₂O emission ranges from manure storages and animal housing facilities.

	No. of Data	Minimum	Maximum	Average	References ^[a]
Manure storages (kg N ₂ O m ⁻³ yr ⁻¹)					
Slurry, covered ^[b]	1	0.05	0.2	0.13	b, g
Slurry, uncovered	5	0.0	0.2	0.01	e, f
Stacked	3	0.1	0.1	0.1	a, f
Animal housing (kg N ₂ O LU ⁻¹ yr ⁻¹)					
All facilities	5	0.0	0.7	0.3	a, c, d

^[a] References: a. Amon et al. (2001); b. Amon et al. (2006); c. Flessa et al. (2002); d. Jungbluth et al. (2001); e. Külling et al. (2003); f. Sneath et al. (2006); g. Sommer et al. (2000).

^[b] Cover consists of a natural crust, straw, or other material that enhances nitrification and denitrification processes on the manure surface.

Table 8. Annual net contributions of each emission source and total emissions from a representative farm reported as mass of each specific gas and as mass of CO₂ equivalents. ^[a] Negative values are sinks and positive values are emission sources.

	Carbon Dioxide CO ₂	Methane		Nitrous Oxide		Total CO ₂ e	Representative Farm	
		CH ₄	CO ₂ e ^[a]	N ₂ O	CO ₂ e ^[a]		Parameter	CO ₂ e Emission
Cropland (kg ha ⁻¹) ^[b]								
Grass	-6,396	-1.4	-35	1.7	507	-5,924	20 ha	-118 Mg
Alfalfa	-6,343	-2.6	-65	4.0	1,192	-5,216	20 ha	-104 Mg
Corn silage ^[c]	-17,745	-1.5	-38	4.1	1,222	-16,561	20 ha	-331 Mg
Corn grain ^[c]	-8,873	-1.5	-38	4.1	1,222	-7,689	30 ha	-231 Mg
Fuel combustion (kg)	44,430	---	---	---	---	---	---	44 Mg
Manure storage (kg m ⁻³) ^[d]	17	5.6	140	0.13	39	196	1100 m ³	216 Mg
Animals and housing (kg LU ⁻¹) ^[e]								
Lactating cows	3,120	106	2,650	0.3	89	5,859	111 LU	650 Mg
Dry cows	2,020	58	1,450	0.3	89	3,559	20 LU	71 Mg
Heifers	2,800	77	1,925	0.3	89	4,814	52 LU	250 Mg
Total farm emission	---	---	---	---	---	---	---	447 Mg

^[a] Assumes 1 CO₂e per unit of CO₂, 25 CO₂e per unit of CH₄, and 298 CO₂e per unit of N₂O.

^[b] 90 ha of land on a silt loam soil with 20 ha of grass, 20 ha of alfalfa and 50 ha of corn.

^[c] Corn silage and corn grain have different emission rates for CO₂, but the same rates for CH₄ and N₂O. Emissions of CO₂ from corn silage were obtained from table 1. Emissions from corn grain were assumed to be 50% of emissions from corn silage. For total CO₂e, CH₄ and N₂O contributions are counted toward both silage and grain so that these emission rates are applied to the entire corn area (i.e., 50 ha).

^[d] 2,500-m³ slurry manure storage emptied twice during each year. Emission values are the average of the reported slurry storage data.

^[e] 100 Holstein cows plus 80 replacement heifers (183 LU with 500 kg body mass per Livestock Unit).

production, the net flux from all corn land was $-562 \text{ Mg CO}_2\text{e yr}^{-1}$. The total cropland had a net flux of $-784 \text{ Mg CO}_2\text{e yr}^{-1}$. With an average amount of manure stored throughout the year of $1,100 \text{ m}^3$, the manure storage emitted $216 \text{ Mg CO}_2\text{e yr}^{-1}$. Animals and their housing facilities emitted $971 \text{ Mg CO}_2\text{e yr}^{-1}$, and the emission from fuel use in crop production, feeding and manure handling totaled to $44 \text{ Mg CO}_2\text{e yr}^{-1}$. The total net annual emission from the farm was $447 \text{ Mg CO}_2\text{e yr}^{-1}$.

As discussed previously, the crop data in table 1 do not reflect the influence of a long-term history of manure application. To account for the recycling of manure on the farm, a worst case scenario was determined where all manure carbon was decomposed in the soil and respired as CO_2 . Including straw bedding material, the herd produces about 400 Mg of manure dry matter each year (*ASABE Standards*, 2008). Assuming this dry matter is 42% carbon (Griffin et al., 2005), there are 168 Mg C applied to cropland annually. If all of this carbon is subsequently respired from the soil as CO_2 , there is an additional emission of $616 \text{ Mg CO}_2\text{e yr}^{-1}$ from the farm giving a total net emission of $1063 \text{ Mg CO}_2\text{e yr}^{-1}$. Depending upon the cropping, tillage, and manure application history of the cropland, a portion of the carbon can be sequestered in the soil of this farm. Therefore, the overall net emission from the farm can fall between the extremes of 447 to $1,063 \text{ Mg CO}_2\text{e yr}^{-1}$, or 2.5 to $5.8 \text{ Mg CO}_2\text{e LU}^{-1} \text{ yr}^{-1}$. Given a milk production of $9,000 \text{ kg cow}^{-1} \text{ yr}^{-1}$, the net GHG emission for producing milk on this farm is 0.50 to $1.2 \text{ kg CO}_2\text{e kg}^{-1}$ of milk.

The long-term carbon balance on most dairy farms should be near neutral, i.e. there should be little change in soil carbon levels. Therefore, the upper end of the range in our results should best represent net farm GHG emissions. The values of $5.8 \text{ Mg CO}_2\text{e LU}^{-1} \text{ yr}^{-1}$ and $1.2 \text{ kg CO}_2\text{e kg}^{-1}$ of milk compare well to other estimates of net GHG emissions from dairy farms. In a simulation study of conventional and organic dairy farms, Olesen et al. (2006) found net emissions of 4.3 to $6.0 \text{ Mg CO}_2\text{e LU}^{-1} \text{ yr}^{-1}$ from conventional dairy farms across various regions of Europe. With lower milk production compared to U.S. dairy farms, this equated to 1.2 to $1.7 \text{ kg CO}_2\text{e kg}^{-1}$ of milk. In an analysis of a dairy farm in the United States, Phetteplace et al. (2001) found a net GHG emission of $5.4 \text{ Mg CO}_2\text{e head}^{-1} \text{ yr}^{-1}$ or $1.1 \text{ kg CO}_2\text{e kg}^{-1}$ of milk.

This representative farm analysis indicates that, despite the potential for farmland to serve as a sink of carbon, dairy farms are an overall source of GHG emissions when total net emissions are quantified. Thus, the carbon sink present in the system due to carbon assimilation is more than offset by other emission sources, resulting in a net flux into the atmosphere. As a comparison, this annual net emission for one LU is similar to the annual CO_2 emission from operating a small automobile (fuel efficiency of $8.0 \text{ L}/100 \text{ km}$) between $12,000$ and $26,000 \text{ km}$ per year (USDOE, 2008).

The net GHG emission from the dairy farm consists primarily of CH_4 and N_2O . The net flux of CO_2 across the farm boundary is near neutral, but this net flux is dependent upon the amount of carbon sequestered in soil and the amount of feed purchased or sold from the farm. When most of the feed required is produced on the dairy farm and little extra is sold, the CO_2 assimilated in growing plants is similar to that released through animal and microbial respiration and fuel use. Considering the greater GWP of CH_4 , 40% to 60% of the net GHG emission comes from CH_4 emission. Although N_2O

emissions are relatively small, they contribute another 30% to 40% of the net GHG emission because of their very high GWP.

This analysis only considers the emissions from within the farm boundaries. For a broader evaluation of the milk production system, GHGs emitted or assimilated in producing materials brought onto the farm can be considered. An important consideration is the carbon assimilated in purchased feed. For our representative farm, the majority of the required feed is produced on the farm. However, an additional 30% of the total feed is purchased in the form of energy and protein supplements. For this farm, that is an additional 250 Mg DM of feed. With an average carbon content of 45% (Loomis and Connor, 1992), this represents an additional 413 Mg of CO_2 assimilated from the atmosphere in the growth of the crops that produced the feed (primarily corn grain and soybeans). Since this carbon is being recycled back to the atmosphere by the livestock consuming the feed, this value can be subtracted from the estimated net farm emission to get an emission from the broader production system. This reduces the range in net annual emission to 34 to $650 \text{ Mg CO}_2\text{e}$ (0.2 to $3.6 \text{ Mg CO}_2\text{e LU}^{-1} \text{ yr}^{-1}$ or 0.04 to $0.72 \text{ kg CO}_2\text{e kg}^{-1}$ of milk).

Emission of GHG during the manufacture of inorganic fertilizers and pesticides could be added to this range. Previous life cycle analyses of cropping systems that rely upon chemical fertilizers have shown these emissions to be relatively small compared to that of the overall production system (Adler et al., 2007). On a dairy farm where most of the crop nutrient requirements are met through cattle manure, this emission source should be relatively unimportant.

As the stocking rate (animals per unit of land) on a given farm is increased, the net GHG emission from within the farm boundaries increases. This occurs primarily because more feed is purchased and brought onto the farm to feed the livestock. A substantial portion of this feed carbon is transformed to CO_2 and CH_4 by the animals. In the broader view of GHG emissions from dairy production, which considers carbon flows beyond the farm boundaries, emissions are less dependent upon farm size and the stocking rate of animals on the farm.

Because of the many sources and sinks, it is impossible to measure or otherwise determine an actual net GHG emission from a dairy farm. Any estimate will have some error or uncertainty. Because the available emission data is limited, a statistical measure of this uncertainty cannot be determined. Through expert opinion, the IPCC (2006a) has estimated uncertainties in their emission factors associated with agricultural production. When emission factors are developed and applied to specific situations less uncertainty can be expected. Based upon our experience with the data and uncertainties reported by the IPCC (2006b), we estimate the uncertainties in our factors for combustion, animal, manure management, and soil N_2O emissions to be $\pm 10\%$, 15% , 20% , and 50% , respectively. These individual uncertainties can be combined (IPCC, 2006a) to give an overall uncertainty in the net farm emission of $\pm 18\%$. This gives the uncertainty of our values in representing an average farm in our region. The uncertainty of our values in representing a farm in the region would be much lower, i.e. with the many farms in our region, the probability of representing at least one of those farms is relatively high.

CARBON SEQUESTRATION AND EMISSION REDUCTION STRATEGIES

Because of the increasing concentration of GHGs in the atmosphere, factors influencing GHG emissions and methods of mitigating or reducing those emissions are being investigated. Previous efforts to reduce GHG emissions have focused on reducing industrial emissions with little attention to that from farms. However, due to new interest and recent legislation, farms may be subject to mandates in the future that require reductions at potentially high costs. Therefore, reduction strategies should be identified to reduce farm-level contributions, particularly as agricultural production intensifies.

One proposed method is carbon sequestration, or the removal of CO₂ from the atmosphere to a sink. Natural carbon sinks include forests, oceans, and soil. Research has shown that implementing different tillage operations and crop management strategies can affect the carbon sequestered in farmland. In other words, with proper management more carbon can be assimilated into crop systems as plant biomass and soil organic matter than is emitted through respiration as CO₂. Various strategies have been shown to increase carbon storage in croplands. These strategies include using reduced tillage operations, incorporating legumes and perennial forages into crop rotations, and eliminating fallow periods (Azam et al., 1985; Ladd and Amato, 1986; Bruce et al., 1999; Robertson et al., 2000; Post et al., 2004). However, soils have a maximum potential to sequester carbon, and the soil is typically saturated after approximately 50 years of using a given production strategy (Sauerbeck, 2001). As a result, sequestration is unlikely to be a long-term solution, and scientists must investigate other reduction strategies.

Gaseous emissions are affected by a number of management factors that may be used in reduction strategies. Some of these factors are timing of manure application, application method, moisture content of stored manure, fertilizer application rate, use of growth hormones or dietary strategies that affect milk production, frequency of emptying a manure storage, and the use of anaerobic digesters. As an example, allowing a natural crust to form on a manure storage increases N₂O emissions (table 7), so a potential reduction strategy is to prevent the forming of a crust. However, this change does not affect all gas emissions in the same manner: a crust actually reduces emissions of ammonia (NH₃), an important, non-GHG environmental pollutant from dairy production (Rotz, 2004). Additionally, reducing the total solids content of manure decreases CH₄ emissions from storage but increases N₂O emissions. As these examples show, the effect of these factors on one gas is often negated by the effect on another gas. In other words, a reduction strategy may reduce emissions of one gas while increasing emissions of another.

Another important consideration is farm profitability. Farms must remain profitable, so reduction strategies must not increase production costs substantially or the producer must be financially compensated to encourage the use of a reduction strategy. Therefore, consideration of reduction strategies must focus on reducing overall GHG emissions while considering other potential pollutants and the economic impact on the farm. The factors described above interact with each other as well as with the climate,

hydrology, soil, and other farm components, making it difficult to predict ultimate impact. As a result, all individual factors and their interactions must be analyzed to identify cost-effective management practices that minimize emissions from farms. Arguably, no field study could feasibly record all of these factors while measuring GHG emissions. Instead, a robust method for analyzing the impact of these factors is to use computer simulation to evaluate proposed reduction strategies in the context of a whole-farm system.

Current methods of predicting GHG emissions from farms often use empirical emission factors that do not adequately account for effects of management and the interactions with other components of the farm. To expand this type of whole farm analysis, a computer model is needed that is based on mechanistic relationships or empirical equations that represent farm processes and the interacting effects of GHG reduction strategies. By integrating this type of module into a whole farm model that simulates other forms of pollution (e.g., NH₃ emissions, nitrate leaching, and phosphorus runoff) as well as the economics of a farm, reduction strategies can be analyzed in the context of overall environmental impacts along with effects on farm profitability.

The USDA Agricultural Research Service (ARS) has developed the Integrated Farm System Model (IFSM; Rotz et al., 2007). As a process-based, whole-farm model, IFSM simulates farm production systems, including the major components of soil, crops, grazing, tillage and planting, crop harvest, feed storage, feeding, herd production, manure handling, and economics. IFSM is used to examine the effects of various management practices on farm nutrient dynamics and economics. To extend the data presented in this article, GHG emission modules have been developed and integrated into IFSM to provide a tool for analyzing the impacts of GHG reduction strategies on farm performance, the environment, and profitability (Chianese et al., 2009a; 2009b; 2009c).

CONCLUSIONS

An extensive review revealed that more data are needed to better quantify GHG emissions from U.S. dairy farms. Specifically, data are needed on CO₂ emissions from manure storage, CH₄ uptake from croplands, and N₂O emissions from manure storages and housing facilities. Experimental studies that quantify GHG emissions from agriculture are needed to better establish typical emission ranges for U.S. farms and the effect of management factors on these emissions.

Although agricultural lands can serve as a carbon sink, the emissions of CH₄ and N₂O from animal-producing farms normally result in a net GHG emission. The actual rate of carbon assimilation and net GHG emission are highly dependent on the management strategies implemented on a farm. A simple but comprehensive evaluation of a representative dairy farm in Pennsylvania estimated a net annual emission in the range of 2.5 to 5.8 Mg CO₂e LU⁻¹ considering all major sources and sinks of CO₂, CH₄, and N₂O. Including the assimilated GHG in purchased feed gave a net emission for milk production of 0.04 to 0.72 kg CO₂e kg⁻¹ of milk.

No experimental study could economically record all of the important factors and measure the relevant sources of pollution in order to determine the overall environmental impact of farm production systems. This emphasizes the need for a whole-farm computer simulation tool for evaluating mitigation strategies in farm production systems.

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