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Article *in* Transactions of the ASABE (American Society of Agricultural and Biological Engineers) · July 2009

DOI: 10.13031/2013.27780 · Source: OAI

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SIMULATION OF CARBON DIOXIDE EMISSIONS FROM DAIRY FARMS TO ASSESS GREENHOUSE GAS REDUCTION STRATEGIES

D. S. Chianese, C. A. Rotz, T. L. Richard

ABSTRACT. *Farming practices can have a large impact on the soil carbon cycle and the resulting net emission of greenhouse gases including carbon dioxide (CO_2), methane, and nitrous oxide. Primary sources of CO_2 emission on dairy farms are soil, plant, and animal respiration, with smaller contributions from microbial respiration in manure. Strategies designed to reduce emissions from one source can cause an increase in emissions from another source. Therefore, a comprehensive whole-farm evaluation is needed, which can be cost-effectively met through computer simulation. The Integrated Farm System Model (IFSM), a process-based whole-farm model, was extended to simulate the carbon cycle. Relationships were added to represent photosynthetic fixation, soil and plant respiration, animal respiration, and emissions from manure storage and barn floors. The new module was verified to predict the mass of carbon present in soil pools at the end of annual simulations and to predict CO_2 emissions within expected emission ranges for both specific sources and overall farm emissions. A farm-level carbon balance was used to further verify that predicted emissions were reasonable across a variety of production strategies. Farm simulations illustrated that changes in cropping practices affected emissions from all farm sources, with a primary effect on the assimilation of CO_2 in feed production. For a representative farm in central Pennsylvania, use of more alfalfa in place of corn production caused a 6% increase in net farm greenhouse gas emission in CO_2-equivalent units, while replacing non-permanent grassland with corn production reduced the net emission by 16%. Changing from a Holstein herd to Jersey animals with animal numbers increased to produce the same amount of milk affected most emission sources, with a net impact of increasing the net greenhouse gas emission by 20%. Incorporation of greenhouse gas emission modules in IFSM provides a more comprehensive tool for evaluating the overall farm-level environmental and economic impacts of management scenarios used to reduce emissions.*

Keywords. *Carbon dioxide, Dairy farm, Greenhouse gas, Model, Simulation.*

The Intergovernmental Panel on Climate Change (IPCC, 2007) has reported that it is "extremely likely" (representing a 95% confidence level or higher) that anthropogenic emissions of greenhouse gases (GHGs) are causing a change in the global climate. In 2005, U.S. CO_2 emissions were reported as 6,009 million metric tons, accounting for 84% of total U.S. anthropogenic GHG emissions (EIA, 2006). The majority of these emissions were due to the combustion of fossil fuel, with contribution estimates ranging from 75% (IPCC, 2001) to 98% (EIA, 2006). The second largest contributor was land use change, with small additional contributions due to emissions from oil and gas production, industrial processes, and waste combustion (IPCC, 2001; EIA, 2006).

Although agriculture is not considered an important global source of CO_2, it is recognized as a major source of the other important GHGs: methane (CH_4; Chianese et al., 2009a) and nitrous oxide (N_2O; Chianese et al., 2009b). Carbon dioxide is sometimes ignored in assessing GHG emissions from farms (IPCC, 2001, 2007). The CO_2 emitted is part of the carbon (C) cycle that begins with photosynthetic fixation by plants. For example, when animals consume feed from crops (fixed C in the plant material), they convert it back to CO_2 through respiration (Kirchgessner et al., 1991; IPCC, 2001). In the overall farm balance, the CO_2 released largely offsets the CO_2 assimilated in the plant material. However, some of the feed intake of C is converted and released from various sources as CH_4, and some is assimilated in the animal products produced. To obtain a full accounting and balance of all C flows through the farm, all sources of C emission must be considered. By including CO_2 emissions, a farm balance of C can be established to ensure a more accurate assessment of all C flows and losses.

On dairy farms, CO_2 emissions result from respiration (animal, plant, and soil) and decomposition of soil organic matter (SOM) and manure (IPCC, 2001; Schlesinger, 2000a, 2000b). A review of agricultural emission data shows that about 90% of on-farm CO_2 emission is due to animal respiration, followed by lower emissions from manure

Submitted for review in July 2008 as manuscript number SE 7614; approved for publication by the Structures & Environment Division of ASABE in July 2009.

The authors are **Dawn Sedorovich Chianese, ASABE Member Engineer,** Associate, ENVIRON International Corporation, Los Angeles, California; **C. Alan Rotz, ASABE Fellow,** Agricultural Engineer, USDA-ARS Pasture Systems and Watershed Management Research Unit, University Park, Pennsylvania; and **Tom L. Richard, ASABE Member Engineer,** Associate Professor, Department of Agricultural and Biological Engineering, The Pennsylvania State University, University Park, Pennsylvania. **Corresponding author:** C. Alan Rotz, USDA-ARS, Building 3702, Curtin Road, University Park, PA 16802; phone: 814-865-2049; fax: 814-863-0935; e-mail: al.rotz@ars.usda.gov.

sources and the combustion of fuels. These emission sources are offset by that assimilated in crop growth, with about 50% more CO_2 assimilated than is emitted from the farm (Chianese et al., 2009c).

As steps are taken to evaluate and reduce GHG emissions in agriculture, tools are needed to quantify the net emission from whole-farm systems. This is particularly relevant for integrated crop and livestock operations such as found on most dairy farms. Considering the many interacting processes throughout the farm affecting emissions, a comprehensive farm-specific evaluation is needed. Computer simulation provides a cost-effective and efficient method of integrating all important emission sources and sinks on a farm and analyzing how management affects the net flow of these emissions. The Integrated Farm System Model (IFSM; USDA Agricultural Research Service, University Park, Pa.) is a process-level whole-farm simulation model that includes major components for soil processes, crop growth, field operations, feed storage, feeding, herd production, manure handling, and economics (Rotz et al., 2009). IFSM predicts the effect of management options on farm profitability and environmental pollutants such as nitrate leaching, ammonia volatilization, and phosphorus (P) runoff.

Our goal was to incorporate a module in IFSM that simulated the C cycle, including CO_2 exchanges with the environment, along with other important aspects of dairy farm performance and economics. Specific objectives were to review published models that simulate C cycling and CO_2 emissions, identify models that best fit our modeling goals, adapt those models for use in IFSM, verify that the models gave reasonable predictions, and illustrate the use of this tool in predicting whole-farm emissions. The CO_2 module was developed along with modules simulating CH_4 (Chianese et al., 2009a) and N_2O (Chianese et al., 2009b) emissions to predict the net farm GHG emission.

Model Development

The Integrated Farm System Model is a simulation model that integrates the major biological and physical processes of a crop, beef, or dairy farm (Rotz et al., 2009). Crop production, feed use, and the return of manure nutrients back to the land are simulated over each of 25 years of weather. Growth and development of alfalfa, grass, corn, soybean, and small grain crops are predicted based upon daily soil and weather conditions. Tillage, planting, harvest, storage, feeding, and manure handling operations are simulated to predict resource use, timeliness of operations, crop losses, and nutritive changes in feeds. Feed allocation and animal response are related to the nutritive value of available feeds and the nutrient requirements of the animal groups making up the herd. The quantity and nutrient content of the manure produced is a function of the quantity and nutrient content of the feed consumed. Nutrient flows through the farm are modeled to predict nutrient accumulation in the soil and loss to the environment. Environmental impacts include nitrogen (N) volatilization from manure sources, soil denitrification and leaching losses, erosion of sediment, and the sediment-bound and soluble P losses in runoff. Whole-farm mass balances of N, P, and potassium are determined as the sum of all nutrient imports in feed, fertilizer, deposition, and legume fixation minus the exports in milk, excess feed, animals, manure, and losses leaving the farm. Simulated performance for each year is then used to determine production costs, incomes, and economic return for the farm production system.

To expand IFSM to simulate GHG emissions and a complete C balance for the farm, component models were needed to represent each of the major processes assimilating or emitting CO_2. These included crop production, animal respiration, and microbial respiration during the handling of manure. For the major farm sinks and sources of crop growth and animal respiration, process models have been published. For the other sources, simple relationships or emission factors had to be established. Criteria used to evaluate potential model components were:

1. The model had to be capable of simulating important processes that affect CO_2 emissions with changes in farm management. Strategies to reduce CO_2 emissions from dairy farms include reducing tillage, managing crop residue, and using different manure storage techniques. In order to analyze how these practices affect CO_2 emissions, the model must account for the factors affected by these changes (e.g., tillage operations, cropping system, and manure storage type).

2. The model had to provide a process-level representation of emission components. Our goal was to select physically and biologically based relationships that satisfied criterion 1 for the major sources and sinks as compared to models based on emission factors. While emission factors are useful as simple tools for estimating gaseous emissions from farms, they do not have the capability of representing the processes that affect CO2 emissions and the effect of management on these processes.

3. The model had to satisfactorily predict observed data over a full range of potential conditions. A primary goal of models is to represent observed data. The chosen relationships had to predict CO_2 emissions within the range of observed emissions from farm components over the full range of possible farm characteristics.

4. The model had to be consistent with the current scale of other components in IFSM. The intent of IFSM is to simulate realistic management scenarios that can be implemented on farms. The characteristics of these scenarios are at the field or farm level (e.g., animal diets, sequence of machinery operations, manure storage duration). Subsequently, IFSM simulates farm processes, normally on a daily time step, according to the assumed farm characteristics. As a result, selected relationships, as well as associated inputs and parameters, had to function well at the field or farm level as opposed to different scales (e.g., microbiological or watershed).

5. Model inputs and parameters were limited to readily available data. Some of the more mechanistic models accurately predict emissions; however, these models typically require many inputs and parameters. The required values are often the result of calibration against observed data, are difficult to obtain, or have little physical or biological basis. The uncertainty added by assuming these parameter values can outweigh the benefit of using a highly mechanistic model. In contrast, the majority of parameters and inputs in IFSM are not calibration parameters, are relatively easily obtained through on-farm observation, and correspond to characteristics of the farm. Thus, our final

criterion was that input and parameter values were easily obtained within, or consistent with, the current structure of IFSM.

For the relatively minor emission sources of manure on the barn floor and in storage, published models were not available. In these cases, simpler models or emission factors were developed and used. This simpler approach was justified given their lesser importance in contributing to whole-farm emissions.

CROPLAND EMISSIONS

Over the course of a full year, croplands normally assimilate C from CO_2 in the atmosphere, i.e., the plants capture more CO_2 through photosynthesis than the croplands emit through respiration. The previous version of IFSM simulated the growth of plants (i.e., the capture of CO_2 through photosynthesis), although the model did not explicitly predict photosynthetic fixation. As a result, a component was needed to simulate the total C fixed through photosynthesis and the emission of CO_2 through plant (autotrophic) and soil (heterotrophic) respiration.

Models simulating the C cycle in crop production were reviewed to select the most appropriate relationships for incorporation. Models have been developed with varying levels of detail. Some of the more frequently used models include TEM, BIOME, and CENTURY. Goldewijk and Leemans (1995) provided an overview of these terrestrial C models in which they classified each model along two continuums: empirical vs. process-based and static vs. dynamic. The majority of models were classified in the middle of the range of each, although a few were classified on the edges of either extreme. Of the available models, the relationships used in the CENTURY model were most appropriate for integration with the structure and level of detail required for use in IFSM.

CENTURY was developed primarily to simulate the long-term effects of climate on SOM (CENTURY, 2007). Parton et al. (1987, 1994) described the sub-models in CENTURY for SOM and decomposition, plant production, and N cycling. The model, which operated on a monthly time step, simulated active, slow, and passive soil C, as well as structural and metabolic C derived from plant residues. Further development of CENTURY produced a daily time step version called DAYCENT. The shorter time step allowed the simulation of other environmental processes (e.g., trace gas fluxes) in addition to SOM dynamics (Del Grosso et al., 2001). Modifications in DAYCENT included a new soil respiration model (Del Grosso et al., 2005b) and sub-models for CH_4 (Del Grosso et al., 2000c) and N_2O emissions (Parton et al., 1996; Del Grosso et al., 2000b; Parton et al., 2001). DAYCENT and CENTURY have been used for a variety of applications including analyzing trace gas fluxes from bioenergy crops (Adler et al., 2007), estimating N_2O emissions from croplands in the U.S. at the county level (Del Grosso et al., 2006), and investigating the interaction of C sequestration and N_2O flux from agricultural systems (Del Grosso et al., 2000a). CENTURY has been one of the most frequently used models to simulate the C cycle in agro-ecosystems. The daily time-step version, DAYCENT, satisfied all five of our criteria.

Photosynthetic fixation by plants is the main input of C for a farm system. Using the existing crop growth modules of IFSM, fixed C is determined as a function of the aboveground accumulation of crop dry matter and crop respiration:

$$C_{ag} = 0.4 \cdot Y_{ag} + C_{resp,ag} \quad (1)$$

where C_{ag} is the total aboveground photosynthetic fixation (kg C ha^{-1} day^{-1}), Y_{ag} is the daily aboveground accumulation of crop dry matter (kg DM ha^{-1} day^{-1}), and $C_{resp,ag}$ is the daily aboveground loss of C through plant respiration (kg C ha^{-1} day^{-1}). The aboveground dry matter is assumed to have a C content of 0.4 g C g^{-1} DM.

From DAYCENT (2007), the aboveground respiration rate is a function of the aboveground fixed C:

$$C_{resp,ag} = C_{ag} \cdot (R_{ag}) \quad (2)$$

where R_{ag} is the fraction of aboveground production respired (kg C kg^{-1} C). For use in IFSM, crop-specific values for R_{ag} were assigned or modeled. The value used for corn, small grains, and soybeans was 0.007 kg C kg^{-1} C, and for alfalfa the value was 0.013 kg C kg^{-1} C. For grass crops, an existing function in the grass crop module of IFSM was used to predict the C loss through plant respiration (Rotz et al., 2009).

Microbial decomposition of organic matter is the driving force behind soil (heterotrophic) respiration. The soil C module was adapted from DAYCENT to simulate three surface C pools (surface structural, metabolic, and microbial C), three soil C pools (soil structural, metabolic, and microbial C) in each of four soil layers making up the soil profile, and two soil pools for C with a long turnover rate (soil slow and passive C) (fig. 1). For each pool, a total flow of C out of the pool was calculated. A portion of the C was respired as CO_2, while the remaining C was cycled into a different pool. From DAYCENT, the total flow of C out of a given pool was calculated as:

$$C_{flow} = \min(C_{pool,current}, C_{max\ flow}) \cdot F_{decomp} \cdot k_{decomp} \cdot F_{pH} \cdot F_{lignin} \cdot F_{cult} \cdot F_{texture} \cdot F_{anaerob} \quad (3)$$

where C_{flow} is the total flow of C from a given pool (g C m^{-2} day^{-1}), $C_{pool,current}$ is the current mass of C in the pool (g C m^{-2}), $C_{max,flow}$ is the maximum mass of C that can leave the pool (g C m^{-2}), F_{decomp} is a decomposition factor based on soil moisture and ambient temperature that is specific to aboveground (surface) or belowground (soil) C pools (dimensionless), k_{decomp} is an intrinsic decomposition rate specific to each pool (day^{-1}), F_{pH} is a factor accounting for the effect of pH on decomposition (dimensionless), F_{lignin} is the effect of the lignin content on decomposition (dimensionless), F_{cult} is the effect of cultivation (dimensionless), $F_{texture}$ is the effect of soil texture (dimensionless), and $F_{anaerob}$ accounts for the presence of anaerobic conditions (dimensionless).

The first five terms were calculated for C flows leaving each pool. The lignin factor equaled one for all pools other than the surface and soil structural pools. From DAYCENT, the effect of lignin content in the structural pools was determined as:

$$F_{lignin} = \exp(-R_{lig/str} \cdot C_{strlig}) \quad (4)$$

where $R_{lig/str}$ is a parameter accounting for the effect of the ratio of lignin to structural C on decomposition (dimensionless), and C_{strlig} is the ratio of lignin to structural C in the structural pool (g lignin C g^{-1} structural C).

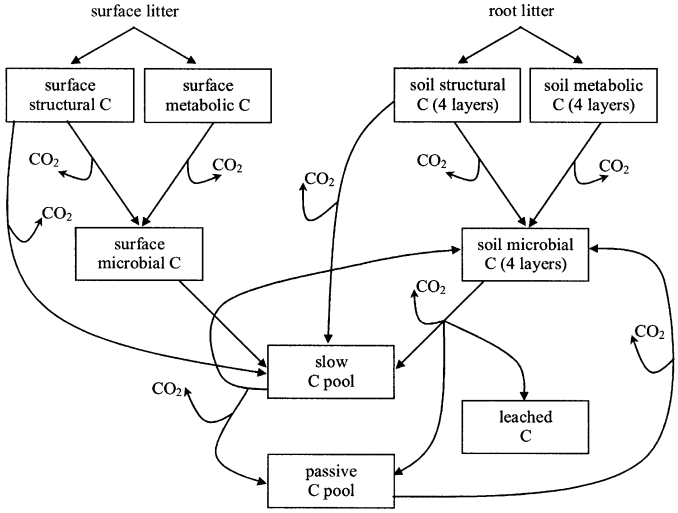

Figure 1. Carbon flow diagram for the C module incorporated into IFSM (modified from Parton et al., 1994).

For the surface C pools (surface structural, metabolic, and microbial), the cultivation factor, F_{cult}, equaled one. For the remaining pools, F_{cult} equaled one on every day of the year that did not have a farm operation occurring. On days with a farm operation (e.g., tillage or harvest), cultivation factors were assigned based on the type of operation and type of machine (e.g., chisel or moldboard plow). The texture factor, $F_{texture}$, affected the decomposition from the soil microbial pool only, and was a function of the silt, sand, and clay contents. Finally, the anaerobic factor, F_{anerob}, only affected the decomposition of soil pools and was calculated based on the soil moisture content.

Respiration of CO_2 was predicted assuming that a fraction of total C flow out of the pool was respired as CO_2-C (DAYCENT, 2007):

$$C_{respired} = C_{flow} \cdot k_{resp} \tag{5}$$

where $C_{respired}$ is the daily respired C (g C m^{-2} day^{-1}), and k_{resp} is the fraction of the daily total C flow that is respired (g C respired g^{-1} C flow). This fraction varied as obtained from DAYCENT input files (table 1).

In addition to respired CO_2 losses, C was also lost due to leaching and erosion. Leaching losses were predicted using relationships from DAYCENT where a given fraction of the total C flow out of the microbial C pool was leached. This fraction was a function of the soil clay content, the water leached from the soil profile, and empirical parameters obtained from DAYCENT:

$$C_{leach} = \begin{cases} 0 & W_{leach} = 0 \\ C_{flow} \cdot K_{texture} \cdot F_{leach} & W_{leach} > 0 \end{cases} \tag{6}$$

$$K_{texture} = 0.03 + 0.12 \cdot F_{clay} \tag{7}$$

$$F_{leach} = \min\left[1.0, \quad 1.0 - \frac{(1.9 - W_{leach})}{1.9}\right] \tag{8}$$

where C_{leach} is the amount of C leached from the soil microbial pool (g C m^{-2} day^{-1}), W_{leach} is the water flow from the soil layer (cm), C_{flow} is the total flow of C from the soil microbial pool (g C m^{-2} day^{-1}), $K_{texture}$ is the effect of soil texture on leaching (dimensionless), F_{leach} is the fraction of C leached (g C leached g^{-1} C flow), and F_{clay} is the soil clay content (decimal). The amount of moisture leached through the soil profile was previously modeled in the soil component of IFSM (Rotz et al., 2009).

Runoff of sediment-bound organic matter represents another pathway of C loss. From the work of Sharpley (1985), loss of C due to erosion was calculated as:

$$C_{erosion} = Y_{sed} \cdot C_{ER} \tag{9}$$

where $C_{erosion}$ is the amount of eroded C (kg C day^{-1}), Y_{sed} is the amount of daily erosion occurring from the given cropland (kg erosion day^{-1}), and C_{ER} is the C enrichment ratio (mg kg^{-1} erosion). The enrichment ratio was calculated using a relationship from Sharpley (1985):

$$C_{ER} = \exp\left(1.63 - 0.25 \cdot Y_{sed}\right) \tag{10}$$

Daily erosion was calculated in IFSM using the modified universal soil loss equation (MUSLE) as described by Sedorovich et al. (2007).

Table 1. Daily respiration rates used in IFSM as obtained from DAYCENT version 4.5.

Source of C[a]	Daily respiration rate[b] (g C respired g^{-1} C flow)
Structural	
Surface pool (to microbial pool)	0.45
Surface pool (to slow SOM pool)	0.30
Soil pool (to microbial pool)	0.55
Soil pool (to slow SOM pool)	0.30
Metabolic	
Surface and soil pools	0.55
Microbial	
Surface pool	0.6
Soil pool	0.17 + 0.68(F_{clay})[c]
Passive pool	0.55
Slow pool	0.55

[a] Source of C represents the pool where C originates, i.e., the respiration rate for the surface pool (to microbial pool) represents the fraction of the total C leaving the surface structural pool respired as CO_2.
[b] Respiration rates were obtained from DAYCENT ver. 4.5 input files.
[c] The respiration rate for the soil microbial pool is a function of the soil clay content (F_{clay}).

Animal Respiration

On dairy farms, animal respiration of CO_2 is a major source relative to other CO_2 emissions. In the overall farm balance, the CO_2 released largely offsets the CO_2 assimilated in the feed consumed. However, some of the feed intake of C is converted and released as CH_4 (Chianese et al., 2009a) and some is contained in the milk produced. Several empirical relationships have been developed to predict CO_2 respiration. The three relationships considered for our application were from Kirchgessner et al. (1991) and Pinares-Patiño et al. (2007). The two linear relationships of Kirchgessner et al. (1991) determined CO_2 as a function of animal live mass and either milk production or feed dry matter intake (DMI), and that of Pinares-Patiño et al. (2007) was a function of only live mass.

All of these models satisfied our five criteria to some extent. Because the model of Pinares-Patiño et al. (2007) was only a function of body weight, this relationship was not able to represent management differences as effectively as those of Kirchgessner et al. (1991). The relationship of Kirchgessner et al. (1991) relating CO_2 emission to DMI was chosen because this equation had a better fit to their original data ($R^2 = 0.71$), and it best represented the natural process. Although milk production is indirectly related to feed intake, prediction directly from feed intake was preferred because this better represented the biological process and this relationship could be applied to non-lactating animals.

The model predicts CO_2 emission as:

$$E_{CO2} = -1.4 + 0.42 \cdot M_{DMI} + 0.045 \cdot M_{BW}^{0.75} \quad (11)$$

where E_{CO2} is the emission of CO_2 from animal respiration (kg CO_2 head^{-1} day^{-1}), M_{DMI} is the daily intake of feed dry matter for each animal (kg DM head^{-1} day^{-1}), and M_{BW} is the animal's body mass (kg). The DMI and body mass for each animal group were available in IFSM. In IFSM, DMI is determined based upon the nutrient requirements (fiber, energy, and protein) and target milk production of a representative animal for each group within the herd and the amount and nutrient content of available feeds including pasture (Rotz et al., 1999; Rotz et al., 2009). Body weight was determined based upon animal breed (as specified by the model user) and age and stage of lactation as simulated in IFSM (Rotz et al., 2009).

Barn Floor Emissions

Floors of housing facilities can be a source of CO_2 emissions due to decomposition of the organic matter in manure deposited by animals. Although not a major source, barn floor emissions were included to obtain a comprehensive simulation of farm-level CO_2 emissions. No published model or data were found for emissions from the free-stall and tie-stall barns commonly used on North American farms. Therefore, CO_2 emission data measured from free-stall barn floors (E. Wheeler, unpublished data, 2008, The Pennsylvania State University, University Park, Pa.) were used to develop an empirical equation relating this emission to the air temperature in the barn and the floor surface area covered by manure. The resulting model ($R^2 = 0.74$) was:

$$E_{CO2,\,floor} = \max(0.0,\, 0.0065 + 0.0192\,T)\; A_{barn} \quad (12)$$

where $E_{CO2,floor}$ is the daily rate of CO_2 emission from the barn floor (kg CO_2 day^{-1}), T is the air temperature in the barn (°C), and A_{barn} is the floor area covered by manure (m^2).

Although this relationship did not fully satisfy our criteria, equation 12 represented the best available information describing CO_2 emissions from barn floors. As a function of temperature and manure surface area, this relationship provided a simple process-level model that predicted reasonable emission rates for temperatures normally found in barns. Because barn floor emissions were found to be small compared to other sources, development of a more sophisticated model was not justified.

Manure Storage

Compared to other farm sources, slurry storages emit relatively low amounts of CO_2 (Chianese et al., 2009c). Because of this minimal contribution to whole-farm emissions, there were no models and few data available to quantify this emission source. Therefore, a constant emission factor represented the best available option. To determine an emission factor, emission rates were obtained from two published studies and the average was used as our emission factor (table 2).

The average emission rate of 0.04 kg CO_2 m^{-3} day^{-1} is applicable to uncovered slurry storages. Covers are sometimes used to reduce gaseous emissions, but no data were available documenting the effect of covers on CO_2 emissions. To model this effect, we assumed that CO_2 emissions were reduced by a similar proportion when using a cover, as found for more important gases such as ammonia. The ammonia emission model in IFSM (Rotz and Oenema, 2006) predicted about an 80% reduction in loss with the use of a cover, depending upon the storage dimensions. Therefore, to simulate CO_2 emission from a covered storage, an emission factor of 0.008 kg CO_2 m^{-3} day^{-1} was used. To represent a sealed storage where biogas is burned, the loss of CO_2 was reduced by 95%. For this management option, though, the total emission of the storage included the CO_2 created through the combustion of CH_4 (Chianese et al., 2009a).

Fuel Combustion

During the operation of tractors and other engine-powered equipment on the farm, C in fuel is transformed to CO_2 that is released in the engine exhaust. The amount of CO_2 produced is proportional to the amount of fuel consumed. The emission factor used was 2.637 kg CO_2 L^{-1} of diesel fuel consumed (Wang, 2007). In a farm simulation with IFSM, all machinery operations on the farm for feed production, feeding, and manure handling are simulated through time, providing a total annual fuel use (Rotz et al., 2009). By multiplying the annual fuel use by the emission factor, the CO_2 released from combustion was determined.

Table 2. Published and average emission rates of CO_2 emitted from uncovered slurry storages.

Reference	Emission Rate (kg CO_2 m^{-3} day^{-1})
Jungbluth et al. (2001)	0.036
Sneath et al. (2006)	0.041
Average	0.04

MODEL EVALUATION

The new components added to the farm model to simulate CO_2 emissions were evaluated in three ways. First, the most important components of soil C and animal respiration were individually evaluated to determine how well they represented measured data. Second, IFSM predictions were compared to typical emissions previously summarized for a representative dairy farm in Pennsylvania. Finally, a whole-farm C balance was determined to ensure reasonable predictions of C loss.

SOIL CARBON MODEL

Limited data were available for evaluating the soil C component as incorporated in IFSM. Experimental studies quantifying CO_2 emissions or C pools often have not provided specific input data required to simulate scenarios in our farm model. In quantifying C pools, most studies have provided long-term changes over many years. Because IFSM performs an annual simulation, these data were not useful for our evaluation. Two studies were chosen that did provide adequate information and appropriate data for comparison. The work of Del Grosso et al. (2002) provided a study to test the ability of IFSM in predicting observed C pools along with a comparison to DAYCENT predictions. A second study by Brye et al. (2002) was used to evaluate predicted soil CO_2 emissions along with changes in soil C pools.

In the previous experiments summarized by Del Grosso et al. (2002), soil organic C was measured for three cropping strategies: no-till wheat, conventional till wheat, and conventional till corn (table 3). The researchers also simulated the three strategies with DAYCENT to compare model predictions of C pools to the observed values. The two wheat systems were located at the High Plains Agricultural Research Laboratory in Sidney, Nebraska. The soil type was a Keith silt loam (39% silt, 25% clay, 36% sand) with pH of 7.0 and organic matter content of 2%. One field utilized conventional tillage and one utilized no till; no fertilizer was applied to either system. Using the crop and soil characteristics described above, C pools were simulated using Sidney, Nebraska, daily weather data from 1991 to 1998. The corn system was located in Sterling, Colorado, at a site designed to test the effects of dryland cropping. A no-tillage system was used for crop establishment. Soil texture varied but was predominantly a clay loam (36% silt, 30% clay, 34% sand). Fertilizer application rates ranged from 22 to 113 kg N ha^{-1}. With these characteristics, IFSM was used to simulate the C pools of this crop using Akron, Colorado (approx. 50 km south of Sterling) daily weather data from 1991 to 1998.

IFSM predictions were similar to the observed data and DAYCENT predictions, with average percent differences of 22% and 21%, respectively (table 3). IFSM disagreed with observed data by predicting more C in conventionally tilled wheat than in no-till corn. However, IFSM predictions followed the trend in DAYCENT predictions with the greatest soil C pool at the end of the simulation being that of the no-till wheat system, followed by conventionally tilled wheat and finally no-till corn. Differences between actual and modeled conditions, such as the minor differences in weather, may have contributed to the differences among the observed and simulated data. In general, this comparison supported that IFSM could represent crop and tillage effects on total soil C.

In another study, Brye et al. (2002) measured gas fluxes from a prairie and corn agroecosystem in Wisconsin from 1995 to 1999. Their objectives were to compare respiration and C pools between prairie and corn fields and to identify factors influencing interannual variability. Because this study quantified both soil CO_2 respiration and soil C pools, these data enabled an evaluation of IFSM's ability to simulate soil CO_2 fluxes as well as the cycling of C in the soil. For our evaluation, only the corn data were used.

The corn fields were located at the Arlington Agricultural Research Station of the University of Wisconsin-Madison. The soil was a Plano silt loam (59% silt, 25% clay, and 16% sand) with an organic matter content of 3.3%, a bulk density of 1.34 g cm^{-3}, and a slope of 2%. Four treatments were used: no tillage with no fertilizer (NT,nf), no tillage with fertilizer (NT,f), conservation tillage with no fertilizer (CT,nf), and conservation tillage with fertilizer (CT,f). Each treatment was established on individual plots measuring 111 m^2. Fertilized treatments received 180 kg N ha^{-1}, which was broadcast on the surface after planting. For tilled treatments, tillage occurred in the fall after harvest, with the seedbed prepared by disking in the spring before planting. With these characteristics, soil respiration and C pools in the fertilized treatments were simulated using 25 years of Madison, Wisconsin (approx. 35 km north of Arlington) daily weather data. Initial soil characteristics were set to reflect observed conditions.

IFSM predicted CO_2 fluxes similar to that observed by Brye et al. (2002) with higher values during the growing season and relatively low values during the winter. IFSM slightly overestimated soil CO_2 emissions measured with CT,f, and underestimated emissions from NT,f (table 4). Brye et al. (2002) observed no difference in CO_2 emissions between CT and NT. This is contrary to other studies that have concluded that reduced tillage decreases soil CO_2 emissions (Reicosky, 1997; Lal, 2004). In addition, IFSM predictions of less CO_2 respired from NT as compared to CT agree with previously published

Table 3. Observed and predicted values for total soil carbon for no-till wheat, conventionally tilled wheat, and no-till corn.

	Total Soil Carbon (kg C ha^{-1} $year^{-1}$)		
Cropping system	Observed[a]	DAYCENT[a]	IFSM[b]
No-till wheat	32,500	33,000	27,000
Conventionally tilled wheat	30,000	30,100	26,800
No-till corn	32,000	29,000	19,600

[a] Observed values and DAYCENT simulation values were obtained from Del Grosso et al. (2002).
[b] Values predicted by the soil carbon component of the Integrated Farm System Model.

Table 4. Observed and IFSM-predicted values for soil CO_2 respiration and change in soil organic matter.

	Soil CO_2 Emissions (kg CO_2 ha^{-1})		ΔSOM (kg C ha^{-1} $year^{-1}$)[a]	
Treatment	Observed[b]	IFSM	Observed[b],[c]	IFSM
CT,f	25,600	26,800	11,150	2,700
NT,f	25,600	11,100	8,250	700

[a] A positive change in SOM represents a loss of soil.
[b] Observed values were obtained from Brye et al. (2002).
[c] Brye et al. (2002) reported ΔSOM values for both fertilizer treatment and tillage treatment. The values shown here represent averages of these two values: CT,f (13,600; 8700); NT,f (7,800; 8,700).

DAYCENT simulations (Del Grosso et al., 2005a). IFSM also underestimated the loss of SOM; however, model predictions followed the trend of observed data. The observed data showed annual losses of 8 and 11 Mg C ha^{-1} averaged over approximately five years. This five-year study began after the system was converted from a corn-soybean-alfalfa rotation to continuous corn. Therefore, the data account for the change in crops grown on the field in addition to the different tillage practices used. In contrast, the cropping systems simulated in IFSM were assumed to be established. In other words, the IFSM data only accounted for differences between tillage systems, and not the conversion from a crop rotation to a single crop. Thus, the change in cropping practice likely contributed to the greater loss in measured SOM.

Animal Respiration

IFSM predictions of CO_2 emissions from animal respiration were evaluated by comparing model predictions to published emissions from a specific study. A study was selected that represented typical emissions, that included the input information required by IFSM, and that was not a source of data for the original model development.

In the selected study by Kinsman et al. (1995), CO_2 emissions were measured from 118 lactating cows over a 6-month period. Cows weighed an average of 602 kg with an average daily milk production of 28.5 kg cow^{-1} (±2.3 kg cow^{-1}). On average, animals were fed 17.5 kg DM cow^{-1} day^{-1} (±1.4 kg DM cow^{-1} day^{-1}) of mixed forage and concentrate. The diet consisted of corn silage, alfalfa silage, hay, roasted soybean, barley, and other supplements. The researchers reported CO_2 emissions ranging from 5,032 to 7,427 L CO_2 cow^{-1} day^{-1} (10 to 14.7 kg CO_2 cow^{-1} day^{-1}) with an average respiration rate of 6,137 L CO_2 cow^{-1} day^{-1} (12.2 kg CO_2 cow^{-1} day^{-1}). Using the average diet characteristics and milk production of the study, IFSM predicted an average daily emission of 12.1 kg CO_2 cow^{-1}. This simulated emission was within the range of, and close to the average, CO_2 respiration rate reported by Kinsman et al. (1995), illustrating that IFSM was capable of predicting CO_2 emissions from animal respiration. In addition, IFSM accurately predicted CH_4 emissions for this same study (Chianese et al., 2009a).

Representative Farm

As an additional evaluation, simulated annual whole-farm emissions were compared to those previously summarized from prior literature for a hypothetical dairy farm in central Pennsylvania (Chianese et al., 2009c). Only a brief description of the farm is provided to document those assumptions most relevant to CO_2 production and emission. This representative farm included 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). Animals were housed in free-stall barns where they were fed total mixed rations consisting of corn, alfalfa and grass silages, high-moisture corn, and purchased supplemental feeds as required to meet animal nutrient needs. Manure was scraped daily, stored in a tank for up to six months, and applied to cropland in the spring and fall. Over the full year, the herd produced 4,400 Mg of manure. The 90 ha farm area consisted of 20 ha of grass, 20 ha of alfalfa, and 50 ha of corn. Most of the crop nutrient requirements were met through manure nutrients generated on the farm, but N fertilizer was applied at rates of 50 and 70 kg N ha^{-1} on corn and grassland, respectively.

Using the above farm characteristics, IFSM predicted annual emissions of 580 Mg CO_2 from animal respiration, 58 Mg from the barn floor, and 16 Mg CO_2 from the manure storage. IFSM predicted that crop production assimilated C or, in other words, emitted -548 Mg CO_2. Including the 45 Mg of CO_2 emitted through fuel combustion, net emission from this representative dairy farm was 151 Mg CO_2 $year^{-1}$ (table 5).

IFSM predictions generally agreed with previously summarized dairy farm emissions for animal respiration and manure storage (table 5). For overall farm emissions, IFSM's predicted rate of 151 Mg CO_2 $year^{-1}$ was less than the rate of

Table 5. Simulated CO_2 assimilation and emission for a representative dairy farm in Pennsylvania compared to average values summarized from published information by Chianese et al. (2009c).

		Representative Farm[a]			IFSM Simulation Emission (Mg)
		Emission Factor	Farm Parameter	Emission (Mg)	
Animals and housing	Lactating cows	3,120 kg CO_2 LU^{-1}	111 LU[b]	346	379
	Non-lactating cows	2,020 kg CO_2 LU^{-1}	20 LU	40	56
	Heifers	2,800 kg CO_2 LU^{-1}	52 LU	146	145
	Barn floor	--	--	--	58
Manure storage		17 kg CO_2 m^{-3}	1,100 m^3	19	16
Croplands	Grass	-6,396 kg CO_2 ha^{-1}	20 ha	-128	--
	Alfalfa	-6,343 kg CO_2 ha^{-1}	20 ha	-127	--
	Corn silage[c]	-17,745 kg CO_2 ha^{-1}	20 ha	-355	--
	Corn grain[c]	-8,873 kg CO_2 ha^{-1}	30 ha	-266	--
	Field-applied manure[d]	140 kg CO_2 m^{-3}	4,400 m^3	616	--
	Total cropland			-260	-548
Fuel combustion				44	45
Net farm				291	151

[a] The representative farm parameters and emission factors were obtained from Chianese et al. (2009c).

[b] LU is a livestock unit of 500 kg body mass.

[c] The CO_2 emission data for corn do not provide separate emission rates from corn silage and corn grain. To accurately reflect conditions on the representative farm, we assumed that 20 ha of the corn area were devoted to silage (13 t DM ha^{-1}) and 30 ha were devoted to grain (6 t DM ha^{-1}).

[d] The CO_2 data for crop emissions do not account for field-applied manure. To account for this, we assumed that 4400 m^3 of manure was produced on the farm in a year. With 9% DM content and 40% carbon content, 616 Mg CO_2e would respire from field-applied manure to maintain a soil carbon balance.

291 Mg CO_2 $year^{-1}$ previously estimated as a typical emission for a dairy farm of this size (Chianese et al., 2009c). The primary difference was that the model predicted about twice the assimilated CO_2 in feed crops compared to that previously estimated from the literature. Many factors influence net emissions from cropland including crop yield, type of harvest (e.g., corn silage vs. corn grain), amount of residue returned to the soil, and the initial amount of soil C. Assumptions made for the simulation of this specific representative farm would not necessarily match the wide range of management practices represented in the previously estimated typical emissions (Chianese et al., 2009c). Despite these caveats, the IFSM-predicted whole-farm emissions matched the previous estimates relatively well.

Whole-Farm Carbon Balance

As a final evaluation of predicted emissions, a farm-level balance of C was determined within the model. The balance included a summation of all C flows into the farm minus all flows leaving the farm. Maintaining a balance at, or near, zero supported that values predicted for individual flows were reasonable. If a substantial error occurred in the prediction of one emission source, then a compensating error had to occur in one or more other sources to maintain the C balance.

Carbon flows into the farm included the net C assimilated in plant growth and that contained in feeds, manure, and other organic materials imported to the farm. The net assimilated in crop growth was predicted by equation 1. For imported manure and feeds, the C brought into the farm was 40% of the imported dry matter of each. Carbon may also be exported in feed, milk, animals, and manure leaving the farm. Carbon contents used for exported feed and animals were 40% and 22.8%, respectively. For milk, the C content was set at 12 times the N content of the milk produced. The C contained in manure produced on the farm was determined through a C balance of the animal groups making up the herd, i.e., the C excreted was that consumed minus that in the milk produced minus that emitted through enteric fermentation (Chianese et al., 2009a) and respiration (eq. 11).

Losses of C from the farm were primarily in the form of CO_2. Emission sources included soil respiration, manure respiration on the barn floor and during storage, and animal respiration. Losses from plant respiration, soil respiration, animal respiration, and the barn floor were predicted by equations 2, 5, 11, and 12, respectively, and that from the manure storage was predicted using the emission factor reported above. To convert CO_2 to units of C, CO_2 emissions were multiplied by the ratio of the molecular weight of C to that of CO_2, or 0.273. Another minor pathway of C loss was that in surface runoff, as predicted by equation 9.

Carbon was also lost through CH_4 emissions, with sources being enteric fermentation and manure on the barn floor, during storage, and following field application. Methane emissions from each of these sources were determined as documented by Chianese et al. (2009a). To convert to units of C, CH_4 emissions were multiplied by the ratio of the molecular weight of C to that of CH_4, or 0.75.

A farm-level C balance was determined for each simulated year by summing all of the C inputs just listed and subtracting that leaving the farm in products and emissions. As an example, the balance of C inputs and outputs for the representative dairy farm in Pennsylvania is given in table 6.

Table 6. Whole-farm carbon balance for a 100-cow representative dairy farm in Pennsylvania.

Carbon inputs (Mg)	Imported in purchased feed	115
	Net fixed in crop growth	417
	Total	533
Carbon outputs (Mg)	Soil respiration emission	250
	Manure CO_2 and CH_4 emissions	26
	Animal CO_2 and CH_4 emissions	168
	Runoff from cropland	1
	Exported in sold feed	5
	Exported in milk and animals	65
	Total	515

That lost through gaseous emissions and surface runoff plus that exported in sold feed, milk, and animals was 18 Mg C less than that assimilated in crop growth plus that in purchased supplemental feed. This small difference was only 3% of the total exchange in C over the farm. Predicted balances (input minus output) for individual years varied from -28 to 68 Mg C. With this negligible difference from long-term C balance, the individual emission predictions were supported as reasonable. Requiring a C balance removed the option of predicting the long-term sequestration or loss of soil C in this version of the model.

Model Application

Whole-farm simulations were done to demonstrate the usefulness of the IFSM model in evaluating management impacts on CO_2 and other GHG emissions. Important factors that effect CO_2 emission on dairy farms include the cropping system and animal characteristics. The model was used to simulate the 100-cow representative dairy farm briefly described above, and then management changes were made to simulate changes in cropping strategy and herd characteristics. Production systems were simulated for 25 years of historical weather for State College, Pennsylvania (1982 to 2006). Weather patterns affected the net farm GHG emission, giving a 6% coefficient of variation across years for the base farm. Relatively small differences in this variability occurred among the production strategies evaluated.

Two cropping system changes were simulated to compare their environmental impact to that of the base farm. First, 10 ha of corn land were switched to alfalfa with a 4-year stand life. This increased the alfalfa crop area rotated to corn, which affected the soil and crop C and N cycles. In addition, more alfalfa forage was produced for use by the herd. Bunker silo sizes were changed to accommodate additional alfalfa silage and less corn silage. This modification caused a change in animal diets and thus the requirements for supplemental grain and protein feeds. All of these factors together led to a small increase in the amount of forage produced and used on the farm and a decrease in corn grain production (table 7). More grain was purchased to offset the lower grain production. This, along with a small reduction in purchased protein supplemental feed, increased purchased feed 12% with a small increase in total feed intake. Overall, these changes increased net farm CO_2 emission by 22% (table 7, column 2 vs. 1). Most of this change was due to a net reduction in the assimilation of C in feed production (lower crop yield with alfalfa compared to corn silage) along with a very small increase in animal respiration. Associated

Table 7. Annual feed production and use and greenhouse gas emissions for four production strategies on a simulated representative dairy farm in central Pennsylvania.

	Base Farm[a]	More Alfalfa, Less Corn[b]	More Corn, No Grass[c]	Jersey Herd[d]
Feed production and use (Mg DM)				
Harvested forage	522	537	515	570
Harvested grain	161	140	221	141
Purchased feed	201	226	119	277
Total feed intake	884	903	855	988
Greenhouse gas emissions (kg)				
Carbon dioxide (net)	150,479	184,266	35,198	266,144
Animal and barn floor	637,279	642,778	627,374	687,746
Manure storage	16,194	16,755	15,298	18,008
Crop production (net)	-547,854	-520,533	-652,904	-487,880
Engine exhaust	44,860	45,266	45,429	48,271
Methane	21,193	22,025	20,043	23,921
Nitrous oxide	642	652	709	641
Net farm emission (CO_2e)[e]	871,620	929,187	747,555	1,055,187

[a] 100 Holstein cows producing 9,000 kg per cow of milk plus 80 replacement heifers housed year round in free-stall barns with feed produced from 50 ha of corn, 20 ha of perennial grassland, and 20 ha of alfalfa.
[b] 10 ha of corn on the base farm is replaced with alfalfa.
[c] 20 ha of grassland is replaced with corn.
[d] Holstein herd producing 900,000 kg milk production replaced by 140 Jersey cows producing 900,000 kg milk.
[e] Total CO_2-equivalent greenhouse gas emission considering the global warming potential of CH_4 and N_2O to be 25 and 298 times that of CO_2, respectively.

effects on predicted CH_4 (Chianese et al., 2009a) and N_2O (Chianese et al., 2009b) emissions were relatively small. The overall impact was a 7% increase in the net GHG emission from the farm.

A second cropping change was to convert all of the non-permanent grassland in the base farm to corn production. This represented a current trend in which high grain prices were encouraging dairy producers to convert more cropland to grain production. With this change, the farm consisted of 70 ha of corn production and 20 ha of alfalfa. Silo sizes were again changed to produce enough corn silage to replace all of the grass forage originally produced in the base farm. Additional corn was harvested as grain, which reduced the need for purchased grain. This cropping change allowed a small reduction in total forage production along with a 37% increase in grain production (table 7, column 3 vs. 1). Corn silage provided forage with a greater energy content, which reduced total feed intake of the herd by 3%. With increased grain production and lower feed intake, purchased supplemental feed decreased 41%.

This cropping change and the associated impacts on feeding greatly reduced the CO_2 emission from the farm (table 7, column 3 vs. 1). This included a 2% reduction in animal respiration loss and a 6% reduction in respiration loss from the manure storage along with a 19% increase in the CO_2 assimilated in on-farm produced feed. The lower fiber and higher starch diets obtained using more corn silage also decreased predicted CH_4 emission (Chianese et al., 2009a), and the increased corn production on the farm increased predicted N_2O emission (Chianese et al., 2009b) by 10%. The overall effect was a 14% decrease in the net GHG emission in CO_2-equivalent units.

This analysis does not represent long-term changes in soil C. The grassland in this scenario is considered to be in rotation with alfalfa and corn on the base farm, which prevents the potential long-term sequestering of C obtained with permanent grassland. Therefore, this change in cropping system does not reflect the release of sequestered C that may be expected with the tilling and conversion of permanent grassland.

As another illustration of the use of the model, the Holstein herd producing 9,000 kg milk cow^{-1} $year^{-1}$ was replaced with smaller, lower-producing Jersey animals. A herd of 140 cows and 110 replacement heifers was used to produce the same amount of milk as that produced by the original Holstein herd. With more animals on the farm, total feed intake increased 12% (table 7, column 4 vs. 1). The additional feed requirement was met by producing more corn silage and purchasing more grain and other supplemental feeds. Although the respiration emission per animal was less for these smaller animals, the increase in animal numbers led to an 8% increase in respiration emission. More manure was produced per unit of milk with the smaller animals, creating an 11% increase in CO_2 emission from the manure storage. A greater portion of the corn produced as silage, along with more manure returned to the cropland, created an 11% reduction in the CO_2 assimilated in crop production. Greater forage production and use also increased fuel consumption and the associated engine emission of CO_2 by 8%. Predicted CH_4 emissions increased 13% by feeding more of the smaller animals, while N_2O emissions were affected little by this management change. The net effect of all emissions was a 21% increase in the net farm GHG emission.

For further application of the model, simulations were done to compare the effects of farm size and location. In table 8, the 100-cow base farm of table 7 is compared to a 1000-cow farm. This larger farm included production strategies normally used on a farm of this size. Major differences between the two farms were the herd, manure storage, and cropping system. The herd consisted of larger-framed, higher-producing Holstein animals fed to maintain a milk production level of 10,600 kg cow^{-1} $year^{-1}$. All animals were housed in free-stall barns, including 770 replacement heifers. Manure was stored in a lined earthen basin. The farm used a smaller land base per animal for producing feed with 300 ha each of corn and alfalfa. This

Table 8. Annual feed production and use and greenhouse gas emissions for 100-cow and 1000-cow dairy farms in either central Pennsylvania or southern Virginia.

	Central Pennsylvania		Southern Virginia	
	100-Cow Dairy[a]	1000-Cow Dairy[b]	100-Cow Dairy[c]	1000-Cow Dairy[d]
Feed production and use (Mg DM)				
Harvested forage	522	6,147	516	6,151
Harvested grain	161	150	151	307
Purchased feed	201	3,646	219	3,422
Total feed intake	884	9,943	886	9,880
Greenhouse gas emissions (kg cow^{-1})				
Carbon dioxide (net)	1,505	3,604	1,776	3,122
Animal and barn floor	6,373	7,014	6,384	7,119
Manure storage	162	262	163	262
Crop production (net)	-5,479	-4,157	-5,235	-4,753
Engine exhaust	449	485	464	494
Methane	212	272	214	324
Nitrous oxide	6.42	3.52	6.37	3.43
Net farm emission (CO_2e)[e]	8,716	11,453	9,024	12,244

[a] 100 Holstein cows producing 9,000 kg per cow of milk plus 80 replacement heifers housed year round in free-stall barns with feed produced from 50 ha of corn, 20 ha of perennial grassland, and 20 ha of alfalfa.
[b] 1000 large Holstein cows producing 10,600 kg per cow of milk plus 770 replacement heifers housed year round in free-stall barns with feed produced from 300 ha of corn and 300 ha of alfalfa.
[c] Same as [a] except longer season corn with earlier planting and harvest dates and a 5-cutting harvest strategy for alfalfa.
[d] Same as [b] except longer season corn with earlier planting and harvest dates and a 5-cutting harvest strategy for alfalfa.
[e] Total CO_2-equivalent greenhouse gas emission considering the global warming potential of CH_4 and N_2O to be 25 and 298 times that of CO_2, respectively.

produced all of the forage needed to feed the herd in the form of corn and alfalfa silages. This forage was supplemented with purchased grain and protein feeds to meet animal energy and protein requirements.

The higher producing animals of the larger farm consumed more feed per animal, which led to a 10% greater respiration of CO_2 per cow (table 8, column 2 vs. 1). Use of a surface-loaded manure storage also increased the storage emission per cow by 60%. The difference in cropping strategy reduced the net assimilation of CO_2 in crop production per cow by 24% but increased the engine exhaust emission by 8%. Overall, the net emission of CO_2 was more than doubled on a per cow basis. Methane emissions (Chianese et al., 2009a) were also increased due to the net effects of diet and milk production level, while N_2O emissions per cow (Chianese et al., 2009b) were reduced primarily due to the lower land use per animal. The net result on GHG emissions was a 31% increase in emission per cow. Expressed per unit of milk produced, this was a 12% increase.

The effect of location was evaluated by simulating the same farms over 25 years of weather data from the warmer climate of Roanoke, Virginia. Most farm parameters were maintained the same, but a few changes were needed to better match the conditions of the milder climate. The four-cutting alfalfa harvest strategy used in central Pennsylvania was changed to a five-cutting system, with the first harvest beginning about two weeks earlier in the spring. A longer-season corn variety was used, with planting and harvest occurring about one week earlier.

Moving the farms to the more southern location had mixed and relatively minor effects on feed use and GHG emissions. Differences in harvested crop yields and quality had small effects on feed production and intake (table 8, column 3 vs. 1, column 4 vs. 2). Cropping changes in the warmer climate reduced the net CO_2 emission from the cropland of the smaller farm by 4% but increased the net emission from the larger farm by 14%. The cropping changes also caused small increases in the engine emission from both farms. The change in climate had little effect on animal and manure storage emissions of CO_2, but there was some effect on CH_4 emission from the manure storage on the larger farm. The net effect over all GHG emissions was a 4% increase from the smaller farm and a 7% increase from the larger farm.

CONCLUSIONS

A module simulating the C cycle including CO_2 emissions from respiration in soil, plants, animals, and manure was developed from previously published relationships and experimental data and added to a farm simulation model (Integrated Farm System Model or IFSM). This new CO_2 module incorporated available models or relationships that were consistent with the modeling objectives and current structure of IFSM.

The expanded IFSM was shown to predict changes in soil C and CO_2 emissions that were consistent with reported values from specific experiments and previously estimated whole-farm emissions. The model predicted negligible whole-farm C balances for a range in production systems, which further verified the reasonableness of simulated C flows and emissions.

Incorporation of the CO_2 module with IFSM, along with modules simulating CH_4 and N_2O emissions, provides a tool for evaluating the overall impact of dairy farm management on GHG emissions. Simulations illustrated that changes in cropping practices affected emissions from all farm sources, with the primary effect on the assimilation of CO_2 in feed production. For a representative farm in central Pennsylvania, use of more alfalfa in place of corn production caused a 6% increase in net farm emission of GHGs in CO_2-equivalent units. Replacing non-permanent grassland with corn production reduced net farm GHG emission by 16%. Changing from a Holstein herd to Jersey animals with

animal numbers increased to produce the same amount of milk affected most emission sources, with a net impact of increasing GHG emissions by 20%. Increasing farm size and moving the farms to a warmer climate each created relatively small increases in net GHG emissions.

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