Simulating Methane Emissions from Dairy Farms

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Written for presentation at the
2008 ASABE Annual International Meeting
Sponsored by ASABE
Rhode Island Convention Center
Providence, Rhode Island
June 29 – July 2, 2008

Abstract. As a sector, agriculture is reported to be the third greatest contributor of methane in the U.S., emitting one-quarter of total emissions. The primary sources of methane on dairy farms are animals and manure storages with smaller contributions from field-applied manure, feces deposited by grazing animals, and manure on barn floors. The Integrated Farm System Model was expanded to include simulation of methane emissions from enteric fermentation and the other farm sources. In simulating a representative 100-cow dairy farm in Pennsylvania, the model predicted a total average annual emission of 20 Mg CH₄. This included an average annual emission of 135 kg CH₄ per cow from the Holstein herd and an average emission of 5.4 kg CH₄ per m³ of stored slurry manure, which were very similar to previously reported emissions. This expanded whole-farm model can be effectively used to evaluate proposed methane reduction strategies along with their impact on other environmental and economic issues.

Keywords. Methane, Greenhouse gas, Dairy farm, Simulation model.
Introduction

In 2007, the Intergovernmental Panel on Climate Change (IPCC, 2007) reported that it is “extremely likely” (i.e., representing a 95% confidence level or higher) that anthropogenic emissions of greenhouse gases (GHGs) are causing a change in the global climate. Although many mitigation plans currently focus on reducing carbon dioxide (CO₂) emissions, methane (CH₄) is a stronger greenhouse gas and has a global warming potential around 23 times that of CO₂ (IPCC, 2007). The Food and Agriculture Organization of the United Nations has claimed that livestock emit more CH₄ in CO₂ equivalents than is emitted through the burning of fossil fuels for transportation (FAO, 2006). In 2005, agriculture was reported to contribute 25% of the total U.S. CH₄ emissions, behind only the energy sector (39%) and human waste management (36%) in overall impact (EIA, 2006). As a result, quantifying and reducing CH₄ emissions from livestock farms is important in reducing overall CH₄ emissions.

Multiple processes emit CH₄ from dairy farms including enteric fermentation in animals and microbial processes in manure. A review of agricultural emission data shows that the majority of CH₄ from dairy farms is created through enteric fermentation, followed by emissions from manure storages (Sedorovich et al., 2007). In addition to these major sources, less significant emissions result from field-applied manure and from manure deposited by animals inside barns or on pasture. Recent research has shown that plants may also emit CH₄, although the mechanism is not currently known (Keppler and Röckmann, 2007). Field studies (e.g., Sherlock et al., 2002), as well as our review of agricultural emissions (Sedorovich et al., 2007), report croplands as a negligible source, or small sink, of CH₄ in the long term. However, field-applied slurry can result in significant emissions for a few days after application (Chadwick and Pain, 1997; Sherlock et al., 2002).

Computer simulation can provide a cost-effective and efficient method of estimating CH₄ emissions from dairy farms and analyzing how management scenarios affect these emissions. The Integrated Farm System Model (IFSM), a model developed by the USDA’s Agricultural Research Service (ARS), is a process-based whole-farm simulation including major components for soil processes, crop growth, tillage, planting and harvest operations, feed storage, feeding, herd production, manure storage, and economics (Rotz et al., 2007). IFSM predicts the effect of management scenarios on farm performance, profitability and environmental pollutants such as nitrate leaching, ammonia volatilization, and phosphorus runoff loss. Expansion of the model to included GHG emissions will enhance its application.

The overall objective of this research was to incorporate a module into IFSM that simulated emissions of CH₄, to obtain a tool for quantifying CH₄ emissions from dairy farms and evaluating how management scenarios affect these emissions. Specific objectives were to review published models that simulate CH₄ emissions, identify relationships that best fit our modeling goals, adapt those models for use in IFSM, and demonstrate the use of this tool in predicting whole-farm CH₄ emissions and the impacts of reduction strategies.

Model Development

Enteric fermentation and manure storage are the major sources of CH₄ from farms, contributing about 63% and 30% of total agricultural CH₄ emissions, respectively (EIA, 2006). Even though manure applied on fields, feces deposited on pasture, and manure on barn floors do not contribute large amounts of CH₄, we included relationships to simulate these emissions to obtain a comprehensive prediction of farm-level emissions. A number of models have been published that predict emissions from the major sources. To create our module, we selected
relationships that best fit our needs for whole-farm simulation. Criteria used to evaluate potential models were:

1. **The model had to be capable of simulating important processes that affect CH₄ emissions with changes in farm management.** Strategies to reduce CH₄ emissions from enteric fermentation primarily involve animal diet. Strategies to reduce CH₄ emissions from manure storages include storage covers and capturing and flaring the gas. In order to analyze how these and other practices affect CH₄ emissions, the model had to account for the associated processes (e.g., animal ration, manure type, and storage design).

2. **The model had to provide a process-level representation of emission components.** Several published models, as well as the IPCC, predict CH₄ emissions from farms using emission factors (e.g., Schils et al., 2005; Lovett et al., 2006). While these models are useful as simple tools for estimating CH₄ emissions from farms, they do not have the capability of representing processes that affect CH₄ emissions. For example, Schils et al. (2005) simulated CH₄ emissions due to enteric fermentation in heifers and calves by multiplying a group-specific emission factor by the number of animals in each group. This model only accounted for the effect of reducing or increasing animal numbers and would not account for diet modifications. As a result, our goal was to select physically- and biologically-based relationships that satisfied criterion 1 as compared to models based on emission factors.

3. **The model had to satisfactorily predict observed data over a full range of potential conditions.** A primary goal of models is to simulate observed data. The chosen relationships had to predict CH₄ 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 designated at a farm scale (e.g., animal diets, sequence of machinery operations, manure storage duration). Subsequently, IFSM simulates processes, normally on a daily time step, at the field- or farm-level 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 available mechanistic models predict emissions with accuracy; however, these models typically require many inputs and parameters. The required values are often the result of calibrating the model against observed data, are difficult to obtain, or have no 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 observations, 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.

**Enteric Fermentation**

Ruminant animals subsist primarily on forages like grasses and leafy plants. Like most animals, ruminants do not have the enzymes necessary to break down cellulose. Instead, enteric methanogens exist in a symbiotic relationship with other microorganisms in the rumen and, through enteric fermentation, break down and obtain energy from cellulose. In the rumen, enteric methanogens prevent the build-up of the hydrogen produced during fermentation by reducing CO₂ to CH₄. The CH₄ produced is released to the atmosphere by eructation, or belching. Other roles of these microorganisms are not fully understood (Madigan et al., 2003).
The amount of CH₄ produced from enteric fermentation is impacted by various factors including animal type and size, digestibility of the feed, and the intake of dry matter, total carbohydrates, and digestible carbohydrates (Monteny et al., 2001; Wilkerson et al., 1995).

Because of the potential role of CH₄ in climate change, various models have been published that attempt to predict the amount of CH₄ produced by ruminant animals. These models can be categorized as mechanistic or empirical. The more mechanistic models (e.g., Baldwin et al., 1987; Dijkstra et al., 1992; Mills et al., 2001) are based on the chemical or microbiological processes occurring in the rumen that produce CH₄. These models are highly detailed and require many state variables and equations to simulate CH₄ emissions. For example, Dijkstra et al. (1992) utilized 17 state variables and more than 100 equations to simulate enteric fermentation. Empirical models are based on equations relating CH₄ emissions to various factors. These models range from equations based solely on statistical correlations to biologically-based relationships.

The first widely used ruminant CH₄ model was an empirical model published by Blaxter and Clapperton (1965, Table 1). Methane production was correlated to feeding (i.e., a multiple of the recommended energy requirement for maintenance) and the digestibility of the animal’s diet. Other empirical models have related CH₄ production to feed characteristics (Moe and Tyrrell, 1979), milk yield and live weight (Kirchgessner et al., 1991), dry matter intake and feed characteristics (Yates et al., 2000), and metabolizable energy intake, a maximum potential CH₄ production and feed characteristics (Mills et al., 2003; Table 1).

Reviews of both mechanistic and empirical models have been published (Wilkerson et al., 1995; Benchaar et al., 1998; and Mills et al., 2003). Mechanistic models, such as Mills et al. (2001), have explained more variation as compared to empirical models. Relative to our model criteria, the mechanistic model of Mills et al. (2001) satisfied only criteria 1, 2, and 3. This model simulated CH₄ production by modeling chemical reactions in the rumen, which created more detail than needed or desired for simulating processes at the whole-farm scale. More importantly, the inputs and parameters required by their model were not readily available. To use this model, a number of assumptions had to be made in setting input parameters. These values were not readily available or were poorly defined for the wide range of management strategies found on different farms. As such, the uncertainty added by assuming these parameter values outweighed the benefit of using a mechanistic model.

To better meet the needs of our model, a simpler approach was taken using the Mitscherlich 3 (Mits3) equation developed by Mills et al. (2003). Mits3 is a simplified, process-based model that satisfies all five criteria. The model is based on dietary composition and is capable of accounting for management practices that alter the animal’s intake and diet, satisfying criterion 1. Mits3 is process-based, relating CH₄ emissions to dietary intake as well as animal type and size, satisfying criterion 2. When compared to data from the U.S., Mits3 yielded a regression slope of 0.89, an intercept of 3.50 (Mills et al., 2003), and a square root of the mean square prediction error (MSPE) of 34.1%. These results verify that Mits3 can satisfactorily predict emissions for U.S. dairy herds, satisfying criterion 3. In addition, Mits3 predicts realistic emissions at the extremes of the parameter ranges. With zero feed intake, the model predicts zero CH₄ production; at the other extreme of very high feed intake, the nonlinear model predicts that CH₄ emissions approach a maximum. Thus, an additional benefit of the nonlinearity of Mits3 is that the model can be applied to conditions outside those for which it was originally developed without predicting unreasonable emissions. In comparison, linear empirical models can predict unrealistic emissions at high feed intakes (Mills et al., 2003; Kebreab et al., 2006).

Mits3 satisfies criterion 4, as the simpler formulation is consistent with the scale needed for whole-farm simulation. Finally, Mits3 satisfies criterion 5 by requiring only three model inputs.
that were readily obtained from the feed and animal components of IFSM: the starch content of the diet, the acid detergent fiber (ADF) content of the diet, and the metabolizable energy intake. These three inputs were directly related to the animal’s diet and indirectly related to animal size and type. This allowed prediction of changes in CH$_4$ production as affected by changes in animal nutrition and management.

A detailed description of the selected model can be found in Mills et al. (2003). This section briefly describes the model, parameters for the model, and integration with IFSM.

Emission of CH$_4$ is predicted as:

$$E_{CH4,ent} = \left( E_{max} - E_{max} \cdot \exp(-c \cdot MEI) \right) \cdot F_{kgCH4} \quad (1)$$

where $E_{CH4,ent}$ is the emission due to enteric fermentation [kg CH$_4$ cow$^{-1}$ day$^{-1}$], $E_{max}$ is the maximum possible emission [MJ CH$_4$ cow$^{-1}$ day$^{-1}$], $c$ is a shape parameter determining how emissions change with increasing $MEI$ [dimensionless], $MEI$ is the metabolizable energy intake [MJ cow$^{-1}$ day$^{-1}$], and $F_{kgCH4}$ is the conversion of MJ to kg of CH$_4$ [0.018 kg CH$_4$ MJ$^{-1}$]. The maximum possible emission, $E_{max}$, is defined as 45.98 MJ CH$_4$ cow$^{-1}$ day$^{-1}$ (Mills et al., 2003).

### Table 1. Summary of empirical models simulating CH$_4$ production through enteric fermentation.

<table>
<thead>
<tr>
<th>Model</th>
<th>Model core equations$^{[a]}$</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Blaxter and Clapperton (1965)</td>
<td>$E_{CH4,ent} = 1.30 + 0.112<em>D – L</em>(2.37 – 0.05*D)$</td>
<td>kcal CH$_4$ per 100 kcal feed</td>
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<tr>
<td></td>
<td>$L = \text{multiple of maintenance level}$</td>
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<td></td>
<td>$D = \text{apparent digestibility}$</td>
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<tr>
<td>Moe and Tyrrell (1979)</td>
<td>$E_{CH4,ent} = 0.439 + 0.273<em>R + 0.512</em>H + 1.393*C$</td>
<td>Mcal CH$_4$</td>
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<tr>
<td></td>
<td>$R = \text{residue (kg)}$</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$H = \text{hemicellulose (kg)}$</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$C = \text{cellulose (kg)}$</td>
<td></td>
</tr>
<tr>
<td>Kirchgessner et al. (1991)</td>
<td>$E_{CH4,ent} = 55 + 4.5<em>M + 1.2</em>W$ (grass)</td>
<td>g CH$_4$ day$^{-1}$</td>
</tr>
<tr>
<td></td>
<td>$E_{CH4,ent} = 26 + 5.1<em>M + 1.8</em>W$ (corn silage)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$M = \text{milk yield}$</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$W = \text{live weight}$</td>
<td></td>
</tr>
<tr>
<td>Yates et al. (2000)</td>
<td>$E_{CH4,ent} = 1.36 + 1.21<em>D_m - 0.825</em>D_{mc} + 12.8*N_d$ (silage)</td>
<td>MJ CH$_4$ day$^{-1}$</td>
</tr>
<tr>
<td></td>
<td>$E_{CH4,ent} = -35.5 + 0.0216<em>N + 27.6</em>S_{dm} + 1.63*G_{dm}$ (all)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$D_m = \text{dry matter intake (kg)}$</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$D_{mc} = \text{dry matter concentrates (kg)}$</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$N_d = \text{ratio of NDF/D_m}$</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$N = \text{N intake}$</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$S_{dm} = \text{ratio of silage D_m/D_m}$</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$G_{dm} = \text{ratio of gross energy/D_m}$</td>
<td></td>
</tr>
<tr>
<td>Mills et al. (2003)</td>
<td>$E_{CH4,ent} = E_{max} - E_{max} \cdot \exp(-c \cdot MEI)$</td>
<td>MJ CH$_4$ day$^{-1}$</td>
</tr>
<tr>
<td></td>
<td>$E_{max} = \text{maximum value of CH}_4 \text{ production}$</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$c = \text{shape parameter}$</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$MEI = \text{metabolizable energy intake}$</td>
<td></td>
</tr>
</tbody>
</table>

$^{[a]} E_{CH4,ent}$ represents the emission of CH$_4$ from enteric fermentation as simulated by the various models being used. The units of $E_{CH4,ent}$ vary for each model as listed under the units column.
This maximum possible emission is constant for all animals; the effect of animal size and type is indirectly included in the value of $MEI$. The shape parameter, $c$, is calculated as:

$$
c = -0.0011 \left( \frac{\text{Starch}}{ADF} \right) + 0.0045
$$

(2)

where $\text{Starch}$ is the starch content and $ADF$ is the acid detergent fiber content of the diet. Equation 2 models the trend for increased $CH_4$ emissions with fibrous diets (i.e., high ADF) and decreased emissions with high starch diets.

To use the above equations, three input values were needed: the starch and ADF contents of diets and the metabolizable energy intake of animal groups making up the herd. IFSM determines the ration that each animal group is fed based upon a representative animal’s nutritional requirements and the available feeds (Rotz et al., 1999). This information includes the required energy content of the diet [MJ kg DM$^{-1}$], the total dry matter intake [kg DM day$^{-1}$ cow$^{-1}$], and the amount of each feed used. The first two parameters were used to calculate $MEI$. The ADF contents of feeds used in IFSM were calculated assuming a linear relationship with neutral detergent fiber (NDF) for each feed type (Table 2). These relationships were developed using feed composition data from the National Research Council (NRC, 2001). The starch contents of feeds used in IFSM were determined assuming a linear relationship with the amount of nonfibrous carbohydrates (NFC) in the feed (Table 2). The fraction of NFC was determined as:

$$
F_{NFC} = 1 - \left( F_{NDF} + F_{CP} + F_{fat} + F_{ash} \right)
$$

(3)

where $F_{NFC}$ is the fraction of NFC in the diet, $F_{CP}$ is the fraction of crude protein (CP) in the diet, $F_{fat}$ is the fraction of fat in the diet, and $F_{ash}$ is the fraction of ash in the diet. The fractions of NDF and CP were available in IFSM; typical fractions of fat and ash (Table 2) were obtained from the National Research Council (NRC, 2001). A given animal group is normally fed a mixture of

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**Table 2. Relationships used to model starch and ADF contents of feeds in IFSM.**

<table>
<thead>
<tr>
<th>Feed type</th>
<th>Starch$^{[a],[b]}$ (fraction)</th>
<th>ADF (fraction)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Alfalfa hay</td>
<td>$0.64(1-F_{NDF}-F_{CP}-0.11)$</td>
<td>$0.78F_{NDF}$</td>
</tr>
<tr>
<td>Alfalfa silage</td>
<td>$0.89(1-F_{NDF}-F_{CP}-0.12)$</td>
<td>$0.82F_{NDF}$</td>
</tr>
<tr>
<td>Grass hay</td>
<td>$0.45(1-F_{NDF}-F_{CP}-0.11)$</td>
<td>$0.61F_{NDF}$</td>
</tr>
<tr>
<td>Grass silage</td>
<td>$0.65(1-F_{NDF}-F_{CP}-0.12)$</td>
<td>$0.64F_{NDF}$</td>
</tr>
<tr>
<td>Corn grain</td>
<td>0.68</td>
<td>0.036</td>
</tr>
<tr>
<td>High moisture corn</td>
<td>0.52</td>
<td>0.004</td>
</tr>
<tr>
<td>Corn silage</td>
<td>$0.80(1-F_{NDF}-F_{CP}-0.07)$</td>
<td>$0.62F_{NDF}$</td>
</tr>
<tr>
<td>Perennial grass/legume</td>
<td>$0.48(1-F_{NDF}-F_{CP}-0.14)$</td>
<td>$0.72F_{NDF}$</td>
</tr>
<tr>
<td>Alfalfa pasture</td>
<td>$0.48(1-F_{NDF}-F_{CP}-0.14)$</td>
<td>$0.55F_{NDF}$</td>
</tr>
<tr>
<td>Protein supplement 1</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>Protein supplement 2</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>Fat additive</td>
<td>0.0</td>
<td>0.0</td>
</tr>
</tbody>
</table>

$^{[a]}$ The last value in the equation in the starch column represents an average total of fat and ash (see Fat + Ash column).  
$^{[b]}$ $F_{NDF}$ (fraction of neutral detergent fiber in feed) and $F_{CP}$ (fraction of crude protein in feed) are available in IFSM.  
$^{[c]}$ Average values for fat and ash were obtained from NRC (2001).
feeds making up the whole diet. A weighted average of feeds in the ration was used to
determine the starch and ADF contents of the ration fed to each of the six possible animal
groups making up the herd (Rotz et al., 1999).

**Manure Storage**

During manure storage, CH₄ is generated through a reaction similar to that described for enteric
fermentation. The cellulose in the manure is degraded, with products of this process serving as
substrates for methanogenesis. Temperature and storage time are the most important factors
influencing CH₄ emissions from stored manure because substrate and microbial growth are
generally not limited (Monteny et al., 2001). Although the processes are similar, there are
important differences between the rumen and manure storage. The temperature in a manure
storage varies, in contrast to the relatively constant temperature in the rumen, and the manure
in storage is more heterogeneous (e.g., the substrate is less well mixed and some
carbohydrates are already partially decomposed) as compared to the consistency of the rumen
(Monteny et al., 2001).

As with enteric fermentation, both mechanistic and empirical equations have been used to
predict CH₄ emissions from manure storages. Unlike some of the empirical enteric fermentation
models that simply utilize correlations that are not necessarily based on biological processes,
the majority of manure storage models are biologically based. Two mechanistic (Hill, 1982; and
García-Ochoa et al., 1999) and four empirical models (Chen and Hashimoto, 1980; Hill, 1991;
Zeeman, 1994; and Sommer et al., 2004) were reviewed. Although many models exist, these
six models represented those most appropriate for simulating manure storage emissions.

Hill (1982) described a comprehensive and dynamic mechanistic model to predict CH₄
production through animal waste methanogenesis. The model satisfied criteria 1, 2, and 3 of our
model requirements. The model was based on biological processes and thus satisfied criterion
2. Input parameters could be changed to account for different reduction strategies, satisfying
criterion 1. Model results showed high goodness of fit for dairy manure, satisfying criterion 3.
However, the model simulated CH₄ production based on the chemical and microbiological
reactions in the storage. As a result, the model scale was not consistent with that of IFSM.
Additionally, there were many model parameters that required iterative solutions, and input
values that were difficult to obtain.

García-Ochoa et al. (1999) published a mechanistic kinetic model that used three stages to
simulate anaerobic digestion and CH₄ production from animal waste. The three stages included
1) the conversion of complex biopolymers to simpler, more accessible substrates, 2) the
conversion of hydrolyzed animal waste to volatile organic acids, and 3) the production of CH₄
from volatile organic acids. Assumptions made in developing the model included lumped
parameter, pseudo-steady state, and first-order kinetics. This model satisfied criteria 1, 2, and 3.
However, the model determined values for ten parameters iteratively using a fourth-order Runge
Kutta algorithm linked to a non-linear multiple response regression. Most parameters in IFSM
are externally determined and hard-coded, or are set by the user through a graphical interface.
The iterative procedure was not consistent with the current structure of IFSM.

Chen and Hashimoto (1980; Table 3) described an empirical model that predicted volumetric
CH₄ production from anaerobic digesters. This model satisfied all five criteria. The model was
process-based, using a maximum possible CH₄ yield to predict emissions. The model
accounted for the reduction of this possible yield due to various factors (e.g., volatile solids
concentration, temperature, and hydraulic retention time). When used to predict CH₄ production
from the anaerobic digestion of beef cattle manure, the average ratio of experimental to
predicted CH₄ production was 0.96 with a standard deviation of ±0.06 (Hashimoto, 1982a).
These results indicated that the model could accurately predict observed data, satisfying criterion 3. The model was also on the same scale as IFSM and utilized readily available data for inputs and parameters (Hashimoto et al., 1981; Hashimoto, 1982b, 1983, and 1984).

Hill (1991; Table 3) described a single equation model to estimate CH$_4$ production based on volatile solids (VS) reduction. This model was based on Hill (1982), but was intentionally simplified. The model was intended for field use, where computing capabilities were limited, and for undergraduate class simulations, where the goal was to teach students how to calculate CH$_4$ production rather than what causes the production. The model of Hill (1991) fully satisfied criteria 2 and 3 and partially satisfied criterion 5. The model was based on biological principles using the concentration and reduction of VS. Hill (1991) reported that the simple model had prediction confidence of at least 97%, satisfying criterion 3. The model required few inputs, and these inputs were readily available. However, the parameters for the model were empirically derived from model output as described by Hill and Bolte (1987). This model was developed for anaerobic digesters, and the empirical parameters thus may not be applicable to predicting emissions from manure storages with no treatment.

Zeeman (1994; Table 3) developed a model to predict the production of CH$_4$ in manure storage using first-order hydrolysis of biodegradable polymers and Monod kinetics to simulate the

### Table 3. Summary of empirical models simulating CH$_4$ emissions from manure storages.

<table>
<thead>
<tr>
<th>Model</th>
<th>Model core equations$^{[a]}$</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chen and Hashimoto (1980)</td>
<td>$E_{CH4,man} = \left( B_0 S_o / \theta \right) \times \left[ 1 - \left( K / (\theta \mu - 1 + K) \right) \right]$</td>
<td>L CH$_4$ L$^{-1}$ day$^{-1}$</td>
</tr>
<tr>
<td></td>
<td>$B_0 = $ ultimate CH$_4$ yield</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$S_o = $ influent volatile solids concentration</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$\theta = $ hydraulic retention time</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$\mu = $ maximum specific growth rate</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$K = $ kinetic parameter</td>
<td></td>
</tr>
<tr>
<td>Hill (1991)</td>
<td>$E_{CH4,man} = \gamma \times \tau \times \sigma$</td>
<td>L CH$_4$ L$^{-1}$ day$^{-1}$</td>
</tr>
<tr>
<td></td>
<td>$\gamma = $ specific CH$_4$ productivity</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$\tau = $ volatile solids reduction</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$\sigma = $ organic loading rate stress factor</td>
<td></td>
</tr>
<tr>
<td>Zeeman (1994)</td>
<td>$E_{CH4,man} = \alpha \times S_p$</td>
<td>g CH$_4$ L$^{-1}$ day$^{-1}$</td>
</tr>
<tr>
<td></td>
<td>$\alpha = $ first order hydrolysis constant</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$S_p = $ concentration of biodegradable polymer substrate</td>
<td></td>
</tr>
<tr>
<td>Sommer et al. (2004)</td>
<td>$E_{CH4,man} = V_{s,d} \times b_1 \times \exp[\ln(A) - E^\left(1/R^*T\right)]$ + $V_{s,nd} \times b_2 \times \exp[\ln(A) - E^\left(1/R^*T\right)]$</td>
<td>g CH$_4$ day$^{-1}$</td>
</tr>
<tr>
<td></td>
<td>$V_{s,d}, V_{s,nd} = $ degradable and nondegradable volatile solids</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$b_1, b_2 = $ rate correcting factors (1, 0.01)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$A = $ Arrhenius parameter</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$E = $ activation energy</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$R = $ universal gas constant</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$T = $ temperature</td>
<td></td>
</tr>
</tbody>
</table>

$^{[a]}$ $E_{CH4,man}$ is the emission of CH$_4$ from manure storage as predicted by the various models. The units of $E_{CH4,man}$ vary for each model as listed under the units column.
growth of methanogenic bacteria. Zeeman’s model was similar in concept to that of García-Ochoa et al. (1999), although much simpler. Unlike Hill (1991), experimentally-determined parameters were provided for both digested and fresh manure. The model satisfied criteria 1, 2, 3, and 5, and partially satisfied criterion 4. The model was accurate and capable of simulating reduction practices, but not completely consistent with the structure of IFSM.

Sommer et al. (2004; Table 3) simulated the production and emission of CH₄ from fresh manure storages. Like many of the models previously described, this model based CH₄ production on the degradation of VS. Additional factors affecting CH₄ production were temperature and storage time. This model also satisfied all five criteria. Unlike the other models, Sommer et al. (2004) was developed more generally for application to either digested or untreated manure.

Based on the above descriptions, we considered three of the six original models: Hashimoto et al. (1981), Zeeman (1994), and Sommer et al. (2004). We concluded that the model of Zeeman (1994) was less suitable than the remaining two. Zeeman used biologically-based equations to predict CH₄ production, but used emission factors or a similar method to predict the actual emission of CH₄. Sommer et al. (2004) also questioned whether the parameters published by Zeeman (1994) were derived solely from anaerobically-digested manure data.

Thus, the models of either Hashimoto et al. (1981) or Sommer et al. (2004) satisfied our criteria. The models were similar, with both based on the VS content of manure. Sommer et al. (2004) utilized the VS content in the manure storage, while Hashimoto et al. (1981) required the influent concentration of VS. Hashimoto et al. (1981) and subsequent publications (Hashimoto 1982b, 1983, and 1984) provided equations to calculate the empirical parameters as functions of temperature and VS concentration. Additionally, both Hashimoto et al. (1981) and Sommer et al. (2004) utilized relationships that account for the effect of temperature on emission rates. Finally, the scale of both models was consistent with that of IFSM. Although the model of Hashimoto et al. (1981) could be applied to fresh manure, several of the parameters were empirically determined based on data from anaerobic digesters. Sommer et al. (2004) employed commonly used empirical relationships (e.g., Arrhenius relationship) that were more general and thus more applicable to conditions outside of which they were developed. Additionally, Sommer et al. (2004) was a more recent model, incorporating more recent developments and data than Hashimoto’s model. As a result, the model of Sommer et al. (2004) was selected.

A detailed description of the development of the chosen model is found in Sommer et al. (2004). This section briefly describes the model, how the parameters were determined, and how the model was integrated with IFSM.

Including factors for the conversion of units, manure storage CH₄ emission is predicted as:

\[
E_{CH_4,man} = \frac{24 \cdot V_{s,d} \cdot b_1}{1000} \cdot \exp\left[\ln(A) - \frac{E}{RT}\right] + \frac{24 \cdot V_{s,nd} \cdot b_2}{1000} \cdot \exp\left[\ln(A) - \frac{E}{RT}\right] \quad (4)
\]

where \(E_{CH_4,man}\) is the emission of CH₄ from manure storage [kg CH₄ day⁻¹], \(V_{s,d}\) and \(V_{s,nd}\) are the degradable and nondegradable volatile solids [g], \(b_1\) and \(b_2\) are rate correcting factors [dimensionless], \(A\) is the Arrhenius parameter [g CH₄ kg⁻¹ VS h⁻¹], \(E\) is the apparent activation energy [J mol⁻¹], \(R\) is the gas constant [J K⁻¹ mol⁻¹], and \(T\) is the temperature [K] (Table 4).

From Sommer et al. (2004), the degradable volatile solids entering storage is:

\[
V_{s,d} = V_{s,sof} \cdot \frac{B_v}{E_{CH_4,pot}} \quad (5)
\]
where $V_{s,tot}$ is the total volatile solids in the manure [g], $B_o$ is the achievable emission of CH$_4$ during anaerobic digestion [g kg$^{-1}$ VS] and $E_{CH4,pot}$ is the potential CH$_4$ yield of the manure [g kg$^{-1}$ VS], which can be estimated using Bushwell’s equation and the carbohydrate, fat, and protein content of the manure. For cattle slurry, Sommer et al. (2004) defined $B_o$ as 0.2 g CH$_4$ kg$^{-1}$ VS and $E_{CH4,pot}$ as 0.48 g CH$_4$ kg$^{-1}$ VS.

Total volatile solids in the manure storage at any point in time is the difference between that entering the storage and that lost from the storage up to that point. That entering can be determined from the manure mass, the total solids content, and the volatile solids content:

$$V_{s,tot} = M_{manure} \cdot P_{TS} \cdot P_{VS} - V_{s,loss}$$

(6)

where $M_{manure}$ is the accumulated mass of manure entering the storage [kg], $P_{TS}$ is the total solids content in the manure [g TS kg$^{-1}$ manure], $P_{VS}$ is the fraction of volatile solids in the total solids [g VS g$^{-1}$ TS], and $V_{s,loss}$ is the accumulated volatile solids lost. To obtain a similar rate of volatile solids loss as that reported by Sommer et al. (2004), this loss was determined as six times the methane loss from the stored manure.

The mass of nondegradable volatile solids, $V_{s,nd}$, is then calculated using a mass balance:

$$V_{s,nd} = V_{s,tot} - V_{s,d}$$

(7)

The inputs required for this model were the mass and temperature of the manure in storage. The amount of manure in the storage at a given time was modeled as the accumulation of that produced by the herd with daily manure excretion determined in the animal component of IFSM (Rotz et al., 1999). The temperature of the manure in storage on a given simulated day was estimated as the average ambient air temperature over the previous ten days. Both the manure quantity produced and daily air temperature were available in IFSM.

The relationships described above were generally applicable to uncovered slurry storages. Some farms use technology such as storage covers to reduce emissions. One such control includes the capture and burning of the CH$_4$ gas. This method greatly decreases the emission of CH$_4$, but also increases the emission of CO$_2$ through the combustion of CH$_4$. To simulate this storage treatment, the emission of CH$_4$ from an enclosed manure storage was calculated as:

$$E_{CH4, cov} = E_{CH4, man} \cdot (1 - \eta_{eff})$$

(8)

where $E_{CH4, cov}$ is the CH$_4$ emitted from the enclosed manure storage [kg CH$_4$ day$^{-1}$], $E_{CH4, man}$ is the calculated emission of CH$_4$ from a storage with no cover using equation 4 [kg CH$_4$ day$^{-1}$], and $\eta_{eff}$ is the efficiency of the collector [dimensionless]. The efficiency of the collector and flare was determined as six times the methane loss from the stored manure.

Table 4. Parameters and values for the manure storage emissions model of Sommer et al. (2004).

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Variable</th>
<th>Value</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Volatile solids content$^{[a]}$</td>
<td>$P_{VS}$</td>
<td>0.726, 0.698, 0.68$^{[b]}$</td>
<td>g VS g$^{-1}$ TS</td>
</tr>
<tr>
<td>Achievable CH$_4$ $^{[c]}$</td>
<td>$B_o$</td>
<td>0.2</td>
<td>g CH$_4$ g$^{-1}$ VS</td>
</tr>
<tr>
<td>Potential CH$_4$ $^{[c]}$</td>
<td>$E_{CH4,pot}$</td>
<td>0.48</td>
<td>g CH$_4$ g$^{-1}$ VS</td>
</tr>
<tr>
<td>Correcting factors$^{[c]}$</td>
<td>$b_1, b_2$</td>
<td>1.0, 0.01</td>
<td>dimensionless</td>
</tr>
<tr>
<td>Arrhenius parameter$^{[c]}$</td>
<td>ln($A$)</td>
<td>43.33</td>
<td>dimensionless</td>
</tr>
<tr>
<td>Activation energy$^{[c]}$</td>
<td>$E$</td>
<td>112,700</td>
<td>J mol$^{-1}$</td>
</tr>
<tr>
<td>Gas constant$^{[c]}$</td>
<td>$R$</td>
<td>8.314</td>
<td>J K$^{-1}$ mol$^{-1}$</td>
</tr>
</tbody>
</table>

$^{[a]}$ From USDA-SCS (1999).
$^{[b]}$ Values for heifers, dry cows, and lactating cows.
$^{[c]}$ From Sommer et al. (2004).
assumed to be 99% (EPA, 1999). The subsequent flaring of the captured CH$_4$ releases CO$_2$, which adds to the overall farm emission of this gas (Sedorovich, 2008). The additional emission of CO$_2$ due to the combustion of CH$_4$ is calculated as:

$$E_{CO2,\text{flare}} = E_{CH4,\text{cov}} \cdot 2.75$$  \hspace{1cm} (9)$$

where $E_{CO2,\text{flare}}$ is the emission of CO$_2$ due to combustion of the CH$_4$ captured from the manure storage [kg CO$_2$ day$^{-1}$] and 2.75 is the ratio of the molecular weights of CO$_2$ and CH$_4$.

**Field-applied Manure**

Research has shown that field-applied slurry is a source of CH$_4$ emissions for several days after application, emitting between 40 to 90 g CH$_4$ ha$^{-1}$ day$^{-1}$ (Sommer et al., 1996; Chadwick and Pain, 1997; Sherlock et al., 2002). Emissions drastically decrease within the first three days, and soils return to a neutral source of CH$_4$ after 11 days (Sherlock et al., 2002).

Sherlock et al. (2002) related CH$_4$ emissions from field-applied slurry to the volatile fatty acids (VFAs) concentration in the soil. Because the VFAs in the soil were due to the application of the slurry (Sherlock et al., 2002), the model of Sherlock et al. (2002) was used to relate CH$_4$ emissions to the VFA concentration in the slurry as compared to the concentration in the soil. Therefore, emission of CH$_4$ from field-applied slurry is predicted as:

$$E_{CH4,app} = (0.170 \cdot F_{VFA} + 0.026) \cdot A_{crop} \cdot 0.032$$  \hspace{1cm} (10)$$

where $E_{CH4,app}$ is the emission of CH$_4$ from field-applied slurry [kg CH$_4$ day$^{-1}$], $F_{VFA}$ is the daily concentration of VFAs in the slurry [mmol kg$^{-1}$ soil], and $A_{crop}$ is the land area [ha] where the manure is applied. Equation 10 is valid for CH$_4$ emissions within the first 11 days of application; after 11 days, CH$_4$ emissions are assumed to be negligible until the next application.

Sherlock et al. (2002) found that the daily VFA concentration exponentially decreased in the days following the application of manure slurry and approached background levels within approximately four days. Using this information, we derived a relationship predicting the daily concentration of VFA in the field-applied slurry.

$$F_{VFA} = F_{VFA,\text{init}} e^{-0.6939 \cdot t}$$  \hspace{1cm} (11)$$

where $F_{VFA}$ is the daily concentration of VFAs in the slurry [mmol kg$^{-1}$ slurry], $F_{VFA,\text{init}}$ is the initial concentration of VFAs in the slurry at the time of application [mmol kg$^{-1}$ slurry], and $t$ is the time since application [days], with $t = 0$ representing the day of application.

Paul and Beauchamp (1989) developed an empirical model relating the pH of manure slurry to VFA and total ammoniacal nitrogen (TAN) concentrations:

$$pH = 9.43 - 2.02 \cdot \frac{F_{VFA,\text{init}}}{F_{TAN}}$$  \hspace{1cm} (12)$$

where $pH$ is the pH of the manure slurry [dimensionless] and $F_{TAN}$ is the concentration of TAN (NH$_4^+$ + NH$_3$) in the slurry [mmol kg$^{-1}$ slurry]. Rearranging Equation 12, we obtained an equation predicting the initial concentration of VFAs based on the pH and TAN of the manure slurry:

$$F_{VFA,\text{init}} = \frac{F_{TAN}}{2.02} (9.43 - p\text{H})$$  \hspace{1cm} (13)$$

To predict an emission from field applied manure, Equation 13 was used to determine an initial VFA concentration and equation 11 was used to track the VFA concentration through time.
following field application. Using this concentration, an emission rate was determined until the remaining VFA concentration approached zero.

**Grazing Animals**

On farms that incorporate grazing for a portion of the year, freshly excreted feces and urine are directly deposited by animals on pastures. Studies have shown that feces are a small source of CH$_4$ and that emissions from urine are not significantly different from background soil emissions (e.g., Jarvis et al., 1995; Yamulki et al., 1999). Because animal-deposited feces contribute only minimally to overall farm CH$_4$ emissions, there were few data quantifying these emissions. A 2004 review of emissions from grazing animals concluded that CH$_4$ emission rates from freshly deposited feces were influenced by environmental conditions and animal rations, which were highly variable and unable to be represented by a constant emission rate (Saggar et al., 2004).

Despite this conclusion, we chose to use a constant emission factor to predict CH$_4$ emissions from feces deposited by grazing animals. The limited research data available and the relatively minor emission from this source did not justify using a more process-based model. As a result, a constant emission factor represented the best available approach. To determine this emission factor, we obtained emission rates from four published studies and used the average of 0.086 g CH$_4$ kg$^{-1}$ feces for our emission rate (Table 5). For grazing systems, the daily emission of CH$_4$ was predicted as the product of this emission rate and the daily amount of feces deposited by grazing animals.

<table>
<thead>
<tr>
<th>Reference</th>
<th>Emission rate [g CH$_4$ kg$^{-1}$ feces]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Jarvis et al. (1995)</td>
<td>0.110</td>
</tr>
<tr>
<td>Flessa et al. (1996)</td>
<td>0.130</td>
</tr>
<tr>
<td>Holter (1997)</td>
<td>0.068</td>
</tr>
<tr>
<td>Yamulki et al. (1999)</td>
<td>0.036</td>
</tr>
<tr>
<td>Average</td>
<td>0.086</td>
</tr>
</tbody>
</table>

**Barn Emissions**

Manure on housing facility floors can be a source of CH$_4$ emissions. No published model or data were found for this emission source. As a result, unpublished CH$_4$ emissions data measured from barn floors (Varga et al., 2007) were used to develop an equation relating CH$_4$ emissions to the ambient temperature ($R^2 = 0.56$). The empirical model used was:

$$E_{CH_4,floor} = \max(0.0, 0.14 T + 0.29) \cdot \frac{A_{barn}}{1000}$$

where $E_{CH_4,floor}$ is the daily rate of CH$_4$ emission from the barn floor [kg CH$_4$ day$^{-1}$], $T$ is the ambient temperature [$^\circ$C], and $A_{barn}$ is the area of the barn floor covered with manure [m$^2$].

Equation 14 satisfies criteria 3 and 5 as an empirical equation that correlates CH$_4$ emission with temperature. We chose to use this relationship because it provided the best available information describing CH$_4$ emissions from barn floors. The temperature dependence of CH$_4$ production is well-documented (Zeikus and Winfrey, 1976; van Hulzen et al., 1999). As a function of temperature, equation 14 is a simplified, process-based equation, thus satisfying criterion 4 as well. This simple relationship predicted reasonable emission rates for ambient
temperatures of 0°C and greater. Because this emission source is a relatively minor contributor to overall farm CH4 emissions, development of a more detailed model was not justified.

**Model Evaluation**

Few data exist on overall emissions of CH4 from dairy farms in the U.S. (Sedorovich et al., 2007). Studies that have quantified CH4 emissions from specific farm sources often have not provided the specific data required to simulate scenarios in IFSM. In addition, these studies were often small-scale or laboratory studies that could not be adequately simulated. Therefore, we evaluated IFSM predictions of CH4 emissions in three ways. First, for the major emission sources of enteric fermentation and manure storage, we compared observed data from previous studies to simulated emissions. We chose studies that represented typical emissions (Sedorovich et al, 2007), that included important input information required to simulate the observed conditions with IFSM and that were not a source of data in the development of the original model. Second, we performed a sensitivity analysis on the important parameters of the major model components. Finally, we used IFSM to simulate a representative farm and compared IFSM predictions to those previously identified as typical (Sedorovich et al., 2007).

**Enteric Fermentation Emissions**

To evaluate our model’s ability to simulate CH4 emissions due to enteric fermentation, we chose Kirchgessner et al. (1991) and Kinsman et al. (1995) as representative studies. Kirchgessner et al. (1991) measured CH4 emissions from 67 lactating cows with an average weight of 583 kg and an average annual milk production of 6000 L cow\(^{-1}\). The animals were fed diets consisting, on average, of 57% roughage composed of a mixture of grass hay and corn silage. They reported an average CH4 emission of 300 g CH4 cow\(^{-1}\) day\(^{-1}\) (± 39 g CH4 day\(^{-1}\)), or 110 kg CH4 cow\(^{-1}\) yr\(^{-1}\) (± 14 kg CH4 cow\(^{-1}\) yr\(^{-1}\)). Using their average diet characteristics, cow weight, and target milk production, IFSM predicted 124 kg CH4 cow\(^{-1}\) yr\(^{-1}\). This simulated emission was within one standard deviation of the results reported by Kirchgessner et al. (1991), demonstrating that IFSM was capable of predicting CH4 emissions from enteric fermentation.

Kinsman et al. (1995) measured CH4 and CO2 emissions from 118 lactating cows weighing an average of 602 kg with an average milk production of approximately 10,100 L cow\(^{-1}\) yr\(^{-1}\). On average, animals were fed 17.5 kg DM animal\(^{-1}\) day\(^{-1}\) (± 1.4 kg DM animal\(^{-1}\) day\(^{-1}\)). The diet consisted of corn silage, alfalfa silage, hay, roasted soybean, barley, and other supplements. Kinsman et al. (1995) reported that CH4 emissions ranged from 436 to 721 L CH4 cow\(^{-1}\) day\(^{-1}\) (290 to 470 g CH4 cow\(^{-1}\) day\(^{-1}\)) with an average rate of 587 L CH4 cow\(^{-1}\) day\(^{-1}\) (390 g CH4 cow\(^{-1}\) day\(^{-1}\)). Using similar diet characteristics and target milk production, IFSM predicted 420 g CH4 cow\(^{-1}\) day\(^{-1}\). This simulated emission was within the range, and close to the average, CH4 emission rate reported by Kinsman et al. (1995), further demonstrating that IFSM could predict very reasonable CH4 emissions from enteric fermentation. IFSM was also able to adequately predict CO2 emissions from this same study (Sedorovich, 2008).

**Manure Storage Emissions**

We chose Husted (1994) as the representative study to test the ability of IFSM to predict CH4 emissions from manure storages. Husted measured CH4 emissions from slurry manure obtained from 160 Jersey cows and their calves that was stored in a 1200 m\(^3\) outdoor tank. Over an annual period, CH4 emissions from an uncovered storage ranged from about 5 to 35 g m\(^{-3}\) d\(^{-1}\) as slurry temperature varied from 6 to 18°C. From the daily emission measurements, an annual emission of 15.5 kg animal\(^{-1}\) was estimated, which gave an annual emission from the storage of 2480 kg CH4. The confidence limits of the data reflected an uncertainty of 30% in this estimate.
A representative farm was simulated with IFSM using the reported animal, manure and storage characteristics. The farm was simulated over 25 years of historical weather data from Thisted, Denmark (1974-1998). Over manure slurry temperatures of 6 to 18°C, simulated daily CH₄ emissions were 4.7 to 34 g CH₄ m⁻³ d⁻¹, which agreed very well with measured values. Simulated average annual emissions ranged from 1,911 to 2,840 kg CH₄ with a 25 year average of 2,366 kg CH₄. These annual values were well within the uncertainty of Husted’s estimated value, and the 25 year average emission was within 5% of his estimated annual emission. This comparison of simulated and measured emissions supports that the model predicts very reasonable emissions from stored cattle slurry manure.

Sensitivity Analysis

Models are more sensitive to some parameters and inputs than others; it is therefore important to quantify this sensitivity to ensure that values of variables with the most impact are accurate. A traditional sensitivity analysis involves varying a selected parameter by a selected percentage and calculating the percent change in the output. For example, to calculate how a 10% change in \( x \) affects the model output \( y \), the original value of \( x = x_{\text{base}} \) is used as an input to the model to obtain \( y_{\text{base}} \). The parameter is then increased by 5% \( (x_{+5\%}) \) and decreased by 5% \( (x_{-5\%}) \) to obtain an overall change of 10%. The model output is determined at both of these values \( (y_{+5\%} \) and \( y_{-5\%} \)) and the ratio of the change in \( y \) to the change in \( x \) is calculated as:

\[
P_{\text{change}} = \frac{y_{+5\%} - y_{-5\%}}{x_{+5\%} - x_{-5\%}} \left( \frac{x_{\text{base}}}{y_{\text{base}}} \right)
\]

A value of one indicates that a 10% change in \( y \) occurs with a 10% change in \( x \); a lesser ratio indicates lesser sensitivity whereas a greater ratio indicates greater sensitivity. This method is useful when evaluating the sensitivity of variables with specific values (i.e., as opposed to categorical variables).

A traditional sensitivity analysis was performed on the modules developed for enteric fermentation, manure storage, and field-applied manure. To perform this analysis, the CH₄ model relationships were incorporated into an ad-hoc program using Matlab®. Modifications to the CH₄ relationships were made as necessary to achieve mathematically-correct and physically-realistic output while maintaining the scientific validity of the equations. Because a function was created for each emission source, the inputs and parameters were easily changed and the relevant outputs obtained. This method allowed the sensitivity of important parameters to be quantified while maintaining the interaction among variables. Sensitivity data generated in Matlab were compiled using a spreadsheet program with the overall sensitivity calculated using equation 15.

The enteric fermentation output was not highly sensitive to any of the model parameters. For a given percent change in the input, all of the parameters caused the same, or less, change in CH₄ emissions. The most important parameter was the maximum possible CH₄ emission; the predicted emission rate was proportional to this assigned value (Table 6).

For the manure storage module, the majority of parameters had percent change values of 1.0. In other words, a given change in the input parameter caused the same change in the output (Table ). However, the model was very sensitive to the Arrhenius parameter with a sensitivity greater than 100. The Arrhenius parameter accounts for the temperature dependency of CH₄ emissions from the storage. In the model, this parameter is not set by the user, but is an internally-set constant. Appropriate values for the Arrhenius parameters were determined by the original developers of the model by fitting the parameters to observed data. Additionally, the values selected ensured that annual CH₄ emissions from slurry storage corresponded to
emissions calculated using IPCC emission factors (Sommer et al., 2004). As a result, the present Arrhenius values represent the best available model. Further studies quantifying CH4 emissions from slurry storage are required to further evaluate and perhaps improve the calculation of this parameter (Sommer et al., 2004).

As with the manure storage model, most parameters in the field applied manure module caused approximately the same percent change in output as the change in input (i.e., sensitivity of 1.0). The pH of the manure slurry was the only variable that caused a major difference in the output, as evidenced by a five-fold change in output for a given change in input. Similar to the Arrhenius parameter, the pH of the slurry is not set by the user, but is an internal variable in IFSM. Currently, IFSM assumes that the pH of applied slurry is 8.0; future work may improve the prediction of CH4 emissions by developing a prediction model for slurry pH.

The majority of CH4 emissions from the farm were due to enteric fermentation. Even though the manure storage and field application modules were very sensitive to certain parameters, the impact of this sensitivity on farm emissions was small relative to enteric fermentation. Thus, changes to parameters in the manure storage and field application modules had a relatively small impact on farm GHG emissions; even though, some parameters were highly sensitive.

**Representative Farm Emissions**

As a final evaluation, simulated annual whole-farm emissions were compared to those previously summarized from prior literature for a hypothetical “typical” dairy farm in central
Pennsylvania (Sedorovich et al., 2007). Only a brief description of the farm is provided to document those assumptions most relevant to CH₄ 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 3000 m³ storage tank for up to six months, and applied to cropland in the spring and fall. On average over the whole year, the storage contained about 1200 m³ of manure. The 89 ha farm area consisted of 19 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 nitrogen fertilizer was applied at rates of 50 and 65 kg ha⁻¹ on corn and grassland, respectively.

Based upon the above farm characteristics, IFSM was used to simulate a representative farm on a clay-loam soil in central Pennsylvania using historical State College weather (1982-2006). The simulated annual emission from animals and housing facilities was 14,167 kg CH₄, primarily from enteric fermentation with a small emission (330 kg CH₄) from barn floors. Other emissions included 5,990 kg CH₄ from the manure storage and 20 kg CH₄ following field application of manure (Table 7). This gave a total annual emission of 20,177 kg CH₄ from this representative dairy farm. For an overall farm emission, this predicted rate was just 1% less than the rate of 20,365 kg CH₄ yr⁻¹ that was estimated as a typical emission for a dairy farm of this size based upon the prior review of published emission data (Table 7). Overall, this comparison verifies that the model simulates CH₄ emissions very similar to those summarized from previous studies.

### Model Application

Two whole-farm simulations were done to illustrate the use of the model for evaluating management impacts on CH₄ emissions from dairy farms. Important factors that affect CH₄ production include animal diets and the capture of CH₄ from the manure storage. The model was used to simulate the 100-cow representative dairy farm briefly described above, and then management changes were made to simulate higher forage diets and a covered manure storage with a flare to burn the biogas produced.

For the base farm, lactating cows were fed a relatively high grain diet. This has been a common practice in the past with relatively inexpensive grain for feed supplementation. With a recent

<table>
<thead>
<tr>
<th></th>
<th>Representative farm [a] emissions [kg CH₄]</th>
<th>IFSM simulated emissions [kg CH₄]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Housing</td>
<td>13,324</td>
<td>14,167</td>
</tr>
<tr>
<td>Manure Storage</td>
<td>7,140</td>
<td>5,990</td>
</tr>
<tr>
<td>Croplands</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Grass</td>
<td>-27</td>
<td>--</td>
</tr>
<tr>
<td>Alfalfa</td>
<td>-52</td>
<td>--</td>
</tr>
<tr>
<td>Corn</td>
<td>-20</td>
<td>--</td>
</tr>
<tr>
<td>Total Cropland</td>
<td>-99</td>
<td>0</td>
</tr>
<tr>
<td>Field application</td>
<td></td>
<td>20</td>
</tr>
<tr>
<td>Total</td>
<td>20,365</td>
<td>20,177</td>
</tr>
</tbody>
</table>

[a] Emission rates were obtained from Sedorovich (2008). Total emissions were calculated using 183 LU in the herd and 1200 m³ for average manure in storage with feed produced from 19 ha of grass, 20 ha of alfalfa, and 50 ha of corn.
increase in grain prices, there is incentive to feed more forage produced on the farm with less
grain supplementation. This management change was simulated by switching the diet
formulation for the lactating herd from a minimum forage to a maximum forage ration (Rotz et
al., 1999). More of the corn produced on the farm was harvested as corn silage with less
harvested as high moisture grain. This produced 115 Mg DM more forage and 50 Mg DM less
grain for feeding the herd (Table 8). Total feed intake was increased about 2% with an annual
average of 44 Mg DM less supplemental feed purchased and brought on to the farm. With the
higher forage diets, animals produced about 21% more CH4. This also increased the volatile
solids content in the stored manure, which increased the emission from the storage by 6%.

This change also impacts the other greenhouse gas emissions of nitrous oxide (N2O) and CO2
(Sedorovich, 2008). Although the details of these processes are not presented here, the
simulation indicates a small decrease in N2O emission with greater use of corn silage. This
occurs because more nitrogen is being removed in the corn silage and recycled through the
animals. Carbon dioxide emission is also reduced with greater use of corn silage. With grain
harvest, greater amounts of stover are left in the field, which creates greater microbial
decomposition and ultimately more CO2 emission. By removing the whole plant in corn silage
harvest, less crop residue is left in the soil to enhance microbial respiration and the resulting
CO2 emission. Overall, this management change had very little effect on the total global
warming potential of the greenhouse gases emitted from the farm (Table 8).

Table 8. Annual production, greenhouse gas emissions and economics of three production
strategies on a simulated representative dairy farm in central Pennsylvania[a].

<table>
<thead>
<tr>
<th></th>
<th>High forage diet[b]</th>
<th>Low forage diet[c]</th>
<th>Enclosed manure storage[d]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Feed production and use, Mg DM</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Harvested forage</td>
<td>637</td>
<td>522</td>
<td>521</td>
</tr>
<tr>
<td>Harvested grain</td>
<td>109</td>
<td>159</td>
<td>159</td>
</tr>
<tr>
<td>Purchased feed</td>
<td>159</td>
<td>203</td>
<td>202</td>
</tr>
<tr>
<td>Total feed intake</td>
<td>905</td>
<td>884</td>
<td>882</td>
</tr>
<tr>
<td>Greenhouse gas emissions, kg</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Methane</td>
<td>23,475</td>
<td>20,177</td>
<td>14,251</td>
</tr>
<tr>
<td>Animal and barn floor</td>
<td>17,100</td>
<td>14,167</td>
<td>14,169</td>
</tr>
<tr>
<td>Manure storage</td>
<td>6,356</td>
<td>5,990</td>
<td>60</td>
</tr>
<tr>
<td>Field application</td>
<td>19</td>
<td>20</td>
<td>22</td>
</tr>
<tr>
<td>Nitrous oxide</td>
<td>668</td>
<td>685</td>
<td>494</td>
</tr>
<tr>
<td>Carbon dioxide</td>
<td>83,519</td>
<td>152,991</td>
<td>168,845</td>
</tr>
<tr>
<td>Net farm emission (CO2 e)[e]</td>
<td>821,069</td>
<td>819,698</td>
<td>642,951</td>
</tr>
</tbody>
</table>

[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 19 ha of alfalfa.
[b] Lactating herd feed fed a maximum forage diet (60% of forage from corn silage) while
maintaining 9,000 kg/cow milk production.
[c] Lactating herd feed fed a minimum forage diet (50% of forage from corn silage) while
maintaining adequate fiber for 9,000 kg per cow milk production.
[d] Farm with low-forage diet and enclosed manure storage. Methane from storage is
converted to CO2 through combustion (99% efficiency).
[e]Total CO2 equivalent greenhouse gas emission considering the global warming potential of
CH4 and N2O to be 23 and 296 times that of CO2, respectively.
With a tight cover on the manure storage, the CH\textsubscript{4} produced can be captured and burned. Combustion of the biogas transforms the CH\textsubscript{4} to CO\textsubscript{2}. Since the CO\textsubscript{2} has 23 times less global warming potential, the net result is a reduction in greenhouse gas emission (Table 8). Methane emission from the storage is reduced by 99% while net farm CO\textsubscript{2} emission is increased 10%. Methane emission following field application is increased a small and unimportant amount. Covering the manure storage also eliminates N\textsubscript{2}O emission from the storage by preventing any crusting on the manure surface (Sedorovich, 2008). The overall net effect of using this strategy is a 22% reduction in the total global warming potential of the whole-farm emission of greenhouse gases (Table 8).

**Conclusions**

Modules simulating CH\textsubscript{4} emissions from enteric fermentation, manure storage, field-applied manure, feces deposited in pasture, and manure on barn floors were developed and added to a farm simulation model (Integrated Farm System Model or IFSM). These new CH\textsubscript{4} modules incorporated the best available models that were consistent with our modeling objectives and with the current structure of IFSM. Model equations were based on previously published relationships and experimental data.

IFSM was shown to predict CH\textsubscript{4} emissions that were consistent with reported emissions from dairy farms, as well as from specific experiments quantifying emissions. A sensitivity analysis illustrated that model predictions responded appropriately to changes in model parameters.

With the incorporation of this CH\textsubscript{4} module, IFSM provides a tool for simulating whole-farm emissions of CH\textsubscript{4} and evaluating the overall impact of management scenarios used to reduce emissions. Farm simulations showed that increasing the use of forage (corn silage) in animal diets increased CH\textsubscript{4} emission by 17% with little impact on the global warming potential of net farm emissions of all greenhouse gases. Using a manure storage cover and burning the CH\textsubscript{4} reduced farm emission of CH\textsubscript{4} by 30% with a 22% reduction in the total global warming potential of the whole-farm emission of greenhouse gases.

**References**


