Simulating Diverse Dairy Management Systems with the RuFaS Model

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Introduction

Dairy industry progress towards sustainable production practices requires methods for whole farm environmental footprinting to support both on-farm decision-making and inventory analyses for emissions tracking to inform corporate and governmental GHG reduction targets. One challenge in the effort to build methods and models that estimate farm footprints is the ability to represent the diverse management practices found in agricultural systems with enough specificity to capture the impact of changes in management or differences between farms. Quantification of GHG emissions from US dairy production epitomizes this challenge with a huge range in both animal and manure management practices that affect production, nutrient use efficiency, and GHG emissions. The Ruminant Farm Systems (RuFaS) model is a next-generation simulation model of dairy production being developed by a trans-disciplinary team of scientists and engineers to meet the needs for environmental footprinting of diverse dairy production systems. We have built the Animal and Manure Modules to flexibly represent the most common management options seen in US dairy. To evaluate the capacity of the RuFaS model to represent diverse dairy animal and manure management systems, we collected information on management practices to inform model inputs from 32 farms across the US and applied the RuFaS model to estimate the GHG emissions from animals (enteric CH_4), manure (CH_4, direct N_2O, and indirect N_2O), and feed production (CO_2-eq). Our sampled farms vary in geographic location, herd size, husbandry practices, and manure management strategies. We summarize the availability of input data and the translation of farm management practices into inputs that achieve the closest representation by the RuFaS modeling framework and the ways in which RuFaS v. 0.9 does and does not represent the management systems found in our sampled farms. We then explore the variability in RuFaS emissions estimates and illustrate alignment of model greenhouse gas (GHG) footprints with existing estimates of dairy farm GHG emissions.

Input Data Collection

RuFaS v. 0.9 requires over 280 user inputs, a library of feed compositions, a weather dataset that includes daily temperature, precipitation, and radiation, and a dataset that includes the embedded emissions associated with feeds. The RuFaS model receives the user input data via a series of JavaScript Object Notation (JSON) files and receives the feed composition, weather, and embedded feed emission data via a series of CSV files. To reduce the burden of collecting the user input data, we identified a subset of 43 minimum required inputs and established default values for the remaining inputs based on published literature and expert opinion. Further, because JSON files are not a commonly used file type for most people collecting farm management data, we created a more user-friendly Data Collection Sheet in an excel worksheet that includes variable names and definitions, indicates which variables were minimum required inputs, provides the default values used for all optional inputs, and explains how to navigate the Data Collection Sheet. The structure and level of detail of the RuFaS model inputs reflect the fact that the model is being developed with multiple categories of model users and applications in mind. As such, there are instances where the direct model inputs are not reflective of data or management descriptions commonly used in commercial dairies. In preparation for application of the RuFaS model for commercial farm footprinting, the data requested of the farm was modified or translated from the RuFaS input variables to increase the likelihood that the request would be interpreted correctly, and that the information would be available.

Farm Enrollment and Data Collection Process

Our objective for farm enrollment in the model evaluation dataset was to include farms that represent the diversity of management practices and environments in the US dairy industry. Our goal was not to conduct an inventory of US dairy farms or dairy emissions and thus the farms are not a representative sample of management practices but rather the widest range of practices that would challenge the ability of the RuFaS model to represent each unique set of management and environmental conditions. To ensure fidelity and consistency in the data collection process, in collaboration with the FARM Environmental Stewardship program, we trained evaluators on the data requirements of the RuFaS model, provided each with a Data Collection Sheet, and provided technical support during the data collection process when needed. Evaluators collected farm management data reflecting management practices for 2022 over 4 months in 2023. In the following sections, we will summarize the methods we used to adapt RuFaS input requirements for collection of commercial farm data and instances where default values were provided to overcome data disparities.

Animal Feeding Data Collection and Translation

The diet recipes in RuFaS are either formulated through least-cost formulation (Li et al., 2021) or provided by the user for each of 4 animal categories (calves, growing heifers, dry and close-up cows, and lactating cows). The composition of the available feeds are provided by a feed library that was adapted from the NASEM Dairy Cattle Nutrient Requirements model (2021). The amount of feed required by the farm is tracked by pen and multiple pens of each animal category can be simulated; however, at this time, the RuFaS model can only accept 1 user-defined diet per animal category even if there are multiple simulated pens for that animal category.

In practice, animal feeding on dairy farms is a constantly evolving process that responds to fluctuations in feed availability, animal requirements and responses, and management goals. Although the feed delivery algorithms will make small modifications to the diet recipe in response to animal nutrient requirements and adjust the total amount of feed delivered based on the number of animals and their requirements, the diversity and degree of fluctuation in the diets is less than what is expected on a commercial dairy. To account for this discrepancy, if a farm provided more than one diet for animals that RuFaS represents as a single category of animals (e.g. a high- and low-lactating cow diet), a weighted average of the diets was used to define the RuFaS diet inputs.

Another element of the feed data inputs that required some translation between farm data and RuFaS inputs are the feed types themselves. Dairy farmers feed numerous feeds that are not represented in the RuFaS feed library. Although the RuFaS feed library can be modified by changing the compositions of the existing feeds or by adding new feeds we did not provide that option during this evaluation study. If a feed was reported by a farm that was not available in the existing library, we selected the feed that most closely represented the reported feed.

Finally, while the case of averaging multiple diets illustrates an example where farms provided more feeding data that RuFaS could accept, lack of availability of feeding data was another common problem. To reduce the burden of collecting and reporting feeding data, we provided the option to use average regional diets for growing animals and dry cows (lactating cow diet information was required) and added 4 by-product mixes to the RuFaS feed library with compositions that represented regional average by-product inclusion rates. Thus, the resulting minimum required data inputs for feeding data was a diet for lactating cows that had the option to include a byproduct mix of feeds common for that region.

Herd Management Data Collection and Translation

The RuFaS Animal Module is a dynamic, process-based model that simulates individual animals on a daily time-step from birth or purchase through their exit from the herd (death or sale) (Hansen et al., 2021; Li et al., 2023). To facilitate flexibility and granularity in simulation of different animal classes, the Animal Module requires detailed inputs of the reproductive management and culling practices that are either not readily available or do not easily translate into farm management information. For commercial farm data collection purposes we translated and simplified 4 groups of RuFaS user inputs within the Animal Module to achieve the desired simulated outcomes. The 4 categories of user inputs are 1) milk production, 2) breeding programs, 3) heifer replacements, and 4) cow exits and are described in more detail below and summarized in Table 1.

Milk Production

The RuFaS model uses a simple model of milk production over time, the Wood’s lactation curve, that uses 3 parameters to determine the shape and total milk production over time. These parameters are not information that most scientists have, let alone a commercial dairy farm. To overcome this barrier to application of the RuFaS model in commercial farm settings, we developed a method to estimate farm-specific lactation curve parameters using previously published parameter estimates (Li et al., 2022) and the farm-provided total annual milk production. Heuristically, we select the 2 parameters that define the shape of the curve (the rate of increase and rate of decrease) based on the location and management practices from the published set of parameter estimates and then fit the scale parameter to farm-specific total milk production.

Table 1. Groups of user inputs required by the RuFaS Animal Module that were modified during data collection to align with farm data availability and granularity

Category of input	RuFaS Animal Module Inputs	Data and Information Collected from Farm
Milk Production	Estimates of the mean and standard deviation of the 3 parameters that define the Wood's lactation curve for parities 1, 2, and 3+	Annual fluid milk production
Breeding Program	Heifer and cow breeding start and end dates, general reproduction strategy, specific reproduction protocols, conception rates	Age or DIM at first service; average conception rates for each service for heifers and cows
Heifer Replacements	Male calf rate, keep female calf rate, still birth rate	Number of replacements raised on farm
Cow Exits	Cow do not breed day in lactation, milk production threshold for culling, non-production cull rates for each parity	Number of cows sold and died

Breeding Programs

In practice, dairy cow breeding programs are made up of a complex series of decisions that determine when the heifer or cow is eligible for breeding, how to know the best time to breed a cow including whether or not to manipulate her estrus cycle, and when to stop trying to breed an animal and sell her. To provide flexibility in representation of reproductive management practices, the RuFaS model requires inputs for the days in an animal's life cycle when she becomes eligible for breeding (age at first breeding and the voluntary waiting period), the general breeding strategy (estrus detection and timed artificial insemination), the specific synchronization and re-synchronization protocols (e.g. Ovsynch-56 and Ovsynch at diagnosis of an open cow), the day in the animal's life when breeding attempts are stopped (for both heifers and cows), and the insemination and conception rates for each breeding protocol. To reduce the complexity and number of inputs required to define the reproduction program for commercial farm footprinting, the FARM-ES evaluators were trained to ask for a description of the practices and average timing of the average timing for first service and protocol for open cows at pregnancy check for cows and heifers separately. From this information, we specified the breeding start dates, success rates, and protocols that aligned with the breeding schedules provided.

Heifer Replacements

RuFaS V0.9 has the option to specify different semen types (conventional, sexed, and beef) as well as expected rate of male calves produced from each type of semen. However, at this time, the model does not support use of multiple semen types in the same simulation which is not representative of what happens on a farm. To account for this gap in desired functionality, we modified the application of how the semen type and male calf rate of the semen type are used in coordination with the input that determines the percent of female calves that are kept and raised on farm to achieve the desired number of replacement heifers. To collect the information needed for defining these inputs from the study farms, we asked for the total number of replacements needed by the farm and the number or percent of those that were raised on the farm. If this information was not available, we assumed all replacements were raised on the farm and calculated the number required to achieve the herd turnover rate. Future versions of RuFaS will improve the representation of semen types so that more than one type of semen can be used in the same scenario/farm.

Cow Exits

RuFaS v0.9 has several mechanisms that determine when cows leave the herd that can be grouped into two categories. The first category of simulated cow exits are when cows do not conceive by the user-defined breeding cutoff date. When the simulated cow exceeds the breeding window cutoff without conceiving, she is tagged for removal from the herd but will proceed with her lactation until her production drops below a milk production threshold (also a user input). The second group of simulated cow exits are when cows leave the herd due to death or other health and disease incidents. These cow exits are determined by designated parity-specific probabilities for death and other diseases. We have found that these two separate mechanisms for cow removals present a challenge for translating the farm management practices to achieve the herd dynamics and demographics based on commonly available management data and strategies in part because the numbers of cows exiting the herd are not grouped into these two categories in practice and because the reasons cows do leave the herd are often complex and no standard reporting/recording metrics exist.

The default inputs for cow death and non-production removal rates are based on a literature report and can be used as a starting place for these values that are not typically available on farm. However, these rates should be adjusted if the combination of the number of cows leaving for production (failure to conceive) and non-production reasons do not match the farm’s herd turnover rate calculated as the ratio of the number of cows sold to the adult herd size. Thus, the number of adult cows sold is the minimum required user input which can be used to adjust the default inputs for the parity specific rates of cow death and sale by parity, after taking into account the expected number of unsuccessful breedings.

Manure Management Data Collection and Translation

The Manure Module provides the option to define as many manure management systems as desired and includes a range of liquid and solid manure management options. The systems follow manure from collection through storage and are assigned to the animal pens with 1:N relationships – meaning each manure system can be assigned to many pens. While this provides a reasonable amount of flexibility, it does not account for settings where animals spend part of their time within a day or across the year in a different location and thus deposit their manure in more than one location. Thus, allocation of manure management systems to pens of animals in RuFaS also required some translation to most closely represent the amount of manure managed in each system. To do this, in addition to collecting information about the number and types of animals contributing to each manure management system, in cases where manure from the same animals contributes to multiple manure management systems, we also gathered information about those animals' time budgets and defined separate animal pens with animal numbers that reflected the percent of time or manure that should be allocated to each system. For example, if a farm had 100 cows in a compost-bedded pack barn for 4 months and on pasture for 8 months, then we would create two pens, one that is assigned a compost bedded pack manure management system and contains 33 cows and the other that would be assigned to a daily spread management system with 67 cows. Farms were required to specify at least one manure management system for their lactating herd.

Farm Characteristics and Input Data Availability

The resulting set of 32 farms included representation of farms from 16 states, 26 of which raised predominantly Holstein cows and 7 of which raised predominantly Jersey cows. The median adult herd size of the farms was 1,014 and ranged from 51 to 9,300 with a median Fat and Protein Corrected Milk (FPCM) production of 33.3 kg ranging from 19.8 kg to 47.7 kg. The herd management strategies included examples of low input practices like estrus detection, long breeding windows, low thresholds for dry-off, and minimal selection pressure that resulted in low herd turnover rates as well as herds with higher input systems that resulted in high turnover rates. Housing and manure management practices also varied widely and included farms in which all cows were housed in confined pens with liquid manure management and those using open-lot or compost-bedded back barns and relying almost exclusively on dry manure management systems.

As the information provided in the Data Collection Sheets was translated into RuFaS JSON input files, we recorded notes about instances where the provided data and information did not directly match or required interpretation to achieve inputs that matched the RuFaS required input. These notes were coded and summarized into 13 different types of input translations, modification, and data availability (Table 2). We found that the 3 most common needs to adapt the farm-provided information for input into RuFaS were in the selection of the appropriate feeds from the feed library, calculation of the non-production cull rates by parity from the total number of cow sales, and calculation of the male calf rate/ keep female calf rate to achieve the desired number of youngstock.

Another common gap between the available data and the model inputs were instances where the combination of the herd management and demographic data did not result in a viable herd (i.e. the reported number of youngstock or conception rates were too small to maintain the reported lactating herd). In addition, there were several farms that required application of pre-planned adaptations of the model to most closely represent their management system. These included 7 cases where manure management systems and animal pens were allocated according to the amount of the animal's time budget contributing to each manure system; 9 cases where the average regional diet for youngstock was used; 6 cases where the average regional diet for dry cows was used; and 5 cases where the farm raised heifers offsite so an average heifer raising management system for that region was assumed.

Table 2. Summary of farm input data availability and instances where management practices were not directly represented by the RuFaS model

Description of missing inputs or lack of representation within RuFaS	**Number of Farms that Required this input translation**
No direct match for feed in feed library	14
Non-production cull rates modified to match farm provided inputs	14
Calculated male calf rate/ keep female calf rate to achieve desired youngstock population	13
Updated death rates by lactation to match farm provided input	11
No youngstock diets provided; default regional diets used	9
Herd demographic inputs not provided or provided demographics are not representative of a realistic herd	8
Pens created to support allocation of manure management by time budget	7
Modified production cull management inputs to align with herd demographics	6
No dry cow diets provided; default regional diets used	6
Heifers raised offsite	5
No heifer reproduction management inputs provided	5
Translated farm manure separator(s) description to a single RuFaS separator option by updating separation efficiency	5
Did not provide manure management info for youngstock; used regional default or same as lactating cow	9

Emissions Estimates

The RuFaS model reports a wide range of results related to production and nutrient cycling in addition to GHG emissions. Here we focus on the GHG emissions outcomes as one of the most important use cases for the dairy industry. As a process-based model, RuFaS directly reports total emission losses from each pen, animal group, and manure management system on a daily basis. Records of animal bodyweights, sales, and purchases enable allocation of emissions milk and meat. To summarize the daily, granular data reported by the RuFaS simulation model, we applied the newly developed data processing features in the larger RuFaS model to calculate more commonly used metrics in alignment with emissions reporting guidance and are reporting annual emission intensity using the biophysical allocation method recommended by the International Dairy Federation (2022).

In our testing dataset, estimates for GHG emissions intensity ranged from 0.831 to 1.91 kg CO_2-eq / kg FPCM with a median value of 1.18 kg CO_2-eq / kg FPCM. These estimates are in line with previously reported values for whole farm carbon footprints of US Dairy Farms (i.e. Capper and Cady, 2020; Rotz et al., 2021; Uddin et al., 2021; Olivo et al., 2024). In their 2021 analysis, Rotz et al. applied a process-based model to a set of archetypal farms designed to create a representative sample of US production in 2019 that resulted in estimates of GHG emissions intensity that ranged from 0.69 to 1.45 kg CO_2-eq / kg FPCM with a weighted average of 1.01 kg CO_2-eq / kg FPCM. Results are not directly comparable due to differences in model structure and assumptions, but it is worth noting that the intensity estimates produced by the RuFaS model encompass a wider range and a higher maximum estimate than those from the IFSM model reported by Rotz et al. (2021).

To further our understanding of the factors contributing to dairy emissions, boxplots of the sources of emissions are provided in Figures 1 and 2. As expected, on average, enteric emissions are the largest contribution to dairy production emissions intensity with an average contribution of 0.46 kg CO_2-eq/kg FPCM which represents 37.7% of the carbon footprint. The second largest source of emissions is feed production which contributed an average of 0.41 CO_2-eq/kg FPCM to the emissions intensity, or 33.4% of the footprint. Manure methane and nitrous oxide emissions combined produced an average of 0.35 kg CO_2-eq/kg FPCM and represented 29.0% of the footprint. The relative contribution of each emission source is similar to the 43% for enteric emissions, 26% for feed production, and 25% from manure emissions reported by Rotz et al. (2021).

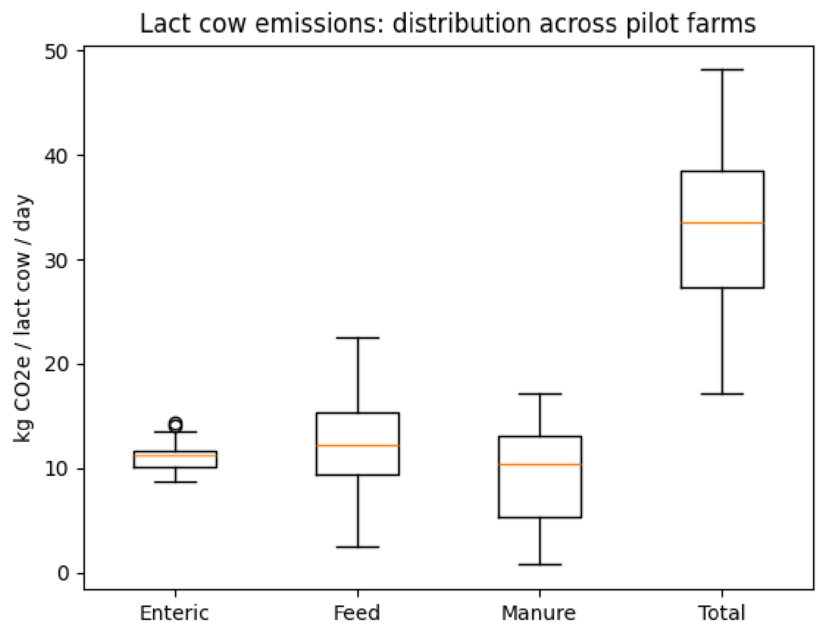

Figure 1. Distribution of whole farm greenhouse gas emissions estimates in units of CO_2-eq per lactating cow per day by emissions category (Enteric, Feed, and Manure), and the total emissions.

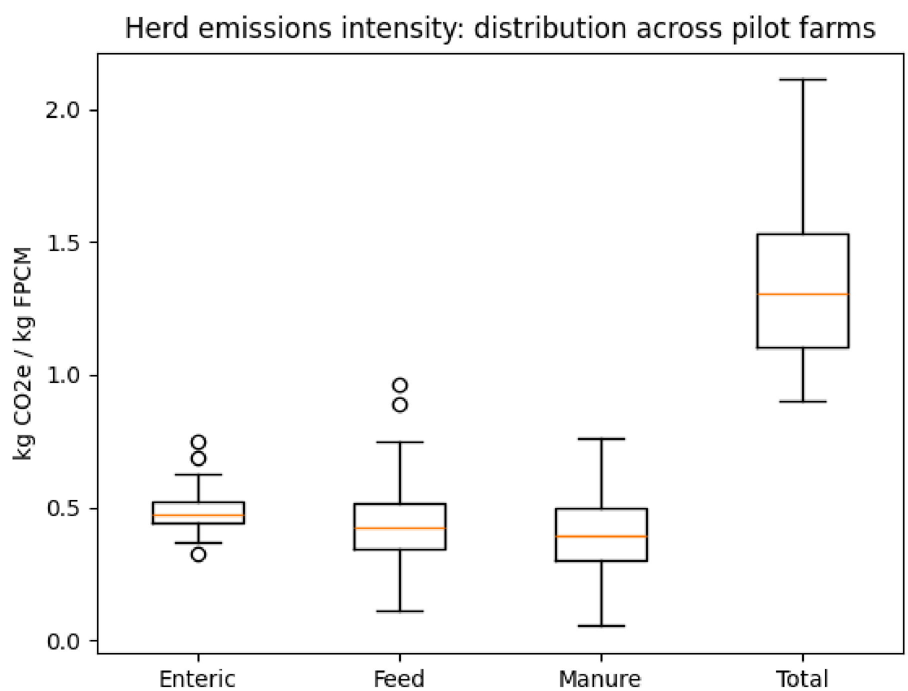

Figure 2. Distribution of whole farm greenhouse gas emissions intensity estimates in units of CO_2-eq per kg of FPCM by emissions category (Enteric, Feed, and Manure), and the total emissions.

Although, Rotz et al. (2021) did not report the distribution of emissions by source, the boxplots in Figure 1 illustrate that predicted emissions per unit of milk and per animal from both feed production and manure management have a larger range than those of enteric emissions. The contribution of emissions from feed production is also likely the most different between the two studies and can be attributed to the different values used to estimate the emissions associated with feed production. In our study, we used a spatially explicit library of emissions associated with feed production developed for the RuFaS model. This library is based on county-specific estimates for 7 of the most common dairy feeds provided by the FoodS^3 group (Pelton et al. 2024, Pelton et al. 2021, http://www.foodscubed.umn.edu/); regionally specific estimates for 17 common by-product feeds produced by an LCA conducted by LEIF, LLC and commissioned by NMPF; and national estimates from the IPCC 2021 report for all remaining feeds. The feed emissions intensities used by Rotz et al. (2021) reported in their Table 2 are often ½ to 1/3 of the median estimates in the database compiled for the RuFaS model. For example, the emissions intensities of corn grain and alfalfa hay used in the IFSM study are 0.37 and 0.18 kg CO_2-eq/kg DM while the median estimates from the FoodS^3 group for these important dairy feeds are 0.63 and 0.50 kg CO_2-eq/kg DM. Similarly, the estimates for byproduct feed emissions intensities produced by the recent LCA resulted in higher estimates than those reported by Rotz et al. (2021). The average estimates for emissions associated with corn gluten feed and dried distiller's grain production in our database were 0.66 and 1.21 kg CO_2-eq/kg DM, respectively which is substantially greater than the values of 0.30 and 0.60 kg CO_2-eq/kg DM used by Rotz et al. (2021) for the same feeds. The higher average values of emissions associated with feeds and the spatially explicit estimates for this source of emissions likely explain much of the higher, wider range of estimates seen in this study compared to that of Rotz et al. (2021). The aggregate CO_2-eq estimates from both the regional LCA and the county level estimates from the FoodS^3 group include both carbon sequestration and the emissions associated with land use change; the latter of which is likely a key factor contributing to the higher estimates of feed emissions. Future work in the RuFaS model will add methods to estimate the carbon sequestration and land use change emissions from purchased feeds separately.

Summary

The RuFaS model is developed for application in both research and industry decision support. To meet these dual objectives, some adaptation of model inputs is required. We found that methods to simplify input requirements for animal diets and available feeds, interpret breeding and herd demographics within the RuFaS dynamic animal life cycle module, and translation of manure management systems based on animal time budgets were required to represent the diverse set of management practices captured in the set of farms enrolled in this study. Simulation of these farms produced estimates for GHG emissions intensity that have a wider range of values than previously reported estimates for emissions associated with feed production and manure management in particular.

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