Development of an Emissions Model to Estimate Methane from Enteric Fermentation in Cattle

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ABSTRACT

Cattle are the largest contributing livestock species to enteric fermentation emissions in the United States, accounting for over 95 percent of the methane emissions from this source. These emissions account for almost 20 percent of the total anthropogenic methane emissions in the United States. In order to more accurately characterize the emissions from this source, EPA has recently focussed its attention on adopting and improving the Intergovernmental Panel on Climate Change (IPCC) Tier 2 method for estimating methane emissions from cattle. In the latest versions of the U.S. Inventory, regional diet characterizations and corresponding digestible energy and methane yield values were used by EPA to implement the IPCC Tier 2 net energy and methane emission equations in a computer model that tracks and estimates emissions from cattle population sub-categories on a regional and temporal basis. The most significant modification to the IPCC Tier 2 method that EPA made was to model cattle sub-populations on a monthly basis. Factors such as weight gain, birth rates, pregnancy, feedlot placements, and slaughter rates were tracked to characterize the U.S. cattle population in greater detail than in previous inventories, in which only end-of-year population data were used. This modification is a significant refinement of the basic IPCC Tier 2 method, in that the energy requirements of the cattle sub-populations are tracked through their development stages across the year.

INTRODUCTION

Methane (CH_4) is produced as part of the normal digestive process in animals. During digestion, microbes resident in an animal's digestive system ferment food consumed by the animal. This microbial fermentation process, referred to as enteric fermentation, produces methane as a by-product, which can be exhaled or eructated by the animal. The amount of methane produced and excreted by an individual animal depends primarily upon the animal's digestive system, and the amount and type of feed it consumes.

Among domesticated animal types, ruminant animals (e.g., cattle, buffalo, sheep, goats, and camels) are the major emitters of methane because of their unique digestive system. Ruminants possess a rumen, or large "fore-stomach," in which microbial fermentation breaks down the feed they consume into products that can be metabolized. The microbial fermentation that occurs in the rumen enables them to digest coarse plant material that non-ruminant animals cannot. Ruminant animals, consequently, have the highest methane emissions among all animal types.

In addition to the type of digestive system, an animal's feed quality and feed intake also affects methane emissions. In general, a lower feed quality and a higher feed intake leads to higher methane emissions. Feed intake is positively related to animal size, growth rate, and production (e.g., milk production, wool growth, pregnancy, or work). Therefore, feed intake varies among animal types as well as among different management practices for individual animal types.

Cattle, including beef and dairy, are the largest contributing livestock species to enteric fermentation emissions in the U.S., accounting for over 95 percent of the methane emissions from this source. In preparing the *Inventory of U.S. Greenhouse Gas Emissions and Sinks* (EPA 2002), EPA uses a spreadsheet-based model, called the Cattle Enteric Fermentation Model (CEFM), to calculate methane emissions from cattle enteric fermentation based on a 'rolling herd' population characterization that tracks cattle energy demand through different growth stages. These energy demands are then correlated with methane production based on diet and animal characteristics.

The CEFM is based on the IPCC Good Practice Guidance Tier 2 approach (IPCC 2000). The fundamental energy utilization equations are from the IPCC guidance, however a significant modification to the IPCC Tier 2 method made by EPA was to model cattle sub-populations on a monthly basis instead of an annual basis. Factors such as weight gain, birth rates, pregnancy, feedlot placements, and slaughter rates are tracked to characterize the U.S. cattle population. This modification is a significant refinement to the basic IPCC Tier 2 method, in that the energy requirements of the cattle sub-populations are tracked through their development stages across the year, instead of applied to end-of-year standing population totals.

These methods for estimating methane emissions from enteric fermentation resulted in increased levels of detail, such as definitions of livestock sub-categories, livestock populations by sub-category, and feed intake estimates for the typical animal in each subcategory. Cattle populations are categorized in much more depth through the modeling of the populations and energy requirements month-to-month.

METHODOLOGICAL FRAMEWORK AND RESULTS

The CEFM estimates methane emissions from U.S. dairy and beef cattle based on projected cattle age and weight distributions, production types, and feed characterization as inputs for the IPCC Tier 2 emission equations. The CEFM applies the IPCC enhanced livestock characterization equations (IPCC 2000) in conjunction with a specialized population transition matrix to first determine the gross energy (GE) intake of each cattle subcategory and then the subsequent emissions. Through inclusion of detailed data addressing: 1) annual animal growth and population changes; 2) diet characterization, and 3) the associated methane yields for each population and diet type, the model provides a process-type method of livestock emissions analysis. This section describes these three distinct processes that the model performs.

Cattle Population Characterization

Methane emissions from cattle vary by animal type, weight, production phase (e.g., pregnant or lactating cow), and feed type. Accounting for these variations in a cattle population throughout a year is important to accurately characterize annual emissions. Emission estimates based on a homogenous population assume that herd size and individual animal characteristics remain constant throughout a given year; however, this assumption is an oversimplification of the population. In order to address the changes in the cattle population that occur through the course of a year, the CEFM uses a Cattle Population Transition Matrix (population matrix) that provides detailed population input data for the model.

The statistics necessary for determining initial conditions and composition of a cattle population include data on beginning and end-of-year population numbers, monthly births and weight gain for calves, set target weights by age for older animals, number of animals imported into a population, pregnancy rates, milk production, natural death rates, and number of animals in varying weight categories that are placed in feedlots. The initial age composition of the population is based on ages of all animals in January of the current modeled year and age distribution in January of the following year. The population matrix distinguishes cattle by males, females, beef, and dairy and tracks their growth in life cycle stages by month from birth to slaughter. See Table 1 for a complete list of the cattle subcategories used in the model.

Table 1. Cattle sub-populations in CEFM.

Dairy Cattle (age)	Weight Range (lbs)	Beef Cattle (age)	Weight Range (lbs)
Calves (0-6 months)	88 – 575	Calves (0-6 months)	88 – 575
Heifer replacements (7-23 months)	500 – 1,225	Heifer replacements (7-23 months)	500 – 1,078
Cows (mature animals)	1,350	Heifer and steer stockers (7-23 months)	500 – 1,000
		Animals in feedlots (7-23 months)	500 – 1,267
		Cows (mature animals)	1,172
		Bulls (mature animals)	N/A

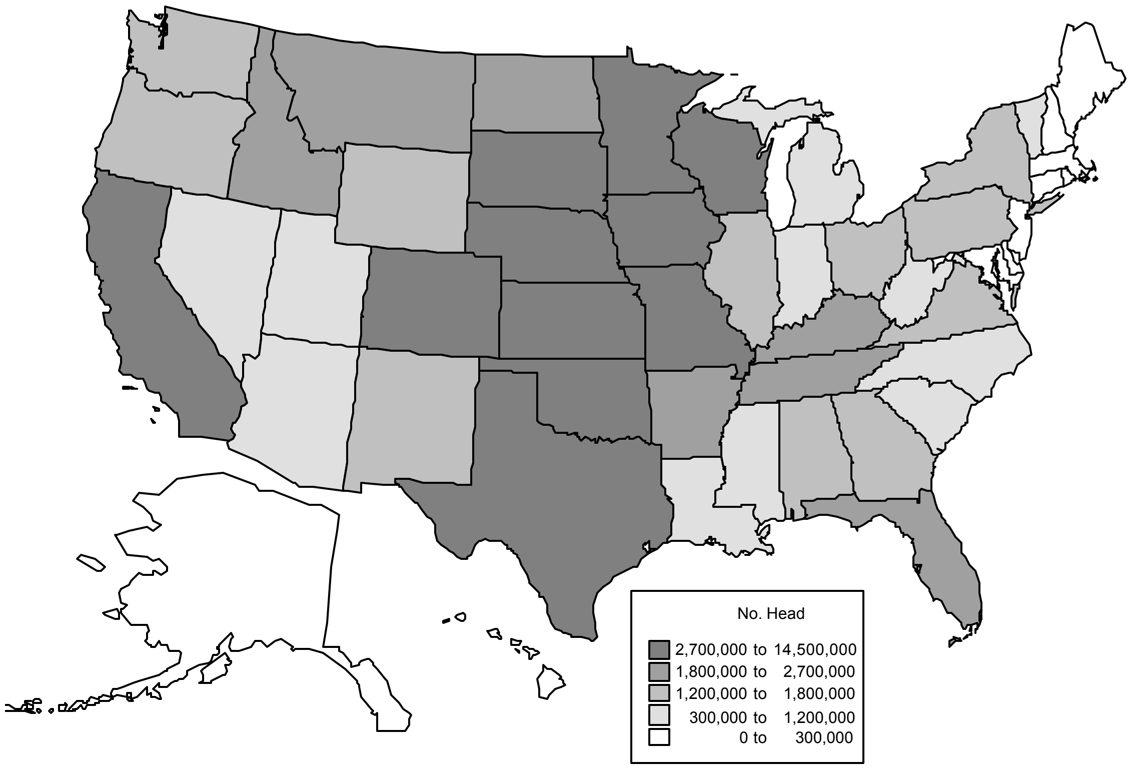
To determine beginning and end-of-year cattle populations, the population matrix uses the U.S. Department of Agriculture (USDA) National Agricultural Statistics Service (NASS) population census by state for cattle and livestock slaughter (USDA 2002a, 2002b). The USDA census statistics for 2001 are shown in Figure 1. The population matrix uses beginning and end-of-year USDA population data along with movement between categories to "back-calculate" monthly population estimates. Modeled cattle populations in the matrix change based on animal "graduation" to different population types (e.g., replacements become dairy cows in dairy cattle populations, or beef or heifer stockers become feedlot animals in the beef cattle populations), natural death rates, rates at which animals are sent to feedlots in preparation for slaughter, and slaughter rates.

To track population changes logically by month, the matrix follows lifecycles of "cohorts" of cattle divided by age group. Cohort populations by month are determined by births or "graduation" to a cohort (e.g., a calf can become a replacement at the age of seven months) and cattle that die, are slaughtered, or move to a new category. Birth rates are assumed to be constant for dairy cows. The percentage of beef versus dairy calves born is determined by data on calving percentages combined with data on total numbers of dairy cows (remaining calves are beef calves). The population matrix assumes that 50 percent of calves born are male and 50 percent are female.

As an example of cohort lifecycles in the population matrix, each individual of a cohort of 24 beef calves born in January can be tracked through the following January. One-third of these calves could be slaughtered for veal production after four months and one-third could become replacements for stockers at seven months, leaving a population of eight stocker heifers and steers that will eventually be placed in feedlots.

Feedlot cohorts are tracked differently than other animal types, as some animals are sent to feedlots near the end of the current modeled year and are slaughtered in the following year. The enteric fermentation model stores data on these animals for the following year. Emissions data for animals that remain in feedlots are subtracted from the current modeled year and later added to emissions estimates for the following year.

Figure 1. Cattle populations in the United States, 2001.



As individuals within each cohort of cattle graduate to different animal types throughout a year, the model tracks weight gain and weights by month. The weight variable is an important component of the gross energy (GE) calculations to determine emission factors. The monthly rate of weight gain is determined by identifying the target weight for animals and the number of months for animals to reach that target weight. As weight gain over time from birth for each cohort is tracked, a weight matrix for animals at current ages is produced. Weight is assumed to remain constant for mature animals. Weight gain in feedlots is based on the special diets that cattle receive in preparation for slaughter. The cattle are first placed on a "step-up" diet to allow transition to the new feedlot diet. Cattle are assumed to consume step-up feed for 25 days, during which they gain 2.8 to 3 pounds per day. The cattle are then placed on a finishing diet prior to slaughter, during which they gain 3 to 3.3 pounds per day. The length of time that cattle remain on finishing diets is determined by target slaughter weight of animals, starting weight when animals are placed on a diet, daily weight gain, and slaughter statistics from USDA NASS.

Another important characteristic, in addition to weight, that determines GE is the number of pregnant and lactating cows within a cattle population. Lactation data are based on the percentage of cows that give birth each month, multiplied by annual milk production estimates in pounds per animal in a given region. The monthly percentage of pregnant beef and dairy cows is estimated using National Animal Health Monitoring System (NAHMS) data on the percentage of cows born monthly and then back-calculated to the month of conception based on nine-month pregnancy periods.

Cattle Diet Characterization

As a cohort of cattle grows through the year, amounts and types of feed consumed change. The type and amount of feed consumed by a ruminant (which varies by region, age, production function, and weight), and the efficiency with which the animal digests the feed, determines methane emissions. Typically, higher-quality feeds such as supplements, high-nutrient pasture, and high-energy diets, result in increased production and reduced methane emissions per feed unit over lower-quality feed such as rangeland. This is because higher quality feed is digested more efficiently and thus more energy is available to meet the animals' production needs for milk, pregnancy, or weight gain. Methane conversion rate (Y_m) values indicate the fraction of gross energy an animal consumes that is converted to methane. Generally, the more digestible a feed is the lower the Y_m will be (and thus lower methane emissions).

Cattle use feed energy for maintenance, growth, and production. Maintenance energy is defined as the amount of energy required for an animal's survival; all remaining energy contributes to growth and production, such as weight gain, lactation, or growth of a fetus. The enteric emissions model characterizes diets separately for dairy, feedlot, and grazing beef animals. Diet types include rangeland, pasture, supplements, and high-energy diets and are modeled for seven regions within the United States in the CEFM. Digestible Energy (DE) values are calculated for each diet type and represent the percent of GE intake of the feed that is digestible to the animal. Where regional DE values are not available for a particular animal's diet, a very similar measure of total digestible nutrients (TDN) as a percent of dry matter is used.

Initial data on dairy cow diets were collected through interviews with dairy experts in the fifteen highest-producing dairy states. For all other states, data from the nearest of the fifteen states were used and extrapolated to representative regional diets. Data from dairy experts included the types of feeds and proportions that constitute the total mixed ration (TMR) of feed, and constituents and proportions of grazing diets for dairy cattle. Experts also provided data on the amount of time animals spent grazing and the percentage of the population that grazed during this time period. DE and Y_m values for dairy cows were then estimated using a model (Donovan and Baldwin 1999) that represents physiological processes in the ruminant animals. The three major categories of input required by the model are animal description (e.g., cattle type, mature weight), animal performance (e.g., initial and final weight, age at start of period), and feed characteristics (e.g., chemical composition, habitat, grain or forage).

To calculate the DE values for grazing beef cattle, diet descriptions obtained from the National Resource Council's publication of beef cattle nutrient requirements (NRC, 2000) were used to estimate weighted DE values for a combination of forage only and supplemented diets. Where DE values were not available for specific feed types, total digestible nutrients (TDN) as a percent of dry matter (DM) intake was used as a proxy for DE as it is essentially the same as the DE value. For forage diets, two separate regional DE values were used to account for the generally lower forage quality of rangeland pasture in the western U.S. as compared to other regions of the country.

Feedlot cattle diet characteristics were determined based on recommendations and input from feedlot nutrient experts. Feedlot diets are highly specialized to achieve maximum growth and production of the animals. Experts provided data on step-up and finishing diet ingredients. Proportions of DE and Y_m data for these two types of feedlot diets were obtained and expanded to be representative of different regions of the county. (Johnson 1999).

Table 2 shows the 2001 model assumptions of cattle feed in various U.S. regions.

Table 2. DE (%) by region of the United States, 2001.

Cattle Type	California	West	Northern Great Plains	Southcentral	Northeast	Midwest	Southeast
Dairy Cows	69	66	69	68	69	69	68
Dairy Repl. Heif.	66	66	66	64	68	66	66
Beef Cows	63	57	64	62	63	63	62
Beef Repl. Heif.	65	59	66	64	65	65	64
Steer Stockers	65	59	66	64	65	65	64
Heifer Stockers	65	59	66	64	65	65	64
Steer Step-Up	73	73	73	73	73	73	73
Heifer Step-Up	73	73	73	73	73	73	73
Steer Feedlot	85	85	85	85	85	85	85
Heifer Feedlot	85	85	85	85	85	85	85

Emissions Estimates

The CEFM employs the population matrix and diet characterization to estimate total methane emissions from cattle in three steps, which include: 1) derivation of gross energy (GE), 2) calculation of an emission factor in kilograms of methane emitted per head per day, based on GE and Y_m, as shown in Equation 1, and 3) total annual emissions based on daily methane emission factors and monthly subpopulations of animals by type.

Equation (1) $$DayEmit = [GE \times Y_m] / [55.65 \text{ MJ/kg } CH_4]$$

where

DayEmit = emission factor (kg CH_4/head/day)
GE = gross energy intake (MJ/head/day)
Y_m = methane conversion rate which is the fraction of gross energy in feed converted to methane (percent)

1. Gross Energy

Gross energy is a calculation of the amount of MegaJoules (MJ) produced daily by cattle based on energy maintenance, animal activity, weight gain, lactation, and pregnancy. Also included in the calculations of GE is the net energy gained from weight loss, the ratio of available net energy to the DE consumed based on diet, and the net energy required for growth. The CEFM uses the fundamental GE calculation equations from the IPCC Tier 2 equations for enteric fermentation (IPCC, 2000). In the CEFM, GE is calculated for each cattle sub-category by month using the IPCC energy equations, DE values from the diet characterization, and the integrated population matrix values.

2. Emission Factors

Y_m values (the fraction of GE that is converted to methane) are multiplied by GE to determine emission factors for cattle, in kilograms of methane emitted per head of cattle per day. To better reflect the diet and feeding characteristics of cattle in the United States, EPA developed country-specific Y_m values as an alternative to the default values provided in the IPCC guidelines. Table 3 presents Y_m values by cattle type and region determined by modeling simulated cattle digestion of various feed types, published data, and statistics from experts (Johnson, 1999 and 2002; Donovan and Baldwin, 1999).

Table 3. Y_m (%) values by cattle type and region of the United States, 2001.

Cattle Type	California	West	Northern Great Plains	Southcentral	Northeast	Midwest	Southeast
Dairy Cows	4.8	5.8	5.8	5.7	5.8	5.8	5.6
Dair. Repl. Heif.	5.9	5.9	5.6	6.4	6.3	5.6	6.9
Beef Cows	6.5	6.5	6.5	6.5	6.5	6.5	6.5
Beef Repl. Heif.	6.5	6.5	6.5	6.5	6.5	6.5	6.5
Steer Stockers	6.5	6.5	6.5	6.5	6.5	6.5	6.5
Heifer Stockers	6.5	6.5	6.5	6.5	6.5	6.5	6.5
Steer Step-Up	4.8	4.8	4.8	4.8	4.8	4.8	4.8
Heifer Step-Up	4.8	4.8	4.8	4.8	4.8	4.8	4.8
Steer Feedlot	3.0	3.0	3.0	3.0	3.0	3.0	3.0
Heifer Feedlot	3.0	3.0	3.0	3.0	3.0	3.0	3.0

3. Estimates of Total Cattle Methane Emissions

Emission factors by cattle type (in kilograms of methane per head per day) are multiplied by population data and number of days per month to produce total monthly methane emissions, in kilograms, from cattle enteric fermentation by region. The totals for all months are summed to estimate total annual emissions. Although the population data are applied regionally, the final output is easily disaggregated back to the state level. The model produces emission estimates in kilograms per year for dairy and beef cows, beef and dairy replacements, steer and heifer stockers, and steer and heifer feedlot animals. Model outputs are presented by region and animal type, age, and production phase. Table 4 presents 2001 methane emissions from U.S. cattle by animal type and region. Figure 2 shows the 2001 emissions by state.

Table 4. 2001 U.S. methane emission totals by cattle type (Gg).

Cattle Type	California	West	Northern Great Plains	South-central	Northeast	Midwest	South-east	Total[a]
Dairy	**208**	**192**	**60**	**65**	**234**	**426**	**97**	**1,282**
Cows	166	164	50	55	192	348	79	1,055
Replacements 0-12 months	9	6	2	2	9	17	4	48
Replacements 12-24 months	33	21	8	7	33	62	14	179
Beef [b]	**94**	**348**	**1,197**	**932**	**56**	**547**	**544**	**3,936**
Cows	58	236	682	654	38	351	473	2,492
Replacements 0-12 months	1	6	16	12	1	8	9	54
Replacements 12-24 months	5	24	60	45	4	28	34	200
Steer Stockers	14	35	152	81	6	67	17	372
Heifer Stockers	4	17	104	48	3	32	8	215
Feedlot Cattle	12	30	183	91	3	62	2	384
Bulls [b]	N/A	N/A	N/A	N/A	N/A	N/A	N/A	219
Total	**302**	**540**	**1,257**	**996**	**290**	**973**	**642**	**5,218**

[a] Totals may not sum due to independent rounding.
[b] Bull statistics were only modeled at the national level and are not included in the regional totals.

In summary, the CEFM process combines the population matrix input with diet characterization data, as described above, to estimate the annual amounts of methane emitted by various cattle types in each year. The model tracks information for individual cohorts and applies this information to groups of similar animals for input into Tier 2 IPCC equations. Animals in the model are distinguished by subcategory and weight.

Figure 3 presents CEFM-modeled annual methane emission estimates for cattle in the United States from 1990 through 2001. The variations by year represent the interaction of all of the variables involved in the CEFM calculations. From 1990 to 2001, emissions from cattle enteric fermentation have decreased by 2.2 percent (5,336 Gg methane compared to 5,218 Gg methane). Emissions overall have been decreasing since 1995, mainly due to decreasing populations of both beef and dairy cattle, improved feed quality for feedlot cattle, and improved productivity and feed quality for dairy cows. Looking more specifically at feedlot cattle during this time period, although average annual populations of cattle in feedlots increased, total emissions from feedlot cattle decreased due to improvements in feed quality that resulted in lower emission factors. In the dairy industry, cow populations in the United States have been decreasing over the last decade, although total milk production has increased as a result of the increase in milk production per cow. The CEFM factor calculations are sensitive to the effects of the increase in dairy cow diet quality and the increase in milk production (which increases the feed intake of the animal), with the net effect being a general decrease in emissions for this cattle sub-group.

Figure 2. Methane emissions from cattle in the United States, 2001.

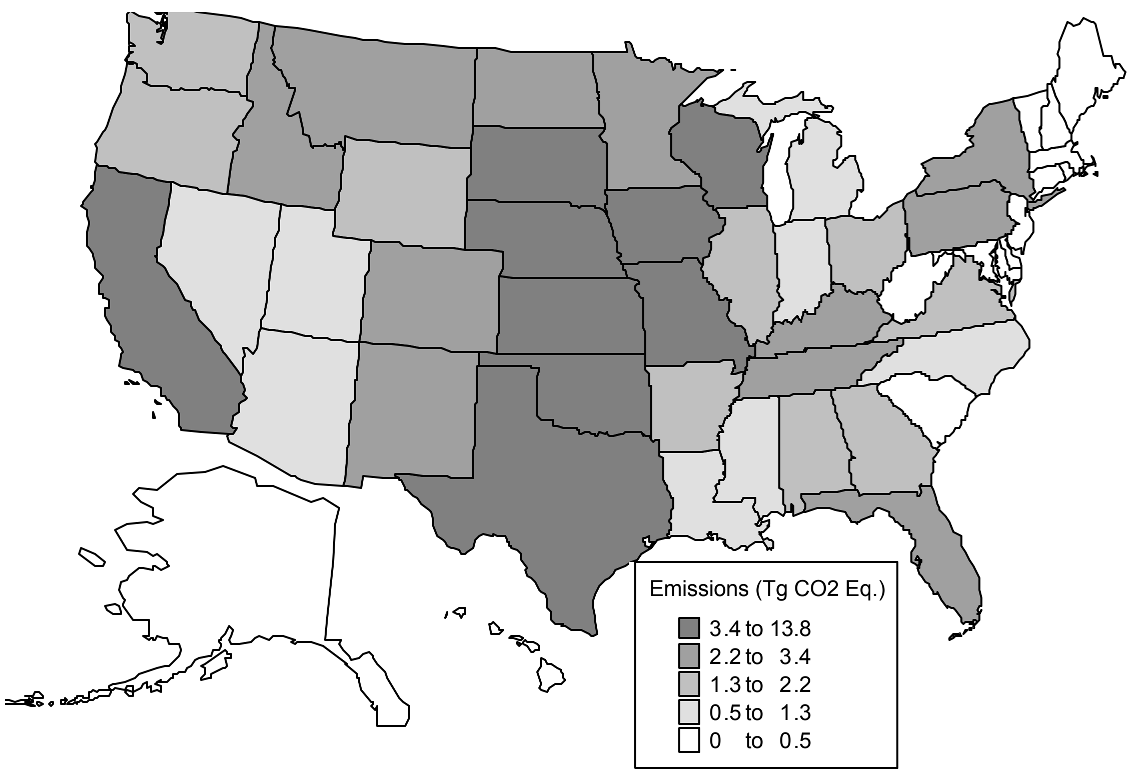
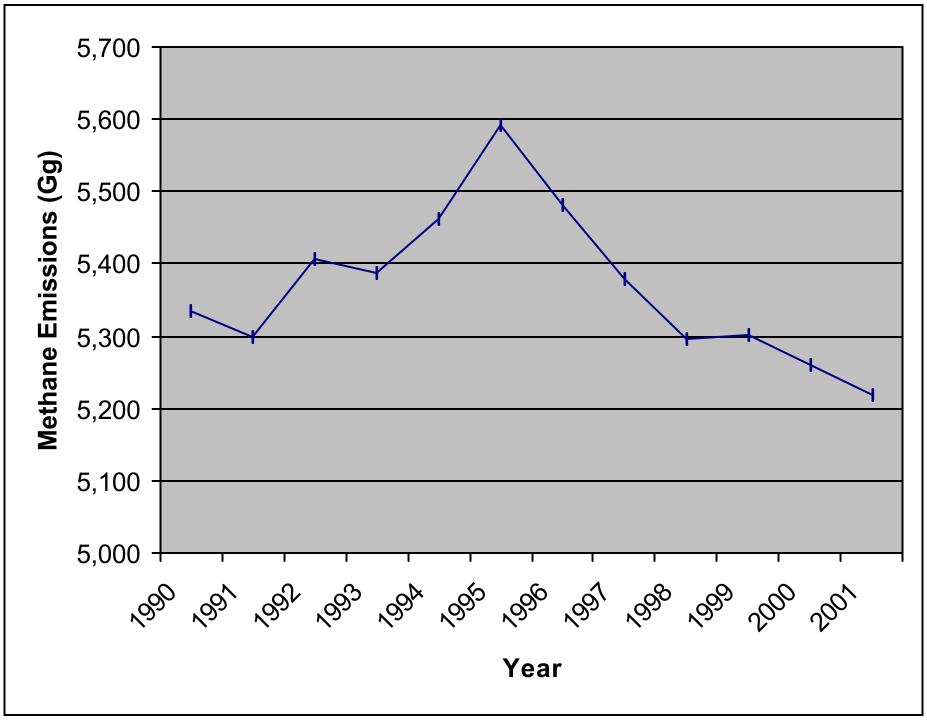


Figure 3. Methane emissions from cattle in the United States, 1999-2001 (Gg).



CONCLUSIONS

In previous EPA national inventories, national emission factors recommended by IPCC/UNEP/OECD/IEA (1997) were used with static information relevant to broader classifications of the cattle industry to estimate total enteric fermentation methane emissions. Over the last couple of years, EPA has used the CEFM to estimate these emissions, which has allowed for a more process-based approach that relies on the cattle energy requirements and feed inputs. This has produced a more spatially and temporally accurate inventory of cattle emissions, by modeling the cattle sub-species by specific stages of growth and regional diet characteristics.

Overall, the net effect of these methodological changes resulted in an approximate increase in annual CH_4 emissions from enteric fermentation of 7.3 Tg CO_2 Eq. (5.9 percent) from 1990 through 1998 as compared to the previous methodology based on static information. Most importantly, the CEFM allows the user to model changes in the cattle production industry, which can have a significant effect on the enteric fermentation emissions. Such changes can include improved diets, increased animal growth rates and size, increased milk production rates, and animal management practices.

Another benefit of using the CEFM has been the use of model output data for solids excretion rates. The excretion rates are developed as a waste energy output from the model, and are utilized directly in the manure management section of the EPA's greenhouse gas inventory. In this manner, a consistency in energy accounting has been created by linking the energy input and utilization from the enteric model to the waste production potential that forms the basis of manure management emissions modeling.

While the CEFM has improved enteric fermentation estimates substantially, uncertainties still remain regarding certain aspects of the model. For example, the values for Y_m and DE reflect the diet characterizations that are assumed for each cattle group, within each region of the country. While these values attempt to reflect the general diet characteristics within each region, there is uncertainty associated with local variations in feed and in the way cattle feed intake is managed. Local management practices may also affect the ultimate energy requirements of the cattle in different phases of growth, which may not be entirely reflected in the energy coefficients that are represented in the base IPCC Tier 2 equations. Future improvements to the model will focus on better representation of these local variations.

There are on-going direct measurement analyses being conducted in different parts of the world. These analyses rely on the capture and quantification of methane emissions directly from the cattle in field situations. It is anticipated that the results of these analyses will help to validate the emissions output of the model and its ability to model different animal and feeding characteristics.

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KEYWORDS

Emission Inventories
Enteric Fermentation
Cattle
Methane Emissions