Resources for the Future:

Examine Agricultural Land Use Practices and Their Effects on Carbon Storage and Flux in the United States

by

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Executive Summary

The terrestrial ecosystem has provided a net carbon sink, equal to 20% of total greenhouse gas (GHG) emission from industrial activities in the past three decades, yet many land use activities, mainly agriculture, can drastically change natural land carbon flux. Our research team worked with Resources for the Future (RFF) to find GHG emission data and evaluate potential approaches to delineate the explicit and accurate carbon flux from different agricultural practices, so that agricultural GHG emissions can be introduced into the Carbon and Land Use Model (CALM) that helps with evaluating the effects of policy decisions on land use and relevant carbon flux changes.

To ascertain carbon flux from different agricultural land use, our team first conducted a review of peer-reviewed literature along with a detailed examination of *the 2006 IPCC Guidelines for National Greenhouse Gas Inventories* and *EPA GHG Emission inventory report 2021*. The IPCC Guidelines provide recommendations for how countries determine which categories to be included in national greenhouse gas inventories and the methods that can be used to estimate those emissions. The IPCC Guidelines classifies GHG inventory calculation methods into three tiers (Tier 1, 2 or 3). The Tier 1 method applies IPCC default emissions factors which do not vary by region. The Tier 2 method employs country-specific emission factors. The Tier 3 method incorporates more details regarding the technology and equipment involved in determine site-specific emissions factors. In the EPA GHG emission inventory report, the US EPA adopted a mix methodology of all three tiers in estimating emissions from agricultural activities.

For RFF, animal-associated emissions from manure management and enteric fermentation can be easily duplicated with sufficient open access data from USDA and the sample emission factor generation excel model provided by the EPA. However, EPA emission calculation method form the inventory report may not be directly used for the needs of the Carbon and Land Use Model (CALM) model considering its mixed nature and varied spatial level of calculation. For manure management and enteric fermentation, RFF can potentially estimate emissions factors at the county-level so that the result can best reflect the effects of policies designed by different levels of governance. However, for emissions associated with agricultural soil management, deriving county-level emissions factors that can be used in the CALM model is not readily

feasible. Emissions factors in this agricultural sector are derived from a research-backed statistical model with a high level of sophistication that relies on machine learning to conduct simulation. Adapting this model to the county-level is not a trivial exercise.

Based on the research process of our team and the complex nature of this problem, we make the following recommendations to RFF for future research into GHG emission from agricultural land:

1. Identify the types of land use practices and specific agricultural policies that RFF wants to examine. Conduct further background studies and scientific literature research to validate the effect of such practices or policies in positively or negatively influencing agricultural emissions, and use findings from scientific research on the underlying physical and chemical processes that affect how fertilizer application leads to N2O emissions under different conditions.;
2. Research and construct a more sophisticated statistical approach based on scientific knowledge from the literature in comparison with simple emission factor calculation, to model N2O correctly:
3. Test the sensitivity of the statistical model by engaging in uncertainty analysis like Monte Carlo simulation to determine how sensitive the emission factor is to change in the effect of different weather and practice variables;
4. Complete an NDA on access to the individual NRI plot data and collect essential information on a desired spatial scale (national level, state level, or county level), and then input such data into the constructed model for test run;
5. Compare the modeling results from different modeling methods with existing methods such as DayCent and FASOM, and choose a major method for extensive application in evaluating the impact of different policies effects and lane use practices.

Introduction

Anthropogenic greenhouse gas (GHG) emissions are the main causes of climate change and human activities are responsible for the increasing GHG concentration in the atmosphere. According to the Intergovernmental Panel on Climate Change (IPCC), it was estimated that human activities have caused around 1.0 °C increase in global mean surface temperature above pre-industrial level, and the IPCC also predicts that global mean surface temperature is likely to increase by 1.5 °C between 2030 and 2052 if no intervention is implemented (IPCC, 2018). To avoid the catastrophic outcomes caused by climate change, parties to the United Nations Framework Convention on Climate Change (UNFCCC) adopted the Paris Agreement in 2015. The goal of this international treaty is to limit global warming to well below 2 degrees Celsius, preferably below 1.5 degrees Celsius, above pre-industrial levels. However, based on IPCC sixth Assessment Report (AR6), it would be almost impossible to limit warming to 1.5 degrees Celsius, and 2 degrees limitation can only be achieved by strong mitigation actions at all scales (IPCC, 2019b). To reach these goals, it is essential to first understand the dynamics of GHGs cycles, the influxes and outfluxes of GHGs, and then decide on how social and economic transformations can be designed and implemented.

The primary sources of GHG emissions from human activities include transportation, electricity, industry, commercial, residential, agriculture, land use and forestry (EPA, 2019), among which land use, forestry and agriculture are unique since they capture and emit GHGs simultaneously. Plants can absorb carbon dioxide (CO2) from the atmosphere and convert CO2 into organic matter through photosynthesis (UN, n.d.-a), becoming carbon sinks. Soils can also store some of the carbon from plants if they are properly managed (Fargione et al., 2018, Lal, 2004). The process of capturing CO2 and storing it in soils, plants and organic matter is called biological carbon sequestration. The soils serve as carbon sinks (UN, n.d.-a, Swift, 2001, Lal, 2004). The significant potential role carbon sinks play to reduce net GHGs emission has long been recognized by the Kyoto Protocol, an earlier international treaty aimed to curb GHG emissions, which incorporates carbon sequestration to the calculation of carbon emissions (Richards and Stokes, 2004).

GHGs Emissions and Land Use

The important roles that land plays in the global cycle of GHGs, including both emitting and sequestering GHGs, have been extensively studied. As indicated in Table 1, the terrestrial ecosystem is believed to be a net carbon sink. The majority of carbon sequestration occurs in forests (Pan et al., 2011), where carbon can be sequestrated in tree biomass. It is estimated that carbon constitutes over 50% of dry tree biomass (Malhi et al., 2002), which can be parts of living and nonliving plant tissues. The carbon is sequestrated in biomass via photosynthesis: the trees capture CO2 through stomata, and with sun and water, CO2 is converted into glucose, a simple sugar. As the trees grow and produce more glucose, more carbon is stored in plant tissues (Sedjo and Sohngen, 2012). Therefore, with tree growth in the forest, the forest can sequester and store more carbon in the plant tissue. Overall, it is believed that forest stores around 47% of total global carbon (Malhi et al., 2002).

From a land use perspective, table 1 indicated that a wide variety of human activities can lead to net GHG emissions through deforestation and several agriculture activities, including soil nutrient management, urea fertilization, etc. It is estimated that the global net GHG emission from the land use sector is positive and annual GHG emission from agriculture production were estimated at 5.0–5.8 Gt CO2eq/yr in 2000 - 2010, and annual GHG flux from land use and land use change was estimated at 4.3–5.5 Gt CO2eq/yr in 2000 – 2010 (Smith et al., 2014). As for the US, agriculture activities accounted for 10 percent of total GHG emissions in 2019. Although these emissions have been largely offset by net carbon sequestration in forests (EPA, 2019), reducing agriculture-related GHG emissions while continuing to have net forest carbon sequestration is one way to reduce overall US emissions of GHGs.

Notably, land use practices, especially agriculture, have drastically changed the natural flux of GHGs in terrestrial ecosystems (Smith et al., 2014), accounting for 33% of total emissions in past 150 years (Houghton, 1999), 20% in the 1980s and 1990s, and 12.5% over 2000 to 2009 (Friedlingstein et al., 2006). It should also be noted that non-CO2 GHGs emissions such as methane (CH4) and nitrous oxide (N2O) from land-use sectors are substantial, mainly through decomposition of plant biomass and organic matter in soil and by combustion (UN, n.d.-a). The primary sources of anthropogenic non-CO2 GHGs emissions include enteric fermentation, manure deposited on pasture, synthetic fertilizers, rice cultivation, manure management, crop residues, biomass burning, and manure applied to soils (Smith et al., 2014).

Sources and sinks	**1990-1999**	**2000-2007**
Sources (Carbon emissions)		
Fossil fuel and cement	6.5 ± 0.4	7.6 ± 0.4
Land-use change	**1.5 ± 0.7**	**1.1 ± 0.7**
Total sources	8.0 ± 0.8	8.7 ± 0.8
Sinks (Carbon uptake)		
Atmosphere	3.2 ± 0.1	4.1 ± 0.1
Ocean	2.2 ± 0.4	2.3 ± 0.4
Terrestrial (Established Forest)	**2.5 ± 0.4**	**2.3 ± 0.5**
Total sinks	7.9 ± 0.6	8.7 ± 0.7

Table 1. *Global carbon budget for 1990-1999 and 2000-2007 (peta grams/year)* Source: Pan et al. (2011)

The UNFCCC encourages mitigation of climate change through sustainable management of forest and other terrestrial ecosystems (UN, n.d.-a). However, the explicit relationships between different types of land use/land use change and the related carbon flux are not sufficiently characterized, mainly because various factors, including climate variability and time changes, can lead to a wide variation of results in analysis (Houghton et al., 2012), as well as incomplete understanding of the biological sequestration process in the agriculture sector (Tubiello et al., 2021). This problem can also lead to inefficiency in land-use related climate policy design and implementation. Thus, the first step to design and implement an efficient and effective land use related policy to mitigate GHG emissions is to establish more accurate carbon inflow and outflow database, especially for agricultural emissions sources.

Resources for the Future and the CALM Model

Resources for the Future (RFF) is an American non-profit organization that conducts research into environmental, energy and natural resources issues mainly through social sciences methods. RFF is now developing a model that can evaluate the effectiveness and efficiency of policies on carbon sequestration in the nation's land and forest vegetation. This Carbon and Land Use Model (CALM) is an important tool for RFF to examine the nation's policies that can affect the land use change and the related sequestration of carbon or the size of terrestrial carbon sink.

There are many other models that address the carbon sink dynamics related to land use of the U.S. For example, the FASOM-GHG model focuses on detailed estimates of carbon emission from agricultural activities and the DAYCENT agricultural-process model can simulate fluxes of C and N among the atmosphere, vegetation, and soil daily. These models explicitly provide information on how land-use activities can alter the dynamic carbon cycles but cannot be used to directly predict how policy decisions and market changes will affect the carbon sequestration process. The CALM model is quite unique in a sense that it has two components: the first part is a model that can predict how land use will change in response to market change and policy decisions, and the second part is a model to predict related land-use carbon sequestration change according to the land's carbon dynamics. By combining these two features together, this model can directly address how land use change dynamics will affect the size of terrestrial carbon sinks. RFF thinks it is of great significance to simultaneously take both market demands for land and carbon sequestration dynamics into account for evaluating the policy decision. By incorporating carbon dynamics into land use climate policy analysis, RFF and other organizations that utilize this tool can better answer important policy decision questions regarding land and soil management, land use choices, and agricultural activities.

Project Objectives

This master project team works with RFF to find GHG emission data and evaluate potential approaches to delineate the explicit and accurate carbon flux from different agricultural practices, so that agricultural GHG emissions can be introduced into the CALM model. Our research is based on literature review to develop research methodology and conduct relevant emission data collection and analyses on the link between different agricultural activities and carbon flux, and examination of uncertainty of emission potential because of time- and spatial-variability. However, due to the unavailability of data sources and the complexity of emission modeling, the team did not conduct in-depth real-world data analysis for those emissions and their variability, but instead provided research synthesis and future research suggestions based on the project findings. The research questions focus on:

- What are sources of data available on the carbon flux of diverse types of land management practices in the agriculture sector, and how can we distinguish the effect of different agricultural practices based on these data available?
- How can environmental factors, such as climate conditions and geographic locations, affect carbon outcomes of agricultural practices? How do anthropogenic factors, such as types of crops, different agricultural techniques, and other human activities, alter carbon flux of agricultural land use?
- If there are not sufficient data sources, how can the knowledge gaps be filled to help promote sustainable land management practices?

Materials and methods

Methodology

The main components of this master project include the following:

1. Conduct a literature review to ascertain carbon flux from different agricultural land use changes.
2. Identify, collect, and assess existing practices of agricultural data emission assessment, searching for best practices.
3. Identify and assess data knowledge gaps in existing methods of emission estimation and carbon fluxes modeling.

Literature review

- Through extensive literature review on the general background for GHG emissions sources in the agriculture sector, and associated carbon flux, the team members gained familiarity with the project topic and the ability to conduct more in-depth analysis of existing methods for assessing agricultural GHG emissions.
- Explore the process of carbon flux among diverse types of agricultural practices and the impact of, e.g., climate conditions and geographical locations, and anthropogenic factors, e.g., agricultural technics and types of crops, on the agricultural emission.

The team members used the following types of literature to find GHG emission background information:

1. Scientific journal articles that illustrate the general GHG cycles in agricultural sector.
2. Scientific journal articles that reveal approaches and models on GHG emission estimate.
3. Reports published by government agencies and non-governmental organizations on GHG emissions accounting in agricultural sector. Including EPA, IPCC, United Nations, etc.
4. Reports published by government agencies and non-governmental organizations on GHG emission inventory.

Data Collection and Research Synthesis

- Conduct initial assessment of the possible sources of data on carbon emissions in the literature review to find out where the emission numbers in these sources come from, and whether they can meet the need of this project's objectives: IF YES, the team will reach out to authors of the identified data source and start databasing based on the best source of data identifiable; IF NO, the team will continue reviewing sources of information until identify something that can be used for the project. The team will also identify and list potential challenges when collecting necessary data.
- With proper understanding of the project topic, the team reviewed and evaluated two key sources of relevant information: (1) the 2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories, and (2) the EPA Inventory of U.S. Greenhouse Gas Emission and Sinks 1990 -2021. From these sources, the team compiled written summary of the methods for agricultural emission calculation and conducted a comparative study.

2006 IPCC Guidelines for National Greenhouse Gas Inventories and the 2019 Refinement

According to the Paris Agreement, all parties are required to submit a national inventory report of anthropogenic emissions by sources and removals by GHG sinks. To this end, the *2006 IPCC Guidelines for National Greenhouse Gas Inventories* provides a technically sound methodological basis for countries to prepare national GHG inventories (IPCC, 2006) and the 2019 Refinement to the 2006 IPCC Guidelines (IPCC, 2019a).

The IPCC Guidelines recommend how countries determine which categories to be included and the methods to be used and classifies GHG inventory calculation methods into three tiers (Tier 1, 2 or 3), based on the additional information required and the complexity of analysis. The Tier 1 method is to apply IPCC default (simplest) emission factors and other parameters that are listed in the IPCC Guidelines and shall be feasible for all countries. The Tier 2 method is to employ emission factors that are country-specific, which gives more accuracy for GHG inventories calculations. The tier 3 method incorporates more details regarding the technology and equipment involved.

EPA Inventory of U.S. Greenhouse Gas Emission and Sinks 2021

The *Inventory of U.S. Greenhouse Gas Emissions and Sinks* (inventory) is an annual report that the US EPA developed and published every year since 1990s. The inventory contains detailed calculation of climate change related GHG emission from all anthropocentric activities that either generate the emission or remove the emission from the Atmosphere (EPA). The report will be submitted to the United Nation every year as part of the UNFCCC reporting commitment. As a UNFCCC Annex 1 party, the US is responsible for submitting a comprehensive annual report that contains "*annual GHG inventory covering emissions and removals of direct GHGs (carbon dioxide (CO2), methane (CH4), nitrous oxide (N2O), perfluorocarbons (PFCs), hydrofluorocarbons (HFCs), Sulphur hexafluoride (SF6) and nitrogen trifluoride (NF3)) from five sectors (energy; industrial processes and product use; agriculture; land use, land-use change and forestry (LULUCF); and waste), and for all years from the base year (or period) to two years before the inventory is due*" (UN, n.d.-b).

Chapter 5: Agriculture

For the purpose of this project, the team focused on the analysis of *Chapter 5: Agriculture* of the complete report and the corresponding Annexes of the chapter. The agricultural emission consists of three out of the seven types of the GHG listed by the UNFCCC: carbon dioxide (CO2), methane (CH4), and nitrous oxide (N2O).

According to Table 2, in 2019, the US agriculture sector was responsible for emissions of 628.6 MMT CO2 Eq., accounting for 9.6 percent of total U.S. greenhouse gas emissions (EPA, 2020a). N2O ranked as the number one GHG emission from agricultural activities. Agricultural soil management through activities such as fertilizer application and other agricultural practices that increased nitrogen availability in the soil accounting for 75.4% of the US N2O emission and 94.57% of agricultural N2O emission, served as the largest source of N2O emission. Manure management and field burning made up the rest of the N2O emission with a comparatively much less emission release.

Among all agricultural CH4 emissions from anthropogenic activities, enteric fermentation accounts for 27% and manure management 9% (EPA). Along with rice cultivation and field burning, CH4 is listed at the second largest GHG emission from agricultural sources.

CO2 emission from the agriculture sector came from Urea fertilization and liming, with a total annual emission of 7.7 MMT equivalent of CO2, it only accounts for 1.22% of the total annual agricultural emission, and served as a much less significant source of emission within the national CO2 emission (EPA).

Table 2

Type of Emission	Activities	CO2 Equivalent (MMT)	Percentage in category	Percentage
CO2	Total	7.7		1.22%
	Urea Fertilization	5.3	68.83%	0.84%
	Liming	2.4	31.17%	0.38%
CH4	Total	256.5		40.80%
	Enteric Fermentation	178.6	69.63%	28.41%
	Manure Management	62.4	24.33%	9.93%
	Rice Cultivation	15.1	5.89%	2.40%
	Field Burning of Agricultural Residues	0.4	0.16%	0.06%
N2O	Total	364.4		57.97%
	Agricultural Soil Management	344.6	94.57%	54.82%
	Manure Management	19.6	5.38%	3.12%
	Field Burning of Agricultural Residues	0.2	0.05%	0.03%
Total		628.6	100.00%	100.00%

Table 2: US Agricultural GHG Emission 2019

Emissions estimates in inventory are developed based on the emission factors and specific emission factor development method according to the 2019 IPCC Refinement to 2006 IPCC Guidelines for National Greenhouse Gas Inventories. Due to limitation of data availability and calculation method complexity, the annual GHG emission for different agricultural activities, however, were calculated using a mixture of the IPCC three tier methodologies. With the data input from U.S. Department of Agriculture's (USDA) database for the current year, e.g., National Resources Inventory (NRI) sample data and the USDA National Agriculture Statistical Service (NASS) Quick Stats database (EPA, 2020a), the inventory report was able to utilize simulate essential information such as US cattle population, their weight distribution, and diet to calculate animal-related emissions, as well as influences on crop related emissions such as geographical difference of the agricultural land fertilizer application. Depending on the availability of required data, EPA would choose the most appropriate method based on the Tier-1,2, 3 methods based on the 2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories for each agricultural activity involved. Such distinction indicated the feasibility for public and other institutions, such as RFF, to come up with their own GHG calculation fulfilling different research or publication purposes. Each year's inventory would look back to previous year's calculation to adjust and revise the results based on newly published data and changes in the calculation method adopted(EPA, 2020a). The detailed summary of the methods and emission results of each agricultural activity presented in the 2021 inventory report may be found in Appendix 1.

Chapter 6: Land Use, Land-use Change and Forestry

This chapter of the EPA GHG report focused on Land Use, Land-Use Change, and Forestry (LULUCF), covering major source of emission resulted from the conversion process among the listed five categories of lands: Forest land, Cropland, Grassland, Wetlands, and Settlements (EPA, 2020b).

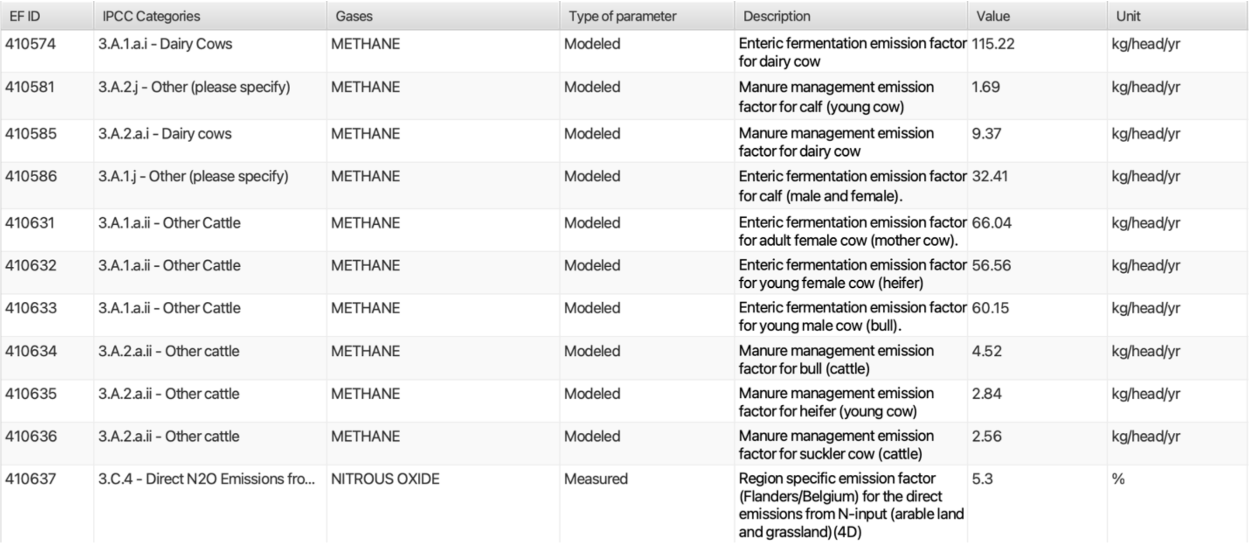
Additional CO2, CH4 and N2O emission can be found from the agriculture-related land-use and land-use conversion activities, such as cultivation of cropland, grassland fires, aquaculture, and conversion of forest land to cropland, which are presented in this Chapter (EPA, 2020b). However, for the purpose of this project to focus on agriculture sector and agricultural land management strategies’ impact of the correlated carbon emission, the team did not go in depth within this chapter.

Results

The IPCC Emission Factors

As discussed above, the IPCC three-tier method is one of the most basic methodologies for GHG calculation and reporting. The default IPCC emission factors can be found in the IPCC emission factor database.

Figure 1. Screenshot of IPCC emission factor database



EF ID	IPCC Categories	Gases	Type of parameter	Description	Value	Unit
410574	3.A.1.a.i - Dairy Cows	METHANE	Modeled	Enteric fermentation emission factor for dairy cow	115.22	kg/head/yr
410581	3.A.2.j - Other (please specify)	METHANE	Modeled	Manure management emission factor for calf (young cow)	1.69	kg/head/yr
410585	3.A.2.a.i - Dairy cows	METHANE	Modeled	Manure management emission factor for dairy cow	9.37	kg/head/yr
410586	3.A.1.j - Other (please specify)	METHANE	Modeled	Enteric fermentation emission factor for calf (male and female).	32.41	kg/head/yr
410631	3.A.1.a.ii - Other Cattle	METHANE	Modeled	Enteric fermentation emission factor for adult female cow (mother cow).	66.04	kg/head/yr
410632	3.A.1.a.ii - Other Cattle	METHANE	Modeled	Enteric fermentation emission factor for young female cow (heifer)	56.56	kg/head/yr
410633	3.A.1.a.ii - Other Cattle	METHANE	Modeled	Enteric fermentation emission factor for young male cow (bull).	60.15	kg/head/yr
410634	3.A.2.a.ii - Other cattle	METHANE	Modeled	Manure management emission factor for bull (cattle)	4.52	kg/head/yr
410635	3.A.2.a.ii - Other cattle	METHANE	Modeled	Manure management emission factor for heifer (young cow)	2.84	kg/head/yr
410636	3.A.2.a.ii - Other cattle	METHANE	Modeled	Manure management emission factor for suckler cow (cattle)	2.56	kg/head/yr
410637	3.C.4 - Direct N2O Emissions fro...	NITROUS OXIDE	Measured	Region specific emission factor (Flanders/Belgium) for the direct emissions from N-input (arable land and grassland) (4D)	5.3	%

The Tier 1 method is to apply IPCC default factors for GHG calculation and reporting, but these numbers can sometimes be very wrong because of the various geographic, climate and even timing factors (Hergoualc'h et al., 2021, Reay et al., 2012, Chen and Dietrich Brauch, 2021). For example, rainfall can influence soil moisture, which is an important regulator of the soil N2O cycles. The uncertainty associated with the default factors can thus result in inaccurate estimate of GHG emissions. However, Tier 1 method is feasible to all countries because this is the simplest method for GHG reporting and provides a reporting method for all countries to comply with the requirement to submit national inventory report on GHG emissions.

The Tier 2 method is to generate country-specific emissions factors, which can improve the accuracy of GHG calculation. However, US is such a big country with wide geographic, climate and timing variability. What RFF needs is spatially explicit data, and to have the best performance, the CALM model requires county-level emission data. The Tier 3 method is to incorporate more factors that can impact GHG cycles, which can better meet the requirement of RFF. However, the IPCC Tier 3 method also requires a large amount of data, which is beyond the scope of our research. Some potential steps to generate required emission factors include utilizing artificial intelligence or machine learning models to compute all relevant data to obtain accurate emission factors. It is generally recommended that a higher-tier method should be applied to obtain more accurate results.

EPA Inventory Report

The EPA GHG Inventory report assessed the US agricultural emission based on the Tier-1,2,3 Calculation method as recommended by the IPCC 2006 report. For all three types of GHG emission and seven types of agricultural activities involved, we can summarize them into two different categories: Animal-related Emission and Land Practice Emission.

USDA data

The United States Department of Agriculture National Agricultural Statistical Survey is a federal statistical organization that manages the most comprehensive agricultural crop plantation and livestock data. NASS manages and implements the data through monthly and annual surveys distributed towards farmers, ranchers, livestock feeders, slaughterhouse managers, grain elevator operators and other agribusinesses participants at individual, county, and state level (USDA, n.d.).The NASS publishes monthly and annual agriculture data report and compiled the Quick Stats Database for open online access towards the general public. The Quick Stats Database allows public access to customize data collection by criteria such as types of commodities, geographical location, or specific time period (USDA).

The National Resources Inventory (NRI) conducts field sampling among 49 states with the United States (excluding Alaska) to produce scientific data regarding land use, land use changes, agricultural practices, and natural resource situations among non-federal lands for every 5 years between 1982 and 1997, and annually from 2000 to 2017. It provides confidential information on the status, condition, and trends of land, soil, water, and related resources for the sampled land segments (USDA).

The EPA GHG Inventory report utilized the USDA NSAA data and the NRI data as important tools when developing country-specific emission factors and complement the DayCent

Model operation. Example usages of the aforementioned databases includes: Annual cattle population data with calf birth rates, end-of-year population statistics, detailed feedlot placement information, and slaughter weight data for methane emission from cattle's enteric fermentation, 2019 national-level Sheep, poultry, and swine population data for calculate methane emission from manure management, Rice cultivation areas data for rice cultivation CO2 emission etc (EPA, 2020a).

Animal-related Emission

As summarized in Appendix 1, Enteric Fermentation and Manure Management emission were both calculated using IPCC Tier-2 method with complimentary Tier-1 emission on minor sources of emission within these categories of emission. Both Enteric Fermentation and Manure Management are animal-related agricultural activities with close association to domestic animal industry. The two agricultural activities also represent more than 93.96% of all CH4 emission from all agricultural GHG emissions according to Table 1.

Take GHG emission from cattle's Enteric Fermentation as an example, EPA uses the USDA NASS data as an input. Both population characteristic data and diet data are collected on a geographical basis through the NASS: Population data includes important information regarding the age and gender distribution of cattle such as the pregnancy rate, calf birth rate, calf population, and calf age distribution, and death rate of cattle and diet data includes grass, hey, grain, or a certain mixture of different diet in a specific geographical region.

EPA inputs such data into an internally develop Excel model named Cattle Enteric Fermentation Model (CEFM). The excel would automatically calculate the input data through pre-determined scientific equations and statistical distribution method and come up with state-specific emission factors for cattle's GHG emission on an annual basis.

Land Practice Emission

According to Table 1, Agricultural Soil Management takes 94.57% of all the N2O emission from agricultural activities and is equivalent to more than half of the total agricultural GHG emission. Soil management includes different practices and techniques that are closely relevant with cropping and agricultural land use strategies.

For Soil Management, the EPA uses a more complicated method when calculating the emission. NRI data points are collected daily with regards to specific values such as the daily temperature maximum and minimum, daily precipitation, specific soil type, land cover type, and daily land practices such as tillage or apply fertilizers. With all the daily data collected, the DayCent model was then used as a machine learning tool to simulate the natural C and N flux resulted from such agricultural activities under the influence of the surrounding environment. Upon the completion of model simulation, which may take up to multiple months, the model would provide the calculation results for the annual emission. Although such method were conducted through the usage of statistical models on a very high level of sophistication, it can still be classified as an IPCC Tier-3 method. However, for the purpose of clarification within this report, we would be referring to such method as the statistical modeling method.

	Type of GHG		
Agricultural Activities	CO2	CH4	N2O
Enteric Fermentation: Cattle		2	
Enteric Fermentation: Buffalo		2	
Enteric Fermentation: Other Domestic Animals		1	
Manure Management: Cattle		1+2	1+2
Manure Management: Other Domestic Animals		1+2	1+2
Rice Cultivation		1+3	
Agricultural Soil Management			1+3
Liming	2		
Urea Fertilization	1		
Field Burning of Agricultural Residuals	2	2	

Table 3: IPCC Tier method usage for agricultural activities based on EPA Inventory of U.S. Greenhouse Gas Emission and Sinks 2021

As Table 2 indicated above, Enteric Fermentation (CH4), Manure Management (CH4 & N2O), Liming (CO2), Urea fertilization (CO2), and Field burning of agricultural residuals (CH4, N2O, CO, and NOx) used the Tier 1 and 2 emission factor method; Agricultural soil management (N2O) and Rice cultivation (CH4) were calculated through statistical modeling via the DayCent model to validate the stock exchange of carbon involved in the activities (EPA, 2020a). As *Table 2* indicated, a combination method of Tier 2 or 3 with Tier 1 is often adopted for areas where the more complicated method does not have enough data to support the corresponding specific emission factor development or modeling simulation (EPA, 2020a).

Discussion

Evaluation of the Emission Factors method and Statistical Modeling method

As presented in the previous sections of the report, the US EPA adopted a mixed methodology for agricultural activities' emission calculations. For animal associated emissions from Manure Management and Enteric Fermentation, a Tier-2 method was used for all cattle related emissions on a state level, and a Tier-1 method was used for all other domestic animals related emissions on a broader geographical level: New England Region, Mid-Atlantic Region, Southern Region, Mid-West Region, South-West Region, Rocky Mountains, and Pacific Coastal Region. For RFF, such practice may be easily duplicated with sufficient open access data from USDA and the sample emission factor generation excel model provided by the EPA. However, the mixture of Tier-1 and Tier-2 method and the varied spatial level of calculation would need to be further revised and determined to best cater to the needs of the CALM model. RFF can potentially go into county level of sophistication when conducting such emission calculations so that the result can best reflect the effects of policies designed by different levels of governance.

However, for Agricultural Soil Management, what we've encountered is a research-backed statistical model with a high level of sophistication and relies on machine learning to conduct simulation. Due to the nature of agricultural activities and the effect of daily weather and surrounding environment on the nature carbon and nitrogen cycle, the statistical models are used to simulate the past environmental interactions throughout the agricultural process and provide the best estimation of emission flux with sufficient input of daily values. Such models are effective in assessing emission based on historical data but are not reliable when used for estimating future emission and corresponding changes in land use practices due to the unpredictable nature of weather and its significant effects on the natural carbon flux. Due to the complex nature of GHG emission from soil, a simplified approach of IPCC Tier-1 cannot be applied for research purposes due to its lack of accuracy to reflect the actual context within the United States. A simple emission factor multiplication using IPCC provided emission factors would be generating very "wrong" numbers that disproportionately reflect the actual emission from the soil and such practice is not in accordance with the initial purpose of the IPCC guidelines.

How important are agriculture emissions in practice for policy?

As discussed above, the agriculture sector accounted for 10% of total US GHG emissions (EPA) and the great potential to mitigate climate change in agriculture practices should be addressed. To achieve the goal, policy design and governance can regulate the techniques utilized in agriculture production, land use changes, etc., which has great potential to reduce GHG emissions. For example, several farming techniques can result in different levels of GHG emissions, among which tillage in farming emerges as a key parameter affecting crop yields, net returns and climate outcome (Claassen et al., 2018). Our team decided to conduct a comprehensive literature review on no-till agriculture as an example of agriculture technique affecting carbon outcomes. We found that compared to conventional tillage, no-tillage agriculture was found to have many advantages for both farmers and the society. No-tillage can improve the soil health, and increased organic matter can lead to higher productivity, and from environmental perspectives, no-tillage can alter the N2O process in soils compared to conventional farming techniques (Toliver, 2010).

Although no-tillage can be a viable option to improve soil health and environmental performance of agriculture, the effects of no-tillage vary across different types of crops. The research was generally conducted on small-scale practices land, which can lead to misleading results when applied to larger scale. In addition, short-term agriculture studies can produce findings that are inconsistent with long-term ones, for instance, Cusser et al. (2020) found that when studying the effects of no-tillage farming, analyses conducted shorter than 15 years indicate statically significant but misleading results. However, to address the uncertainty associated with crop types, timing, and other factors is difficult, since it requires a large amount of data to calibrate the study model. This knowledge gap can impede the efficiency of policy design in agriculture to reduce GHG emissions. Therefore, we would suggest that investing in more scientific analyses now to promote better designed agriculture-carbon policies in a few years might have more benefit than just launching a lot of policies now with uncertain effects.

Proposed Next Steps

Because exploring and duplicating such models involves an extensive amount of work and content knowledge that is essentially beyond the scope and purpose of this master project, our team decided to not proceed with any of the duplicating attempts, but to analysis the modeling approach and provide suggestions on the next steps that RFF may take from this project forward:

1. Identify types of land use practices and specific agricultural policies. Conduct further background studies and scientific literature research to validate the effect of such practice or policy in positively or negatively influencing agricultural emission, and use findings from scientific research on the underlying physical and chemical processes that affect how fertilizer application leads to N2O emissions under different conditions.;
2. Research and construct a more sophisticated statistical approach based on scientific knowledge from the literature in comparison with simple emission factor calculation, to model N2O correctly:
    a. Throughout this project, our team was able to examine the EPA approach along with some major modeling approaches within the US, such as DayCent and FASOM. It would be helpful to look beyond the scope of the US and look further into European and Asian practices where detailed emission estimation is also conducted;
    b. Conduct relevant literature and validate the model developed;
3. Test the sensitivity of the statistical model by engaging in uncertainty analysis like Monte Carlo simulation to determine how sensitive the emission factor is to change in the effect of different weather and practice variables;
4. Complete an NDA on access to the individual NRI plot data and collect essential information on a desired spatial scale (national level, state level, or county level), and then input such data into the constructed model for test run;
5. Compare the modeling results from different modeling methods with existing methods such as DayCent and FASOM, and choose a major method for extensive application in evaluating the impact of different policies effects and lane use practices.

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Appendix

Appendix 1: EPA Inventory of U.S. Greenhouse Gas Emission and Sinks 2021: Chapter 5 Agriculture Summary

[Note: this appendix is a summary and compiled note based on Chapter 5 of the EPA GHG inventory report and only serves the purpose for readers to gain familiarity with details of the calculation method utilized by the EPA.]

1.1 Main GHG involved:

1. methane (CH4) and nitrous oxide (N2O) emissions:
    a. enteric fermentation in domestic livestock, livestock manure management, rice cultivation, agricultural soil management, and field burning of agricultural residues
2. carbon dioxide (CO2) emissions:
    a. liming and urea fertilization
3. Note: Additional CO2, CH4 and N2O fluxes from agriculture-related land-use and land-use conversion activities, such as cultivation of cropland, grassland fires, aquaculture, and conversion of forest land to cropland, are presented in the Land Use, Land-Use Change, and Forestry (LULUCF) chapter.

1.2 General Emission Pattern

In 2019, the agriculture sector was responsible for emissions of 628.6 MMT CO2 Eq. or 9.6 percent of total U.S. greenhouse gas emissions:

- Enteric fermentation: **27.1%** and manure management **9.5%** of total CH4 emissions from all anthropogenic activities.
- agricultural soil management through activities such as fertilizer application and other agricultural practices that increased nitrogen availability in the soil was the largest source of U.S. N2O emissions, accounting for **75.4%**
- Between 1990 and 2019, CO2 and CH4 emissions from agricultural activities increased by **9.9%** and **17.5%,** respectively, while N2O emissions from agricultural activities fluctuated from year to year, but increased by **10.4%** overall.
- Recalculation EVERY YEAR to incorporate new method and update historical data as the USDA updates their relevant dataset.

1.3 Enteric Fermentation (CRF Source Category 3A)

GHG emission type: Methane

- normal digestive processes in animals
- Ruminant animals (e.g., cattle, buffalo, sheep, goats, and camels) are the major emitters of CH4

- Animal’s feed quality and feed intake also affect CH4 emissions.

Emission Pattern: Total livestock CH4 emissions in 2019: 178.6 MMT CO2 Eq. (7,142 kt).

- Beef cattle: 72% in 2019
- Dairy cattle: 24% in 2019
- Remaining emissions were from: horses, sheep, swine, goats, American bison, mules and asses
- 1990 – 2019: increase by 8.4%
- Largely subject to beef cattle population change

Method:

- Cattle – IPCC Tier 2
    - “Significant scientific literature exists that provides the necessary data to estimate cattle emissions using the IPCC Tier 2 approach” (Agriculture 5-6)
    - Cattle Enteric Fermentation Model (CEFM) – Annex 3.10
        - 1990 – 2017
            - Key variables: Calf birth rates, end-of-year population statistics, detailed feedlot placement information, and slaughter weight data
            - Annual cattle population data were obtained from the U.S. Department of Agriculture’s (USDA) National Agricultural Statistics Service (NASS) QuickStats database (USDA 2016)
            - Diet characteristic estimation by region: dairy, grazing beef, and feedlot beef cattle
        - 2018 and 2019
            - Simplified approach
                - First, 2018 and 2019 populations for each of the CEFM cattle subpopulations were estimated,
                - These populations were multiplied by the corresponding implied emission factors developed from the CEFM for the 1990 to 2017 Inventory year
            - Dairy cow, beef cow, and bull populations: USDA QuickStats data
            - Other cattle categories: extrapolation based on 2017 data
- Other domestic animal – IPCC Tier 1
    - Average emission factors (Tier 1 default IPCC emission factors) representative of entire populations of each animal type
    - Population: mix of USDA data and extrapolation

Limitations/Questions

- Difficulty in estimating Diet characteristic for beef cattle grazing patterns – major uncertainty
- Does breed of cattle affect methane emission in this category?

1.4 Manure Management (CRF Source Category 3B) *MAPS

GHG emission type:

- Methane
    - Total CH4 emission in 2019: 62.4 MMT CO2 Eq
    - Emission ranking by animal type: Dairy cattle, swine, poultry, beef cattle, horses, sheep, goats, American bison, mules and assess
    - Produced from anaerobic decomposition of manure (usually in liquid system). If manure is processed aerobically, more CO2 and little or no CH4 is produced (mostly in dry system or handled as solid).
- Nitrous Oxide (N_2O)
    - Total N2O emission in 2019: 19.6 MMT CO2 Eq
        - Emission ranking by animal type: Beef cattle, dairy cattle, swine, poultry, sheep, horses, goats, mules and asses, American bison
    - Direct emission: Produced from nitrification and denitrification
        - Dry systems have greater aerobic conditions that promote N2O emission
    - Indirect emission: Loss of N from the system through volatilization
        - Majority of N loss are NH3
        - No quantified estimates available for use, so losses of NH3 are only based on NH3 loss factors

Emission Pattern:

- Methane
    - The total CH4 emission from manure management was 37.1 MMT CO2 Eq in 1990, increasing by 68% from 1990 to 2019. Largely because of swine and dairy cow manure, increasing by 49% and 117% respectively.
- Nitrous Oxide (N_2O)
    - Total N2O emission in 1990, 14.0 MMT CO2 Eq.
    - Overall shifts to liquid systems decreased emission per unit of nitrogen excreted

Method:

- The methodologies presented in IPCC (2006) form the basis of the CH4 and N2O emission estimates for each animal type, including Tier 1, Tier 2, and use of the CEFM. This combination of Tier 1 and Tier 2 methods was applied to all livestock animal types.
    - Methane
        - Calculation for 1990 through 2018
            - Key inputs: Animal population data (by animal type and state); Typical animal mass (TAM) data (by animal type); Portion of manure managed in each WMS, by state and animal type; Volatile solids (VS) production rate (by animal type and state or United

States); Methane producing potential (B0) of the volatile solids (by animal type); Methane conversion factors (MCF), the extent to which the CH4 producing potential is realized for each type of WMS (by state and manure management system).

        - Methane emissions were estimated by first determining activity data, including animal population, TAM, WMS usage, and waste characteristics.
        - The estimated amount of VS managed in each WMS was used to estimate the CH4 emissions (kg CH4 per year) from each WMS. The amount of VS (kg per year) was multiplied by the B0 (m3 CH4 per kg VS), the MCF for that WMS (percent), and the density of CH4 (kg CH4 per m3 CH4). The CH4 emissions for each WMS, state, and animal type were summed to determine the total U.S. CH4 emissions
    - For 2019, a simplified approach was used to calculate the methane emission.
        - EPA obtained 2019 national-level animal population data: Sheep, poultry, and swine data were downloaded from USDA-NASS Quickstats (USDA 2020). Cattle populations were obtained from the CEFM (see NIR Section 5.1 and Annex 3.10). Data for goats, horses, bison, mules, and asses were extrapolated based on the 2009 through 2018 population values to reflect recent trends in animal populations.
        - EPA multiplied the national populations by the animal-specific 2018 implied emission factors8 for CH4 to calculate national-level 2019 CH4 emissions estimates by animal type. These methods were utilized in order to maintain time-series consistency as referenced in Volume 1, Chapter 5 of the 2006 IPCC Guidelines.
- Nitrous Oxide (N_2O)
    - Calculation for 1990 through 2018
        - Key inputs: Animal population data (by animal type and state); TAM data (by animal type); Portion of manure managed in each WMS (by state and animal type); Total Kjeldahl N excretion rate (Nex); Direct N2O emission factor (EFWMS); Indirect N2O emission factor for volatilization (EFvolatilization); Indirect N2O emission factor for runoff and leaching (EFrunoff/leach); Fraction of N loss from volatilization of NH3 and NOx (Fracgas); and Fraction of N loss from runoff and leaching (Fracrunoff/leach).
        - Nitrous oxide emissions were estimated by first determining activity data, including animal population, TAM, WMS usage, and waste characteristics. All N2O emission factors (indirect and direct) were taken from IPCC (2006)

- Direct N2O emissions were calculated by multiplying the amount of N excreted (kg per year) in each WMS by the N2O direct emission factor for that WMS (EFWMS, in kg N2O-N per kg N) and the conversion factor of N2O-N to N2O. These emissions were summed over state, animal, and WMS to determine the total direct N2O emissions (kg of N2O per year).
- Indirect N2O emissions from volatilization (kg N2O per year) were then calculated by multiplying the amount of N excreted (kg per year) in each WMS by the fraction of N lost through volatilization (Fracgas) divided by 100, the emission factor for volatilization (EFvolatilization, in kg N2O per kg N), and the conversion factor of N2O-N to N2O. Indirect N2O emissions from runoff and leaching (kg N2O per year) were then calculated by multiplying the amount of N excreted (kg per year) in each WMS by the fraction of N lost through runoff and leaching (Fracrunoff/leach) divided by 100, and the emission factor for runoff and leaching (EFrunoff/leach, in kg N2O per kg N), and the conversion factor of N2O-N to N2O. The indirect N2O emissions from volatilization and runoff and leaching were summed to determine the total indirect N2O emissions.
- For 2019, a simplified approach was used to calculate N2O emission, similar to methane 2019 methods.

Limitations/Questions

- Do biogas practices have a positive influence in reducing emission from manure? If so, has there been any large scale biogas practices in the US, and have these practices, and possible emission reduction, been counted into this category and how have them been qunatified?
- How CEFM models are used differently in manure management and enteric fermentation? Are there any more resources on CEFM modesl?

1.5 Rice Cultivation (CRF Source Category 3C) *MAPS

GHG emission type: Methane

- Flooded area creating anaerobic conditions leading to CH4 production
    - Most important factor: water management
    - Other factors: rice residue straw management, application of organic amendments, cultivar selection
    - Environmental factors: soil temperature and soil type
- Thirteen states: Arkansas, California, Florida, Illinois, Kentucky, Louisiana, Minnesota, Mississippi, Missouri, New York, South Carolina, Tennessee and Texas

    - Soil types, rice varieties, and cultivation practices vary
    - Most apply Fertilizers, not harvest crop residuals
    - ratoon rice crop in Southeastern of the states – higher CH4

Emission Pattern

- Not a major source of CH4
- Most emissions occur in Arkansas, California, Louisiana, Mississippi, Missouri and Texas.
- 2019, CH4 emissions: 15.1 MMT CO2 Eq. (602 kt).
- Annual emissions fluctuate between 1990 and 2019
    - largely due to differences in the amount of rice harvested areas over time, which has been decreasing over the past two decades.
- Emissions in 2019 are 6% lower than emissions in 1990.

Method

- A combination of Tier 1 and 3 methods
    - Tier 3: a DayCent process-based model (Cheng et al. 2013)
        - simulates hydrological conditions and thermal regimes, organic matter decomposition, root exudation, rice plant growth and its influence on oxidation of CH4, as well as CH4 transport through the plant and via ebullition
        - captures the influence of organic amendments and rice straw management on methanogenesis in the flooded soils, and ratooning of rice crops with a second harvest during the growing season.
    - Tier 1: the Agriculture and Land Use National Greenhouse Gas Inventory (ALU) software (Ogle et al. 2016), used for
        - Non-rice rotation crops: vegetable crops
        - Land use conversions
        - Organic soils
    - Rice cultivation areas: USDA National Resources Inventory (NRI) survey (USDA-NRCS 2018)
- Surrogate method for 2016 to 2019
    - a linear regression model with autoregressive moving-average (ARMA) errors was used to estimate the relationship between the surrogate data and emissions data from 1990 through 2015

1.6 Agricultural Soil Management (CRF Source Category 3D)

GHG emission type:

- Nitrous oxide

- naturally produced in soils through the microbial processes of nitrification and denitrification that is driven by the availability of mineral nitrogen (N) (Firestone and Davidson 1989)
    - decomposition of soil organic matter and plant litter
    - asymbiotic fixation of N from the atmosphere
    - Direct emission:
        - synthetic N fertilization; application of managed livestock manure; application of other organic materials such as biosolids (i.e., treated sewage sludge); deposition of manure on soils by domesticated animals in pastures, range, and paddocks (PRP) (i.e., unmanaged manure); retention of crop residues (N-fixing legumes and non-legume crops and forages); and drainage of organic soils
    - Indirect emission:
        - (1) volatilization and subsequent atmospheric deposition of applied/mineralized N, and
        - (2) surface runoff and leaching of applied/mineralized N into groundwater and surface water

Emission Pattern:

- Estimated emissions in 2019 are 344.6 MMT CO2 Eq. (1,156 kt)
- Annual N2O emissions from agricultural soils: 9% greater from 1990 to 2019
- Emissions fluctuated between 1990 and 2019 due to
    - interannual variability largely associated with weather patterns, synthetic fertilizer use, and crop production
- Direct Emission:
    - cropland 68%
        - **high** in the Midwestern Corn Belt Region (Illinois, Iowa, Indiana, Ohio, southern Minnesota and Wisconsin, and eastern Nebraska), where a large portion of the land is used for growing highly fertilized corn and N-fixing soybean
        - Kansas, South Dakota and North Dakota have **relatively high emissions** from large areas of crop production that are found in the Great Plains region。
        - Emissions are also **high** in the Lower Mississippi River Basin from Missouri to Louisiana, and highly productive irrigated areas, such as Platte River, which flows from Colorado through Nebraska, Snake River Valley in Idaho and the Central Valley in California.
        - Low in many parts of the eastern United States because only a small portion of land is cultivated, and in many western states where rainfall and access to irrigation water are limited.
    - Grassland 32%
        - more evenly distributed throughout the United States

        - total emissions tend be highest in the **<u>Great Plains and western United States</u>**:
            - where a large proportion of the land is dominated by grasslands with cattle and sheep grazing.
        - Relatively large emissions from **<u>local areas in the Eastern United States</u>**, particularly Kentucky and Tennessee, in addition to areas in Missouri and Iowa,
            - where there can be higher rates of Pasture/Range/Paddock (PRP) manure N additions on a relatively small amount of pasture. These areas have greater stocking rates of livestock per unit of area, compared to other regions of the United States
- Indirect Emission:
    - Croplands 79%
        - Volatilization: a similar pattern as the direct N2O emissions with higher emissions in the Midwestern Corn Belt, Lower Mississippi River Basin and Great Plains.
        - surface runoff and leaching of applied/mineralized N
            - highest in the Midwestern Corn Belt
            - relatively high emissions associated with N management in the Lower Mississippi River Basin, Piedmont region of the Southeastern United States and the Mid-Atlantic states.
            - areas of high emissions occur in portions of the Great Plains that have relatively large areas of irrigated croplands with high leaching rates of applied/mineralized N.
    - Grasslands 21%
        - Volatilization: is higher in the Southeastern United States, along with portions of the Mid-Atlantic and southern Iowa.
        - surface runoff and leaching of applied/mineralized N
            - higher in the eastern United States and coastal Northwest region.
            - Greater precipitation and higher levels of leaching and runoff compared to arid to semi-arid regions in the Western United States.

Method:

Direct N2O Emission from Soil Management

- Tier 1 + Tier 3 + splicing method where data are not yet available
    - A Tier 3 process-based model (DayCent):
        - estimate direct emissions from a variety of crops that are grown on mineral (i.e., non-organic) soils, as well as the direct emissions from non-federal grasslands except for applications of biosolids (i.e., treated sewage sludge) (Del Grosso et al. 2010).
        - address direct N2O emissions and soil C stock changes from mineral cropland soils in a single analysis.

    - Based on crop and land use histories recorded in the USDA National Resources Inventory (NRI) (USDA-NRCS 2018a).
      - statistically-based sample of all non-federal land and includes 349,464 points
    - production of alfalfa hay, barley, corn, cotton, grass hay, grass-clover hay, oats, peanuts, potatoes, rice, sorghum, soybeans, sugar beets, sunflowers, tobacco and wheat,
    - not applied to estimate N2O emissions from other crops or rotations with other crops, or land use changes
  - Tier 1:
    - multiplying activity data on different N inputs (i.e., synthetic fertilizer, manure, N fixation, etc.) by the appropriate default IPCC emission factors to estimate N2O emissions on an input-by-input basis.
    - 175,527 locations in the NRI survey across the time series, which are designated as cropland or grassland
    - Used for areas not included by Tier 3
      - (1) direct emissions from N inputs for crops on mineral soils that are not simulated by DayCent; (2) direct emissions from PRP N additions on federal grasslands; (3) direct emissions for land application of biosolids (i.e., treated sewage sludge) to soils; and (4) direct emissions from drained organic soils in croplands and grasslands
  - Splicing:
    - 2016 to 2019 at the national scale because new NRI activity data are not available for those year
    - linear regression models with autoregressive moving average (ARMA) errors (Brockwell and Davis 2016) for Tier 3
      - with surrogate data: corn and soybean yields from USDA-NASS statistics,21 and weather data from the PRISM Climate Group (PRISM 2018).
    - linear-time series model for Tier 1
      - without surrogate data

Indirect N2O Emissions from Soil Management

- Indirect N2O Emissions from Atmospheric Deposition of Volatilized N
  - Tier 1 + Tier 3: area same as direct emission
- Indirect N2O Emissions from Leaching/Runoff
  - Tier 3: N transported from lands
  - Tier 1: N transported from all other areas
  - 2016 to 2019: splicing – recalculation using Tier 1 and 3 when future data report is available

1.7 Liming (CRF Source Category 3G)

- GHG emission type:
  - Carbon dioxide (CO2)
    - Total CO2 emission in 2019: 2.4 MMT CO2 Eq
    - CO2 emissions occur when crushed limestone and dolomite applied to soils react with hydrogen ions.
- Emission Pattern:
  - Carbon dioxide (CO2)
    - Total CO2 emission between 1990 and 2019 ranges from 2.2 to 6.0 MMT CO2 Eq, driven by the amount of limestone and dolomite applied to soils over the time period
- Method:
  - Carbon dioxide emissions from application of limestone and dolomite to soils were estimated using the Tier 2 methodology consistent with IPCC (2016)
    - The annual amount of limestone and dolomite applied to soils, are multiplied by CO2 emission factors (West and McBride 2005)
    - The country-specific emission factors (0.059 metric ton C/metric ton limestone, 0.064 metric ton C/metric ton dolomite) are lower than IPCC default factors, largely due to that most lime application in U.S occurs Mississippi River basin or in areas that have similar soil and rainfall regimes, under which a significant amount of dissolved lime is transported into ground water and eventually deposited in ocean basins. (West and McBride 2005)
    - Specified limestone and dolomite amounts can be directly used in the emission calculation. For unspecified and estimated categories, the amount of used limestone and dolomite amounts are estimated by multiplying the percentage of specific limestone and dolomite production that is applied to soils, by the total number of unspecified production.
    - Data on fractions of total crushed stone production that were limestone and dolomite were unavailable for 1990, 1992 and 2019. 1991 and 1993 data were used to estimate 1990 and 1992 data. 2018 data was used to estimate 2019 data.

- Limitations:
  - Uncertainty regarding the amount of limestone and dolomite applied to soils
    - Estimated at ±15 percent with normal densities (Tepordei 2003; Willett 2013b)
  - Uncertainty regarding the emission factors
    - The fraction of lime dissolved by nitric acid versus the fraction that reacts with carbon acid.

        - The portion of bicarbonate that leaches through the soil and is transported to the ocean.
    - Uncertainty associated with leaching and transport was not addressed, but assumed to be relatively small.

1.8 Urea Fertilization (CRF Source Category 3H)

- GHG emission type:
    - Carbon dioxide (CO2)
        - Total CO2 emission in 2019: 5.3 MMT CO2 Eq
        - CO2 emissions occur through the use of urea as a fertilizer, releasing CO2 that was fixed during the production stage.
- Emission Pattern:
    - Carbon dioxide (CO2)
        - CO2 emissions have increased by 121 percent from 1990 to 2019 due to an increasing amount of urea that is applied to soils.
        - The variation in emissions are associated with the difference in the amounts of fertilizers applied each year
- Total CO2 emission between 1990 and 2019 ranges from 2.2 to 6.0 MMT CO2 Eq, driven by the
- Method:
    - IPCC Tier 1 methodology
        - C in the urea is released after application to soils and converted to CO2.
        - The annual amounts of urea applied to croplands were derived from the state-level fertilizer sales data, which were multiplied by the default IPCC emission factor (0.20 metric ton of C per metric ton of urea).
        - Fertilizer sale data were unavailable for 2016 to 2019. Urea application data from 2016 to 2019 were estimated using a linear, least squares trend of consumption of the data from the previous five years at the state scale.
- Limitations/Questions
    - The CO2 emission from urea fertilization is associated with the sales data instead of being summarized by land-use category. Are there currently any approaches to estimate the carbon emission from urea fertilization by different land-use type?

1.9 Field Burning of Agricultural Residues (CRF Source Category 3F)

- GHG emission type:
  Field burning of crop residues is not considered a net source of CO2 emissions because the C released to the atmosphere as CO2 during burning is reabsorbed during the next growing season by the crop. However, crop residue burning is a net source of CH4, N2O, CO, and NOx, which are released during combustion.

  - Methane
    - Total emission in 2019: 0.4 MMT CO2 Eq
  - N_2O
    - Total emission in 2019: 0.2 MMT CO2 Eq
  - CO
    - Total emission in 2019: 337 kt
  - NOx
    - Total emission in 2019: 14 kt
- Emission Pattern:
  Annual emissions of CH4 and N2O have increased from 1990 to 2019 by 14 percent and 16 percent, respectively. The increase in emissions over time is partly due to higher yielding crop varieties with larger amounts of residue production and fuel loads, but also linked with an increase in the area burned for some of the crop types.
- Method:
  - Key variables to determine C and N released from burning
    - Annual production of crop, by state, kt crop production
    - Amount of residue produced per unit of crop production, kt residue/kt crop production
    - Amount of dry matter per unit of residue biomass for a crop, kt residue dry matter/ kt residue biomass
    - Fraction of C or N per unit of dry matter for a crop, kt C or N /kt residue dry matter
    - Proportion of residue biomass consumed, unitless; determined by Total area of crop burned, by state, ha and Total area of crop harvested, by state, ha
    - Proportion of C or N released with respect to the total amount of C or N available in the burned material, respectively, unitless
  - A country-specific Tier 2 method is used to estimate the GHG emission from field burning of agricultural residues from 1990 to 2014
    - Based on the method developed by the IPCC/UNEP/OECD/IEA (1997) rather than the method provided in the 2006 IPCC guidelines:
      - the equations from both guidelines rely on the same underlying variables (though the formats differ)
      - the IPCC (2006) equation was developed to be broadly applicable to all types of biomass burning, and, thus, is not specific to agricultural residues
      - the IPCC (2006) method provides emission factors based on the dry matter content rather emission rates related to the amount of C and N in the residues
      - the IPCC (2006) default factors are provided only for four crops (corn, rice, sugarcane, and wheat) while this Inventory includes emissions from twenty-one crops.

    - To determine the area burned, a sample of states are included in the analysis with high, medium and low burning rates for agricultural residues, including Arkansas, California, Florida, Indiana, Iowa and Washington. The area burned is determined directly from the analysis for these states.
    - For other states within the conterminous United States, the area burned for the 1990 through 2014 portion of the time series is estimated from a logistical regression model that has been developed from the data collected from the remote sensing products for the six states. The logistical regression model is used to predict occurrence of fire events.
  - A data splicing method with a linear extrapolation is applied to complete the emissions time series from 2015 to 2019
    - linear extrapolation of the trend is applied to estimate the emissions in the last five years of the inventory.
    - a linear regression model with autoregressive moving-average (ARMA) errors is used to estimate the trend in emissions over time from 1990 through 2014, and the trend is used to approximate the CH4, N2O, CO and NOx for the last five years in the time series from 2015 to 2019 (Brockwell and Davis 2016).
- Limitations/Limitations:
  The crop production data and the area burned is estimated on state level, are there any sources of data that can provide county level data?
  How precise is the regression model to predict the area burned? Is it possible to use this model to predict the area burned on county-level?